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Article

MISO System with Intelligent Reflecting Surface-Assisted Cellular Networks

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Abstract: This paper proposes an architecture based on Intelligent Reflecting Surfaces (IRSs) to improve the performance of future cellular networks. Specifically, we investigate the use of IRSs in combination with statistical Channel State Information (CSI) to enhance the coverage of Base Stations (BSs) in Multiple-Input Single-Output (MISO) systems. Furthermore, we exploit IRSs to reduce the complexity of the proposed architecture, and therefore the total cost, by reducing the number of required antennas at the transmitters (i.e., BSs). At first, we consider a Rayleigh fading channel between the transmitter and the receiver, and we assume the existence of a Line of Sight (LoS) between the BS and the IRS, as well as between the IRS and the destination. In the second part, we investigate the case of a Single-User Multiple-Input Single-Output (SU-MISO) system, where we study the benefits of IRSs in terms of coverage of the BS; then, we formulate a problem for a Multi-User Multiple-Input Single-Output (MU-MISO) system where the IRS is considered as a block of resources that can assist a certain number of users. The problem of managing the IRS resources is formulated as a nonlinear integer problem. We solve the optimization problem using an exhaustive search and propose two low-complexity heuristic algorithms. The performance of the system is evaluated with respect to a variable number of users, the position of the IRS, the required SNR, and the size of the cell. Simulation results corroborate the proposed approach and show that the introduction of the IRS in the network architecture enhances the overall performance of the network, extends the coverage area, enhances users' satisfaction, and improves the SNR value, while optimizing the required number of antennas at the BS.

Keywords: beyond 5G (B5G); Intelligent Reflecting Surfaces; cellular networks; resource allocation; MISO; SNR



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1. Introduction

To extend the coverage and increase the capacity of communication systems beyond 5G (B5G), several approaches have been proposed. Among the most prominent candidates are massive Multiple-Input Multiple-Output (MIMO) and millimeter-wave (mm-wave) communication [1]. Although the aforementioned technologies are capable of significantly enhancing the cellular network coverage, they generally result in increased energy consumption and hardware costs. This is primarily due to the need to deploy more active antennas and/or more expensive Radio Frequency (RF) chains operating at higher frequency bands. As such, deploying more active components in cellular networks might not be a scalable solution for sustainable growth in the future.

Intelligent Reflecting Surfaces (IRSs) have recently emerged as one of the most promising low-cost approaches to tackle the previously mentioned problem by smartly controlling a large number of passive reflecting elements, each of which can independently reflect the incident signal with an adjustable phase shift [2]. Since IRSs consist of passive elements

that do not need to actively transmit RF chains, they can be densely deployed with low energy consumption and low costs. Compared to the existing active relays, IRSs operate in full duplex without requiring additional power for signal amplification/regeneration besides the advanced processing for self-interference cancellation [2]. An IRS is a planar meta-surface connected to a smart controller, which is capable of inducing an independent phase shift and/or amplitude attenuation to the incident signal at each reflecting element in real time, and thus modifying the wireless channels between transmitters and receivers [3].

Researchers began to optimize the performance of the IRS by improving various performance metrics. They explored various optimization objectives to improve the performance of these surfaces. These objectives may include phase shift optimization, total transmit power optimization, sum rate maximization, or capacity enhancement. In [4,5], the authors jointly optimized the transmit beam at the Access Point (AP) with the phase shift beam at the IRS to minimize the total transmit power, while, in [6], they optimized, with the phase shift, the transmit power allocation for each user. Moreover, in [7], the authors had the same objective as before, but the practical constraint of a discrete phase shift was considered, where a mixed-integer non-linear program was developed.

Sum rate maximization is studied in [8], where the author focuses on an integrated sensing and IRS backscatter communication system that supports low-power communications for Internet of Things (IoT) devices. Moreover, in [9], the study focuses on the problem of maximizing the sum rate in an uplink cooperative Cognitive Radio Network (CRN) with wireless powered primary users and conventional energy sources for cognitive users. The authors provide theoretical proofs and conduct numerical simulations to compare the performance of Non-Orthogonal Multiple Access (NOMA) and Time Division Multiple Access (TDMA), revealing the conditions under which TDMA achieves equal or higher primary user sum rates compared to NOMA.

In [10–12], the authors focus on Cognitive Radio. First, in [10], the study investigates the impacts of sensing energy and data availability on the secondary throughput in Energy-Harvesting Cognitive Radio Networks (EH-CRNs), considering both heavy and general data arrival cases. Simulation results demonstrate that the sensing energy negatively affects the secondary throughput and optimal energy threshold, while data availability positively correlates with the secondary throughput but negatively correlates with the optimal energy threshold. Additionally, the study compares non-contiguous spectrum sensing (NCSS) and concurrent spectrum sensing (CSS) scenarios and provides guidelines for adjusting the energy threshold dynamically to maximize the secondary throughput in response to changes in sensing energy or data availability. Meanwhile, in [11], the researchers consider a CRN with an IRS, where they include the impact of deploying the IRS on spectrum sensing (SS) in CRNs. They consider two scenarios: one where the IRS enhances the secondary user's reception of the primary user's signal, and another where the IRS assists the primary receiver. Moreover, in [12], the authors address the long-term throughput maximization problem in a multi-channel backscatter-aided EH-CRN. They propose a hybrid active-passive communication scheme that dynamically selects channels and makes action decisions based on energy availability, achieving superior throughput compared to other schemes in multi-channel scenarios.

In addition to all the above optimization parameters, some researchers have studied the integration of the IRS with other technologies, such as mm-wave communications [13,14], Non-Orthogonal Multiple Access (NOMA) [15,16], physical layer security [17,18], and Simultaneous Wireless Information and Power Transfer (SWIPT) [19,20].

All the above studies to improve the system performance mainly focused on single signal reflection using one IRS, which may not be enough to improve the wireless link capacity in harsh conditions. In [21], the authors used multi-IRS-aided wireless networks, highlighting the challenges and opportunities associated with employing multiple IRSs to enhance the wireless link capacity. Their study emphasized the need for innovative design approaches and optimization methods to address the complexities of multi-IRS systems. Then, researchers began to pursue the optimal deployment of IRSs. In [22], the

authors compared conventional strategies of deploying IRSs near the BS or users, proposed a hybrid deployment strategy, discussed challenges and solutions, and provided numerical results for a performance comparison and practical insights. Channel State Information (CSI) plays a key role in research. In [23], the authors study an IRS-assisted Multi-User Multiple-Input Single-Output (MU-MISO) wireless system under an imperfect CSI, where the authors estimate the IRS-assisted channel vectors and exploit the prior knowledge of the large-scale fading statistics at the BS. Meanwhile, in [24], the authors focus on the design of robust beamforming for a Single-User MISO (SU-MISO) wireless system assisted by an IRS under an imperfect CSI. The goal is to minimize the average Mean Squared Error (MSE) for the user. The availability of CSI is essential to fully realize the potential of the IRS [2,24]. However, due to the passive architecture of the IRS, as well as its massive number of elements, acquiring CSI is also a difficult task. To overcome the drawbacks of the above channel estimation approaches, statistical CSI is used, such as in [25]. Statistical CSI is relatively less complex to obtain through long-term observation. Moreover, the statistical CSI changes slowly, since no frequent update is required.

Existing work on IRS-aided systems mainly focused on wireless communication with Single-Input Single-Output (SISO), MISO, or Multiple-Input Multiple-Output (MIMO) systems. In contrast to the existing studies, our work focuses on SU-MISO as well MU-MISO systems assisted by an IRS in cellular networks.

- We investigate the SNR of users in a cellular network assisted by an IRS system for different channel models, where the channels between the BS and the IRS or the IRS and the end-user may exhibit either Rician or Rayleigh fading.
- We explore various configurations among the network elements (BS, IRS, end-users), with the objective of optimizing the number of antennas at the BS under a specified SNR. This task is essential in the planning phase of cellular networks to reduce the complexity and cost of their infrastructure.
- We examine the case of a MU-MISO system, which utilizes the IRSs as blocks of resources. The problem of selecting the users to be assisted and resource blocks to be allocated to selected users is formulated as a non-linear integer problem. We solve the problem using an exhaustive search and we propose two heuristic algorithms.

The remainder of the paper is organized as follows. Section 2 presents the model formed by the BS and an end-user with and without an IRS. We also introduce the case of the MU-MISO system. The planning phase is presented in Section 3, the coverage maximization is described in Section 4, and the proposed algorithm is given in Section 5; simulation results are presented in Section 6. Finally, Section 7 concludes the paper.

Notation: Throughout this paper, \mathbb{C} is the set of complex numbers; $(\cdot)^T$, $(\cdot)^*$ represent the transpose and the conjugate, respectively. $|\cdot|$ and $\|\cdot\|$ denote the complex modulus and the vector Euclidean norm, while $E\{\cdot\}$ denotes the mathematical expectation.

2. System Model

We consider a three-node system, where the BS with M antennas communicates with a single antenna destination (user) assisted by an IRS, as illustrated in Figure 1b. The BS and the IRS have Uniform Linear Arrays (ULA). We assume that statistical CSI is available at the BS. We consider that the destination requires a predetermined SNR. Recall that the channel between the BS and the destination is always considered to be a Rayleigh one, which justifies the need for the assistance of the IRS.

Our analysis comprises three primary cases. Firstly, we examine a system that operates without the assistance of the IRS. Secondly, we introduce the IRS to our analysis with an SU-MISO system, which involves three primary sub-cases. Finally, we consider the case of the MU-MISO system with the assistance of the IRS.

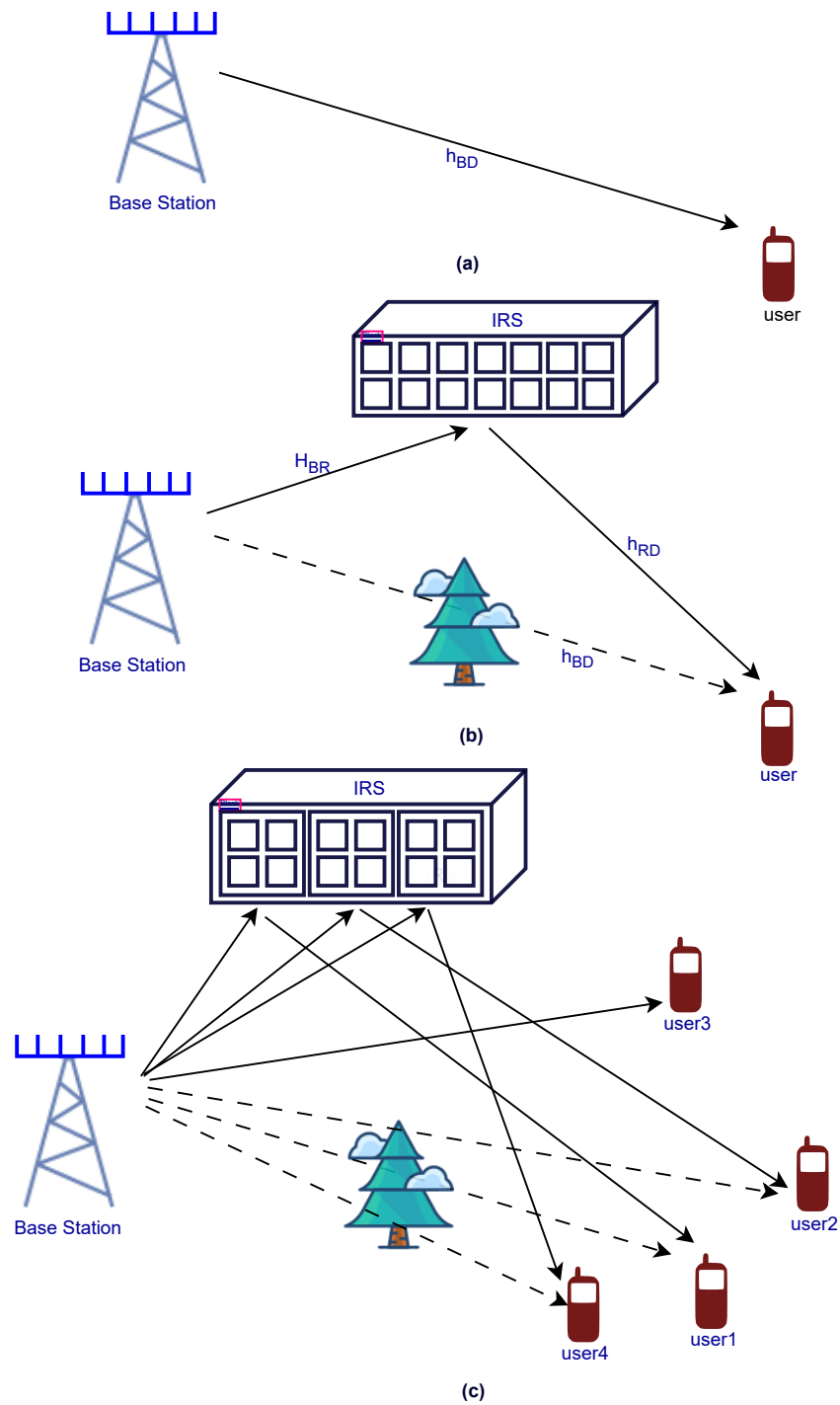


Figure 1. System model without (a) and with the assistance of IRS; single user (b), multi-user (c).

1. A system formed by the BS and only one user considered with a Rician channel. For this scenario, we estimate the number of antennas needed to achieve a predetermined SNR. This scenario is considered as a reference for some other considered scenarios.
2. In the second case, we consider a three-node system where the channel between the BS and the IRS and the channel between the IRS and the user can be Rician or Rayleigh, whereas the channel between the BS and the single user is always taken as Rayleigh. Then, we calculate the parameters needed to achieve the predetermined SNR.
3. At the end, a MU-MISO system is chosen, where the IRS, in this case, is divided into blocks of elements. The choice of users selected to be assisted by the IRS can be

formulated as a non-linear integer problem; then, we propose two low-complexity algorithms to solve this problem.

2.1. First: BS Destination without IRS

The received signal y from the BS at the destination can be expressed as

$$y = \sqrt{\frac{P}{d^{\alpha_{BD}}}} \mathbf{h}_{BD}^T \mathbf{s} x + n, \tag{1}$$

where P is the transmitted power, x is the Gaussian input signal that satisfies $E\{xx^*\} = 1$, and $\mathbf{s} \in \mathbb{C}^{M \times 1}$ is the transmit beamforming vector, where $\|\mathbf{s}\|^2 = 1$. $\mathbf{h}_{BD} \in \mathbb{C}^{M \times 1}$ represents the channel between the BS and the destination with path loss exponent α_{BD} . n is the Additive White Gaussian Noise (AWGN) with zero mean and N_0 variance. Moreover, d represents the distance between the BS and the destination.

We consider the case of Rician fading between the BS and the destination; the channel vector is expressed as

$$\mathbf{h}_{BD} = a_{BD} \bar{\mathbf{h}}_{BD} + b_{BD} \tilde{\mathbf{h}}_{BD}, \tag{2}$$

$a_{BD} = \sqrt{\frac{K_{BD}}{K_{BD} + 1}}$ and $b_{BD} = \sqrt{\frac{1}{1 + K_{BD}}}$, where K_{BD} is the Rician K factor. (The Rician K -factor measures how much stronger the direct signal is compared to the scattered signals in wireless communication. A high K -factor means that there is a strong direct signal and less scattering, while a low K -factor means a weaker direct signal and more scattering. When $K = 0$, there is no direct signal, and the Rician distribution becomes a Rayleigh distribution. In practice, the K -factor values are usually between 0 and 30 dB [26]). $\tilde{\mathbf{h}}_{BD}$ represents the non-LOS components, whose elements follow the zero mean complex Gaussian distribution with unit variance. Moreover, $\bar{\mathbf{h}}_{BD} = \mathbf{a}_M(\theta_{AoD,BD})$, where $\mathbf{a}_M(\theta) \triangleq [1, \exp^{j\theta}, \dots, \exp^{j(M-1)\theta}]^T$ represents the LOS component, which is given by the response of the ULA, and where $\theta_{(AoD,BD)}$ is the Angle of Departure (AoD) from the BS.

With CSI at the destination, the instantaneous channel capacity of the system can be expressed as [2]

$$C = \log_2 \left(1 + \gamma_0 |\mathbf{h}_{BD}^T \mathbf{s}|^2 \right), \tag{3}$$

where $\gamma_0 = \frac{P}{d^{\alpha_{BD}} N_0}$.

We consider the realistic scenario that the BS only has access to the statistical CSI; as such, instead of maximizing the instantaneous channel capacity, our objective is to maximize the ergodic capacity (the ergodic capacity represents the average rate at which information can be transmitted over a channel, assuming that the channel conditions are varying randomly over time [27]) by designing the beamforming vector \mathbf{s} .

For the optimal transmit beam, the ergodic capacity of the system is upper bounded by [2]

$$C_{up} = \log_2 \left(1 + \gamma_0 (a_{BD}^2 + b_{BD}^2 M) \right), \tag{4}$$

As we are concerned with the SNR, we have, in general, and without the assistance of the IRS,

$$\text{SNR}_{NIRS} = \gamma_0 (a_{BD}^2 + b_{BD}^2 M), \tag{5}$$

Therefore, the number of antennas needed at the BS to achieve the required SNR is given by

$$M = \frac{\frac{\text{SNR}}{\gamma_0} - a_{BD}^2}{b_{BD}^2}, \tag{6}$$

In the absence of the IRS, the relationship between the SNR and the number of antennas at the BS is linear.

2.2. Second: IRS-Supported Transmission

In all below sub-cases with the SU-MISO system, the received signal y from the BS can be expressed as [2]

$$y = \sqrt{P} \left(\frac{\mathbf{h}_{RD}^T \Theta \mathbf{H}_{BR}}{\sqrt{d_{BR}^{\alpha_{BR}} d_{RD}^{\alpha_{RD}}}} + \frac{\mathbf{h}_{BD}^T}{\sqrt{d_{BD}^{\alpha_{BD}}}} \right) \mathbf{s}x + n, \tag{7}$$

where $\Theta = \text{diag} \{ \theta \}$ represents the phase shift matrix, with $\theta = [\theta_1, \theta_2, \dots, \theta_N]^T \in \mathbb{C}^{N \times 1}$ and $|\theta_n| = 1, n = 1, \dots, N$. Moreover, $\mathbf{H}_{BR} \in \mathbb{C}^{N \times M}$ represents the channel between the BS and the IRS with a path loss exponent α_{BR} of the channel; $\mathbf{h}_{RD} \in \mathbb{C}^{N \times 1}$ represents the channel between the IRS and the destination with a path loss exponent α_{RD} of the channel. Further, d_{BR}, d_{RD} represent the distances between the nodes of our system.

In the scenario in which a Rayleigh fading channel exists between the BS and the destination, the use of an IRS becomes efficient. The channel vector is expressed as

$$\mathbf{h}_{BD} = a_{BD} \tilde{\mathbf{h}}_{BD}, \tag{8}$$

$a_{BD} = \sqrt{\frac{K_{BD}}{K_{BD} + 1}}$, where K_{BD} is the Rician K factor; $\tilde{\mathbf{h}}_{BD}$ represents the non-LOS components, whose elements follow the zero mean complex Gaussian distribution with unit variance.

To avoid repetition, we express the channels between the BS and the IRS and between the IRS and the destination as Rician fading channels. This encompasses both the special cases of Rayleigh fading and Rician fading, which are considered separately. Hence, the expression of the channels is

$$\mathbf{H}_{BR} = a_{BR} \tilde{\mathbf{H}}_{BR} + b_{BR} \tilde{\mathbf{H}}_{BR}, \tag{9}$$

and

$$\mathbf{h}_{RD} = a_{RD} \tilde{\mathbf{h}}_{RD} + b_{RD} \tilde{\mathbf{h}}_{RD}, \tag{10}$$

$a_{BR} = \sqrt{\frac{K_{BR}}{K_{BR} + 1}}$ and $b_{BR} = \sqrt{\frac{1}{K_{BR} + 1}}$, $a_{RD} = \sqrt{\frac{K_{RD}}{K_{RD} + 1}}$ and $b_{RD} = \sqrt{\frac{1}{K_{RD} + 1}}$, where $\tilde{\mathbf{H}}_{BR}$, and $\tilde{\mathbf{h}}_{RD}$ represent the non-LOS components, whose elements follow the zero mean complex Gaussian distribution with unit variance, and K_{BR} and K_{RD} are the Rician K factors. Furthermore, the LOS components represented by $\tilde{\mathbf{h}}_{RD}$ and $\tilde{\mathbf{H}}_{BR}$ can be expressed as

$$\tilde{\mathbf{h}}_{RD} = \mathbf{a}_N(\theta_{AoD,RD}), \tag{11}$$

and

$$\tilde{\mathbf{H}}_{BR} = \mathbf{a}_N(\theta_{AoA,BR}) \mathbf{a}_M^T(\theta_{AoD,BR}), \tag{12}$$

where $\mathbf{a}_N(\theta) \triangleq [1, \exp^{j\theta}, \dots, \exp^{j(N-1)\theta}]^T$, $\theta_{(AoA,BR)}$ represents the Angle of Arrival (AoA) at the IRS, and $\theta_{(AoD,RD)}$ and $\theta_{(AoD,BR)}$ represent the Angles of Departure from the IRS and the BS, respectively.

Moreover, with CSI at the destination, the instantaneous channel capacity of the system, with the assistance of the IRS, can be expressed as [2]

$$C = \log_2 \left(1 + \gamma \left| \left(\mathbf{h}_{RD}^T \Theta \mathbf{H}_{BR} + \vartheta \mathbf{h}_{BD}^T \right) \mathbf{s} \right|^2 \right), \tag{13}$$

where $\gamma = \frac{P}{d_{BR}^{\alpha_{BR}} d_{RD}^{\alpha_{RD}} N_0}$ and $\vartheta = \sqrt{\frac{d_{BR}^{\alpha_{BR}} d_{RD}^{\alpha_{RD}}}{d_{BD}^{\alpha_{BD}}}}$.

As such, instead of maximizing the instantaneous channel capacity, the objective is to maximize the ergodic capacity by the joint design of the phase shift beam Θ and the beamforming vector \mathbf{s} . Based on [2], the capacity of the system is upper bounded by

$$C_{up} = \log_2(1 + \gamma(a_{RD}^2 a_{BR}^2 MN^2 + b_{RD}^2 a_{BR}^2 MN + b_{BR}^2 N + \vartheta^2)), \tag{14}$$

Therefore, the SNR is given by the following equation:

$$\text{SNR} = \gamma \left(a_{RD}^2 a_{BR}^2 MN^2 + b_{RD}^2 a_{BR}^2 MN + b_{BR}^2 N + \vartheta^2 \right), \quad (15)$$

In the preceding, we evaluated the SNR in two primary scenarios: one with the aid of the IRS and the other without it. Next, we intend, in four different cases, to investigate the impact of varying the models of the channels, between the nodes of the system, on the SNR.

Case 1: BS–IRS and IRS–destination channels are Rayleigh

When \mathbf{H}_{BR} and \mathbf{h}_{RD} undergo Rayleigh fading, i.e., $K_{BR} = 0$ and $K_{RD} = 0$, the SNR becomes

$$\text{SNR} = \gamma \vartheta^2,$$

It can be inferred that the SNR is not impacted by variations in the number of antennas at the BS or the number of elements in the IRS. Instead, the distance between nodes and the transmitted power are the key determinants of the SNR.

Case 2: BS–IRS channel is Rayleigh, IRS–destination channel is Rician

In this case, the link between the IRS and the destination is subject to Rician fading, whereas the connection between the BS and the IRS experiences Rayleigh fading. In this case, K_{BR} is null. Therefore, the number of elements in the IRS can affect the SNR and this can be expressed as

$$\text{SNR} = \gamma \left(b_{BR}^2 N + \vartheta^2 \right), \quad (16)$$

Therefore, the SNR varies linearly with the variation in the number of elements in the IRS.

Case 3: BS–IRS channel is Rician but IRS–destination channel is Rayleigh

Here, we can infer that the Rician channel exists between the BS and the IRS, whereas the Rayleigh fading channel is present between the IRS and the destination. The SNR has the following expression [2]:

$$\text{SNR} = \gamma \left(b_{RD}^2 a_{BR}^2 MN + b_{BR}^2 N + \vartheta^2 \right), \quad (17)$$

From the equation, we can observe that the SNR is directly proportional to both N and M . As the number of elements in the IRS N increases, the SNR increases. Similarly, increasing the number of antennas at the BS M also contributes to an increase in the SNR.

Case 4: All channels are Rician except BS–destination, which is Rayleigh

The optimal scenario is presented here, in which the SNR exhibits a linear dependence on the number of antennas at the BS and a quadratic dependence on the number of elements in the IRS, as expressed by the equation

$$\text{SNR} = \gamma \left(a_{RD}^2 a_{BR}^2 MN^2 + b_{RD}^2 a_{BR}^2 MN + b_{BR}^2 N + \vartheta^2 \right), \quad (18)$$

2.3. Third: MU-MISO System-Supported Transmission

The received signal by user k can be expressed as

$$y_k = \sqrt{P_k} \left(\frac{\mathbf{h}_{RDk}^T \mathbf{\Theta} \mathbf{H}_{BRk}}{\sqrt{d^{\alpha_{BRk}}} d^{\alpha_{RDk}}} + \frac{\mathbf{h}_{BDk}^T}{\sqrt{d^{\alpha_{BDk}}}} \right) \mathbf{s}x_k + n_k, \quad (19)$$

where P_k and n_k are, respectively, the power transmitted and the noise at user k . In this case, we take the channel between the BS and the destination as Rayleigh, whereas other channels are taken as Rician. Each user needs to achieve a required SNR_k :

$$\text{SNR}_k = \gamma_k \left(a_{RDk}^2 a_{BRk}^2 M_k N_k^2 + b_{RDk}^2 a_{BRk}^2 M_k N_k + b_{BRk}^2 N_k + \vartheta_k^2 \right), \quad (20)$$

where $\gamma_k = \frac{P_k}{d^{\alpha_{BRk}} d^{\alpha_{RDk}} N_{0k}}$ and $\vartheta_k = \sqrt{\frac{d^{\alpha_{BRk}} d^{\alpha_{RDk}}}{d^{\alpha_{BDk}}}}$. M_k and N_k are, respectively, the number of antennas and the number of elements needed by user k to achieve the predetermined SNR_k .

Our focus in the above is on investigating the impact of channel models on the SNR for SU and MU systems, while, in the next section, we shift our attention to examining the effect of the number of elements of the IRS on achieving the desired SNR.

3. Planning Phase: SU-MISO System

When planning the installation of a new BS, the objective is to minimize the number of antennas required at the BS while still achieving a predetermined SNR. This contrasts with other papers that aim to maximize the SNR, as our approach is to conserve resources and obtain only what is necessary. We focus on achieving an SNR value that is either equal to or slightly higher than the required level, enabling the BS to cater to a larger number of users, with the assistance of the IRS.

Depending on Equation (18), the number of prerequisite antennas can be calculated as follows:

$$M = \frac{\frac{\text{SNR}}{\gamma} - b_{BR}^2 N - \vartheta^2}{a_{RD}^2 a_{BR}^2 N^2 + b_{RD}^2 a_{BR}^2 N'} \tag{21}$$

Our objective is to find the minimum number of antennas M needed at the BS and the number of assisted elements N in the IRS to attain the desired SNR. It is important to note that certain SNR values cannot be achieved with any combination of M and N . As per Equation (18), increasing the values of M and N enhances the SNR. However, there is a threshold that these numbers cannot exceed. It is worth mentioning that certain values of M and N depend on the specific application and the dimensions of the IRS. It is possible to have a large IRS area, but it may not always be suitable for the intended purpose.

To determine the maximum number of elements in the IRS for every required SNR, we can utilize the fact that the minimum value of M is equal to one. Then, we can assess whether the number of elements in the IRS is reasonable and whether we can implement this IRS with this number of elements or we need to increase the value of M . To accomplish this, we can plot N versus SNR for the minimum number of antennas at the BS. However, to provide information about the relationship between N and M for a given SNR, we compute this relation; first, in general,

$$N = \frac{-(b_{RD}^2 a_{SR}^2 M + b_{SR}^2) - \sqrt{(b_{RD}^2 a_{SR}^2 M + b_{SR}^2)^2 - 4a_{RD}^2 a_{SR}^2 (\vartheta^2 - \frac{\text{SNR}}{\gamma})}}{2a_{RD}^2 a_{SR}^2 M}, \tag{22}$$

It should be noted that when $M = 1$, the value of N reaches its maximum, denoted as N_{max} . It is important to note that each user requires a specific N_{max} value to achieve the desired SNR. Furthermore, utilizing Equation (22) enables us to calculate the maximum number of elements for various numbers of antennas at the BS, rather than only one.

In a cellular network, specifically during the planning phase, our objective is to decrease the number of antennas at the BS, and thus the cost, with the assistance of the IRS. To achieve this, we aim to place the IRS as close to the BS as possible. For every number of antennas used, we obtain a maximum number of elements in the IRS needed, which also depends on the user’s location within the cell.

Hereafter, we discuss the form and the size of the cell. We assume that the BS has the same transmit power, and that the IRS is being used to assist the user by allocating a certain number of elements at various positions within the cell.

At the beginning, we need to establish certain parameters used throughout the paper: Coverage, Percentage of coverage P_{cov} , and Percentage of assistance P_{ass} . In our context, we consider a user to be covered by the BS if their calculated SNR meets or exceeds the required value at their particular application.

To determine the P_{cov} , we make use of a simplified model in which the BS is considered to have a square shape with a side length of R_s . We divide the cell into smaller squares of

size r_s and the user can occupy only the center of each square. Through this method, we can calculate the total number of possible user positions within the cell, n_p :

$$n_p = \left(\frac{R_s}{r_s}\right)^2$$

By dividing the total number of positions where a user is served n_p^{ser} by the BS with the assistance of the IRS, acquiring the predetermined SNR, by the number of total positions in the cell n_p , we can determine the percentage of coverage Per_{cov} :

$$Per_{cov} = \frac{100 n_p^{ser}}{n_p}$$

Hence, our initial aim is to enhance the P_{cov} of the BS by using the IRS, which should be available to assist the user in every position. Therefore, for every predetermined SNR, in the planning phase, we have to reach the maximum defined Per_{cov} of the BS assisted by the IRS. This issue is limited by finding, at a certain position of the user, the optimal combination of two parameters M and N with a different priority of minimization and a predetermined SNR. Initially, we prioritize the minimization of the number of served antennas at the BS due to their higher costs; then, we wish to minimize the number of assisted elements at the IRS to assist more users.

Our purpose is to determine, at every position p_k in the cell, where $k = 1 \dots K$ and $K = n_p$, the combination of (M, N) required to achieve the desired SNR. In cellular networks, there are two main phases involved.

- Planning phase: This typically refers to the stage where a BS is being designed and configured to provide wireless coverage and capacity within a specific geographic area or cell. Therefore, in this phase, we must define the number of antennas that we wish to install at the BS.
- Operation phase: Once the BS is installed and it has some tasks involved, such as traffic management, ensuring a high-quality service for mobile users, etc., we use the IRS to assist some users to attain a required SNR, and this provides an easy, cost-efficient solution to improve the performance of the existing cellular network.

Note that the planning phase offers certain advantages over the operation phase. Depending on the situation, one of these benefits is the ability to adjust the number of antennas at the BS, whereas this number is fixed during the operational phase. During the planning phase, we prioritize achieving the maximum Per_{cov} , by reducing the number of antennas at the BS and then by minimizing the number of assisted elements N at the IRS.

4. Problem Formulation

IRS-Assisted MU-MISO System

In the planning phase, the BS can serve multiple users with one antenna each. The percentage of assistance, denoted by Per_{ass} , is used in this scenario. We consider that the IRS is formed of blocks of elements of size N_{min} . These blocks can assist a certain number of users by allocating a certain number of blocks n_b , which can be calculated using the following equation:

$$n_b = \frac{N_{tot}}{N_{min}} \quad (23)$$

where N_{tot} represents the total number of elements in the IRS module. Note that n_b also represents the maximum number of users that can be assisted by the IRS. Therefore, when distributing a certain number of users in the cell, the P_{ass} represents the number of users that the IRS can assist n_{ass} between n_b . Therefore, the Per_{ass} can be calculated as

$$Per_{ass} = \frac{100 n_{ass}}{n_b} \quad (24)$$

Our primary goal is to assist more users when using the IRS, therefore increasing Per_{ass} by reducing the number of antennas at the BS and the number of blocks in the IRS that we give to each user, to enable the assistance of a greater number of users.

Several factors influence the selection of users to be assisted, including their locations with respect to the IRS and to the BS, as well as the positioning of the IRS and the BS relative to each other, and the size of the cell. Without loss of generality, we take the BS at the origin of a Cartesian coordinate system. Hereafter, the number of users to be assisted depends on the users' conditions and the number of elements in the IRS. Assisting several users via the IRS can be achieved in more than one way. For example, it is possible to optimize the phase shift in order to increase the SNR of all assisted users. Another strategy is to focus on optimizing the phase shifts of the IRS so that a target SNR is achieved by all assisted users [28]. Moreover, it is possible to consider the IRS as a resource that can be shared by users. For example, the IRS can be shared according to a time division protocol. This is possible due to the real-time switching of the IRS. From another view, it is possible, at the same time, to share the IRS among several users, where each user is allocated a certain number of blocks. Interference between signals at the IRS can be neglected, given that the users are working on different frequencies. Indeed, the number of elements in the IRS to be allocated should not be small, so as to guarantee the minimum gain [29].

In this study, we explore the allocation of a block of IRS elements to a designated user, with the minimum number of elements denoted by N_{min} . Additionally, this simplifies the allocation policy by reducing the number of possibilities.

We assume that the effect of assisting a user with any of the blocks is the same because the IRS is assumed to be sufficiently far from both the BS and the users. However, if the IRS is in close proximity to the BS (e.g., near field), the position of the block should be taken into consideration. Nonetheless, this is beyond the scope of this study. The system model is depicted in Figure 1c, where the BS is providing services to four users, out of which only three are receiving assistance from the IRS.

The problem can be formulated as determining, for each number of antennas at the BS M_i , the vector $X_K = [x_1, x_2, \dots, x_K] \in \mathbb{N}^{1 \times K}$ that represents the number of blocks assigned to each user as follows:

$$\max_{X_K} Per_{ass} \quad (25)$$

Note that the number of elements of the IRS allocated to user k is $x_k \times N_{min}$. In addition, the optimization problem, in determining the number of IRS blocks, to maximize the Per_{ass} , is subject to constraints, such as

$$\begin{aligned} \sum_{k=1}^K x_k &\leq n_b \\ 0 &\leq x_k \leq n_b \\ SNR_k &\geq SNR_{pred} \\ M_i &\in \mathbb{N}^* \\ M_{i_{max}} &\leq M, \end{aligned} \quad (26)$$

The above constraints guarantee that each user is allocated a positive number of blocks, and that the total number of allocated blocks across all users matches the number of available blocks. The non-linearity in the objective function (Equations (24) and (25)) in the scenario of MU-MISO and the integer nature of the variables x_1, x_2, \dots, x_K lead to a non-linear integer problem [30].

5. Proposed Algorithms

The IRS is composed of multiple blocks. Our objective is to manage these blocks amongst users, for every number of antennas at the BS, in order to provide the maximum number of assisted users that require a specific SNR. We intend, at every position of the cell, to find, for a certain number of antennas at the BS, the allocated number of blocks in the IRS by examining the effect of all possibilities (users to be assisted and number of blocks allocated to each assisted user), and then selecting the one with the largest and nearest value to the predetermined SNR.

First, the IRS must be close the BS to efficiently assist the users [31]. We randomly distribute a number of users in the cell. To evaluate the gain that can be achieved by sharing the IRS among several users, we evaluate the percentage of assistance of the BS with the IRS. We use an exhaustive search to find, for every position of the user p_k , and for a number of antennas at the BS, the optimal number of allocated IRS blocks, by examining the effect of all possibilities. Then, we select users that have the required SNR with the minimum number of blocks in the IRS.

For example, for a certain number of antennas at the BS, if we have 3 blocks and 4 users, as in Figure 1, then the maximum number of assisted users can be 3. Considering that 3 of these users have obtained the required SNR when using 1 block each, then the best case is selected and the percentage of assistance is 100%. However, considering that one user needs only 1 block to acquire the demanded SNR and another one needs 2 blocks, then we can assist only 2 users out of 3 users, and the percentage of assistance decreases in this case. Moreover, we can, in this case, increase the number of antennas at the BS to assist more users.

Although the exhaustive search gives the best possible solution, it requires a high computational cost. Thus, we propose two low-complexity algorithms:

- MAX-BS: Identifies the users with the highest distance from the BS and allocates them the maximum number of available IRS blocks. This approach ensures that users with the greatest need for assistance from the IRS are given priority.
- MIN-IRS: This algorithm prioritizes users based on their proximity to the IRS and assigns them the largest number of IRS blocks. Users with optimal radio conditions concerning the IRS are given the highest preference.

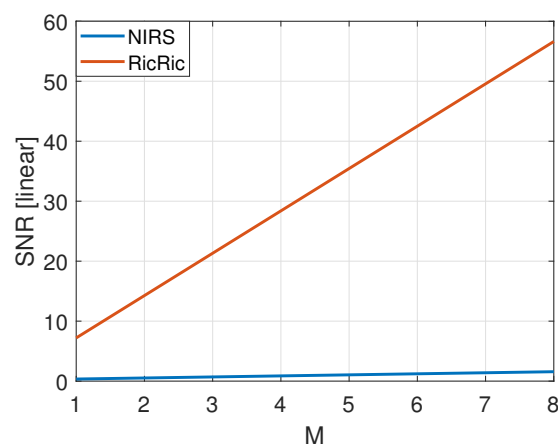
6. Simulation Results

We consider a macro-base station serving a square cell of side R_s . In the planning phase, we consider that the user is at the center of a small square with sides of length r_s . The BS operates with a 3 GHz carrier frequency and 10 MHz bandwidth. Table 1 summarizes the parameters considered in the system.

Figure 2 shows the impact of the number of antennas at the BS M on the SNR in a system with and without the IRS. This figure is in line with Equation (5), where the system is taken without the assistance of the IRS, with a Rician channel model between the BS and the user. The SNR varies linearly with M but the slope is very small versus the other variations in this figure. Meanwhile, according to Equation (18), with 100 elements in the IRS, we obtain a figure with a faster slope, allowing a greater effect in terms of increasing the number of antennas. Therefore, we can conclude, from this figure, that the existence of the IRS can affect the variation in the number of antennas at the BS.

Table 1. Simulation parameters.

| Parameters | Values and Assumptions |
|--------------------------------|--|
| Number of users | 1 to 30 |
| Cell size in m^2 | $(300\text{ m} \times 300\text{ m})$ |
| Number of elements in the IRS | variable (50 to 500) |
| Number of antennas | at the BS (1 to 8), 1 at user |
| Environment | urban |
| Carrier frequency f_c | 3 GHz |
| x_R, y_R of IRS in m | near $(-5, 50)$, far $(-5, 200)$ |
| Path loss exponent with IRS | (BS, IRS) = 2.2; (BS, user) = 3.5; (IRS, user) = 2.2 |
| Path loss exponent without IRS | (BS, user) = 2.8 |
| Noise power | -94 dbm |
| Transmitted power | 5 dbm for all users |
| Rician K factor | normalized to 1 |

**Figure 2.** SNR with respect to the number of antennas at the BS for a system model without and with the assistance of the IRS ($N = 100$).

When using the IRS, different channel models can exist between the nodes of our system. Our objective is to identify the effect of these channel models on the required SNR. Figure 3 shows the variation in the SNR as a function of the number of elements in the IRS for 2 antennas at the BS. The different channel models that were discussed earlier exist. In Figure 3a, we compare Ric-Ray (where the model of the channel between the BS and IRS is Rician, while the model is Rayleigh between the IRS and the user) with Ray-Ric (where the model of the channel between the BS and IRS is Rayleigh, while Rician is used between the IRS and the user). The effect of the existence of LOS between the BS and the IRS is more significant than between the IRS and the user. Moreover, when this LOS exists from both sides, the effect is greater, as we can see in Figure 3b. It is worth noting that the primary objective of using the IRS is to overcome obstacles between the BS and the user. Therefore, the existence of the IRS aims to create an LOS first between the BS and the IRS, and then between the IRS and the destination.

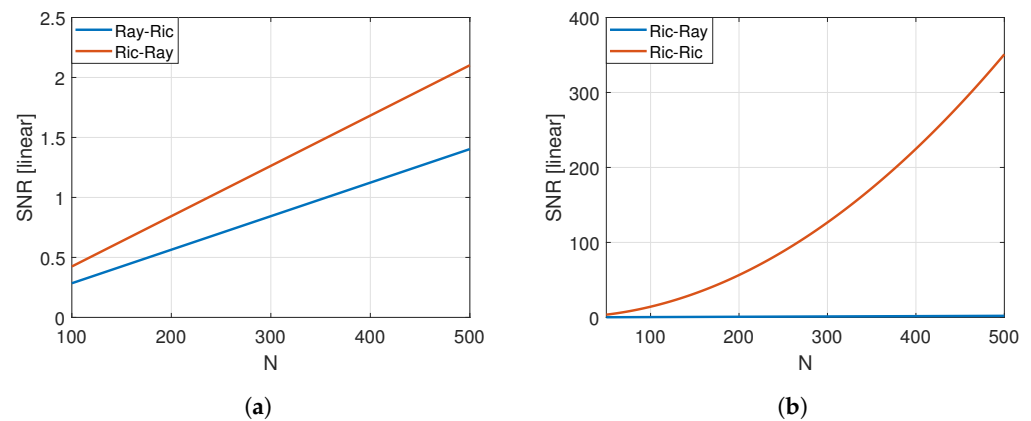


Figure 3. SNR with respect to the number of elements in the IRS, two types of channel model ($M = 2$): (a) Ric-Ray, Ray-Ric; (b) Ric-Ray, Ric-Ric.

According to Equation (21), the relation between M and N can be determined for a required SNR. To explore the complete range of variations between these variables, Figure 4 is plotted with a wide range of N values to identify any unacceptable regions. This figure shows the curve of M with respect to N with an SNR = 20 dB, for a user placed at the edge of the cell and the IRS placed near the BS. We observe that M decreases significantly at the initially increasing N , and then this variation decreases gradually, while, at the end, the impact of the increasing N becomes less effective. Note that the variation is confined to the region of the graph where M is a positive integer value. Our objective in analyzing this graph is to determine the specific values of M and N that are required to achieve the desired SNR. It is important to note that this variation depends on the position of the user in the cell and the position of the IRS. This graph can offer an idea about the maximum number of elements (since the user is at the edge) that the user needs to achieve the desired SNR.

Figure 5 shows the maximum number of elements required in the IRS to achieve different SNR levels for a user located at the edge of the cell and an IRS placed close to the BS, considering the scenario where the BS has a different number of antennas ($M = 1, 2, 4, 8$). For example, for an SNR of 20 dB, a user placed at the edge of the cell requires 374 elements in the IRS. It is worth noting that in our simulations, we consider the user at the farthest distance from both the BS and from the IRS, which represents the worst-case scenario with only one antenna at the BS. These values of N tell us how large the IRS needs to be to obtain a desired SNR. Adding more antennas at the BS can decrease the number of elements in the IRS. Our objective is to determine how many elements in the IRS we need to replace a certain number of antennas at the BS. Therefore, to obtain an SNR equal to 20 dB, we have more than one choice. When we use 2 antennas, we need almost 265 elements in the IRS; this means that if we add 109 elements, we can replace one antenna at the BS. Moreover, the addition of 243 elements can satisfy 7 antennas at the BS. Therefore, with an increase of 243 low-cost elements in the IRS, almost passive, we can replace a high-cost number of antennas at the BS for a required SNR of 20 dB, for a user placed at the edge of the cell.

In Figure 6a, we consider an IRS placed near the BS and study the variation in the number of antennas at the BS for three different values of SNR as a function of the number of elements in the IRS. A small change in N (only 23 elements) with an SNR of 0 dB can lead to a decrease in the number of antennas at the BS from 8 to 1. However, when the IRS is far from the BS, as shown in Figure 6b, the required variation in N increases, with a change of 88 elements needed for an SNR of 0 dB, and 885 elements needed for an SNR of 20 dB, both measured at the edge of the cell. Therefore, the position of the IRS plays a substantial role in achieving the required SNR. Even a small variation in the number of elements in the IRS and the number of antennas at the BS can lead to the desired SNR.

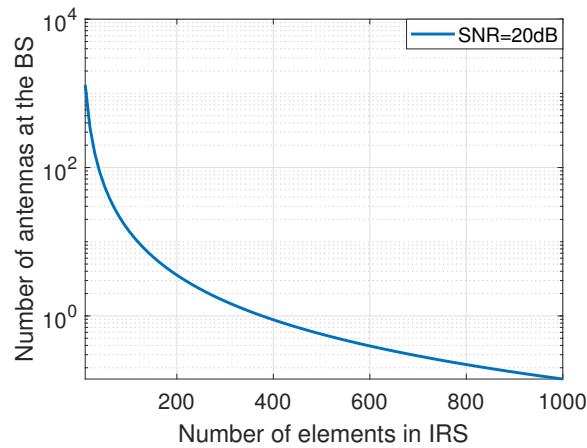


Figure 4. Number of antennas with respect to the number of elements in the IRS for SNR = 20 dB.

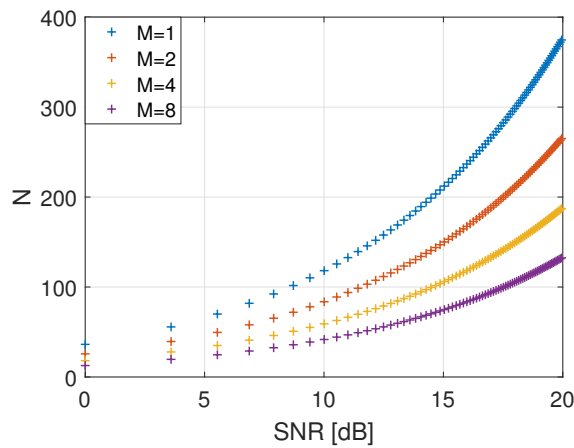


Figure 5. Maximum number of elements in the IRS with respect to SNR (IRS near the BS, user at the edge, $M = 1, 2, 4, 8$).

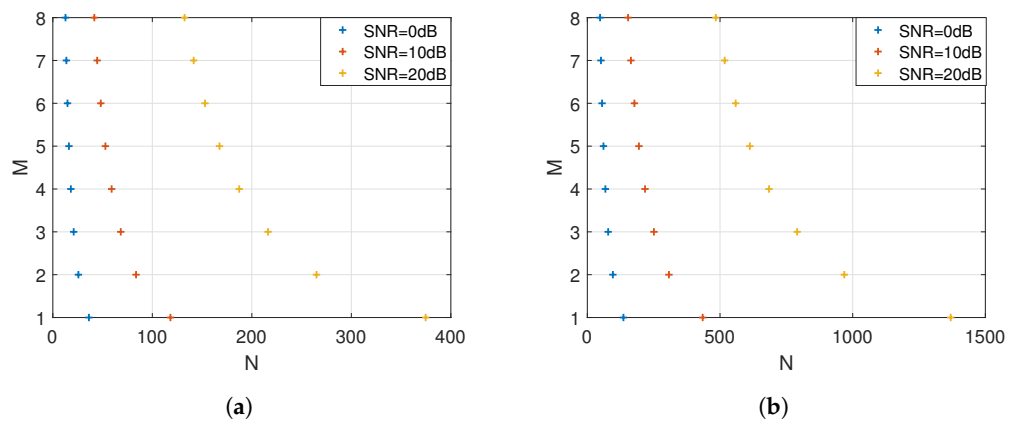


Figure 6. Number of antennas with respect to the number of elements in the IRS for different SNRs (user at the edge): (a) IRS near the BS, (b) IRS far from the BS.

Figure 7 represents only the integer number of antennas at the BS as a function of the SNR for different numbers of elements in the IRS. The importance of this figure is that it shows that the variation in M is not continuous when N increases. Mention that after a certain number of elements in the IRS (in this case 400 elements; it is in green color but it does not appear because it is under the blue line), the number of antennas have the same value for all values of SNR. We need only 1 antenna at the BS to attain 20 dB.

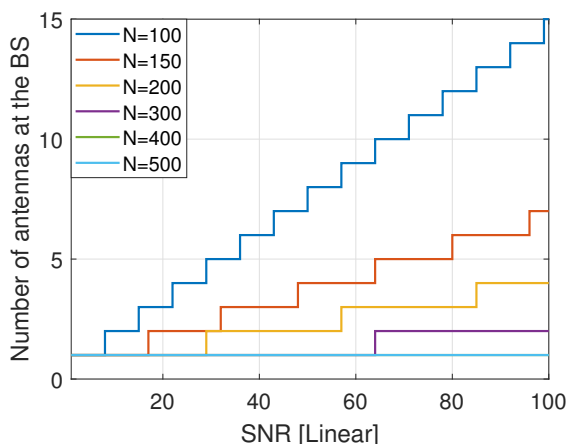


Figure 7. Number of antennas at the BS with respect to the SNR.

To study the coverage area of the BS, i.e., the percentage of coverage, with the assistance of the IRS, we consider a square cell with a side length of 300 m. The user is located at the center of a smaller square with a side length of 20 m. The BS is represented by a black circle at the origin of a Cartesian coordinate system, while the IRS is shown as a green circle near the BS. The users who can achieve the required SNR are represented by red circles, while the non-covered users are indicated by a black cross. Non-covered users are those who cannot achieve the required SNR even with the assistance of the IRS.

In Figure 8, we show the effect of the number of antennas at the BS on the percentage of coverage. Figure 8a represents the covered users when only 50 elements are used from the IRS and for 2 antennas at the BS, where, in Figure 8b, we increase the number of antennas at the BS to 4. This variation in M gives a variation of 8.3%.

To illustrate the effect of the position of the IRS on the coverage, we provide Figure 9, where only 2 antennas at the BS are taken and there are 250 elements in the IRS. One user in this case is not covered when the IRS is near the BS. The effect of the number of elements in the IRS on the coverage is considered in Figure 10, where we take also 2 antennas at the BS and we consider that the IRS is near the BS. Only 25 users are covered when the number of elements in the IRS is 50, whereas only 1 user is not covered when $N = 250$ elements.

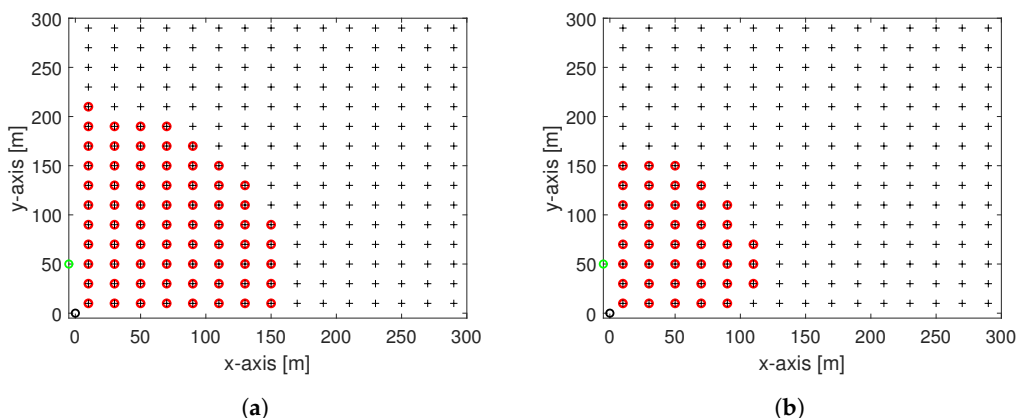


Figure 8. Covered area (red circles), IRS (green circle) is near the BS (black circle) ($N = 50$): (a) $M = 2$, (b) $M = 4$.

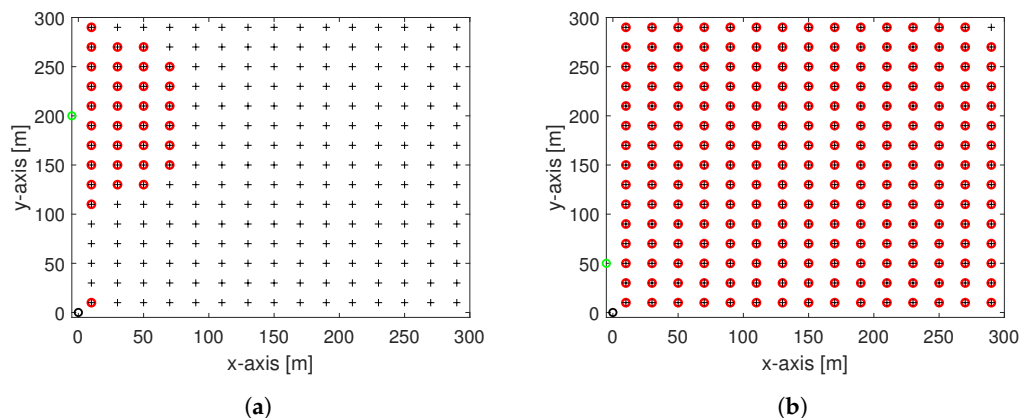


Figure 9. Covered area (red circles), ($M = 2, N = 250$): (a) IRS (green circle) far from the BS (black circle), (b) IRS near the BS.

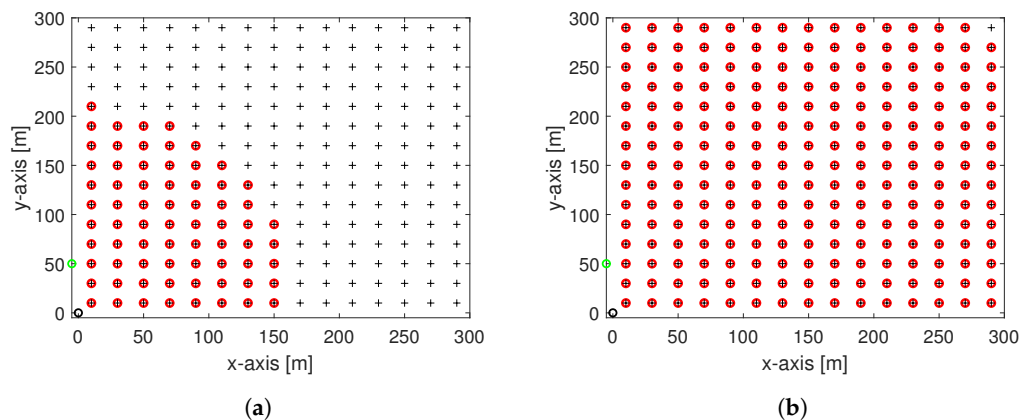


Figure 10. Covered area (red circles) when IRS (green circle) is near the BS (black circle, $M = 2$): (a) $N = 50$, (b) $N = 250$.

In all the figures shown above, we have the case of an SU-MISO system assisted by the IRS. Hereafter, we discuss the case of an MU-MISO system assisted by the IRS. We consider the percentage of assistance P_{ass} and compare the cases of a system with and without the IRS. In Figure 11, we compare the P_{ass} when we have 2 antennas at the BS with the case with 4 antennas. The IRS is considered to be formed of blocks of resources of 50 elements and it is placed near the BS. With and without the assistance of the IRS, we run a Monte Carlo simulation over 10,000 independent trials. We distribute randomly 30 users in the cell, and then we consider different sizes for the cell—in our case, from 100 m to 500 m. Notice that the IRS is formed of 300 elements and it is divided into 6 blocks; therefore, if the number of blocks equals the number of assisted users, we can say that the percentage of assistance is 100%, since, in this case, we do not waste any resources that we have from the side of the IRS. When using the IRS, the Per_{ass} changes from almost 58% to 69%, whereas the change without the IRS is noted from almost 15% to 22%. We note that the IRS cannot assist all users since it is formed of a certain number of elements; therefore, we wish to discern how to choose the assisted users. First, we begin by choosing users with an SNR smaller than the required one by using an exhaustive search (Figure 12). Then, we try to decrease the complexity of the search; we propose two low-complexity algorithms. For the first algorithm, we choose users with the minimum distance from the IRS to distribute the blocks. For the second algorithm, we choose users with the maximum distance from the BS, since these users are less likely to be served by the BS. We take also two cases, where the number of antennas at the BS is 2 and 4 as a function of the cell size. When the cell has a side size of 100 m, the percentage of assistance reaches almost 55% with the two algorithms, and it is less than 20% when using the maximum distance from the BS. When the size of

the cell increases to 500 m, the 3 algorithms are close to each other, since the users in this case have a greater probability of being far from the other nodes of the system.

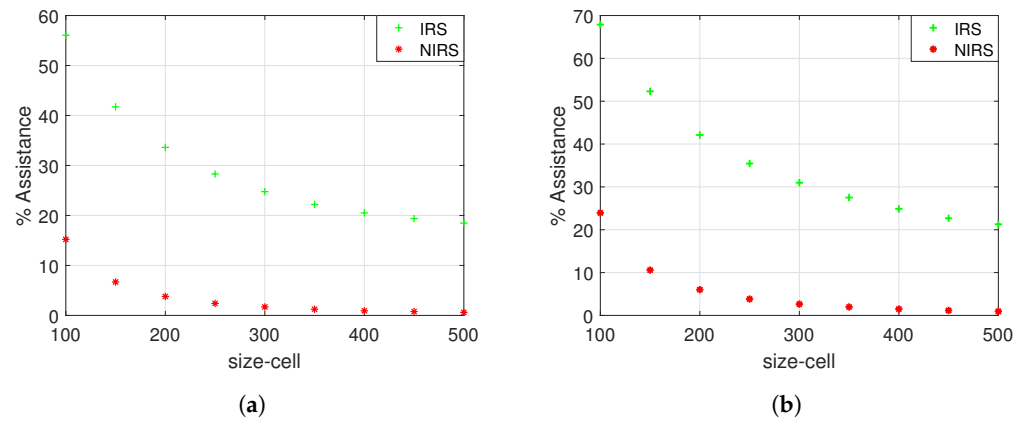


Figure 11. Percentage of assistance with respect to the cell size, IRS near BS ($N = 50$ to 300): (a) $M = 2$, (b) $M = 4$.

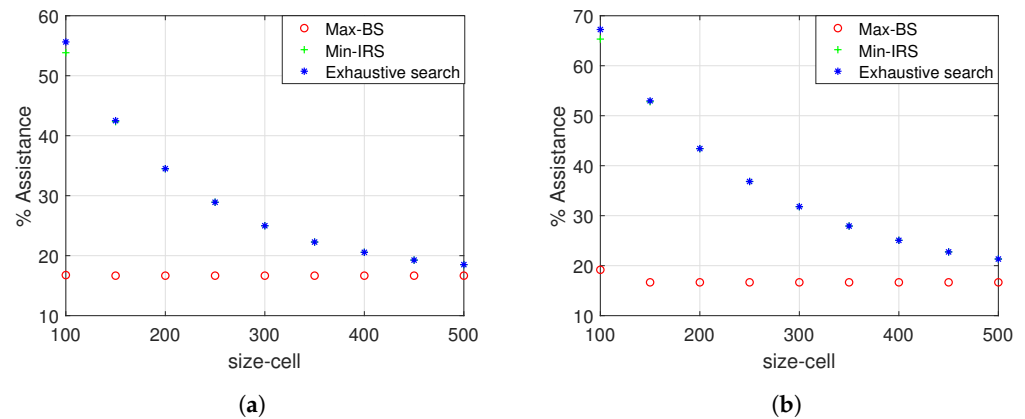


Figure 12. Percentage of assistance with respect to the cell size, IRS near BS ($N = 50$ to 300). (a) $M = 2$, (b) $M = 4$.

7. Conclusions

This research study introduces a novel approach to improve the performance of future cellular networks by utilizing Intelligent Reflecting Surfaces (IRSs). We investigate the use of IRSs under statistical Channel State Information (CSI) to enhance the coverage of Base Stations (BSs) in Multiple-Input Single-Output (MISO) systems. We study the effect of the channel on the required SNR. Then, in the planning phase, we propose to reduce the number of antennas required at the transmitter, with the assistance of the IRS, to decrease the installation costs. In a Multi-User (MU) MISO system, we consider that the IRS consists of blocks that can be used to assist several users. The problem is formulated as a non-linear integer problem. We solve the optimization problem using an exhaustive search, and propose two low-complexity heuristic algorithms. Results show that using the IRS, we can achieve a significant increase in the percentage of coverage (from 11% to 58% with only 2 antennas at the BS and an increase of 100 elements in the IRS) and a meaningful reduction in the number of antennas when the IRS is located near the BS and the IRS resources are well managed. In future work, we aim to jointly optimize the percentage of coverage when considering a MIMO system.

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