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Research paper

Edge User Performance Improvement by Intelligent Reflecting Surface-Assisted NOMA System

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Abstract

Background and Objectives: This research addresses the performance drop of edge users in downlink non-orthogonal multiple access (NOMA) systems. The challenging issue is paring the users, which becomes more critical in the case of edge users due to poor signal quality as well as the similarity of users' channel gains.
Methods: To study this issue, the capabilities of intelligent reflecting surface (IRS) technology are investigated to enhance system performance by modifying the propagation environment through intelligent adjusting of the IRS components. In doing so, an optimization problem is formulated to determine the optimal user powers and phase shifts of IRS elements. The objective is to maximize the system sum rate by considering the channel gain difference constraint. Additionally, the study addresses the effect of the IRS location in the cell on system performance.
Results: The proposed approach is evaluated for various scenarios and compared with benchmarks in terms of average bit error rate (BER) and sum rate. The numerical results show that IRS-assisted NOMA improves the performance of edge users and distributes resources more fairly than conventional NOMA.
Conclusion: Simulation results demonstrate that using IRS-assisted NOMA can effectively address the issue of edge users. By modifying the channel between the BS and the edge users using IRS, the channel gain difference of the users is increased, thereby enhancing the overall system performance. Particularly, the proposed IRS-NOMA system offers a gain of about 4 dB at a BER of 10^{-2} and 3 dB at the sum rate of 10^{-1} bps/Hz compared to conventional NOMA. In addition, it was observed that the location of the IRS in the cell affects the system's performance.

Introduction

As a promising technology for 5G networks, non-orthogonal multiple access (NOMA) enables different users to multiplex signals on a shared channel within a particular domain [1]-[3]. In power-domain downlink NOMA, the base station (BS) performs superposition coding (SC) by allocating more power to the far (weak) user and less power to the near (strong) user.

Signal detection is then carried out on the user equipment (UE). In this process, the far user considers the signal of the near user as interference plus noise, while the near user uses successive interference cancellation (SIC) to decode its signal. The NOMA results in higher spectral efficiency, reduced latency, improved user fairness, and enhanced connectivity compared to the orthogonal multiple access (OMA) scheme [4], [5]. In the

NOMA system, user pairing is based on the difference between the users' channel gains. The system performance is improved when there is a significant difference between the channel gains of paired users. Hence, it is preferred to pair the near users with far users [6]. A challenging issue is associated with the paring of the middle users which causes a degradation in the performance of the NOMA system [7], [8].

The importance of this issue is heightened for edge users for two main reasons. The first reason is poor signal quality and high attenuation due to the long distance from the BS, and the second one is related to low performance due to the similarity of users' channel conditions. The approach presented in this work centers on leveraging an emerging technology for 6G known as intelligent reflecting surface (IRS) to overcome the challenge. IRS is a surface of numerous reflecting components that can be fine-tuned to steer electromagnetic waves in specific directions. This capability leads to improved coverage, higher data rates, and superior energy efficiency. As an enabler of the 6G wireless communication system, the seamless integration of IRS with other emerging technologies yields a more efficient, secure, and intelligent wireless network [9], [10]. In this way, IRS-NOMA is used in the present study to leverage the capabilities of IRS and NOMA simultaneously. In this study, we are using IRS-NOMA to take advantage of the capabilities of IRS and NOMA simultaneously. The IRS-NOMA is expected to play an essential role in developing future wireless communication systems by improving spectral efficiency, enabling more connected devices, and reducing energy consumption [11]-[14].

Numerous research works have been conducted on the benefits of IRS in conjunction with NOMA, indicating an increasing focus on IRS-NOMA applications in wireless communication. Paper [15] introduces the phase shift estimation in IRS-assisted systems under correlated Rayleigh fading. The study covers two scenarios including fully-active-IRS and hybrid-IRS, considering the number of active IRS elements. The paper presents the derivation of the maximum likelihood estimator for the channel phases of IRS elements based on the observations of active IRS elements. In [16], a low-complexity resource allocation method is introduced to maximize sum throughput by jointly optimizing phase shifts and time allocation. It first derives the problem with phase shifts as variables, and then deduces the optimization problem for the downlink wireless energy transmission process.

Authors in [17] examine the tradeoff between spectral efficiency (SE) and energy efficiency (EE) in the IRS-assisted MISO cognitive radio networks (CRN)-NOMA system. It is conducted by formulating a multi-objective optimization problem under perfect and imperfect channel state information (CSI) scenarios. An iterative block coordinate descent (BCD) algorithm is utilized to optimize the beamforming design and IRS phase shifts. The paper [18] focuses on the IRS-assisted multi-carrier (MC)-NOMA system to accommodate users in each channel and allocate the available IRS units to the respective channels. The work formulates a power minimization problem to minimize the overall transmit power while meeting the quality of service (QoS) requirements.

The IRS-NOMA network performance with two users at the border is examined in [19]. An analysis of the channel statistics of the BS-IRS-UE with Nakagami-m fading distribution is conducted and the closed-form expressions for the ergodic rate, outage probability, and approximate ratio of UEs' ergodic rate to the SINR are derived for both low and high values. Letter [20] presents an optimization algorithm in downlink IRS-assisted NOMA systems to design active and passive beamforming for the BS and IRS. The goal is to solve the interference issue among users and decrease power consumption, considering the user's QoS. The subproblems of power minimization and phase shift feasibility are defined and solved iteratively using alternating optimization.

The work [21] derives analytical expressions to evaluate the Ergodic capacity of the IRS-NOMA over the Nakagami-m faded channel by considering inter-cell interference, imperfect-CSI, and SIC. Paper [22] addresses the issue of energy efficiency optimization in IRS-assisted NOMA systems by handling passive beamforming, user clustering, and power allocation problems. The passive beamforming is tackled using the univariate search technique, the user clustering is addressed using a matching algorithm, and the power allocation is optimized using the difference of convex (DC) programming.

Most of the mentioned works focus on investigating the efficiency of IRS-NOMA with far and near users. The focus of this study is on edge users with close channel conditions. The study explores leveraging IRS capabilities to modify the transmission environment and improve system performance. In this regard, an optimization problem is presented to intelligently adjust the IRS elements' phase shifts considering the channel gain difference constraint. The system performance is evaluated under different channel conditions in terms of sum rate and average bit error rate (BER). The main contributions of the work are described as follows:

- To improve the performance of edge users in NOMA systems, IRS technology is used to modify the propagation environment by adjusting the reflection elements, thereby enhancing overall system performance.
- With considering the user channel gain conditions, a

new approach has been introduced to intelligently control IRS and allocate the power resources to edge users.

- An optimization problem is formulated to determine the optimal phase shifts of IRS elements and NOMA user powers with the aim of maximizing the system sum rate.
- The effect of the IRS location in the cell on system performance has been studied through simulation, taking into account the IRS distance from the BS and edge users.
- The performance of the IRS-assisted NOMA approach is examined in various scenarios, considering BER and sum rate as evaluation metrics.

The rest of this paper is organized as follows. Section 2 introduces the concept of the IRS-NOMA system. Section 3 presents the proposed approach for IRS control and formulates the IRS-NOMA optimization problem. Section 4 includes the simulation system setup and evaluate the proposed approach through extensive simulation tests. Finally, Section 5 presents the conclusion.

Notations: in respective order, non-boldface, boldfaced lowercase, and boldfaced uppercase letters represent the scalar, vector, and matrix.

IRS-assisted NOMA Communication System

The IRS-NOMA scheme combines IRS technology with NOMA to enhance wireless communication. The IRS involves deploying a planar array of passive reflecting elements to improve wireless communication systems' performance. It manipulates the reflection and scattering of radio signals, altering the signal's phase and controlling the propagation of electromagnetic waves. By placing the IRS between the transmitter and receiver, it can manipulate the signal to interfere with the direct signal constructively, resulting in a stronger and more reliable signal at the receiver. Additionally, the IRS can help mitigate fading effects and multipath propagation, which causes signal degradation in wireless communication systems [23]. On the other hand, NOMA is a type of multiple-access technique used in wireless communication systems, allowing multiple users to share the same radio frequency resources. Unlike traditional OMA techniques where users are assigned separate channels to avoid interference, NOMA assigns users the same frequency band and time slot but with different power and code assignments. NOMA utilizes superposition coding to encode multiple signals onto the same frequency band and time slot, thereby increasing spectral efficiency. At the receiver, the SIC technique separates individual signals from each user. This involves decoding the strongest signal first and subtracting it from the total received signal to cancel out interference. The process is repeated for each signal until all interference is removed and the original signals can be accurately decoded [24].

The IRS-NOMA offers significant benefits such as improved spectral efficiency, reduced interference, lower power consumption, reduced costs, and greater flexibility for wireless communication [25]. In IRS-NOMA, an IRS is positioned between the transmitter and the receiver to reflect the wireless signal, enhancing signal power for a specific user in the NOMA group. This enables the receiver to separate signals from different users more efficiently, resulting in higher data rates and better QoS. Additionally, IRS-NOMA allows for flexible resource allocation, which can be adjusted to meet the varying QoS requirements of different users [26].

Fig. 1 illustrates the schematic of the IRS-NOMA system with two users. In this setup, a base station (BS) communicates with the users through an IRS with reflecting elements. The signal model involves the signal sent to the IRS by the BS, which is then reflected in a controlled manner. The reflected signal is received by the user and combined with the line of sight (LOS) signal to generate a stronger and more reliable signal [27]. The signal model considers the phase, which can be adjusted by controlling the position and orientation of the reflecting elements in the IRS. By optimizing the reflection of the signal, it is possible to constructively interfere with the direct signal, leading to an enhanced signal for the user.

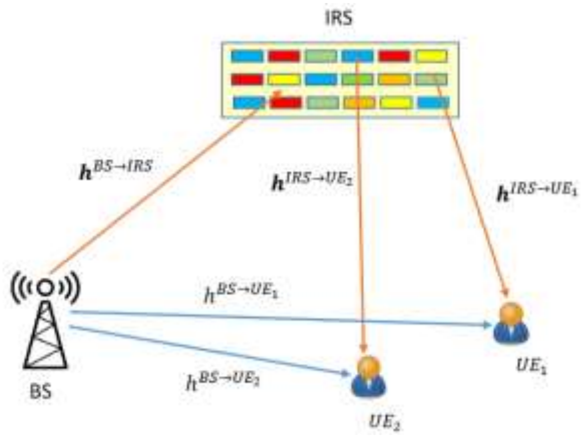


Fig. 1: IRS-NOMA system.

We consider an IRS-NOMA system consisting of a BS, an IRS, and the number of K users. It is assumed that the BS and users are equipped with one antenna for sending and receiving signals. The signal received by the k-th user could be expressed as follows [18]:

$$y_k = \tilde{h}_k s + n = \tilde{h}_k \sum_{k=1}^{K} \sqrt{p_k}\, x_k + n \tag{1}$$

in which $\tilde{h}_k$ is the effective channel between BS and k-th user [18]:

$$\tilde{h}_k = h^{BS\to UE_k} + \boldsymbol{h}^{IRS\to UE_k\,T} \boldsymbol{\Theta} \boldsymbol{h}^{BS\to IRS} \tag{2}$$

where $h^{BS\rightarrow UE_k}$ represents the scalar quantity that models the channel between BS and k-th user. The $N \times 1$ vector $\boldsymbol{h}^{IRS\rightarrow UE_k} = [h(1)^{IRS\rightarrow UE_k} \dots h(N)^{IRS\rightarrow UE_k}]^T$ model the channel between the IRS and k-th user, and $N \times 1$ vector $\boldsymbol{h}^{BS\rightarrow IRS} = [h(1)^{BS\rightarrow IRS} \dots h(N)^{BS\rightarrow IRS}]^T$ denotes the channel between BS and IRS. The $[.]^T$ operation represents the transpose of the vector. All $h^{BS\rightarrow UE_k}$, $h(i)^{IRS\rightarrow UE_k}$ and $h(i)^{BS\rightarrow IRS}$ are defined as $CN(0,1)/\sqrt{1+d^{\alpha}}$ [28], where $CN(0,1)$ stands for a zero mean, complex normal random of variance 1 which models the small scale fading. Also, d and α represent the distance between the transmitter to the receiver terminals of the relevant link and the path loss factor, respectively. In addition, $\boldsymbol{\Theta} = diag[e^{j\theta_1} \quad \cdots \quad e^{j\theta_N}]$ stands for an $N \times N$ diagonal matrix that models the IRS consisting of N reflecting elements. In this model, $\theta_i \in [0,2\pi]$ represents the phase shift of the i-th IRS element.

Moreover, $s = \sum_{k=1}^{K} \sqrt{p_k}\, x_k$ [1] denotes the signal transmitted by the BS to the users, where x_k denotes the signal intended for the k-th user, normalized to unit power ($\mathrm{E}[|x_k|^2] = 1$). The term p_k represents the power allocated by the BS for transmission of this user. Typically, more power is assigned to users with poorer channel conditions, resulting in earlier decoding during signal detection. Assuming that $|\tilde{h}_1|^2 < |\tilde{h}_2|^2 < \cdots < |\tilde{h}_K|^2$, the BS distributes power among users, ensuring that $p_1 > p_2 > \cdots > p_K$. It is important to note that the power allocation must satisfy the constraint $\sum_{k=1}^{K} p_k = P^{MAX}$; where P^{MAX} is the available power at the BS for each group. This approach empowers the users to recover their data symbols successfully. The last term, n, is additive white Gaussian noise (AWGN) with zero mean and variance σ^2. The data rate of the k-th user is calculated as [16]:

$$R_k = \log_2(1+\gamma_k) \tag{3}$$

where γ_k is the signal-to-interference plus noise ratio (SINR) of the k-th user equal to [16]:

$$\gamma_k = \frac{|\tilde{h}_k|^2 p_k}{|\tilde{h}_k|^2 \sum_{i=k+1}^{K} p_i + \sigma^2} \tag{4}$$

IRS-NOMA Optimization Problem

In the NOMA system, the difference in channel gains is a key factor in assigning users to common channels. However, pairing users with close channel conditions causes decoding difficulties, leading to degraded performance, especially in terms of BER. This issue is further exacerbated when edge users are accommodated in the same group in the NOMA scenario [29]. The signal decoding process encounters a high error rate, leading to a decrease in the overall performance of the NOMA system. This challenge becomes more significant as the number of users increases.

To tackle this problem, one approach involves manipulating the reflection of radio signals. This entails altering the signal phase to control the propagation of electromagnetic waves, thereby improving the performance of the users with close channel conditions. To achieve this, the capabilities of the IRS are exploited to control the propagation of electromagnetic waves by manipulating the reflection of radio signals. In this regard, the difference in user channel gains is used to evaluate the pairing quality. The aim is to manipulate the users' channel conditions by adjusting the phase shifts of IRS elements so that the channel gain difference of two users exceeds the threshold value. This section presents an optimization problem for the IRS-NOMA system that involves maximizing the system sum rate while adhering to specific constraints. The goal is to allocate available power to different users and adjust phase shifts of the IRS elements to maximize overall system performance. The optimization problem is formulated while the threshold condition for channel gains is established as a constraint:

$$\max_{\boldsymbol{p},\boldsymbol{\theta}} \sum_{k=1}^{K} \log_2(1+\gamma_k) \tag{5-a}$$

$$s.t. \sum_{k=1}^{K} p_k = P^{MAX} \tag{5-b}$$

$$p_1 > p_2 > \cdots > p_K \tag{5-c}$$

$$|\tilde{h}_m|^2 - |\tilde{h}_n|^2 > g_{th}, \quad m,n \in \{1,\dots,K\}, m \neq n \tag{5-d}$$

$$\theta_i \in [0,2\pi], \forall i \in \{1,\dots,N\} \tag{5-e}$$

where $\boldsymbol{p} = [p_1 \dots p_k]$ denotes the power of the users and $\boldsymbol{\theta} = [\theta_1 \dots \theta_N]$ represents the IRS phases. γ_k is the SINR of the k-th user and P^{MAX} is the available power at the BS for each group. The terms (5-b) and (5-c) are power constraints that allocate the available power at the BS terminal among multiple users, based on the power allocation pattern of the downlink NOMA systems. Constraint (5-d) guarantees that the difference in channel gain of the users meets a minimum threshold value. Finally, the constraint (5-e) sets the permissible range for the IRS phase shifts.

To fully take advantage of IRS-NOMA, an optimization problem must be tackled to determine the optimal powers and phase shifts to maximize the sum rate of the system. The problem can be expressed as a non-convex optimization problem. Undoubtedly, inverting the problem to a convex one would provide more accurate results. However, by adding some restrictions, our attempts for this matter reached a high-order fractional problem which is again non-convex. Consequently, we decided to utilize the YALMIP toolbox within MATLAB [30]. It is a powerful toolbox supporting a wide range of optimization problems. The advantage of this toolbox is that it allows us to work with the non-convex problem directly, without imposing any restrictions. It utilizes an appropriate nonlinear solver to address the problem.

Results and Discussion

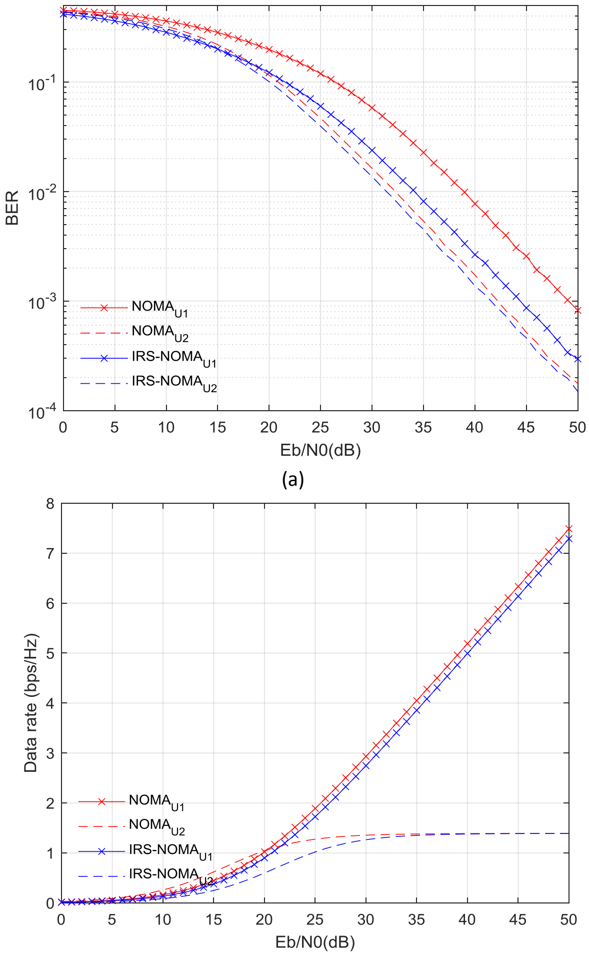
In this section, we conducted a series of simulations to evaluate the performance of the proposed approach under various scenarios, focusing on the system's average BER and sum data rate. It is necessary to clarify that the proposed method, referred to as IRS-NOMA in the figures, is compared with conventional NOMA as a benchmark. The simulation setup involves a single-cell IRS-NOMA system with a radius R, where the BS is located at the center, and users are randomly distributed along the cell's edge. The simulations were carried out using MATLAB and employed the Monte Carlo method. In these simulations, the path loss exponent (α) and the number of the IRS elements (N) are set to 2 and 5, respectively. The signal-to-noise ratio per bit (E_b/N_0) ranged from 0 to 50 (dB) and data transmission was performed using binary phase-shift keying (BPSK) modulation. Simulation parameters are detailed in Table 1.

Table 1: Details of simulation setting and parameters

$\boldsymbol{R}$	10m
$\boldsymbol{\alpha}$	2
N	5
$\boldsymbol{E_b/N_0}$	0 to 50 (dB)
Number of users	2
Number of symbols	1e6
Modulation	BPSK
Channel realizations	1e6

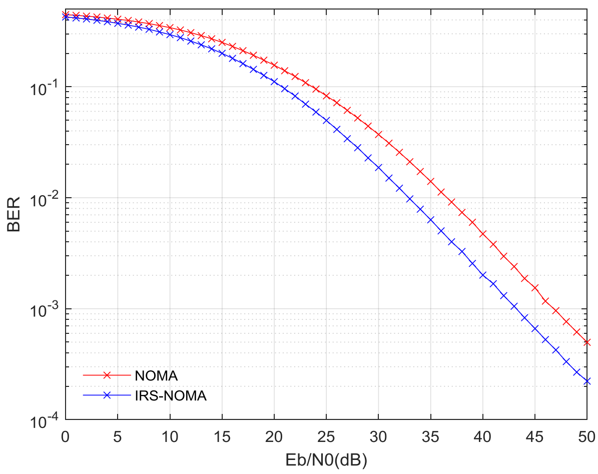
Fig. 2 compares the performance of IRS-NOMA with conventional NOMA for each user in terms of BER and the data rate. As depicted, IRS-assisted NOMA enhances the system's performance for the corresponding users. Also, comparing the difference in BER and rate indicates that IRS-NOMA distributes resources (i.e., power) more fairly than NOMA. To gain more insight into the impact of the IRS on the NOMA system, the proposed IRS-NOMA method is compared with NOMA in terms of average BER and sum rate in the next set of simulations. Fig. 3 confirms that IRS-NOMA outperforms NOMA, resulting in a lower average BER and higher sum rate.

In the continuation, we will examine how the placement of an IRS affects system performance based on different scenarios shown Fig. 4. In these scenarios, the BS, edge users, and IRS are located at the three vertices of a triangle. The BS is fixed in the cell center, and the users are fixed on the circle's perimeter. The aim is to investigate the effect of the IRS position on system performance from various aspects. Given that a, b, and c are the distances from the BS to the users, BS to the IRS, and IRS to the users respectively. In the first scenario, the IRS is positioned at an equal distance from the edge users $(b = c)$. The IRS is considered to be close to the BS $(b < c)$ in the second scenario. Finally, in scenario 3, the IRS is located near the cell edge users $(b > c)$. It's important to note that in all cases, $a > b, c$.

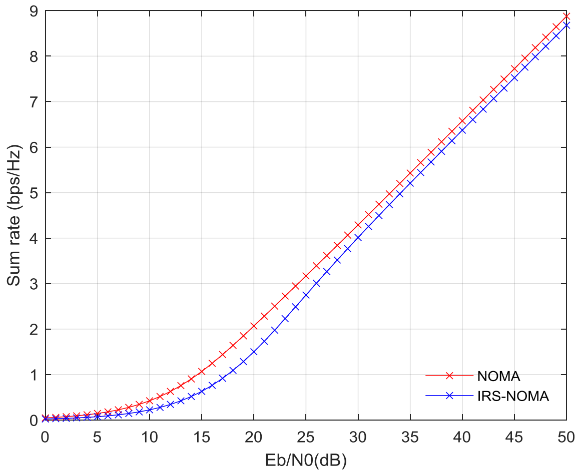


(b)

Fig. 2: Comparison of user performance in the NOMA and IRS-NOMA systems in terms of (a) BER and (b) data rate.



(a)



(b)

Fig. 3: NOMA vs. IRS-NOMA in terms of (a) average BER and (b) sum rate.

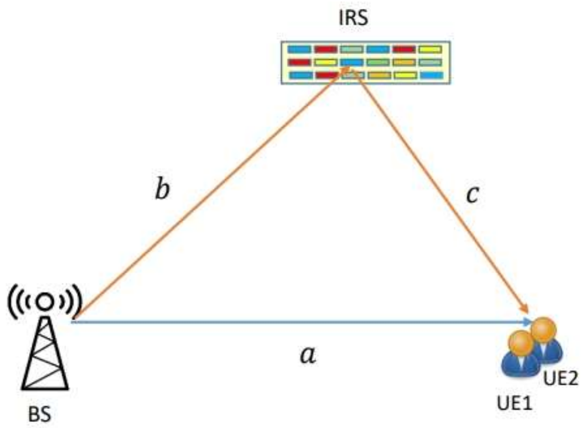
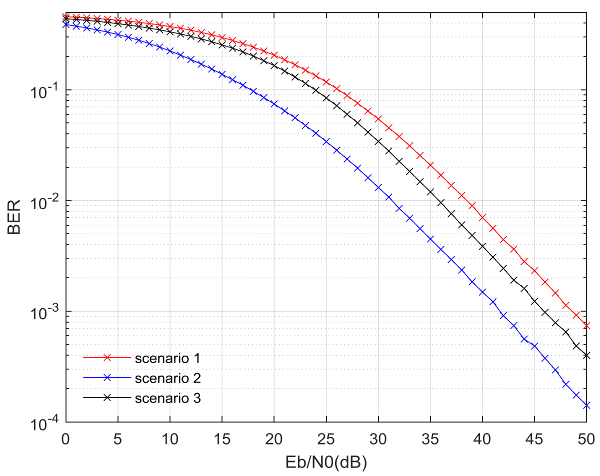
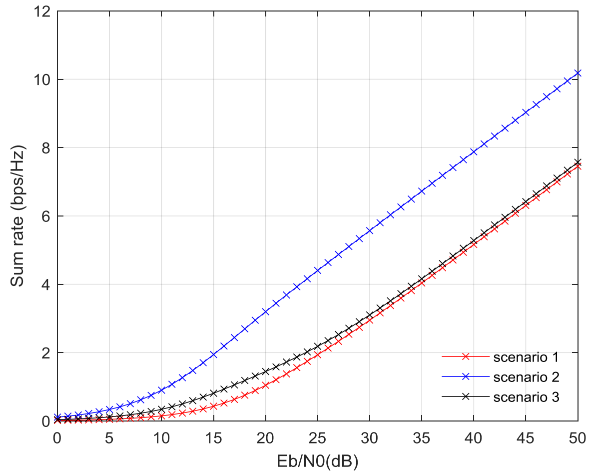


Fig. 4: Position of system components on the vertices of a given triangle.

Fig. 5 displays the simulation results for these three scenarios. Upon comparing the results, it is obvious that the second scenario demonstrates superior performance in terms of average BER and sum rate when compared to the other two scenarios. It confirms that the system performs better when the IRS position is closer to the BS.



(a)



(b)

Fig. 5: Effect of the IRS location on system performance in terms of (a) average BER and (b) sum rate.

Conclusion

This study investigates the performance challenges of edge users in the NOMA system due to poor signal quality and similar channel conditions. The aim is to utilize IRS capabilities to modify the time-varying transmission environment and improve overall system performance. To achieve this, an optimization problem is introduced to intelligently adjust the phase shifts of the IRS elements and allocate the power resources to edge users considering the channel gains constraint. The proposed IRS-assisted NOMA improves overall system performance and distributes resources more fairly than conventional NOMA. Compared to NOMA, the proposed IRS-NOMA system demonstrates a gain of about 4 dB at a BER of 10^{-2} and 3 dB at the sum rate of 10^{-1} bps/Hz. Furthermore, it has been observed that the placement of the IRS within the cell impacts system performance, suggesting that the system operates better when the IRS is positioned closer to the BS. In future work, we aim to find classical solutions for the sum rate optimization problem, particularly for groups with more than 2 users. Additionally, we plan to integrate machine learning (ML) models with IRS-NOMA systems to bring intelligence to the IRS controller.

Author Contributions

F. Rahdari and M. Sheikh-Hosseini designed the experiments. F. Rahdari and M. Sheikh-Hosseini, and M. Jamshidi formulated the optimization problem. M. Jamshidi implemented the optimization problem and obtained the results. F. Rahdari conducted the experiments and interpreted the results with M. Sheikh-Hosseini. F. Rahdari wrote the manuscript.

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Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Abbreviations

NOMA	Non-Orthogonal Multiple Access
BS	Base Station
SC	Superposition Coding
UE	User Equipment
SIC	Successive Interference Cancellation
OMA	Orthogonal Multiple Access
IRS	Intelligent Reflecting Surface
MISO	Multiple-Input Single-Output
SE	Spectral Efficiency
EE	Energy Efficiency
CRN	Cognitive Radio Networks
CSI	Channel State Information
BCD	Block Coordinate Descent
MC	Multi-Carrier
QoS	Quality of Service
DC	Difference of Convex
BER	Bit Error Rate
LOS	Line of Sight
SINR	Signal to Interference plus Noise Ratio
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase-Shift Keying
ZC	Zero Forcing
ML	Machine Learning

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