# EMI Performance Analysis in IRS-aided Multi-user Wireless Communication Systems

Rhana M. Elshishtawy*[1], Shimaa S. Ali*[2], Adly S. Tag Eldien*[3], Mostafa M. Fouda‡§[4], Mohamed I. Ismail¶[5], and Esraa M. Eid*[6]
*Department of Electrical Engineering, Faculty of Engineering at Shoubra, Benha University, Egypt.
‡Department of Electrical and Computer Engineering, Idaho State University, Pocatello, ID, USA.
§Center for Advanced Energy Studies (CAES), Idaho Falls, ID, USA.
¶Department of Electronic Engineering & Communication Technology, Modern Academy for Engineering, Egypt.
Emails: r.elshishtawy@yahoo.com[1], shimaa.salama@feng.bu.edu.eg[2], adlytag@feng.bu.edu.eg[3], mfouda@ieee.org[4], mohamed.ismail@eng.modern-academy.edu.eg[5], and esraa.soliman@feng.bu.edu.eg[6].

***Abstract*—This paper presents a comprehensive investigation into the effect of Electromagnetic Interference (EMI) on wireless systems employing single and distributed Intelligent Reflecting Surfaces (IRSs) in three distinct conditions by varying the number of antennas, elements, and users. Through extensive numerical simulations, the performance of the wireless systems is rigorously evaluated under different EMI scenarios. Firstly, the influence of varying the number of antennas on the system performance is thoroughly analyzed. The results demonstrate that an increased number of antennas contributes to improved signal reception and reduced interference levels. Moreover, the enhanced beamforming capabilities offered by additional antennas lead to higher signal quality and increased system Achievable Rate (AR). Secondly, the impact of changing the number of elements within the IRS under EMI conditions is investigated in detail. The simulations reveal that an augmented number of elements facilitates efficient EMI mitigation, enabling advanced signal manipulation and more precise signal focusing. As a result, the system exhibits improved performance in terms of signal strength, coverage, and AR. Lastly, the effect of varying the number of users on system performance in the presence of EMI is thoroughly assessed. The findings unveil that an increased number of users under EMI conditions leads to elevated interference levels, degraded signal quality, and diminished system AR. Thus, it is crucial to develop effective EMI mitigation strategies and resource allocation schemes to ensure reliable and efficient communication in IRS-enabled wireless systems.**

***Keywords*-Intelligent reflecting surfaces, electromagnetic interference, MIMO, and wireless systems.**

## I. Introduction

Intelligent Reflecting Surfaces (IRSs) have gained significant attention in recent years as a promising technology for enhancing wireless communication systems [1]–[4]. An IRS is a planar surface composed of a large number of low-cost, passive reflecting elements that can be electronically controlled to reflect incident electromagnetic waves in a desired manner [5]. By adjusting the phase shift of the reflected waves, the IRS can create constructive or destructive interference patterns, thus enhancing the signal power at the receiver and reducing the interference from other sources [6].

The use of IRSs in communication systems has been shown to provide significant benefits, including increased spectral efficiency, improved coverage, and reduced power consumption [7]. However, the deployment of IRSs in practical systems also raises a number of challenges, particularly in the presence of interference from other sources. In this paper, we review the recent research on the use of IRSs in communication systems, with a focus on interference management techniques. However, the performance of IRSs can be affected by various factors, such as the size and shape of the reflecting elements, the distance between the elements, and external electromagnetic interference (EMI) from other sources. Several recent studies have investigated the impact of EMI on the performance of IRSs, and proposed various techniques to mitigate its effects [8]–[10]. EMI is a byproduct of any wireless signal that cannot be controlled. It is an unavoidable aspect of wireless communication systems. The IRS is susceptible to EMI from all spatial directions, which is then absorbed and re-radiated proportionally to its surface area. Although the re-radiated EMI may not be directed towards the intended receiver, a significant portion of its energy can still reach the receiver and cause degradation in the end-to-end signal-to-noise ratio (SNR) of the system. This is particularly concerning as the system is typically designed to perform optimally in the presence of only thermal noise. In this paper, we investigate the effect of external EMI on IRSs with varying the number of antennas, elements, and users. Through extensive numerical simulations, the performance of the wireless systems is rigorously evaluated under different EMI scenarios and compared with the performance of a system without EMI.

## II. Related Work

The IRSs have recently emerged as a promising technology for enhancing wireless communication systems. The ability of these surfaces to reflect and manipulate electromagnetic waves has the potential to improve signal strength, increase coverage, and reduce interference in wireless communication systems. The use of IRSs has been explored in various applications, including physical layer security, energy efficiency, and millimeter wave communication.

One of the earliest works on IRS was published in [11]. In this paper, the authors proposed a method for designing a reconfigurable intelligent surface that could adjust its reflection

2023 IEEE Virtual Conference on Communications (VCC) | 979-8-3503-1880-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/VCC60689.2023.10474995

coefficients to optimize the received signal strength at a receiver. They demonstrated that this approach could significantly improve the SNR in a wireless communication system.

Since then, numerous studies have been conducted on the topic of IRS, and several different approaches have been proposed for optimizing the performance of these surfaces. One common approach is to use machine learning algorithms to train the surface to optimize its reflection properties. For example, in [5], the authors proposed a deep learning-based approach for designing an IRS that could optimize the received signal strength in a wireless communication system. They achieved significant improvements in performance over traditional approaches. Another popular approach is to use optimization algorithms to design the surface. For example, in [12], the authors proposed an approach for designing an IRS that could optimize the coverage area of a wireless communication system. They used an optimization algorithm to determine the optimal reflection coefficients for the surface.

Additionally, there has been significant interest in the use of multiple IRSs to further improve the performance of wireless communication systems. In [13], the authors proposed a method for using multiple IRSs to improve the coverage and AR of a wireless communication system. They demonstrated that their approach could achieve significant improvements in performance over traditional approaches.

The authors in [14] provide a model, showing that EMI affects the SNR linearly with IRS size and can even reduce performance when a direct link is present. They address electromagnetic interference (EMI) in IRS-aided communications, highlighting its non-negligible impact on performance and the need to consider it for accurate analysis and design. Interference can arise from multiple sources, including other wireless communication systems, electronic devices, and environmental factors. Interference can degrade the performance of wireless communication systems and reduce the effectiveness of IRSs. Therefore, several studies have focused on developing methods to mitigate interference in IRS-based communication systems.

For example, in [15], the authors proposed a method for joint interference management and beamforming in an IRS-assisted wireless communication system. They demonstrated that their approach could significantly improve the signal quality and reduce the interference level in the system.

In another paper [16], the authors proposed an interference-aware resource allocation algorithm for an IRS-assisted wireless communication system. They demonstrated that their approach could improve the system's AR and reduce the interference level. The paper [17] presents a comprehensive survey on the use of IRSs and Unmanned Aerial Vehicles (UAVs) in Internet of Things (IoT) networks, highlighting their potential to enhance system performance and maximize energy efficiency. Overall, the literature on Intelligent Reflecting Surfaces is relatively new, but it has already generated significant interest and produced many promising results. Future research in this area will likely focus on further optimizing the performance of these surfaces, developing methods to mitigate interference, and exploring their potential applications in a variety of different contexts. Interference is a significant issue in wireless communication systems, and this is also true for IRS-based systems. Interference, which can originate from wireless communication systems, electronic devices, and environmental factors, has the potential to degrade wireless communication performance and hinder the effectiveness of IRSs. Consequently, multiple studies have been carried out to devise strategies for mitigating interference in communication systems based on IRS technology. In addition to these studies, other research has explored the effect of interference on IRS-based communication systems. For example, in [18], the authors investigated the impact of interference on the performance of IRS-assisted wireless communication systems. They showed that interference could significantly degrade the system's performance and that the use of multiple IRSs could mitigate this effect. Overall, interference is an important consideration in the design and deployment of IRS-based communication systems. Mitigating interference is essential to achieve the full potential of IRSs in improving the performance of wireless communication systems. Future research in this area will likely focus on developing more efficient and effective methods for interference mitigation in IRS-based communication systems.

## III. System Model

We consider a massive MIMO scattering environment, aided with an IRS with *N* re-configurable elements. The IRS elements are arranged in a two-dimensional square grid [19]. Fig. 1 depicts the arrangement in three-dimensional space, such that the IRS defines a local spherical coordinate system with $\phi_l$ being the azimuth angle and $\theta_l$ being the elevation angle. The elements are indexed row by row by the numbers $\bar{1}, ..., N$, also A represents the area. As a result, the $\hat{t}h$ element is found at $t_a = [t_{x,a}, t_{y,a}, 0]^T$ where $t_{x,a} = -\frac{(\sqrt{N}-1)\sqrt{A}}{2} + \sqrt{A}$ $mod(a-1, \sqrt{N})$ and $t_{y,a} = \frac{(\sqrt{N}-1)\sqrt{A}}{2} - \sqrt{A}[\frac{a-1}{\sqrt{N}}]$.

Each IRS element penetrates the incoming signal with a controlled phase shift while not increasing its power. Prior literature has ignored EMI (incoming waves from external sources):

- The paradigm is used to reveal that EMI has a considered impact on the performance of the communication process.
- channel matrix between the Access Point (AP) of M-antennas and IRS is $H_{M,N}$, $H_{M,N} = [h_{M,1}, ......, h_{M,N}]^T$ .
- channel matrix between the IRS and the U receivers is $H_{N,U}$, $H_{N,U} = [h_{N,1}, ......, h_{N,U}]^T$
- The matrix determines the IRS configuration.

$$\theta_l = \Gamma \phi_l \tag{1}$$

$\Gamma = diag(\gamma_1, \gamma_2, ...., \gamma_N) \qquad \gamma_1, ...., \gamma_N \in [0, 1]$
$\phi_l = diag(e^{j\phi_{l1}}, e^{j\phi_{l2}}, ...., e^{j\phi_{lN}}) \qquad \phi_{l1}, ...., \phi_{lN} \in [0, 2\Pi]$ $\gamma_a e^{j\phi_{l1}}, \qquad a = 1, ..........., N$

### A. The Model of the Signal

Received signal at IRS is $X \in C^N$

$$X_l = H_{M,N} S + n_l \tag{2}$$

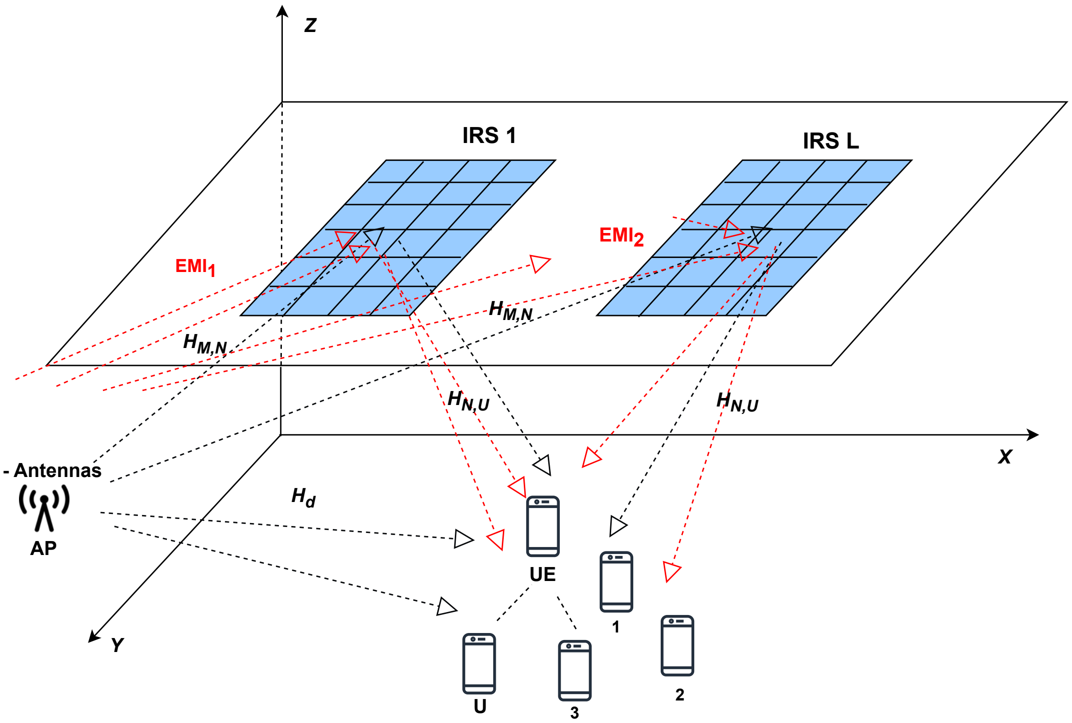


Fig. 1. IRS-aided communication system model.

As the transmitted power P is known by S

$$P = E|\ S\ |^2 \tag{3}$$

Here, n represents the EMI which is a result of the incoming electromagnetic waves. $n_l \in C^N$ Also, Y is the received signal at the User Equipment (UE).

where it is the effective channel (including IRS phase shift) and $h_d$ is the direct path channel gain. w is the noise $w\ tendstoN_C(0, \sigma_w^2)$ substitution from (1) in (2)

$$Y = (g l_{N,U}^H + H_d)S + g l_{N,U}^H n_l + w \tag{4}$$

We want to evaluate the impact of the EMI $n_l$ on communication performance which is neglected in the IRS literature.

## B. Electromagnetic interference paradigming

- The EMI $n_l$ is a result of the incoming plane waves that are made by external sources
- In the far field of the half-space opposite to the IRS the waves are generated.
- Representing each one as a plane wave that reaches the IRS from: azimuth angle $\phi_l \in [-\pi/2, \pi/2]$ and elevation angle $\theta_l \in [-\pi/2, \pi/2]$
- The EMI field $n_l$

$$n_l = \iint_{-\pi/2}^{\pi/2} V(\phi_l, \theta_l) d\phi_l d\theta_l \tag{5}$$

$$V(\phi_l, \theta_l) = b(\phi_l, \theta_l) e^{jk(\phi_l,\theta_l)^T t_a} \quad \in C^N \tag{6}$$

$$b(\phi_l, \theta_l) = [e^{jk(\phi_l,\theta_l)^T t_1}, \ldots\ldots\ldots\ldots\ldots, e^{jk(\phi_l,\theta_l)^T t_N}]^T \tag{7}$$

$b(\phi_l, \theta_l)$ is a Gaussian zero mean complex random process,w.r.t three Cartesian coordinates at the receiving volume the phase variation of the plane wave uses $k(\phi_l, \theta_l)$ that describes a wave vector.

$$k(\phi_l, \theta_l) = 2\pi/(\lambda)[\cos\theta_l \cos\phi_l, \cos\theta_l sin\phi_l, \sin\theta_l]^T \tag{8}$$

by substituting in (4)

$$n_l = \iint_{-\pi/v2}^{\pi/2} b(\phi_l, \theta_l) e^{jk(\phi_l,\theta_l)^T t_n} d\phi_l\ d\theta_l \tag{9}$$

Where,

$$b(\phi_l, \theta_l) = [e^{jk(\phi_l,\theta_l)^T t_1} \ldots\ldots\ldots e^{jk(\phi_l,\theta_l)^T t_N}]^T \tag{10}$$

Therefore,

$$n_l = \iint_{-\pi/v2}^{\pi/2} [e^{-k(\phi_l,\theta_l)^T (t_n - t_m)} d\phi_l\ d\theta_l \tag{11}$$

$b(\phi_l, \theta_l)$ is a zero mean complex Gaussian random process with: $E\{b(\phi_l, \theta_l)\ b(\grave{\phi_l}, \grave{\theta_l})\} = A\sigma^2 f(\phi_l, \theta_l)\delta(\phi_l - \grave{\phi_l}\delta(\theta_l - \grave{\theta_l})$ where: $\delta^2 f(\phi, \theta)$ is angular density of interference power with $\iint_{-\pi/v2}^{\pi/2} f(\phi_l, \theta_l) d\phi_l\ d\theta_l = 1$and $\delta^2$ is measured in $\omega/m^2$ $E\{n_l n_l^H\} = A\delta^2 R$ with

$$[R_l]_{n,m} = \iint_{\pi/v2}^{\pi/2} e^{jk(\phi_l,\theta_l)^T (t_n - t_m)} f(\phi_l, \theta_l) d\phi_l\ d\theta_l \tag{12}$$

such that $\sigma$ is the thermal noise $\sigma_w^2$ electromagnetic waves interference.

### C. Performance Analysis

The system parameters are defined, including the total radiated power, carrier frequency, speed of light, wavelength, bandwidth, and thermal noise. The positions of the IRS, transmitter, and receiver are also specified, as well as the number of Monte Carlo trials.

$$Y = g1_{N,U}^{H} X_1 + H_d S + g2_{N,U}^{H} X_2 + w \tag{13}$$

where $g1_{N,U} = \theta_{11} H_{N,U}$ , $g2_{N,U} = \theta_{lN,U} H_{N,U}$, which represents the effective channel (including IRS phase-shifts), $X_1 = H_{M,N} S + n_1$, $X_2 = H_{M,N} S + n_2$, assume $n_1 = n_2 = n$

The elements located at the same row i(n)=i(m) and (j(n)-j(m)) dv=$\| t_n - t_m \|$ , n,m =1,2,... N
The received signal-to-noise ratio $SNR_1$ in the case of Single IRS (SIRS) is given by:

$$SNR_1 = \left( \frac{P * |g_{N,U}^{H} * H_{M,N} + H_d|^2}{A * \sigma^2 * g_{N,U}^{H} * R1 * g_{N,U} + \sigma_w^2} \right) \tag{14}$$

In equation (15), $SNR_2$ represents the received signal-to-noise ratio in the case of Distributed IRS (DIRS)

## IV. Results and Discussion

In this section, we conducted a series of numerical simulations to investigate the impact of EMI on the performance of single and distributed Intelligent Reflecting Surfaces (IRS) in various scenarios. Our simulations focused on three specific cases: varying the number of antennas (M), changing the number of elements (N), and adjusting the number of users (U) in the system.

**Number of Antennas:** Firstly, we examined the effect of changing the number of antennas on the system's performance in the presence of EMI. By systematically varying the number of antennas while keeping other parameters constant, we assessed how EMI affected signal quality, interference levels, and overall system Achievable Rate (AR). Using the following equation:

$$\rho = \frac{p\beta_1}{\sigma^2} \tag{16}$$

which is equivalent to the ratio between the received signal power and EMI power at each antenna element of the IRS. Our simulations revealed that as the number of antennas increased, the system exhibited improved resistance to EMI, resulting in enhanced signal reception and reduced interference.

In Fig. 2, it appears to depict the relationship between the AR from [20] as an N function. Using $\rho = 5, 10$ and 15. Single antenna Access point (AP) and single antenna user are used, which are equivalent to M=1 and U=1 respectively. The AR shows the best performance while neglecting the presence of EMI for both cases of the Single IRS (SIRS) and distributed IRS (DIRS). At $N = 20$, in case of SIRS the AR is [7.9, 9.3, and 10.6] bps/Hz for $\rho$ values 5, 10, and 15 respectively. On the other hand, while using DIRS, we find that the AR is [9, 10.4, and 12] bps/Hz for $\rho$ values 5, 10, and 15 respectively. which is logic in confirming a better achievable rate when using DIRS that mitigates the effect of EMI on the system.

Fig. 3 describes the relation between the AR vs N, with the effect of EMI for multiple AP, M=10, and single antenna user U=1; on both the SIRS and DIRS system. It reveals that the AR shows the best performance while neglecting the presence of EMI for both cases of SIRS and DIRS. After taking into consideration the $\rho = 5, 10$ and 15 in our calculations for SIRS, it is equal to [14.8, 17, and 17.5] bps/Hz respectively. On the other hand, using DIRS with the same value of $\rho$ achieves AR= [16, 17.5, and 18] bps/Hz which increases the system performance due to mitigating the EMI effect.

Fig. 4 declares the AR vs. N, using a massive number of antennas with M=100 vs. a single receiver. our numerical simulations provided valuable insights into the effects of EMI on SIRS and DIRS systems across varying scenarios. At N=20, in both cases of using SIRS and DIRS, we found that the AR is approximately equal to 22.5 bps/Hz when $\rho = 5$ The results underscore the significance of considering the number of antennas, elements, and users when evaluating the system's performance under EMI conditions.

**Number of Elements:** Fig. 5 demonstrates the relation between AR vs. the number of AP antennas, such that without EMI, both SIRS and DIRS configurations exhibit favorable performance. However, as the level of EMI increases, the performance of the IRS system deteriorates. Specifically, by using N=15 and U=1 for the SIRS configuration, as the $\rho$ level rises from 5 to 15, there is a noticeable increase in performance. Similarly, for the DIRS configuration, an increase in the $\rho$ value from 5 to 15 leads to a significant enhancement in system performance. The findings also suggest that both SIRS and DIRS configurations are susceptible to EMI, and careful consideration must be given to system design and resource allocation to minimize the effects of EMI. The relation between AR vs number of AP Antennas was repeated in Fig. 6 but with using a higher number of elements in both SIRS and DIRS with the same single user. Using N=30 and U= 1, we have noticed that for SIRS a noticeable enhancement as $\rho$ levels up from 5 to 15. on the same side by using DIRS the results show better AR performance as $\rho$ levels up from 5 to 15 which confirms our analysis.

**Number of Users:** Fig. 7 shows AR vs. U at N=15 and M=10, it illustrates the effect of EMI on SIRS and DIRS systems. It shows that without EMI, both single and distributed IRS configurations exhibit good performance. However, increasing EMI levels lead to performance degradation. For the SIRS, higher EMI levels result in noticeable declines in performance. Similarly, the distributed IRS configuration experiences significant performance degradation with increasing EMI.For Using the same N but M=50 in Fig. 8 we find for SIRS and DIRS the best performance without the EMI. On the other hand, taking EMI into consideration shows degradation and coincidence in the results. By repeating the calculations but with N=30 and M=50, both the SIRS and DIRS in Fig. 9 show the same performance as the last two figures. overall, in this part, we measure the effect of EMI on the number of users, at the absence of EMI as the number of users increases, the AR will increase in proportion. On the other hand, in the

$$SNR_2 = \left( \frac{P * |g_{N,U}^H * H_{M,N} + g_{N,U}^H * H_{M,N} + h_d|^2}{A * \sigma^2 * g_{N,U}^H * R1 * g_{N,U} + A * \sigma^2 * g_{N,U}^H * R2 * g_{N,U} + \sigma_w^2} \right) \tag{15}$$

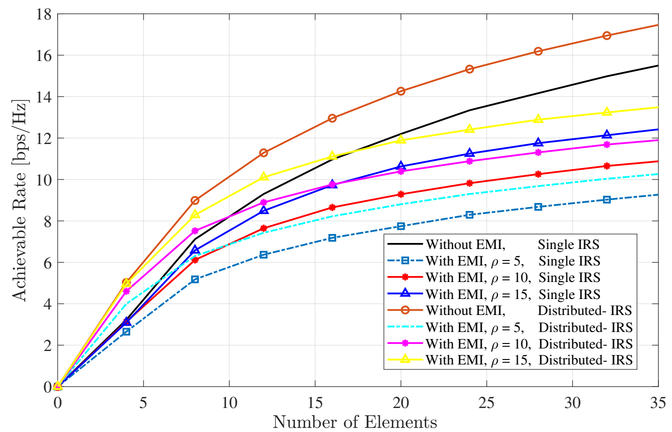


Fig. 2. Achievable rate vs. the number of elements for a single antenna Access Point and a single antenna user for (M=1) and (U=1) for the IRS system.

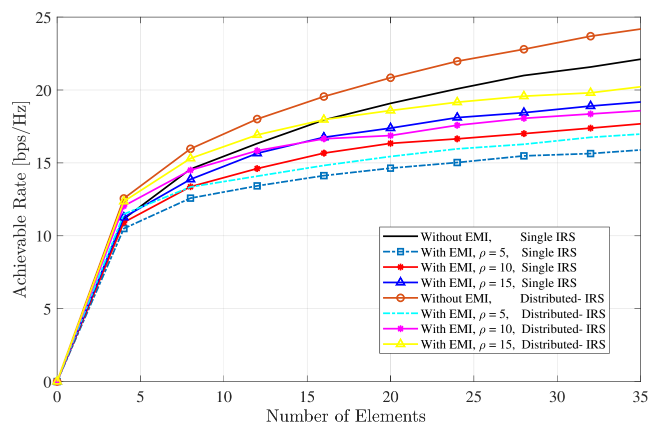


Fig. 3. Achievable rate vs. the number of elements for a single antenna access Point and a single antenna user for (M=10) and (U=1) for the IRS system.

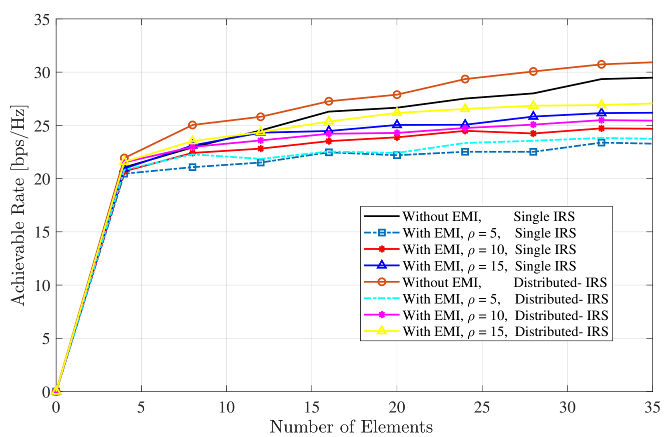


Fig. 4. Achievable rate vs. the number of elements for a single antenna access point and a single antenna user for (M=100) and (U=1) for the IRS system.

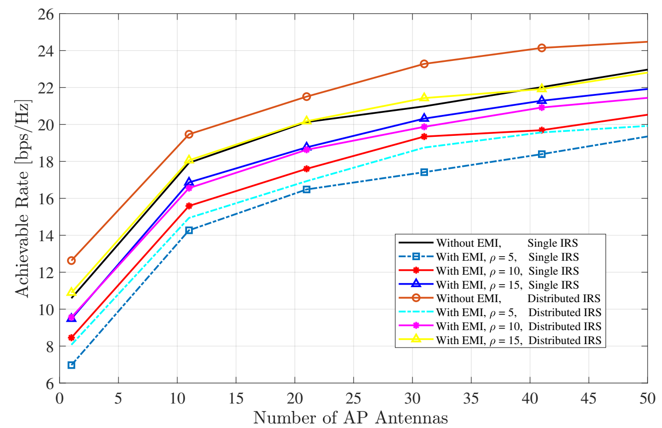


Fig. 5. Achievable rate vs. the number of access point antennas and a single antenna user for (N=15) and (U=1) for the IRS system.

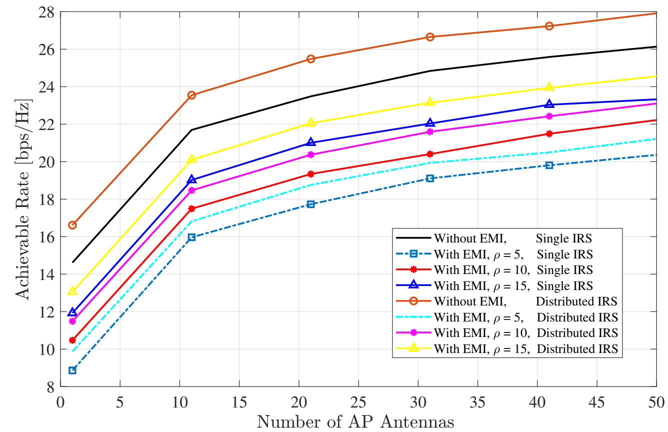


Fig. 6. Achievable rate vs. the number of access point Antennas and a single antenna user for (N=30) and (U=1) for the IRS system.

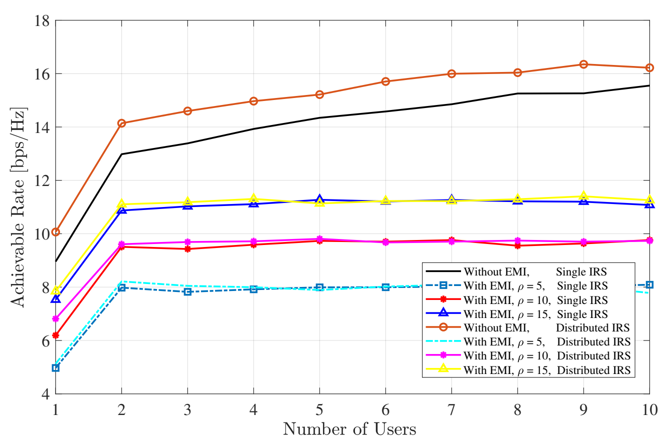


Fig. 7. Achievable rate vs. the number of users and a single antenna user for (N=15) and (M=10) for the IRS system.

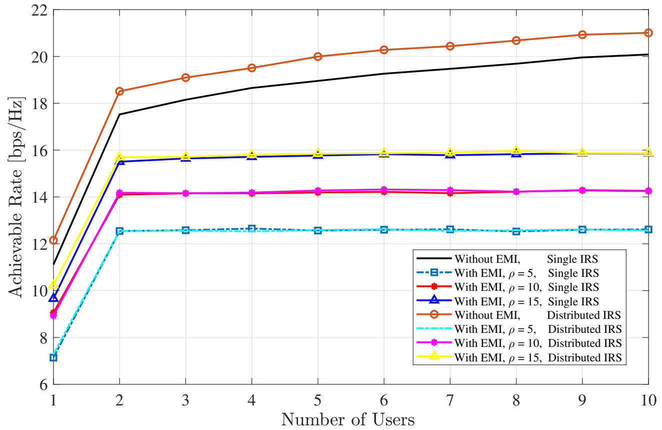


Fig. 8. Achievable rate vs. the number of users and a single antenna user for (N=15) and (M=50) for the IRS system.

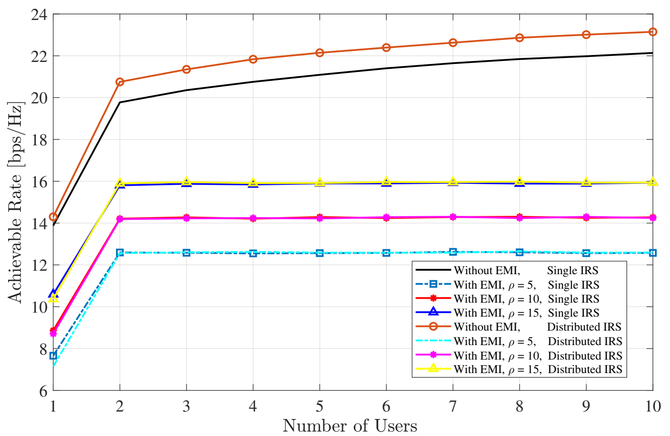


Fig. 9. Achievable rate vs. the number of Users for (N=30) and (M=50) for the IRS system.

presence of EMI as the number of users increases, the AR improvement will remain constant after the number of users reaches two users and this is because of the equality in the AR performance value vs. the impact of EMI on the system which leads to constant performance.

## V. Conclusion

This paper presents key findings regarding the effects of EMI on wireless systems with Intelligent Reflecting Surfaces (IRS). It concludes that increasing the number of antennas improves signal reception, reduces interference, and enhances system AR. A higher number of elements within the IRS enables efficient EMI mitigation, leading to improved signal strength, coverage, and AR. However, an increased number of users under EMI conditions results in elevated interference levels, degraded signal quality, and reduced system AR. Effective EMI mitigation strategies and resource allocation schemes are crucial. The study emphasizes the need to consider external EMI and develop mitigation techniques. Additionally, multiple IRSs can further enhance wireless systems by improving coverage, AR, and interference management. Future research should focus on optimizing IRS performance and exploring potential applications.

## References


[1] E. M. Mohamed, S. Hashima, K. Hatano, and M. M. Fouda, "Cost-effective MAB approaches for reconfigurable intelligent surface aided millimeter wave relaying," *IEEE Access*, vol. 10, pp. 81 642–81 653, 2022.

[2] M.-S. Van Nguyen, D.-T. Do, V.-D. Phan, W. Ullah Khan, A. L. Imoize, and M. M. Fouda, "Ergodic performance analysis of double intelligent reflecting surfaces-aided NOMA-UAV systems with hardware impairment," *Drones*, vol. 6, no. 12, article no. 408, 2022.

[3] H. Hashida, Y. Kawamoto, and N. Kato, "Machine learning-based infrastructure sharing and shared operations for intelligent reflecting surface-aided communications," *IEEE Transactions on Cognitive Communications and Networking*, pp. 1–1, 2023.

[4] Y. Zhu, B. Mao, and N. Kato, "On a novel high accuracy positioning with intelligent reflecting surface and unscented kalman filter for intelligent transportation systems in B5G," *IEEE Journal on Selected Areas in Communications*, pp. 1–1, 2023.

[5] Q. Wu, R. Zhang, J. Xu, and H. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Transactions on Wireless Communications*, vol. 18, no. 11, pp. 5394–5409, 2019.

[6] Z. Zhang, C. Xiao, Q. Wu, and F. Hu, "Intelligent reflecting surface: A programmable wireless environment for physical layer security," *IEEE Network*, vol. 34, no. 3, pp. 92–99, 2020.

[7] E. Basar, M. Di Renzo, and M. Debbah, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116 753–116 773, 2019.

[8] Y. Liu, A. Li, J. Zhang, and X. Zhang, "Intelligent reflective surface-assisted wireless network with channel estimation errors," *IEEE Transactions on Wireless Communications*, vol. 20, no. 2, pp. 1167–1181, 2021.

[9] B. Huang, J. Zhang, Y. Li, T. Huang, and X. Zhang, "Optimization of intelligent reflecting surface-aided wireless networks: A comprehensive survey," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 505–545, 2021.

[10] H. Zhu, R. Zhang, X. Zhang, and X. You, "Intelligent reflecting surface aided communications: A survey and tutorial," *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 9, pp. 2623–2640, 2021.

[11] C.-K. Huang, A. Zoha, and M. Dohler, "Reconfigurable intelligent surfaces for energy-efficient wireless communications," *IEEE Access*, vol. 7, pp. 99 512–99 530, 2019.

[12] J. Ntontin, E. Kartsakli, A. Pitsillides, and L. Georgiadis, "Intelligent reflecting surfaces for wireless networking: A survey and tutorial," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 16–42, 2021.

[13] Y. Hu, M. Chen, Y. Shi, and K. B. Letaief, "Beyond massive MIMO: The potential of positioning-enabled intelligent reflecting surfaces," *IEEE Transactions on Signal Processing*, vol. 68, pp. 303–315, 2020.

[14] A. de Jesus Torres, L. Sanguinetti, and E. Björnson, "Electromagnetic interference in RIS-aided communications," *IEEE Wireless Communications Letters*, vol. 11, no. 4, pp. 668–672, 2021.

[15] Y. Li, H. Guo, R. Zhang, and S. Jin, "Joint interference management and beamforming for intelligent reflecting surface assisted wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 3, pp. 849–863, 2021.

[16] J. Zhang, L. Zhang, and R. Zhang, "Interference-aware resource allocation for intelligent reflecting surface assisted wireless communication systems," *IEEE Transactions on Wireless Communications*, vol. 20, no. 4, pp. 2380–2393, 2021.

[17] S. A. Alsarayreh, N. A. M. Radzi, A. A. Alkahtani, and K. H. M. Azmi, "Intelligent reflecting surface-UAV systems in the internet of things network: A survey," *IEEE Access*, 2023.

[18] P. Adhikari, J. Cho, and S. Durrani, "Intelligent reflecting surfaces: The impact of interference," *IEEE Wireless Communications Letters*, vol. 9, no. 2, pp. 226–230, 2020.

[19] M. Di Renzo, A. Zappone, M. Debbah, M.-S. Alouini, C. Yuen, J. De Rosny, and S. Tretyakov, "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead," *IEEE journal on selected areas in communications*, vol. 38, no. 11, pp. 2450–2525, 2020.

[20] J.-C. Chen, "Capacity improvement for intelligent reflecting surface-assisted wireless systems with a small portion of active elements," *IEEE Access*, vol. 10, pp. 100 438–100 445, 2022.