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Impact of the Number of Reflecting Elements and Positioning of the Reconfigurable STAR-Passive-ORIS in MIMO FSO Systems

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Abstract

This study aims to improve the performance of reconfigurable STAR-passive-OIRS in multiple input multiple output-based free-space optical (FSO) communication systems. The study focuses on analysing the influence of two main factors: the number of reflective elements and the location of the smart surface. STAR-RIS technology has shown great potential in improving spectrum efficiency and signal-to-noise and interference ratio (SINR) and in increasing channel gain by providing 360° coverage and reducing interference in environments with line-of-sight constraints. Results reveal that increasing the number of reflective elements enhances signal strength and improves SINR, whilst placing the smart surface closer to the source or receiver achieves optimal performance. The study highlights STAR-RIS technology's ability to overcome traditional FSO systems' limitations and improve network performance in modern wireless communication environments.

Keywords: *Free space optics (FSO); Intelligent reflecting surface (IRS); Nonorthogonal multiple access (NOMA); Radio frequency (RF); and simultaneous transmitting and reflecting reconfigurable intelligent surface (STAR-RIS).*

1. Introduction

In recent years, the high speed and simplicity of wireless communication environments have become essential [1]. Free space optical (FSO) communications are considered a potential alternative to offer quick data transfer rates [2]. FSO is a promising candidate to meet the requirements of 5G and beyond (B5G), such as high capacity, high bandwidth, fast speed and low power consumption [3]. However, the trees and walls are regarded as obstacles and limitations; therefore, FSO technology has certain fundamental drawbacks, such as little to no support and limited mobility for nonline of sight (NLOS) [4]. In addition, the quality of FSO is affected by several factors, such as atmospheric turbulence (AT) (e.g. fog and rain) [5], [6]. FSO's performance might be enhanced by many methods such as the hybrid models of dual-hop RF-FSO integrating the advantages of FSO and RF communication [7].

Research in this direction has many types which use hybrid RF-FSO technologies together [7], [8], [9], [10]. Although using FSO/RF together has the advantage of helping overcome the disadvantages of FSO, this solution increases the complexity and cost of the system [10]. The decode and forward (DF) relay strategy can improve quality to enhance performance and mitigate disturbances [11], but it has drawbacks such as latency and high power consumption [11].

An intelligent reflecting surface (IRS), which is a surface with many reflecting elements, can be used to reflect signals in the desired direction. Furthermore, it can overcome FSO's NLOS limitations, increase signal coverage, enhance channel conditions and create a virtual line of sight

LOS [5], [4]. Hybrid FSO/RF communication systems that use a reconfigurable intelligent surface (RIS) can further improve FSO performance [12]. Optical intelligent reflecting surfaces (OIRS) have the potential to improve the capabilities of future generations of optical wireless communication systems by reconfiguring the propagation environment of optical waves [13]. IRS and OIRS can be passive or active and reconfigurable or nonreconfigurable [14][15][16][17]. RISs capable of simultaneous transmission and reflection, known as STAR-RIS, are increasingly prevalent. STAR-RIS can reflect and refract signals, providing complete wireless coverage and enhanced degrees of freedom (DOFs) and providing transmitters for users on both sides. This type is different from the traditional IRS, which only reflects signals to users on the same side, thus solving the limitation of traditional IRS, which cannot be used when the transmitter and receiver are on different sides [18]. In addition, the number of reflecting elements and IRS improve performance and increase gain, and this number depends on the type of application and the requirement of the design of the communication system [12].

Furthermore, integrating multiple access methods with the IRS is essential to address communication requirements efficiently for a wide range of services. These methods play a role in optimising the allocation of frequencies, ensuring speedy communication and promoting the development and expandability of the communication systems. One of these methods is orthogonal multiple access (OMA), which is employed by the IRS and offers advantages such as reducing interference [19]. OMA includes techniques such as frequency division multiple access, orthogonal frequency division multiple access, code division multiple access and time division multiple access, which are effective in reducing interference to users, thereby improving reliability [19]. However, OMA encounters impediments as an effect of altered channel conditions and data patterns, which can lead to the underutilisation of spectrum resources and a reduction in capacity [19].

On the one hand, nonorthogonal multiple access (NOMA) techniques offer an idea of shared resource utilisation, which substantially enhances efficiency through intelligent power allocation [20]. It effectively deals with signal weakening by strategic power allocation and using advanced coding methods that allow multiple data transmissions simultaneously [21][22]. By judicious use of resources, NOMA improves the resilience and efficiency of IRS. Successive interference cancellation (SIC) plays a role in this context. SIC helps untangle overlapping signals, which is important when multiple users are involved in NOMA scenarios [21].

Multiple-input multiple-output (MIMO) strategies have been extensively studied to enhance data rates and reliability without putting strain on time and spectrum resources [23]. This system consistently outperforms the single-input single-output system [23].

In the modern world of FSO, reconfigurable STAR-passive-OIRS is a potential technology that can enhance the efficacy of spectrum and network coverage. By manipulating the environment surrounding the radio waves, reconfigurable STAR-passive-OIRS technology offers the ability to enhance the overall system performance whilst reducing interference and increasing the SINR. In addition, strategically locating reconfigurable STAR-passive-OIRS plays a crucial role in increasing efficiency, especially in systems with LOS limitations. In this study, we investigate the effect of optimising IRS location and the number of reflective elements on the performance improvement of a STAR-RIS-based FSO communication system. The paper is organised as follows: Section 1 contains the introduction. Section 2 details the associated work. Section 3 presents the mathematical model, whilst Section 4 provides numerical results and discussions. Section 5 presents the study's conclusion.

2. Related Work

A future technique for future 5G and B5G wireless communications to improve coverage and capacity is RIS, which has a low hardware cost and energy consumption [24]. In [25], the authors examined the potential of IRSs to alleviate the LOS constraint of FSO systems.

In [12], the authors suggested a novel wireless transmission method that employs RIS for hybrid RF/FSO communications. In [26], the researchers investigated the mathematical model and design of IRS-assisted optic communication systems, which are employed to reduce the LOS demand for multilink FSO systems. In [27], the impact of defects in SIC technology when using IRS with NOMA systems was discussed. In [28], the researchers improved the use of reconfigurable RIS in radio frequency systems. The focus was on choosing the optimal number of adjustable reflective elements within the RIS to achieve improved data transfer rates and energy efficiency. In [29], the authors discussed how to optimise the location of the IRS to achieve optimal performance in wireless communication systems. The paper presented an analytical study to determine the optimal location of IRS by analysing the effect of different settings, such as surface height and stability, phase signal distribution and the effect of antenna orientation.

A new STAR system design, which is based on reconfigurable intelligent surfaces (STAR-RISs), was proposed [30]. The conventional RIS was contrasted and investigated in comparison with STAR-RISs [31]. IRS and STAR-RIS were systematically reviewed in [32] and [33], with a detailed explanation of them, clarifying their benefits and their general impact on the performance of networks for 5G, B5G and 6G. Furthermore, their uses and challenges were presented with possible future research directions.

In [34], a mathematical model was proposed to describe the mechanism of simultaneous transmission and reflection in STAR-RIS, and new resource allocation schemes were designed to improve the efficiency of transmission and reflection, including power distribution between the two directions and development of algorithms to improve performance, such as optimising beamforming and maximising data transfer rate. In [35], the integration of active STAR-RIS with massive MIMO communication systems was proposed. In [36], STAR-RIS was proposed to enhance covert communications in NOMA networks. The researchers focused on designing a system that ensures the existence of the communication is hidden from eavesdroppers whilst improving the efficiency of data transmission.

The table below shows some previous works using RIS or STAR-RIS with different technologies and channels and their most important contributions.

Table 1,
Comprehensive review of RIS and STAR-RIS with many techniques in RF and FSO communication systems

Ref.	Type of IRS	Techniques	Channel type	Contribution
[25]	IRS	No	FSO	Focused on improving signal quality and increasing communication distance
[12]	IRS	no	RF/FSO	Improved the performance of hybrid communication systems that combine RF and FSO systems
[26]	IRS	MIMO	FSO	Developed mathematical models to analyse the performance of systems and proposed strategies to improve communication efficiency
[28]	IRS	no	RF	Determined the optimal number of reflective elements in RIS to achieve remarkable improvements in the performance of wireless communication systems
[27]	IRS	NOMA	RF	Analysed the system’s performance under nonideal SIC conditions and proposed improvements to increase communication efficiency
[29]	IRS	no	RF	Proposed algorithms to determine the optimal location of RIS with the aim of enhancing signal quality and extending coverage
[34]	STAR-RIS	no	RF	Developed algorithms to optimise active beamforming in the base station and passive beamforming in STAR-RIS, with the aim of improving system performance and reducing power consumption
[35]	STAR-RIS	MIMO	RF	Developed algorithms for power distribution and beamforming optimisation
[36]	STAR-RIS	NOMA	RF	Analysed the probability of eavesdroppers discovering the communication and developing strategies for packet design and resource allocation to ensure confidentiality of communication

This study aims to address the research gaps related to determining the optimal location and number of elements for STAR-passive reconfigurable optical systems (STAR-passive-OIRS) in the MIMO-FSO environment. Although previous research has provided mathematical models for the simultaneous transmission and reflection mechanism in STAR-RIS and designed algorithms to optimise beamforming and resource allocation, the detailed impact of STAR-RIS location and number of reflective elements on system performance has not been sufficiently studied. This study presents an integrated theoretical and experimental analysis to determine the optimal number of reflective elements and the ideal location of STAR-RIS in MIMO-enabled FSO systems by developing accurate mathematical models and analysing the system performance under effects such as dispersion, environmental disturbances and optical interference, thereby improving data transmission efficiency, reducing signal loss and maximising network resource utilisation.

3. System Model

Figure 1 shows a single base station (BS) with eight optical sources, i.e. laser diodes (LDs); hence, S = 8. An LED system is not as suitable in this situation as LDs, which could allow for communication over long distances. There are users at the receiver. Each user has eight photodetectors (PDs) per user, P = 8. The STAR-Passive-OIRS should not be located in the midpoint between BS and clusters, as this would result in a low channel gain. However, in the proposed network, STAR-Passive-OIRS is located closer to BS. Reconfigurable-STAR-Passive-OIRS is utilised to get beyond the restrictions of FSO communications provide 360° coverage for both sides, and reach the signal to far-users.

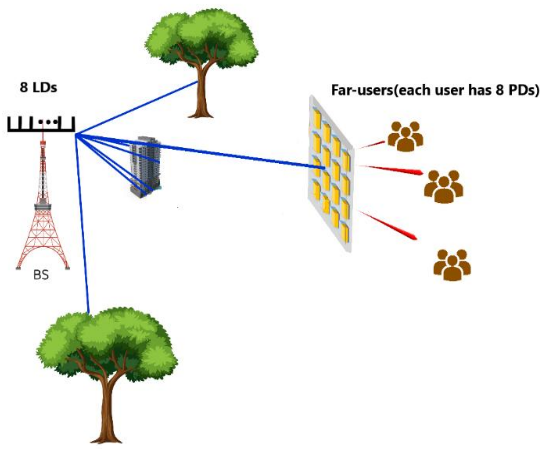

Fig. 1. Proposed system model.

With heights of BS (h_B), IRS (h_I), and UE (h_U), all users—BS and OIRS – are considered in a static position and are distinct from one another. The number of reflecting elements is (NI = 256), and RIS has a rectangular form (N_{IV}×N_{IH}). On–off keying (OOK) is used as the modulation type. OOK is a binary-level modulation scheme in which the "1" is used to indicate the presence of light, whilst "0" is used to indicate the absence of light in OOK. Huygens Fresnel is employed due to its facilities for the middle and far fields; ray-tracing is better appropriate for the near field. Huygens' principle is essential to understanding how signals are designed and routed in STAR-RIS systems. It provides the theoretical basis for how waves propagate and interact with smart surfaces, allowing for improved network performance and ensuring that signals reach the user with high efficiency. A zero mean and variance σ2 additive noise is used to model AWGN, the system also accounts for the effects of path loss, shadowing, and scattering, which further impact the received signal quality.

The Successive Interference Cancellation (SIC) technology is used. It enables increased spectrum utilisation efficiency, improved signal quality, reduced interference between users, support for a larger number of users in the same frequency resource, and reduced decoding error, making it essential for improving the performance of modern communications systems such as NOMA and 5G networks. The RIS is always utilised in a Rician channel distribution. It is suitable for AT and high altitudes. Furthermore, Let's say the working area is (W_{Ax}, W_{Ay}), and the transmit power is 50 mW. The reception noise power is −60 dBm.

The transmitted signal between BS's LDs and STAR IRS is denoted by:

$$X_s(t) = \gamma(\sqrt{P_s}x_s(t)e^{j\omega_t} + I_{DC}) \quad \ldots(1)$$

Each LD's current conversion is represented as γ [W/A], where γ ε [0,1] and I_{DC} are constant DC currents that guarantee the transmitted power's positivity. P_s is the power transmitted from the laser source s (s from 1 to 8 because we have 8 LDs), $x_s(t)$ is the signal sent from the laser source s, which is a time function containing the data. ω is an angular frequency of the carrier signal. $X_s(t)$ denotes the ook symbol with zero mean and unit variance from the LD s, and $X_s(t) \in R^{NB\times1}$.

The STAR RIS components receive the signal that is transmitted from the laser sources, the following is a representation of the signal that reaches the STAR RIS surface:

$$y_{RIS}(t) = \sum_{s=1}^{8} h_s X_s(t) \quad \ldots(2)$$

Where h_s is the channel between laser source s and the STAR RIS as follows:

$$h_s = (h_1, h_2, \ldots\ldots\ldots., h_8)^T \quad \ldots(3)$$

Each element on the STAR RIS can either reflect or transmit the signal. The reflected or transmitted signal from element n can be represented as:

$$s_{Rn}(t) = R_n\, y_{RIS}(t) \quad \ldots(4)$$

$s_{Tn}(t) = T_n\, y_{RIS}(t)$ …(5)

Where R_n is the reflection coefficient of element n, T_n is the transmission coefficient of element n, and the number of elements is $N = 1$ to 256 n elements.

The reflection and transmission coefficients of element n are:

$R_n = \sqrt{\beta_n^R}\, e^{j\phi_n^R}$ ...(6)

$T_n = \sqrt{\beta_n^T}\, e^{j\phi_n^T}$ ...(7)

Where β_n^R , β_n^T ∈ [0, 1] are real-valued coefficients satisfying $\beta_n^R + \beta_n^T \leq 1$, and $\phi_n^R, \phi_n^T \in [0, 2\pi)$ are the phase shifts introduced by element n for the transmitted and reflected signals, $\forall n \in \{1, 2, \cdots, N\}$.

For passive STAR-RIS elements, the local transmission and reflection coefficients must satisfy the following constraint by the law of energy conservation:

$|R_n|^2 + |T_n|^2 \leq 1$ ...(8)

The near users reach the signal directly from LDs in BS, so we null the reflecting signal from STAR-RIS to near users, the STAR-RIS's elements only transmit the signal to far users.

After being transmitted by the elements of the STAR RIS, the signal reaches distant users through the channel between the STAR RIS and the PDs. The signal reaching user k with eight photodetectors can be represented as

$$Y(t) = \mathcal{R}\Big(\sum_{k=1}^{K}\sum_{p=1}^{8}\sum_{s=1}^{8}\sum_{n=1}^{256} T_n\, g_p^k\, h_s X_s(t) e^{j(\theta s+\phi_n+\phi_{p,k,n})} + \bar{N}(t)\Big). \quad …(9)$$

Sub. (1) in (9):

$$Y(t) = \gamma\mathcal{R}\Big(\sum_{k=1}^{K}\sum_{p=1}^{8}\sum_{s=1}^{8}\sum_{n=1}^{256} T_n\, g_p^k\, h_s\big(\sqrt{P_s}x_s(t)e^{j(\omega_t)} + I_{DC}\big)e^{j(\theta s+\phi_n+\phi_{p,k,n})} + \bar{N}(t)\Big), \quad …(10)$$

where p refers to the photodetector p of user k, and $g_{x,p}^k$ is the channel between element n and photodetector p of user k. θs is the phase shift added by the channel between laser source s and STAR RIS and $\phi_s \in [0, 2\pi)$. ϕ_n is the phase shift added by the transmission process of element n on the STAR RIS and $\phi_n \in [0, 2\pi)$, $\phi_{p,k,n}$ is the phase shift added by the channel between element n and photodetector p of user k and $\phi_{p,k,n} \in [0, 2\pi)$, and $n_{p,k}(t)$ is the noise added to user k. Additionally, $\mathcal{R}$ is the responsibility of the photodetector of photodetectors p.

The channel between element n and photodetector p of user k is denoted by

$$g_{T,p}^k = (r_{T,k})^H diag\big(\sqrt{\beta_{T,1}}e^{j\phi_{T,1}}, \dots\dots, \sqrt{\beta_{T,n}}e^{j\phi_{T,n}}\big)h_s, \quad …(11)$$

where h_s is the channel vector between the transmitter and the STAR-RIS elements (Eq. [3]), $r_{T,k} = (r_{T,k,1}, r_{T,k,2}, \dots\dots\dots, r_{T,k,8})T$ is the channel vector between the STAR-RIS elements and the receiver k in the transmission group, $\beta_{T,n}$, $\phi_{T,1}$ are the amplitude and phase shift for the n-th element of the STAR-RIS. We can write $g_{T,p}^k$ as g_p^k.

To calculate the SINR, we calculate the signal power as

$$P_k = E[\gamma^2\mathcal{R}^2 \textstyle\sum_{k=1}^{K}\sum_{p=1}^{8}\sum_{s=1}^{8} P_s |\sum_{n=1}^{256} T_n\, g_p^k\, h_s|^2] = \gamma^2\mathcal{R}^2 \sum_{k=1}^{K}\sum_{p=1}^{8}\sum_{s=1}^{8} P_s E[|\sum_{n=1}^{256} T_n\, g_p^k\, h_s|^2] = \gamma^2\mathcal{R}^2 \sum_{k=1}^{K}\sum_{p=1}^{8}\sum_{s=1}^{8} P_s \sum_{n=1}^{256}|T_n|^2 E[|g_p^k|^2]\ E[|h_s|^2], \quad … (12)$$

where $|e^{j(\omega_t+\theta s+\phi_n+\phi_{p,k,n})}|^2 = 1$, and P_κ is the signal power for user k.

The interference for each user can denoted as

$$I_\kappa = \gamma^2\mathcal{R}^2 \textstyle\sum_{i\neq k}\sum_{p=1}^{8}\sum_{s=1}^{8} P_s \sum_{n=1}^{256}|T_n|^2 E[|g_{x,p}^i|^2]\ E[|h_s|^2], \quad …(13)$$

where I_κ is the interference power for user k from other users, p refers to the photodetector p of user k, s refers to the laser source s, i refers to the other users $i \neq k$, T_n *the the* transmission coefficient of element n on the STAR RIS, $g_{x,p}^i$ is the far-field channel between element n and the photodetector p of user i, and P_s is Power transmitted from the laser source s.

We use the perfect SIC to cancel the interference, if T_n represents the transmission coefficient for each element on the RIS, and $g_{n,k}$ represents the channel gain from element n to user k, the equations for total channel gain are as follows:

For user 1 (U_1): Total gain for $U_1 = \sum_{n=1}^{256} T_n\, g_{n,1}$

For user 2 (U_2): Total gain for $U_2 = \sum_{n=1}^{256} T_n\, g_{n,2}$

For user 3 (U_3): Total gain for $U_3 = \sum_{n=1}^{256} T_n\, g_{n,3}$

On the basis of the calculated total channel gain for each user, we can order the users by their channel strength. For example, if the ordering is Total gain for U_1 > Total gain for U_2 > Total gain for U_3,

then user U_1 receives the strongest signal from the RIS.

The decoding order is determined as $Q_1 < Q_2 < Q_3$.

Thus, interference cancellation begins with user Q_1, followed by user Q_2, and finally, user Q_3.

The noise power is

$$noise\ power = E[(\bar{N})^2] = E[\bar{N}\bar{N}^H] = E\left\{\begin{bmatrix} N_1 \\ N_2 \\ \vdots \\ N_K \end{bmatrix}\begin{bmatrix} N_1^* & N_2^* & \cdots & N_K^* \end{bmatrix}\right\} = \begin{bmatrix} \sigma_{N1}^2 & 0 & 0 & 0 \\ 0 & \sigma_{N2}^2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \sigma_{NK}^2 \end{bmatrix} = \sigma_N^2, \quad …(14)$$

where N is an AWGN.

Signal-to-interference-plus-noise ratio (SINR):

$$SINR = \frac{signal\ power}{interference\ power + noise\ power}, \quad \ldots(15)$$

$$SINR = \frac{P_k}{\sigma_N^2}, \quad \ldots(16)$$

$$SINR = \frac{\gamma^2 \mathcal{R}^2 \sum_{k=1}^{K} \sum_{p=1}^{8} \sum_{s=1}^{8} P_s \sum_{n=1}^{256} |T_n|^2 E[|g_p^k|^2]\, E[|h_s|^2]}{\sigma_N^2} \quad \ldots(17)$$

The average channel capacity determines how well an FSO communication system performs. It is the maximum amount of information that can be transferred in a specific time. The capacity of the i-th parallel channel for MIMO channels is represented by

$$C_i = \log_2(1 + SINR) \quad \ldots(18)$$

Then, the total MIMO capacity (C) is

$$C = \sum_{i=1}^{q} \log_2(1 + SINR), \quad \ldots(19)$$

which represents the sum of individual capacities of each q information stream.

The flowchart of the proposed system setup is shown below:

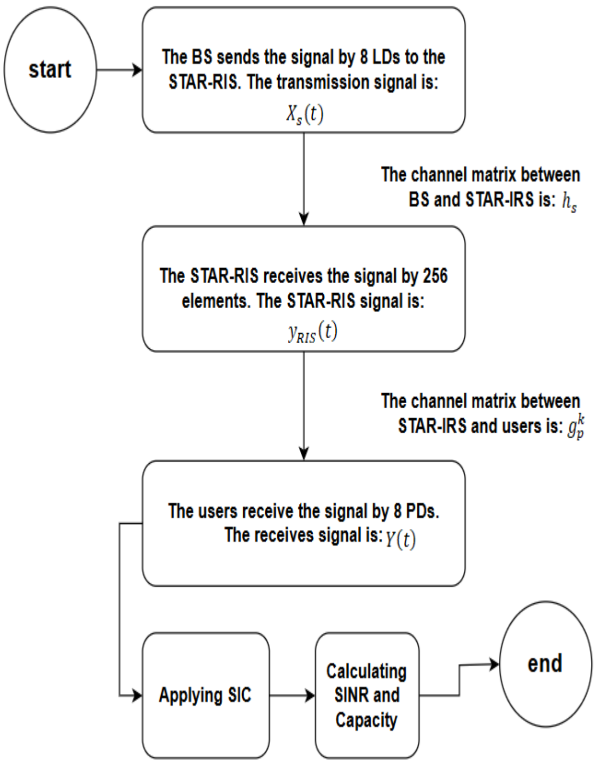

Fig. 2. Flowchart of the proposed system

4. Numerical Results and Discussions

In this section, we present the results of analysing the effect of reconfigurable STAR-RIS location and number of reflective elements on the performance of FSO systems. The results aim to clarify the relationship between these key variables and spectrum efficiency, SINR and channel gain. Through graphs and quantitative analysis, we demonstrate how performance can be improved using STAR-RIS techniques in wireless communication environments with different challenges.

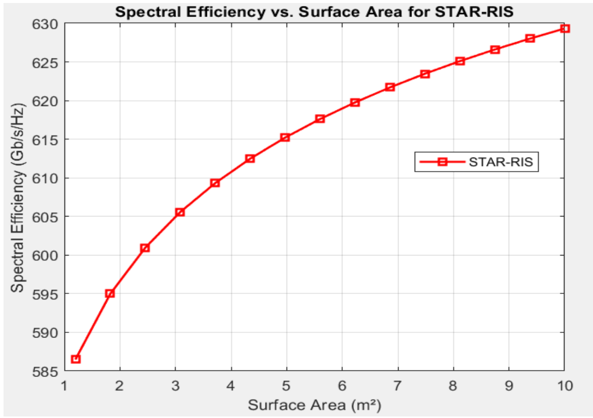

Fig. 3. Spectral efficiency vs. surface area of STAR-RIS

The graph in Figure 3 displays the relationship between surface area and spectral efficiency. When using the STAR-RIS system, spectral efficiency increases remarkably as the reflective surface area increases because increasing the surface area allows more control over the reflected or directed signal, which enhances the signal at the receiver and reduces interference.

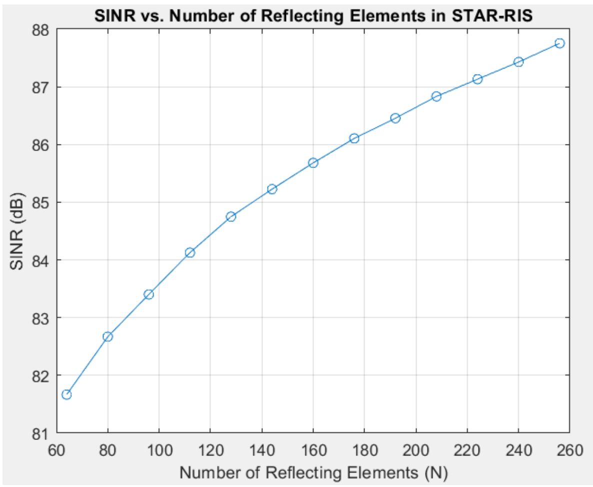

Fig. 4. SINR vs. number of reflecting elements of STAR-RIS

In Figure 4, we notice that SINR increases continuously as the number of reflecting elements increases. The reason for this is that increasing the number of elements allows signals to be directed more accurately to receivers, which increases the received signal strength. STAR-RIS works to reduce noise caused by dispersion and improve the received signal by controlling the phases of the reflected signals. As the elements increase, more constructive interference is achieved between the reflected signals, thus increasing the signal strength and improving the SINR. STAR-RIS proves its efficiency in enhancing signal quality as the number of elements increases, making it an ideal choice for improving the performance of wireless networks.

We can use 16 elements for small, experimental, or space-constrained systems and 32 to improve performance in medium environments. The use of 64 elements is common in medium to large deployments to improve beamforming power. For advanced systems that provide good coverage in business environments, 128 elements are used. For high-performance systems such as 5G/6G systems or areas with high interference, 256 elements are used. For systems centred around large areas with great interference and beamforming advantages, 512 elements are used. In advanced model applications such as future 6G, especially in urban areas with a population orientation, 1024 elements are used. In large-scale environments or systems that require excellent chips and high-precision control, 4096 elements are used. For large applications at an advanced level such as stadium coverage, smart cities or space applications, where the available layouts are large and overall performance can be improved, 10,000 elements are used. The choice of number depends on the operating environment (indoor or outdoor), the availability of sufficient space and the performance requirements (such as improving SINR). Therefore, the choice depends on the balance between performance and complexity.

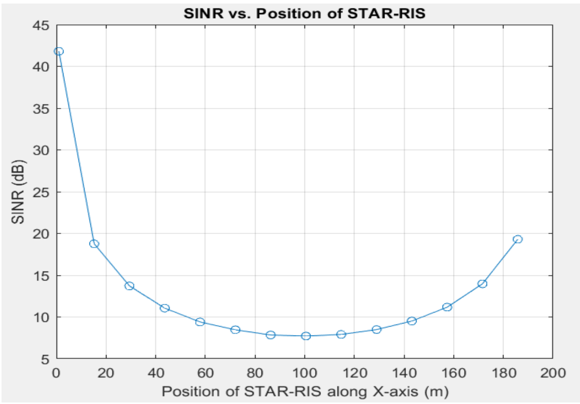

Fig. 5. SINR vs. position of STAR-RIS.

Figure 5 shows the relationship between SINR and the position of STAR-RIS. For an increase in SINR at the edges, the highest SINR values appear when the STAR-RIS position is close to one of the edges (at values close to 0 or 200 meters). The reason is that placing the STAR-RIS close to the source or receiver increases the routing efficiency and reduces dispersion.

For a decrease in SINR in the middle, in the middle of the X-axis (at approximately 100 meters), the SINR values decrease considerably. This decrease occurs because of the increased effect of dispersion and noise when no strong direct path exists between the source and the receiver. The STAR-RIS should be placed close to the source or receiver to achieve the highest SINR and best system performance.

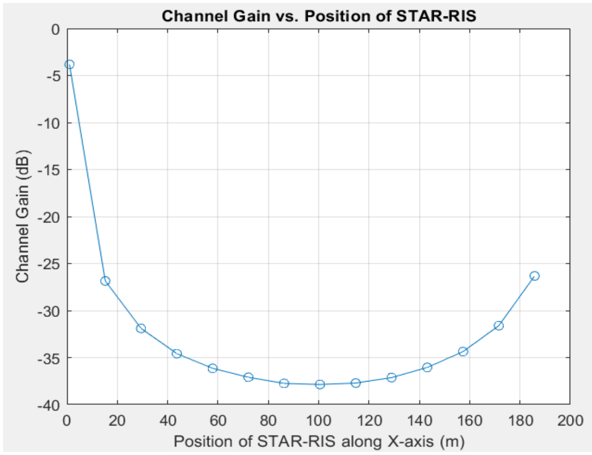

Fig. 6. Channel gain vs. position of STAR-RIS.

Figure 6 shows the relationship between the channel gain and the position of STAR-RIS. For the highest gain at the ends, the highest channel gain is shown when the STAR-RIS is positioned close to one of the ends (at 0 or 200 meters). The reason for this is that placing the STAR-RIS close to the source or receiver reduces signal loss and increases signal routing efficiency. The lower gain is in the middle because at the middle of the X-axis (approximately 100 meters), the channel gain drops considerably. This decrease indicates increased signal loss due to dispersion and poor signal routing when the STAR-RIS is placed far from the source and receiver. To achieve the best channel gain, the STAR-RIS should be placed close to the source or receiver rather than in the middle locations.

5. Conclusions

This study demonstrated the effectiveness of STAR-passive-OIRS reconfigurable smart surfaces in enhancing the performance of MIMO-based FSO communication systems. The analysis revealed that increasing the number of reflective elements considerably boosts SINR and spectral efficiency, facilitating improved signal routing and reduced interference. Additionally, strategically positioning the smart surface closer to the source or receiver optimises channel gain and minimises signal loss and dispersion. These findings underscore the transformative potential of STAR-RIS technology in overcoming LOS dependency and mitigating atmospheric disturbances, which are critical challenges in optical communication networks. The results offer valuable insights into designing advanced optical networks, particularly in urban and challenging weather environments. Integrating STAR-RIS technology with hybrid (RF/FSO) systems presents a promising direction for enhancing the efficiency and reliability of next-generation communication networks. Future work can integrate STAR-RIS with adaptive control algorithms and AI for real-time optimisation. Additionally, reinforcement learning can be applied to determine optimal STAR-RIS placement in multiuser systems whilst optimising resource allocation. AI-driven intelligent elements could further enhance system adaptability by automatically adjusting reflection characteristics based on environmental variations. Finally, large-scale STAR-RIS implementations with thousands of reflective elements (e.g. 4,096 or 10,000 elements) could enable advanced applications such as smart cities, stadium coverage and satellite communications, thus balancing performance improvements with technical complexity.

Abbreviations

FSO	Free Space Optical
RF	Radiofrequency
B5G	Beyond 5G
DF	Decode and Forward
OWC	Optical Wireless Communication
NOMA	Nonorthogonal Multiple Access
OMA	Orthogonal Multiple Access
SIC	Successive Interference Cancellation
IRS	Intelligent Reflecting Surface
OIRS	Optical Intelligent Reflecting Surface
STAR-IRS	Simultaneously Transmitting and Reflecting Intelligent Reflecting Surfaces
MIMO	Multiple Input And Multiple Output
AT	Atmospheric Turbulence
DOFs	Degrees-Of-Freedom
LOS	Line Of Sight
NLOS	Nonline of Sight
BSs	Base Stations

References

[1] M. A. Atiyah, L. F. Abdulameer, and G. Narkhedel, "PDF Comparison based on Various FSO Channel Models under Different Atmospheric Turbulence," *Al-Khwarizmi Engineering Journal*, vol. 19, no. 4, pp. 78–89, 2023. Available: https://doi.org/10.22153/kej.2023.09.004

[2] A. A. Abdullah, "Study the effect of Iraqi weather parameter in FSO communication using different wavelength (650, 532) nm," *Iraqi Journal of Physics*, vol. 16, no. 36, pp. 104–112, 2018. Available: https://doi.org/10.30723/ijp.v16i36.35

[3] M. J. Al-Dujaili and M. A. Al-dulaimi, "Fifth-generation telecommunications technologies: Features, architecture, challenges and solutions," *Wirel Pers Commun*, vol. 128, no. 1, pp. 447–469, 2023. Available: https://doi.org/10.1007/s11277-022-09962-x

[4] Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface-aided wireless communications: A tutorial," *IEEE transactions on communications*, vol. 69, no. 5, pp. 3313–3351, 2021 .Available: https://doi.org/10.1109/TCOMM.2021.3051897

[5] T. N. Do, G. Kaddoum, T. L. Nguyen, D. B. Da Costa, and Z. J. Haas, "Multi-RIS-aided wireless systems: Statistical characterization and performance analysis," *IEEE Transactions on Communications*, vol. 69, no. 12, pp. 8641–8658, 2021. Available: https://doi.org/10.1109/TCOMM.2021.3117599

[6] L. F. Abdulameer and H. Fadhil, "Performance Analysis of FSO under Turbulent Channel Using OSTBC," *Al-Nahrain Journal for Engineering Sciences (NJES) Vol*, vol. 2, pp. 344–349, 2018 . Available: http://doi.org/10.29194/NJES.21030344

[7] I. I. Kim and E. J. Korevaar, "Availability of free-space optics (FSO) and hybrid FSO/RF systems," in *Optical Wireless Communications IV*, SPIE, 2001, pp. 84–95. Available: https://doi.org/10.1117/12.449800

[8] F. Nadeem, V. Kvicera, M. S. Awan, E. Leitgeb, S. S. Muhammad, and G. Kandus, "Weather effects on hybrid FSO/RF communication link," *IEEE journal on selected areas in communications*, vol. 27, no. 9, pp. 1687–1697, 2009. Available: https://doi.org/10.1109/JSAC.2009.091218

[9] M. Usman, H.-C. Yang, and M.-S. Alouini, "Practical switching-based hybrid FSO/RF transmission and its performance analysis," *IEEE Photonics J*, vol. 6, no. 5, pp. 1–13, 2014 . Available: http://dx.doi.org/10.1109/JPHOT.2014.2352629

[10] B. Bag, A. Das, I. S. Ansari, A. Prokeš, C. Bose, and A. Chandra, "Performance analysis of hybrid FSO systems using FSO/RF-FSO link adaptation," *IEEE Photonics J*, vol. 10, no. 3, pp. 1–17, 2018. Available: https://doi.org/10.1109/JPHOT.2018.2837356

[11] T. Wang, A. Cano, G. B. Giannakis, and J. N. Laneman, "High-performance cooperative demodulation with decode-and-forward relays," *IEEE Transactions on communications*, vol. 55, no. 7, pp. 1427–1438, 2007. Available: https://doi.org/10.1109/TCOMM.2007.900631

[12] G. Alnwaimi and H. Boujemaa, "Hybrid RF/FSO communications through Reconfigurable Intelligent Surfaces in the presence of pointing errors," *Telecommun Syst*, vol. 78, no. 2, pp. 155–162, 2021. Available: https://doi.org/10.1007/s11235-021-00802-0

[13] R. Salam, A. Srivastava, V. A. Bohara, and A. Ashok, "An optical intelligent reflecting surface-assisted underwater wireless communication system," *IEEE Open Journal of the Communications Society*, 2023. Available: https://doi.org/10.1109/OJCOMS.2023.3303190

[14] Z. Zhang *et al.*, "Active RIS vs. passive RIS: Which will prevail in 6G?," *IEEE Transactions on Communications*, vol. 71, no. 3, pp. 1707–1725, 2022. Available: https://doi.org/10.1109/TCOMM.2022.3231893

[15] J. Lončar and Z. Šipuš, "Challenges in design of power-amplifying active metasurfaces," in *2020 International Symposium ELMAR*, IEEE, 2020, pp. 9–12. Available: https://doi.org/10.1109/ELMAR49956.2020.9219017

[16] J. W. Goodman, *Introduction to Fourier optics*. Roberts and Company publishers, 2005.

[17] Y. Liu *et al.*, "STAR: Simultaneous transmission and reflection for 360° coverage by intelligent surfaces," *IEEE Wirel Commun*, vol. 28, no. 6, pp. 102–109, 2021. Available: https://doi.org/10.1109/MWC.001.2100191

[18] H. Ma, H. Wang, H. Li, and Y. Feng, "Transmit power minimization for STAR-RIS-empowered uplink NOMA system," *IEEE Wireless Communications Letters*, vol. 11, no. 11, pp. 2430–2434, 2022. Available: https://doi.org/10.1109/LWC.2022.3205703

[19] A. F. M. S. Shah, A. N. Qasim, M. A. Karabulut, H. Ilhan, and M. B. Islam, "Survey and performance evaluation of multiple access schemes for next-generation wireless communication systems," *IEEE Access*, vol. 9, pp. 113428–113442, 2021. Available: https://doi.org/10.1109/ACCESS.2021.3104509

[20] S. A. Yosef and L. F. Abdulameer, "A Systematic Review on Non-Orthogonal Multiple Access (NOMA) Based on Visible Light Communication for Intelligent Transportation Systems," *Tikrit Journal of Engineering Sciences*, vol. 31, no. 1, pp. 278–290, 2024. Available: DOI: https://doi.org/10.25130/tjes.31.1.23

[21] H. Liu, G. Li, X. Li, Y. Liu, G. Huang, and Z. Ding, "Effective capacity analysis of STAR-RIS-assisted NOMA networks," *IEEE Wireless Communications Letters*, vol. 11, no. 9, pp. 1930–1934, 2022. Available: https://doi.org/10.1109/LWC.2022.3188443

[22] S. A. Yosef and L. F. Abdulameer, "Performance Enhancement of VLC-NOMA Employing Beamforming Function based vehicle-to-multivehicle Communication system," *IETE J Res*, pp. 1–12, 2023. Available: https://doi.org/10.1080/03772063.2023.2290092

[23] E. Ali, M. Ismail, R. Nordin, and N. F. Abdulah, "Beamforming techniques for massive MIMO systems in 5G: overview, classification, and trends for future research," *Frontiers of Information Technology & Electronic Engineering*, vol. 18, pp. 753–772, 2017. Available: https://doi.org/10.1631/FITEE.1601817

[24] X. Wei, D. Shen, and L. Dai, "Channel estimation for RIS assisted wireless communications—Part I: Fundamentals, solutions, and future opportunities," *IEEE communications letters*, vol. 25, no. 5, pp. 1398–1402, 2021. Available: https://doi.org/10.1109/LCOMM.2021.3052822

[25] M. Najafi, B. Schmauss, and R. Schober, "Intelligent reflecting surfaces for free space optical communication systems," *IEEE transactions on communications*, vol. 69, no. 9, pp. 6134–6151, 2021. Available: https://doi.org/10.1109/TCOMM.2021.3084637

[26] H. Ajam, M. Najafi, V. Jamali, B. Schmauss, and R. Schober, "Modeling and design of IRS-assisted multilink FSO systems," *IEEE Transactions on Communications*, vol. 70, no. 5, pp. 3333–3349, 2022. Available: https://doi.org/10.1109/TCOMM.2022.3163767

[27] H. Wang, Z. Shi, Y. Fu, and S. Fu, "On intelligent reflecting surface-assisted NOMA uplinks with imperfect SIC," *IEEE Wireless Communications Letters*, vol. 11, no. 7, pp. 1518–1522, 2022 .Available: https://doi.org/10.1109/LWC.2022.3177733

[28] A. Zappone, M. Di Renzo, X. Xi, and M. Debbah, "On the optimal number of reflecting elements for reconfigurable intelligent surfaces," *IEEE Wireless Communications Letters*, vol. 10, no. 3, pp. 464–468, 2020. Available: https://doi.org/10.1109/LWC.2020.3034686

[29] J. Zhu, Y. Huang, J. Wang, K. Navaie, W. Huang, and Z. Ding, "On the position optimization of IRS," *IEEE Internet Things J*, vol. 9, no. 14, pp. 11712–11724, 2021. Available: https://doi.org/10.1109/JIOT.2021.3131771

[30] Y. Liu *et al.*, "STAR: Simultaneous transmission and reflection for 360° coverage by intelligent surfaces," *IEEE Wirel Commun*, vol. 28, no. 6, pp. 102–109, 2021. Available: https://doi.org/10.1109/MWC.001.2100191

[31] J. Xu, Y. Liu, X. Mu, and O. A. Dobre, "STAR-RISs: Simultaneous transmitting and reflecting reconfigurable intelligent surfaces," *IEEE Communications Letters*, vol. 25, no. 9, pp. 3134–3138, 2021. Available: https://doi.org/10.1109/LCOMM.2021.3082214

[32] M. Ahmed *et al.*, "A survey on STAR-RIS: Use cases, recent advances, and future research challenges," *IEEE Internet Things J*, 2023. Available: https://doi.org/10.1109/JIOT.2023.3279357

[33] F. C. Okogbaa *et al.*, "Design and application of intelligent reflecting surface (IRS) for beyond 5G wireless networks: a review," *Sensors*, vol. 22, no. 7, p. 2436, 2022. Available: https://doi.org/10.3390/s22072436

[34] X. Mu, Y. Liu, L. Guo, J. Lin, and R. Schober, "Simultaneously transmitting and reflecting (STAR) RIS aided wireless communications," *IEEE Trans Wirel Commun*, vol. 21, no. 5, pp. 3083–3098, 2021. Available: https://doi.org/10.1109/TWC.2021.3118225

[35] A. Papazafeiropoulos, H. Ge, P. Kourtessis, T. Ratnarajah, S. Chatzinotas, and S. Papavassiliou, "Two-timescale design for active STAR-RIS aided massive MIMO systems," *IEEE Trans Veh Technol*, 2024. Available: https://doi.org/10.1109/TVT.2024.3367037

[36] X. Li *et al.*, "Covert communication of STAR-RIS aided NOMA networks," *IEEE Trans Veh Technol*, 2024. Available: https://doi.org/10.1109/TVT.2024.3349543

تأثير عدد العناصر العاكسة وموقع نظام STAR-passive-ORIS القابل لإعادة التكوين في أنظمة MIMO FSO

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المستخلص

ترمي هذه الدراسة إلى تحسين أداء نظام STAR-passive-OIRS القابل لإعادة التكوين في أنظمة الاتصالات الضوئية في الفضاء الحر القائمة على MIMO. تركز الدراسة على تحليل وتأثير عاملين رئيسيين هما: عدد العناصر العاكسة وموقع السطح الذكي. لقد أظهرت تقنية STAR-RIS إمكانات كبيرة في تحسين كفاءة الطيف ونسبة الإشارة إلى الضوضاء والتداخل (SINR) وزيادة مكسب القناة، من خلال توفير تغطية بزاوية ٣٦٠ درجة وتقليل التداخل في البيئات ذات قيود خط البصر (LOS). وتكشف النتائج أن زيادة عدد العناصر العاكسة يعزز قوة الإشارة ويحسن نسبة الإشارة إلى الضوضاء والتداخل بينما يحقق وضع السطح الذكي أقرب إلى المصدر أو المستقبل الأداء الأمثل. تسلط الدراسة الضوء على قدرة تقنية STAR-RIS على التغلب على قيود أنظمة FSO التقليدية وتحسين أداء الشبكة في بيئات الاتصالات اللاسلكية الحديثة.