Multi-unit Based IRS Supported Non-Line-of-Sight Communication for Signal Quality Performance Improvement

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***Abstract*-Intelligent Reflecting Surface (IRS) has emerged as a transformative technology to enhance wireless communication systems by intelligently reconfiguring the propagation environment. This paper proposes a multi-unit-based IRS to improve communication capability in a Single Input Single Output (SISO) system, explores its implementation model, and proposes a double-unit IRS network architecture to optimize communication efficiency. This work considers an IRS-assisted SISO network consisting of an array of multiple IRS elements located between source and destination. The proposed network compares the strengths of IRS-supported networks to achieve superior performance in terms of required transmit power and achievable data rate. Numerical results validate the effectiveness of deploying IRS to assist the SISO network and considerable improvements are achieved.**

***Keywords*: Data Rate, Intelligent Reflecting Surface, Power Consumption, Wireless Communication.**

I. INTRODUCTION

The sixth-generation (6G) system is set to dramatically enhance performance and user Quality of Service (QoS) in wireless communication with significantly higher data speeds, lower latency, and improved reliability compared to the fifth-generation (5G). It will also introduce advanced features for better system protection, stronger data security, and more personalized services, ensuring a more efficient and secure communication experience [1]. To support the technology and productivity goals of the 6G system, it is crucial to have a network infrastructure that is robust, adaptable, flexible, economical, and quickly deployable. This type of infrastructure will be essential for accommodating the advanced features and performance demands of 6G technology [2]. Conventional methods to achieve these goals, such as increasing antenna numbers or deploying additional base stations, often incur significant costs and energy consumption. The intelligent reflecting surface (IRS), controlled by reflective radio technology, has garnered considerable interest from academic and industrial sectors. This is because of its capability to dynamically adjust wireless communication environments using cost-effective reflective elements [3]–[5]. IRS offers an innovative solution by altering the wireless environment itself to enhance communication quality and efficiency, especially for non-line-of-sight communication. An IRS comprises a vast array of passive reflecting elements, each capable of independently adjusting the phase of incoming signals. Through intelligent manipulations of these elements, the IRS can direct reflected signals to specific locations, thereby amplifying signal strength and reducing interference. The phase shift configuration among these elements determines the direction in which the reflected beam forms. While the surface area can be extensive, individual elements are typically smaller than the wavelength of the signal [6], [7]. Specifically, adjustable components enable modification of electromagnetic wave behaviors, such as phase, amplitude, and polarization [8], [9], transitioning the wireless propagation environment from passive adaptation to active control [10]. Furthermore, IRS finds application in diverse settings including indoor environments, urban areas, and satellite communication systems [11].

The implementation of the IRS faces several challenges that impact its effectiveness in enhancing wireless communication. One significant challenge is the deployment and optimization of IRS units, which requires careful planning to ensure they are positioned and configured to maximize signal quality. Key challenges a single-unit IRS faces include limited signal path diversity, higher transmit power, lower data rate, and inadequate performance in long-range coverage scenarios. These limitations can hinder effective communication, particularly in complex environments with obstacles. A double-unit IRS will be able to address these issues by providing additional reflection points, enhancing signal coverage, and reducing power loss over longer distances, leading to improved overall communication efficiency.

This study provides a foundational understanding of how the IRS aids conventional Single Input Single Output (SISO) systems, laying the groundwork for optimized design and deployment strategies in future wireless systems. As part of the investigation, this paper presents a comparative analysis of the performance between single-unit and double-unit IRS systems over a finite distance range. By quantifying metrics such as required transmit power, and data rate, this comparison seeks to offer insights into the effectiveness of multi-unit IRS configurations in enhancing communication performance.

The rest of the paper is organized as follows. Section II presents a detailed system overview, Section III outlines the methodology employed, Section IV analyzes the performance, and finally, Section V wraps up with the conclusions.

II. SYSTEM OVERVIEW

This paper examines communication between a single-antenna transmitter and a single-antenna receiver. The deterministic flat-fading channel is represented by h_{sd}. The signal received at the destination is expressed as

$$y = h_{sd}\sqrt{ps} + n, \tag{1}$$

where p denotes transmit power, s is the unit-power information signal, and n represents receiver noise. The capacity of this SISO channel is given by [12]

$$R_{SISO} = \log_2\left(1 + \frac{p\left(h_{sd}\right)^2}{\sigma^2}\right). \tag{2}$$

When we consider NLOS communication introduced by a blockage between transmitter and receiver, the signal quality decreases gradually. To potentially enhance capacity, additional equipment is introduced into the communication setup. Specifically, we consider an IRS designed to redirect signals toward the destination. This IRS setup consists of N numbers of discrete elements, as depicted in Fig. 1. The deterministic channel from the source to the IRS is denoted by, h_{sr} where $\left[h_{sr}\right]_n$ denotes the n^{th} component. The channel between the IRS and the destination is denoted by h_{rd}. Each element is smaller than the wavelength, enabling it to scatter incoming signals with nearly constant gain across all desired directions [13]. The IRS's properties are therefore fully represented by the diagonal matrix [9] as

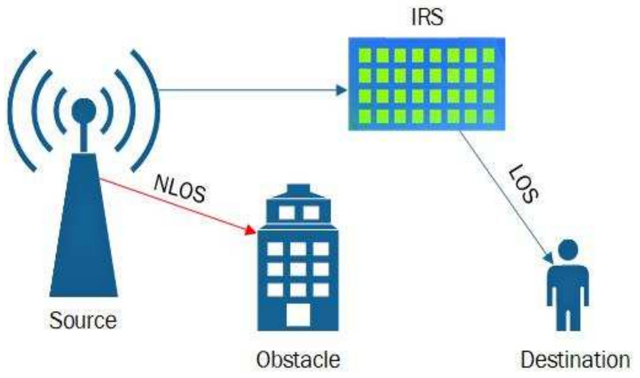

Fig. 1. Single unit IRS-supported transmission.

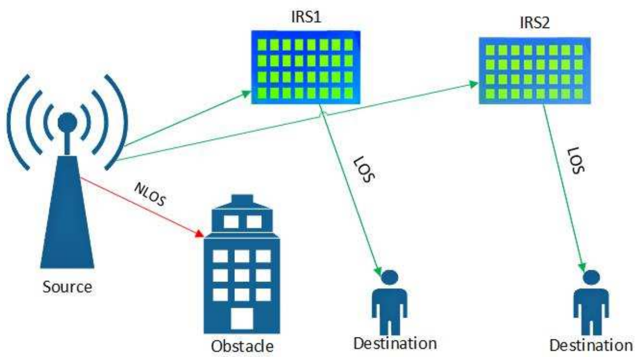

Fig. 2. Double unit IRS-supported transmission.

$$\Theta = \alpha diag\left(e^{i\theta_1}, \ldots\ldots, e^{i\theta_N}\right). \tag{3}$$

Following the system model derived in [13], [14], the received signal at the destination is

$$y = \left(h_{sd} + h_{sr}^T \Theta h_{rd}\right)\sqrt{ps} + n. \tag{4}$$

When IRS supported transmission system enhances the transmission quality, path loss and attenuation affect the transmission efficiency for long distances. Deploying multiple IRS units at suitable places between source and destination this problem can be minimized to some extent. Fig. 2 shows such a network architecture, where two IRS units are placed to assist efficient communication.

III. METHODOLOGY

The capacity of the SISO channel [5] is

$$R_{SISO} = \log_2\left(1 + \frac{p\beta_{sd}}{\sigma^2}\right), \tag{5}$$

where $\sqrt{\beta_{sd}} = \left|h_{sd}\right|$.

According to [15], the channel capacity of the IRS-supported network is

$$R_{IRS}(N) = \log_2\left(1 + \frac{p\left(\sqrt{\beta_{sd}} + N\alpha\sqrt{\beta_{IRS}}\right)^2}{\sigma^2}\right), \quad (6)$$

where $\sqrt{\beta_{sr}} = |h_{sr}|$ $\sqrt{\beta_{rd}} = |h_{rd}|$ and

$$\sqrt{\beta_{IRS}} = \frac{1}{N}\sum_{n=1}^{N}\left|[h_{sr}]_n [h_{rd}]_n\right|.$$

Interestingly, the expressions only depend on the amplitudes of the channel elements, but not on their phases.

If the destination requires a particular data rate R, the rate expressions in (5) and (6) can be used to identify the required transmit power for each of the two communication setups.

To achieve a data rate R, the SISO case requires the transmit power,

$$P_{SISO} = \left(2^R - 1\right)\frac{\sigma^2}{\beta_{sd}}. \quad (7)$$

The IRS-supported transmission requires the transmit power,

$$p_{IRS}(N) = \left(2^R - 1\right)\frac{\sigma^2}{\left(\sqrt{\beta_{sd}} + N\alpha\sqrt{\beta_{IRS}}\right)^2}. \quad (8)$$

IV. PERFORMANCE ANALYSIS

In this part, we evaluate the performance of IRS units at single and double-unit supported configurations in terms of transmit power and achievable data rate. Fig. 3 depicts a distance versus transmit power comparison for SISO and a single-unit IRS-supported case with a different number of IRS elements to obtain an achievable data rate R=10 bit/s/Hz everywhere in the specified range. From Fig. 3, we can see that the required transmitted power for the SISO case is increasing exponentially with an increase in distance between source and destination. However, IRS supported system needs less power compared to the SISO case and the required power decreases near the IRS location. Furthermore, the required transmit power drops noticeably as the number of IRS elements increases. From this plot, we can conclude that when the destination is at the near point of IRS it requires minimum transmit power.

As we increase the number of IRS elements from 20 to 200, the required transmit power decreases accordingly. This is because increasing IRS elements enhances signal focusing and beamforming, improving signal strength and coverage. Following this conclusion, we redesigned the system with two IRS units located at a distance of 100 m and 150 m from the source position. The distance versus required transmit power comparison for this case are shown in Fig. 4. The achievable data rate R is the same as the previous set-up.

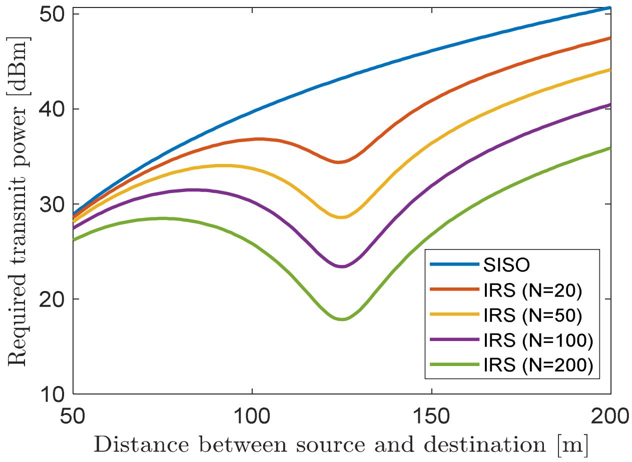

Fig. 3. Transmit power comparison for SISO and single-unit IRS case with different numbers of IRS elements as a function of the distance.

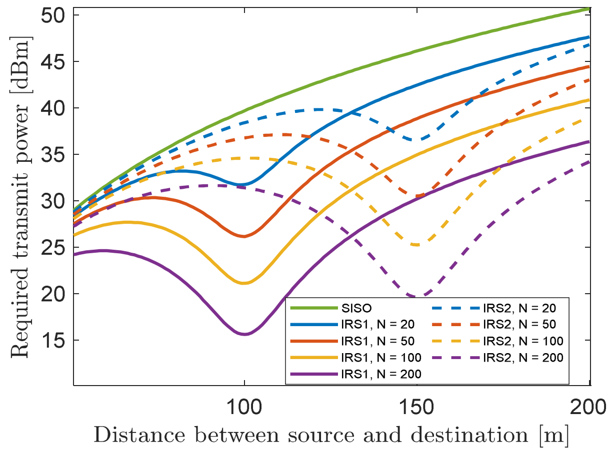

Fig. 4. Transmit power comparison for SISO and double-unit IRS case with different number of IRS elements as a function of the distance.

Fig. 4 suggests that to optimize transmit power, we should assign IRS Unit-1 to cover distances from 50 m to 130 m, given its position at 100 m, and IRS Unit-2 to cover distances from 130 m to 200 m, considering its position at 150 m. This allocation ensures efficient use of power and by matching each IRS unit to its optimal range.

Accordingly, we can redesign the system as shown in Fig. 5 in such a way that, the signal will transmit from source to destination through IRS Unit-1 when the destination position is between 50 m to 130 m and through IRS unit-2 when the destination position is between 130 m to 200m. This approach optimizes signal reflection and focusing for different distances, resulting in improved signal quality and a lower required transmit power compared to using a single IRS unit for the entire range.

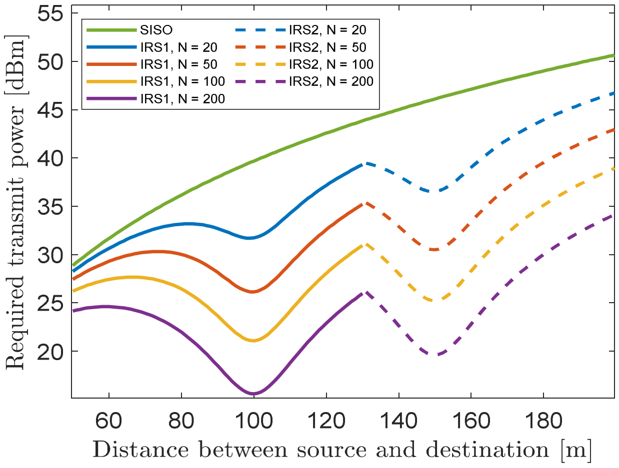

Fig. 5. Transmit power comparison for double-unit with a different numbers of IRS elements as a function of the distance in the specified range.

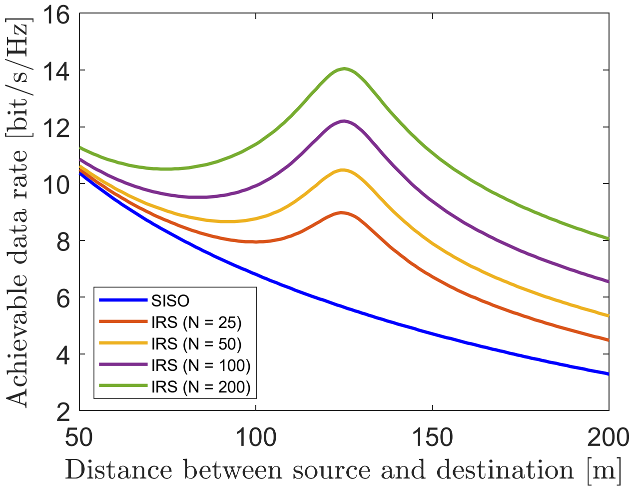

Fig. 6. Data rate comparison for SISO and single IRS case with different number of IRS elements as a function of distance.

At this stage, we analyze and compare the achievable data rates for different system setups: SISO, single-unit IRS, and double-unit IRS-supported systems. Fig. 6 illustrates the data rate versus distance for the SISO and single-unit IRS case when using a transmit power of 30 dBm.

In these setups, the data rate is maximized when the receiver is near the IRS unit, benefiting from optimal signal reflection and focusing. As the distance between the source and the destination increases, the data rate diminishes gradually due to increased path loss and reduced signal enhancement.

This behavior highlights the advantage of having IRS units closer to the receiver for maintaining high data rates. The single-unit IRS improves performance compared to SISO by focusing the signal, but its effectiveness diminishes with distance. Comparing this with the double-unit IRS setup as shown in Fig. 7, which can manage signal enhancement over longer distances more effectively, will show further

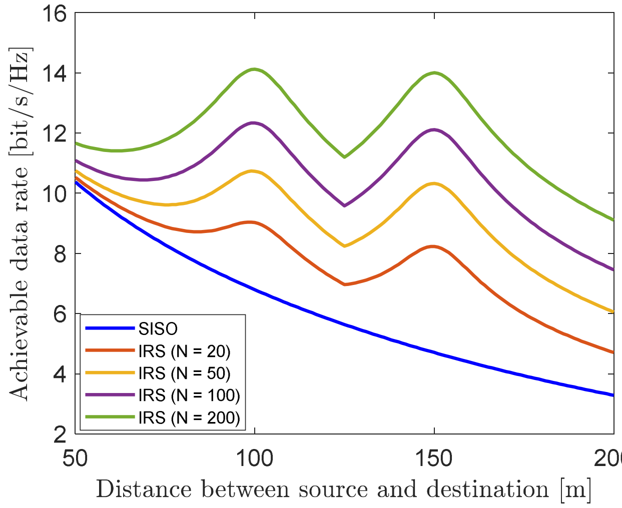

Fig. 7. Data rate comparison for SISO and Double IRS case with different number of IRS elements as a function of distance.

improvements in data rate consistency. As depicted in Fig. 7, the double unit IRS-supported system also favors data rates by providing higher data rates at most of the places.

V. CONCLUSIONS

SISO communication is a fundamental approach, suitable for basic communication needs due to its simplicity. However, when it is enhanced by the IRS, the system's performance improves significantly specially for the NLOS cases. IRS technology offers substantial benefits in terms of signal quality, coverage, and data rates, particularly in challenging or obstructed environments. Our analysis indicates that using multiple IRS units, strategically positioned, provides superior performance compared to a single IRS unit. This setup enhances transmit power efficiency, reduces overall power consumption, and improves data rates over extended distances. Moreover, this approach allows for the use of fewer IRS elements in each unit, simplifying system design and reducing complexity. By distributing the IRS units across different locations, the system maintains robust performance and efficient power usage, addressing the limitations of a single IRS unit and making it easier to manage and deploy.

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