# Single versus Double IRS-Assisted Networks: A Comparative Analysis using Practical Phase Shifting

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***Abstract*—Intelligent reflecting surfaces (IRSs) have been considered to revolutionize the beyond 5G and 6G systems as they help increase signal strength through their ability to control radio environments effectively. Introducing IRS assistance in a single-input single-output (SISO) network has proven to improve the system's performance. This paper compares the performance of a single IRS-assisted SISO system against a double IRS-assisted system under various wireless network setups. Our work relies on a shared allocation scheme of IRS elements, where a practical phase-dependent amplitude phase shift model, utilizing discrete phase shifts, is considered to develop a reliable and energy-efficient system. We observe energy efficiency while altering system parameters to identify the limits where each system works better. The simulation results show that a double IRS-assisted network performs better at large deployments with higher variable factors, whereas a single IRS-assisted network performs better in compact environments.**

***Index Terms*—Single-input single-output (SISO), intelligent reflecting surface (IRS), practical phase-shift model, element sharing, energy efficiency.**

## I. Introduction

Intelligent reflecting surfaces (IRSs) are a recent breakthrough in beyond 5G and 6G wireless communication systems. An IRS enhances the signal quality and data rate at lesser costs than the costs associated with conventional antenna arrays. Structurally, the IRS comprises a planar structure containing several tiny passive reflecting elements. Each IRS element can reflect the incident signal independently with an appropriate amplitude and/or phase shift [1]. IRS reflections follow an ideal or practical model. The ideal reflection model assumes a constant amplitude with perfect phase shifts and is frequently used to maximize system energy efficiency and data rate [2], [3]. However, the ideal model is challenging to implement as it is impervious to hardware limitations that exist in reality. On the contrary, the practical reflection model of the IRS is simpler and more reliable to implement, as it caters to hardware limitations. The model uses varying amplitude with imperfect phase shifts, similar to what happens in reality [4].

The phase shifts of IRS for the ideal phase shift model are continuous. They consume more power when implemented and are less energy efficient. In contrast, practical phase shift models utilize discrete phase shifts, which consume less power due to their use of quantized phases. This makes them energy efficient, as the system only has uniformly specific values to choose from a determined range of phases. Furthermore, increasing quantization bits of discrete phase shifts increases the system's efficiency since the phase shifts resemble the continuous phase shifts more while consuming relatively low power.

An element-sharing-based allocation scheme of IRS has been proven to handle more users and is robust to phase optimization errors, as demonstrated in [5]. The approach divides all the IRS elements into clusters, each serving a specific set of users, where all users share an equal number of IRS elements.

Employing a single IRS is sufficient to improve the performance of a system, but altering the system's variable factors may require another IRS deployment. Introducing a second IRS in the system can cause a change in the efficiency results of the system, but it doesn't ensure better results for all values of the variable factors. The thresholds that make one system more efficient than the other can be explored by observing the results of both systems, one employing a single IRS and the other employing a double IRS.

This paper provides a comparative performance analysis between a double-IRS-assisted and a single-IRS-assisted multi-user (MU) SISO system. The main contributions of this paper are as follows.

- This paper helps identify whether a MU-SISO system requires the assistance of a single or a double IRS to achieve maximum energy efficiency.
- We thoroughly compare the energy efficiencies of two systems, one using single IRS and the other using double IRS, against variable factors including the number of users, user distance from the BS, cell radius, transmit

power of BS, and the number of IRS elements to identify which system performs better under which circumstances.
- Our findings indicate that the double IRS-assisted system exhibits higher energy efficiency for larger magnitudes of the variable factors, while the system with a single IRS is more energy efficient for smaller magnitudes.

The remaining paper is structured as follows. Section II explains the developed system model, and Section III presents the performance analysis that includes the system parameters. Section IV presents the simulation setup and numerical results used to evaluate the performance of the system. Finally, Section V draws conclusions and suggests future diretions.

*Notations*: Scalars and vectors are represented by lowercase italic letters and bold-face lowercase letters, respectively, $\mathbb{C}$ denotes the set of complex numbers, $(.)^H$ represents the conjugate-transpose operation, and $\mathbb{E}\{.\}$ denotes the statistical expectation.

## II. System Model

As shown in Fig. 1, we consider a MU-SISO downlink communication system. For simplicity, we consider a single-antenna BS that simultaneously serves $K$ single-antenna users. The two IRSs, each consisting of $N$ reflecting elements spaced half a wavelength apart, cooperate with one another to serve the users by enhancing the downlink transmission signal and the system's energy efficiency. Let $\mathcal{R} = \{1, 2\}$, $\mathcal{K} = \{1, \dots, K\}$, and $\mathcal{N} = \{1, \dots, N\}$ be the index sets defining the number of IRSs, the number of users, and the number of reflecting elements on each IRS, such that $r \in \mathcal{R}$, $k \in \mathcal{K}$, and $n \in \mathcal{N}$, respectively. In our entire study, we assume an element-sharing allocation scheme, where for every $r^{\text{th}}$ IRS, $S = N/K$ elements are responsible for serving a single user $k$. For $k \in \mathcal{K}$, the range of assigned IRS elements is given as $\mathcal{S} = (S\times(k-1), \dots, S \times k)$, which is determined for each $k^{\text{th}}$ user in the network. The allocation of IRS elements to the users continues as long as $S \times k \neq N$.

It is considered that an IRS micro-controller controls the phase shifts of the IRS elements. The signals reflected multiple times by the IRS(s) are assumed to exhibit minimal power due to significant path loss and, therefore, are disregarded in our study. Moreover, we adopt a quasi-static flat-fading model, assuming that all wireless channels remain constant throughout each transmission block. At the BS, it is assumed that perfect channel state information (CSI) has been acquired.

### A. Signal Model

At the $k^{\text{th}}$ user, the received signal, $y_k$, is given as

$$y_k = \sqrt{P_t}\left[h_k + \sum_r \mathbf{h}_{r,k}^H \mathbf{\Phi}_{r,k}\mathbf{g}_{r,k}\right] x_k + n_k, \tag{1}$$

where $P_t$ represents the BS transmit power for the $k^{\text{th}}$ user, and $x_k$ denotes the data symbol and satisfies $\mathbb{E}\{|x_k|^2\} = 1$. The direct link between the BS and the $k^{\text{th}}$ user is $h_k \in \mathbb{C}^{1\times 1}$. For the indirect channels, $\mathbf{h}_{r,k} \in \mathbb{C}^{S\times 1}$ defines the channel vector that exists between the $r^{\text{th}}$ IRS and the $k^{\text{th}}$ user, whereas

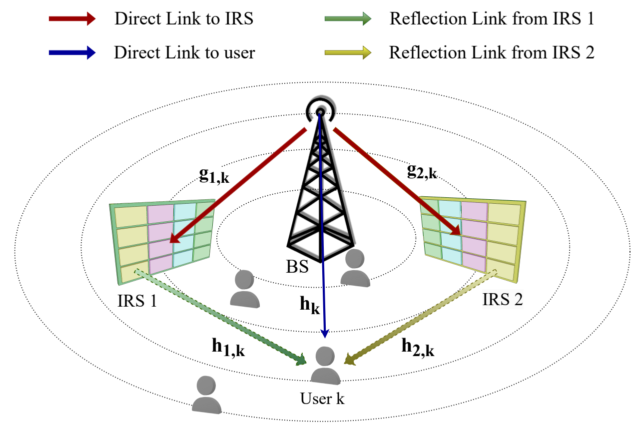


Fig. 1. An illustration of a Double-IRS-aided SISO downlink system.

channel vector from the BS to the $r^{\text{th}}$ IRS is represented as $\mathbf{g}_{r,k} \in \mathbb{C}^{S\times 1}$. Furthermore, for each user $k$, $n_k$ represents the additive white Gaussian noise (AWGN) defined as $n_k \sim \mathcal{CN}(0, n_o^2)$, where $n_o^2$ is its variance. The reflection coefficient vector, computed for adjusting the amplitude coefficients and phases on the $r^{\text{th}}$ IRS for the $k^{\text{th}}$ user, is represented as $\mathbf{\Phi}_{r,k} \in \mathbb{C}^{S\times S}$ which is given as follows

$$\mathbf{\Phi}_{r,k} = \text{diag}(\phi_{S\times(k-1)}, \dots, \phi_{S\times k}), \tag{2}$$

where, $\forall s \in \mathcal{S}$, $|\phi_s| \in [0, 1]$ and $\arg(\phi_s) \in [-\pi, \pi)$ denote the amplitude and the phase shift induced onto the incident signal, respectively. For the ideal phase shift models that we incorporate later for the purpose of comparison, $|\phi_s| = 1$ for $s \in \mathcal{S}$, irrespective of the value of $\arg(\phi_s)$.

For the user $k$, the signal-to-noise ratio (SNR) is computed using the channel gain present in (1) as

$$\gamma_k = \frac{P_t}{n_o^2}\left|h_k + \sum_r \mathbf{h}_{r,k}^H \mathbf{\Phi}_{r,k}\mathbf{g}_{r,k}\right|^2. \tag{3}$$

Using (3), we compute the achievable rate of the $k^{\text{th}}$ user as

$$R_k = \log_2(1 + \gamma_k), \tag{4}$$

which is then used to determine the achievable sum rate of the system as

$$R = \sum_k R_k. \tag{5}$$

### B. Channel Model

All the communication channels in the system follow Rayleigh fading. The channels $\mathbf{h}_k$, $\mathbf{h}_{r,k}$ and $\mathbf{g}_{r,k}$ are defined as follows

$$\mathbf{h}_k = \frac{\mathbf{u}_k}{\sqrt{d_k^{\alpha}}}, \tag{6}$$

$$\mathbf{h}_{r,k} = \frac{\mathbf{v}_k}{\sqrt{d_{r,k}^{\beta_1}}}, \tag{7}$$

$$\mathbf{g}_{r,k} = \frac{\mathbf{w}_k}{\sqrt{d_r^{\beta_2}}}, \tag{8}$$

where $\mathbf{u}_k$, $\mathbf{v}_k$ and $\mathbf{w}_k$ are the complex Gaussian random variables (RVs), where their magnitudes follow Rayleigh distribution and phases are uniformly distributed in $[0, 2\pi)$ [6]. The variables $d_k$, $d_{r,k}$ and $d_r$ denote the distances between the $k^{th}$ user and the BS, the $r^{th}$ IRS and the $k^{th}$ user, and the $r^{th}$ IRS and the BS, respectively. Moreover, $\alpha$, $\beta_1$, and $\beta_2$ are the path loss exponents for the channels between the users and the BS, the IRSs and the users, and the IRSs and the BS, respectively.

## III. Performance Analysis

### A. Energy Efficiency Analysis

To evaluate the performance of a double-IRS and a single-IRS-assisted MU-SISO system, we use energy efficiency as our metric, which gives us a general overview of how much power is consumed in the entire system while constituting a minimum acceptable sum rate of the system by achieving the minimum rate threshold for each user $k$. For this purpose, we formulate the total power consumption of the entire network, illustrated in [7] as

$$P_{total} = vP_t + P_{BS} + \sum_k P_k + \sum_{r,n} P_{IRS}, \tag{9}$$

where $v$ represents the efficiency of the transmit power amplifier, such that $0 \leq v \leq 1$, $P_t$ is the BS transmit power, $P_{BS}$ and $P_k$ denote the hardware static consumption at the BS and the users present inside the system, respectively, and $P_{IRS}$ is responsible for considering the effects of quantization, where the hardware static power consumed by the $n^{\text{th}}$ element on the $r^{\text{th}}$ IRS, is included for various cases. Using (5) and (9), the energy efficiency is defined as

$$\eta = \frac{(BW)(R)}{P_{total}}, \tag{10}$$

where $BW$ represents the bandwidth of the system.

Since we predominantly compare the difference in the energy efficiencies of the double and single IRS systems. it becomes imperative to formulate it as

$$\Delta = \eta_D - \eta_S, \tag{11}$$

where $\eta_D$ and $\eta_S$ denote the energy efficiency for the double IRS and the single IRS-assisted network configurations, respectively, for a given phase shift model.

### B. Practical Phase Shift Model

We consider a practical phase shift model that considers the effect of phase shift on the amplitude of the reflection coefficient by the IRS. The model has been derived in [4] and is based on the equivalent circuit model, which includes the effect of various impedances inside a single IRS element. Before referring to the closed-form expression, it must be noted that the reflection coefficient applied by the IRS to the impinging signal is $\phi_s = \omega_s(\theta_s)e^{-j\theta_s}$ where $\theta_s \in [-\pi, \pi)$ and $\omega_s(\theta_s) \in [0, 1]$ represent the phase shift and its corresponding amplitude value, respectively.

Throughout the paper, for the phase shift models implemented, we refer to the computation of coherent phase shift $\theta_s$ at the element $s$ of the $r^{\text{th}}$ IRS, which is computed using the following relation

$$\theta_s = \arg(\mathbf{h}_{r,k}\mathbf{g}_{r,k}) - \arg(h_k). \tag{12}$$

The analytical model, which encapsulates the impact of phase shift on the amplitude response, is given as

$$\omega_s(\theta_s) = (1 - \omega_{\min}) \left( \frac{\sin(\theta_s - \psi) + 1}{2} \right)^{\varepsilon} + \omega_{\min}, \tag{13}$$

where $\omega_{\min} \geq 0$ is the minimum amplitude of the response, $\psi \geq 0$ is the horizontal distance between the phase shifts $-\pi/2$ and $\theta_s$, where the latter is responsible for minimizing $\sin(\theta_s - \psi)$ component in the model, and $\varepsilon \geq 0$ is a factor used to adjust the overall steepness of the amplitude response curve [4]. As previously discussed, we utilize an ideal phase shift model to evaluate the impact of disregarding amplitude considerations on the system's performance. For that case, rather than using (13), $\omega_s(\theta_s) = 1$ for all values of $\theta_s$.

### C. Phase Shift Quantization

The hardware implementation of the reflecting elements on an IRS determines the reconfigurable phase shift that the IRS applies to the impinging signal. Generally, continuous phase shifts are employed in simulated IRS-assisted networks, providing valuable results. However, it is essential to consider a practical phase shift model in its entirety, which is done by utilizing the discrete phase shift design to populate the phases inside $\mathbf{\Phi}_{r,k}$ matrix. As given in [8], the set for the discrete phase shifts is defined as

$$\theta_s = \{\frac{2\pi}{2^B}b - \pi \mid b = 0, \ldots, 2^B - 1\}, \forall s \in \mathcal{S}, \tag{14}$$

where $B$ denotes the quantization bit, and $2^B$ represents the total number of discrete phase shifts available for a given quantization bit value. For the ideal phase shift model, which employs continuous phase shifts and neglects the quantization effects, it is assumed that the $\theta_s$ values are chosen from the range $[-\pi, \pi)$.

## IV. Simulation Results

In this section, we present the simulation results used to compare a single-IRS-assisted system with a double-IRS-assisted system by evaluating the energy efficiency across different factors. We consider a three-dimensional Cartesian coordinate system with uniformly distributed users and a coverage radius of 1000 m.

The transmission bandwidth of the system is set to $BW$ = 20 MHz, while the AWGN power is calculated as $n_o^2 = -174 + 10\log_{10}(BW)$ with a noise figure $N_F$ of 10 dB. Rayleigh fading channels in the environment are all assumed to have zero mean and variance $\sigma^2 = 3$. For an IRS, the total number of elements $N$ is used variably to illustrate the analysis of the system's energy efficiency. The practical phase shift model parameters are set as $\omega_{\min} = 0.2$, $\varepsilon = 1.6$, and

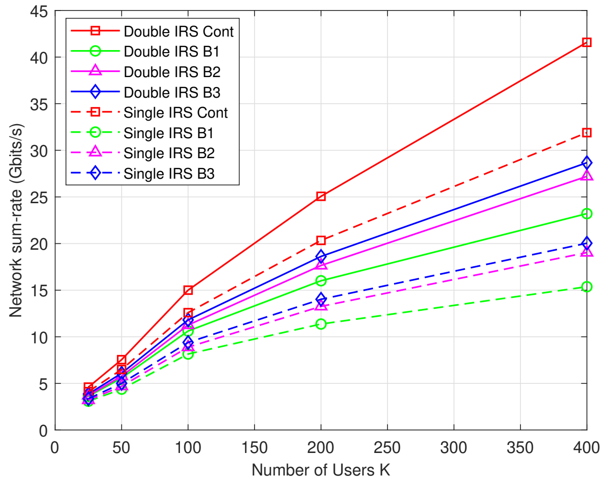


Fig. 2. Network sum-rate versus $K$ for $P_t = 36$ dBm and $N = 400$ elements on each IRS

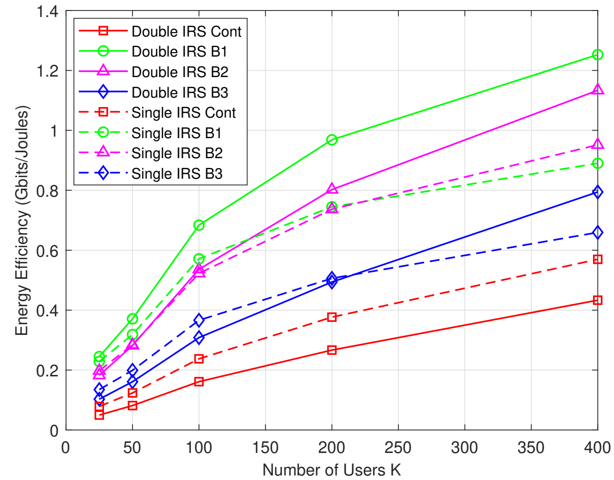


Fig. 3. Energy efficiency versus $K$ for $P_t = 36$ dBm and $N = 400$ elements on each IRS

$\psi = 0.43\pi$, as given in [4]. The following three quantization bits are used for evaluation: $B = 1$, 2, and 3.

Other specific parameters used for the simulation are specified in Table I.

Fig. 2 shows the trend the network sum-rate follows against an increase in the number of users. The results show that the continuous phase shift model achieves the highest sum-rate, followed by practical phase shift models using 3-bit quantization. Regarding energy efficiency, Fig. 3 shows that the performance of the IRS using continuous phase shifts degrades since the IRS has an infinite range of phase shifts to apply to the impinging signal and hence consumes more power. Even though the quantization bits $B = 1$ and 2 improve the system's energy efficiency, they are unable to provide the users with the maximum data rates, which is a stringent requirement to be fulfilled in our system. For this reason, 3-bit quantization is given significance in our study.

For users less than 200, a single IRS-assisted system is more energy-efficient than a double IRS system. Therefore, the latter achieves better results when the cell is populated with more users since the sum-rate provided by a double IRS system rises by a large factor, hence compensating for the increased power consumption.

TABLE I
SIMULATION PARAMETERS

| Parameters | Values |
|---|---|
| Transmit Power $P_t(W)$ | 4 |
| Path-loss exponent of BS to User $\alpha$ | 3.8 |
| Path-loss exponent BS to IRS $\beta_1$ | 2.8 |
| Path-loss exponent IRS to User $\beta_2$ | 2.2 |
| Power consumption of BS $P_{BS}$ (dBm) | 40 |
| Power consumption of IRS element for continuous phase shift (dBm) | 25 |
| Power consumption of IRS element for 1-bit quantization (dBm) | 5 |
| Power consumption of IRS element for 2-bit quantization (dBm) | 10 |
| Power consumption of IRS element for 3-bit quantization (dBm) | 15 |
| Power consumption of each user $P_U$ (dBW) | 10 |

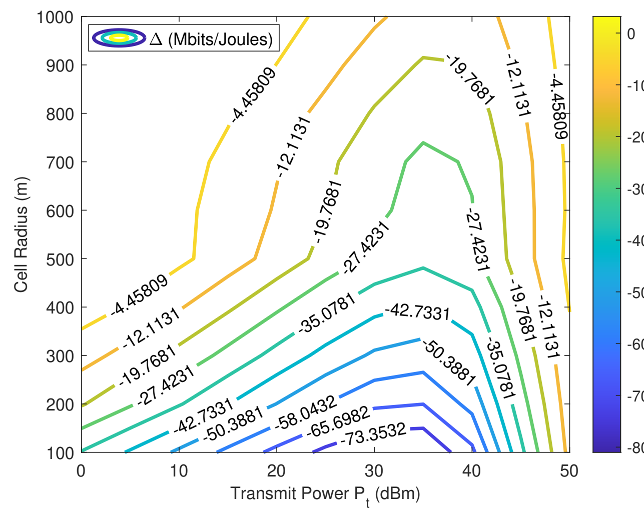


Fig. 4. Contour plot of difference in energy efficiency as a function of $P_t$ and cell radius using ideal phase shift model

Fig. 4 and 5 portray the effect of varying the coverage area on the system's energy efficiency. For the setup, $K = 16$, $N = 100$, and the quantization bit $B = 3$ are used. Along with varying the BS transmit power, the cell radius (in other words, the grid radius) is also increased while uniformly distributing users in each cell. For this entire case, we plot the differences in energy efficiency $\Delta$ to observe the variation in the performance of double and single IRS-assisted networks.

For practical phase shifting, the single IRS performs better at lower distances, with the double IRSs outperforming at larger grid radii. However, the energy efficiency gain provided by the double IRS system vanishes when we employ the ideal

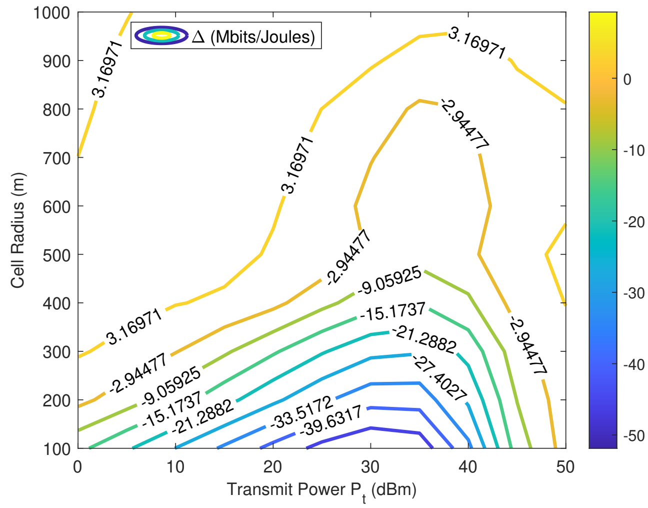


Fig. 5. Contour plot of difference in energy efficiency as a function of $P_t$ and cell radius using practical phase shift model

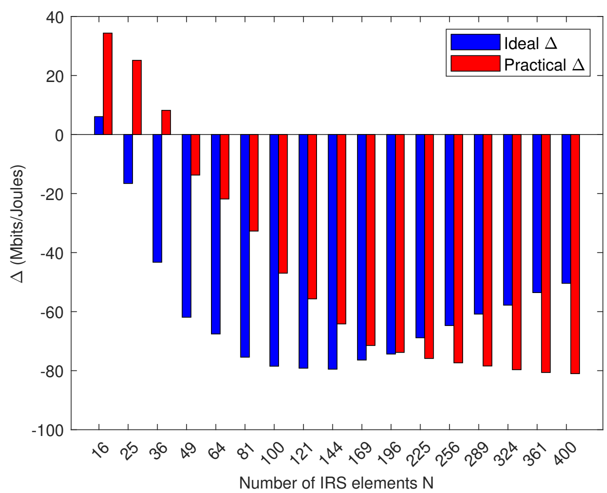


Fig. 6. Energy Efficiency versus $N$ for $P_t = 36$ dBm

phase shift model for the same range of distances since it is the single IRS that is shown to have a better performance. This is because the ideal models are unable to compensate for the performance degradation at larger distances, which is perfectly dealt with by practical reflection models where each reflection coefficient is determined using the corresponding IRS phase shifts.

The impact of increasing the number of elements on the IRSs can be seen in Fig. 6, where the difference in the system's energy efficiency $\Delta$ is plotted for both the ideal and practical phase shift models. It is observed that at a smaller number of IRS elements, the energy efficiency of the double IRS system peaks, as we get a higher sum-rate with lesser power dissipation as compared to deploying a single IRS in the same environment. However, for a high number of IRS elements, the power dissipation increases well beyond a certain threshold; thus, the performance of the double IRS system degrades. In the case of continuous phase shifts using an ideal model, the performance switch is less gradual from double to single IRS than the discrete phase shifts. It is evident that the difference in energy efficiency for the ideal case starts declining for each IRS having greater than 200 elements. Therefore, it can be concluded that there exists only an optimal number of IRS elements to be deployed for both systems exceeding which leads to the degradation of the system's energy efficiency.

## V. Conclusion

In this paper, we compared the performance of a single IRS-assisted SISO system against a double IRS system by observing energy efficiency. Using a practical phase shift model and shared element allocation scheme, we observed that the choice of using a single or double IRS in a system depends on an array of variable factors. Our results revealed that a single IRS-assisted system has better energy efficiency for compact environments with smaller values of variable factors. However, at larger deployments, the power consumption of the system demands the use of a double IRS to keep it energy efficient. These performance gains were better realized for the practical reflection/phase shift model.

Our findings can be generalized to be used for potential future research work exploring optimal IRS deployment, transmit power, and number of IRS elements by using reinforcement learning. Our work can also be scaled to deploying multiple IRSs in a system and utilizing massive-MIMO.

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