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Performance Analysis of Intelligent Reflecting Surfaces in Multi-Input-Single-Output Indoor Hotspot Environment

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Abstract: The evolution of 5G and beyond is boosting the development of telecommunication technology. In the future communication system, achievable rate and energy efficiency become the main aspects due to highly reliable and low latency requirements. Applying multiple antennas and applying cooperative communication scenarios to the system may enhance the network's performance. Intelligent reflecting surfaces (IRS) and relaying protocols are some examples of cooperative communication applications. IRS is multiple two-dimensional meta-surface elements that can reflect the incoming signal to get the desirable beam-forming based on its phase. While the relay is a device that can be used to enhance the performance of the networks based on its protocols such as amplify forward (AF) and decode forward (DF). Accordingly, this paper studies an IRS supporting MISO transmission and compares it with the relay deployment scenario. As a result, IRS has higher performance compared with any other scenario, and adding more IRS elements may enhance the achievable rate.

Keywords: MISO, IRS, relay, achievable rate, energy efficiency

1. INTRODUCTION

The development of wireless communication is driving the emergence of new technologies used in a mobile communication system [1]. Interestingly, mobility in an outdoor environment does not become the dominating traffic of all wireless communication. In the 5G and beyond, the researcher predicts that 80 percent of the traffic is dominated by indoor environment communication [2]. Many activities in indoor wireless communication may require high reliability and low latency, such as operating smart-home devices, streaming high-resolution video, playing games, and online meetings, etc. Enabling seamless connectivity in indoor communication requires a low delay and high data rate as the user in that indoor environment gets more [3]-[5]. One of the ways for achieving a high data rate is using multiple antennas or usually called multi-input. With a higher number of antennas, the capacity of the system will increase [6],[7]. Besides applying multiple-input scenarios directly, utilizing cooperative communication models also can enhance the performance of the system.

Cooperative relaying is one of the strategies for improving network capacity to achieve a reliable communication system [8],[9]. In cooperative relaying, there are some protocols where the relay can work as amplify-and-forward (AF) or decode-and-forward (DF) [10]. Compared to DF relaying protocols, AF relaying protocols have a simple implementation where relay only amplifies the received signal from a source and forwards it to the destination without noticing the noise it is amplifying [11]. Meanwhile, DF relaying protocols have a better result because the signal is decoded at first and encoded at the end of a node. By decoding the desired signal, these protocols can avoid the amplified noise that happen in AF relaying protocols [12]. Based on the explanation mentioned above, we are using DF relaying to represent traditional relaying protocols as a comparison scheme in the next section.

Compared with traditional relaying, intelligent reflecting surfaces (IRS) may enhance the performance of communication systems with less power consumption as a passive beam-former by reflecting transmitted signals towards the destination without amplifying the signal [13],[14]. An IRS is a two-dimensional meta-surface made from electromagnetic materials with multiple elements. Each element is re-configurable to change the electromagnetic properties of the incoming signal, called a phase shift [15]. By changing the phase shift, the reflecting phases can improve the signal power and mitigate interference [16],[17].

Related work conducted by Emil et al. in [18] analyzed a comparison between DF relaying and IRS-assisted wireless communication based on a single-input-single-output (SISO) with an urban micro scenario. The main point of that research is finding the minimum transmit power required by the system to achieve a desirable transmission rate. To fit up the previous work, in this paper, we analyzed a comparison between DF relaying and IRS-assisted communication based on multiple-input-single-output (MISO). Different from related research, we generate channel gain based on Rayleigh fading with an indoor hotspot scenario. The main focus of this paper is to present an extensive numerical result by performing computer simulations under realistic channel conditions. Analysis performed with respect to IRS/DF relay location, its number of antenna, its number of IRS element, and transmit power. We show that applying IRS will bring the system into a significant improvement in terms of achievable rate and energy efficiency compared to DF relaying and the basic MIMO scheme.

The rest of this paper is organized as follows. Section 2 introduces the system model of IRS-assisted transmission and DF relay-assisted transmission. Section 3 presents the simulation setup for our system model. In section 4, we provide numerical results and take a conclusion in section 5.

The notations used in this paper are listed as follows. $\mathbb{C}$ and $\mathbb{R}$ denote complex and real number respectively. $\mathbf{H}, \mathbf{h},$ and h denotes a matrix, a vector, and a scalar, respectively. $\mathbf{H}^{\mathrm{T}}$ is the transpose of the matrix **H**. $\|\mathbf{h}\|$ is the second norm of vector **h.** diag$\{.\}$ is the operator that generates a diagonal matrix form a given vector.

2. SYSTEM MODEL

In this section, we consider one access point with M multiple antennas communicating with a single antenna user. Access point and the user communicate through a direct channel and supported channel with the help of IRS which has N passive reflector element or DF relay. An illustration is shown in Figure 1. where the blue dotted line denotes the supported channel, while the black line represents the direct channel.

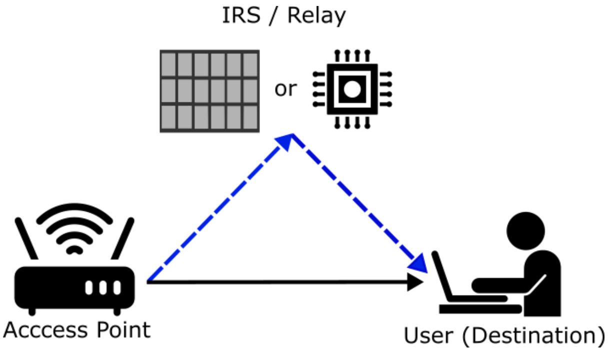


Figure 1. An illustration of IRS and relay supported indoor hotspot transmission

Define the channel coefficient vector from the access point to the user as $\mathbf{h}_{\mathrm{AU}} \in \mathbb{C}^{1\times M}$. The signal received by user can be expressed as

$$y_{\mathrm{direct}} = \mathbf{h}_{\mathrm{AU}} x + n \tag{1}$$

Where $\mathrm{x} = \sqrt{ps} \in \mathbb{R}$ is the transmitted signal from access point to the user while $\mathbb{p}, s,$ and n denote the transmit power, the transmit data symbol corresponding to access point, and additive white Gaussian noise (AWGN) with zero mean and covariance σ^2, respectively. Using equation (1), the signal to noise ratio (SNR) at the user can be written as

$$\gamma_{\mathrm{MISO}} = \frac{\|\mathbf{h}_{\mathrm{AU}}\|^2 p}{\sigma^2} \tag{2}$$

Based on Shannon's capacity theorem, the achievable rate of the user is given by

$$R_{\mathrm{MISO}} = \log_2\left(1 + \frac{\|\mathbf{h}_{\mathrm{AU}}\|^2 p}{\sigma^2}\right) \tag{3}$$

The achievable rate of this MISO communication can be increased by deploying a supporting devices. As supporting devices, IRS and DF relay will be present in the next subsection. In addition, total power consumption is a summation of transmit power and power consumed by the access point and the user. Thus, total power consumption can be expressed as

$$P_{\mathrm{total}}^{\mathrm{MISO}} = p + p_{\mathrm{AP}} + p_{\mathrm{user}} \tag{4}$$

Using (3) and (4), energy efficiency can be defined as a ratio between achievable rate and total power consumption [19]. Accordingly, the energy efficiency is given by

$$\mathrm{EE}_{\mathrm{MISO}} = \frac{\log_2(1+\gamma_{\mathrm{MISO}})}{p + p_{\mathrm{AP}} + p_{\mathrm{user}}} \tag{5}$$

2.1 IRS as Supporting Device

Since we are adding IRS into the system, the reflected channel will be available. Channel coefficient matrix from access point to IRS and channel coefficient vector from the IRS to user are denoted by $\mathbf{H}_{\mathrm{AI}} \in \mathbb{C}^{N\times M}$ and $\mathbf{h}_{\mathrm{IU}} \in \mathbb{C}^{N\times 1}$ respectively. The phase-shift matrix is defined as diagonal matrix $\mathbf{\Theta} = \mathrm{diag}\{\theta_1, \theta_2, \theta_{n,}, \dots, \theta_N\}$, where $\theta_{n,} = \mathrm{e}^{j\phi n}$ is one of phase reflection of IRS element. The received signal at IRS can be expressed as

$$y_{\mathrm{IRS}} = \mathbf{H}_{\mathrm{AI}} x \tag{6}$$

After receiving signal from access point, IRS will reflect the signal into user. The reflected signal from IRS can be written as

$$x_{\mathrm{IRS}} = \mathbf{\Theta} \mathbf{H}_{\mathrm{AI}} x \tag{7}$$

Hence, the received signal from reflected channel is

$$y_{\mathrm{reflect}} = \mathbf{h}_{\mathrm{IU}}{}^{\mathrm{T}} \mathbf{\Theta} \mathbf{H}_{\mathrm{AI}} x \tag{8}$$

Since the user received two signals from different links, the received signal at the user can be expressed as

$$\begin{aligned} y_{\mathrm{total}}^{\mathrm{IRS}} &= y_{\mathrm{direct}} + y_{\mathrm{reflect}} + n \\ &= \mathbf{h}_{\mathrm{AU}}\mathrm{x} + \mathbf{h}_{\mathrm{IU}}{}^{\mathrm{T}} \mathbf{\Theta} \mathbf{H}_{\mathrm{AI}} x + \mathrm{n} \\ &= \left(\mathbf{h}_{\mathrm{AU}} + \mathbf{h}_{\mathrm{IU}}{}^{\mathrm{T}} \mathbf{\Theta} \mathbf{H}_{\mathrm{AI}}\right) x + n \end{aligned} \tag{9}$$

Using the same way, the SNR of IRS supported system will become

$$\gamma_{\mathrm{IRS}} = \frac{\left\|\mathbf{h}_{\mathrm{AU}} + \mathbf{h}_{\mathrm{IU}}{}^{\mathrm{T}} \mathbf{\Theta} \mathbf{H}_{\mathrm{AI}}\right\|^2 p}{\sigma^2} \tag{10}$$

And make the achievable rate of the system as

$$R_{\mathrm{IRS}} = \log_2\left(1 + \frac{\left\|\mathbf{h}_{\mathrm{AU}} + \mathbf{h}_{\mathrm{IU}}{}^{\mathrm{T}} \mathbf{\Theta} \mathbf{H}_{\mathrm{AI}}\right\|^2 p}{\sigma^2}\right) \tag{11}$$

With an IRS as a supporting device, total power consumption also depends on IRS material type and the number of reflecting elements which doing the phase-shifting process to the incoming signals [20]. Thus, total power consumption can be written as

$$P_{\mathrm{total}}^{\mathrm{IRS}} = p + p_{\mathrm{AP}} + p_{\mathrm{user}} + p_{\mathrm{IRS}} \tag{12}$$

Since there are $\mathbb{N}$ reflecting element at the IRS, the total power dissipation at the IRS can be expressed as $p_{\mathrm{IRS}} = N p_{\mathrm{b}}$ where p_{b}denotes power consumed by each element. By using (11) and (12), energy efficiency can be defined as

$$\mathrm{EE}_{\mathrm{IRS}} = \frac{\log_2(1+\gamma_{\mathrm{IRS}})}{p + p_{\mathrm{AP}} + p_{\mathrm{user}} + N p_{\mathrm{b}}} \tag{13}$$

2.2 DF Relay as Supporting Device

In DF relaying protocols, the channel coefficient from access point to relay will become $\mathbf{h}_{\mathrm{AR}} \in \mathbb{C}^{1\times M}$, and the channel coefficient from relay to user will become $\mathrm{h}_{\mathrm{RU}} \in \mathbb{C}$. The transmission is also divided into two phases. In the first phase, an access point will send its signal to the relay and user simultaneously. The received signal at the user in the first phase given by

$$y_{\text{user}}^{1\text{st}} = \mathbf{h}_{\text{AU}} x_1 + n_{\text{user}}^{1\text{st}} \tag{14}$$

Where x_1 is the transmitted signal with transmit power p_1 and $n_{\text{user}}^{1\text{st}}$ is the AWGN at the user in the first phase. While received signal at the relay given by

$$y_{\text{relay}}^{1\text{st}} = \mathbf{h}_{\text{AR}} x_1 + n_{\text{relay}}^{1\text{st}} \tag{15}$$

Where $n_{\text{relay}}^{1\text{st}}$ is AWGN at the relay. The DF relay using this received signal to decode the information and encodes it for transmission in the second phase. In the second phase, the received signal at the user is given by

$$y_{\text{user}}^{2\text{nd}} = \text{h}_{\text{RU}} x_2 + n_{\text{user}}^{2\text{nd}} \tag{16}$$

Where x_2 is the transmitted signal with transmit power p_2 and $n_{\text{user}}^{2\text{nd}}$ is the AWGN at the user in the second phase. Based on [11], by using (14) and (16) for maximum ratio combining (MRT), achievable rate can be expressed as

$$R_{\text{relay}} = \frac{1}{2}\log_2\left(1 + \frac{\|\text{h}_{\text{RU}}\mathbf{h}_{\text{AR}}\|^2 2p}{(\|\mathbf{h}_{\text{AR}}\|^2 + \|\text{h}_{\text{RU}}\|^2 - \|\mathbf{h}_{\text{AU}}\|^2)\sigma^2}\right) \tag{17}$$

With assuming In the relaying scenario, access point is only active half of the time, thus total power consumption can be written as

$$P_{\text{total}}^{\text{IRS}} = p + 0.5p_{\text{AP}} + p_{\text{user}} + p_{\text{relay}} \tag{18}$$

Where p_{relay} is power dissipation at the relay. From (17) and (18), energy efficiency is given by

$$\text{EE}_{\text{IRS}} = \frac{R_{\text{relay}}}{p + 0.5p_{\text{AP}} + p_{\text{user}} + p_{\text{relay}}} \tag{19}$$

3. SIMULATION SETUP

In this section, we provide a complete simulation scenario based on the MATLAB application. The user placed 120m away from an access point. For supporting devices, the minimum distance from the access point will be set at 20m away as illustrated in Figure 2.

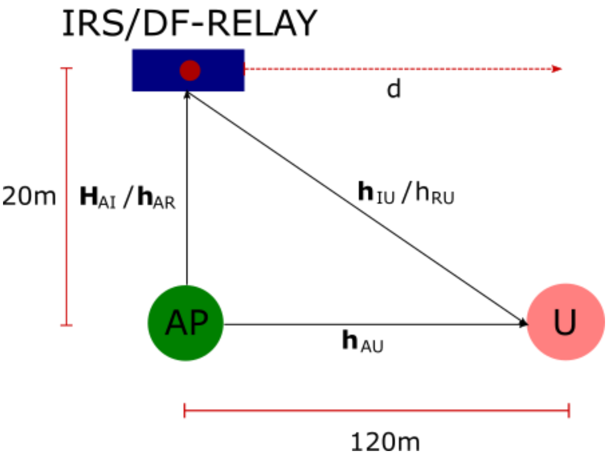


Figure 2. Simulated IRS/DF-Relay assisted indoor hotspot transmission scenario

The direct propagation path between an access point and the user is assumed to be dominated by the non-line-of-sight (NLoS) component and hence follows Rayleigh fading. Therefore, channel $\mathbf{h}_{\text{AU}}$ can be generated as $\mathbf{h}_{\text{AU}} \sim \mathcal{CN}(\mu, \sigma^2)$ multiplied with $\sqrt{L(d)_{NLoS}}$, where $\mathcal{CN}(\mu, \sigma^2)$ denotes the circularly symmetric complex Gaussian (CSGC) distribution with mean μ and variance σ^2. $\sqrt{L(d)_{NLoS}}$ represent a NLoS path-loss model based on indoor hotspot environment [20, Table A1-2].

$$\begin{aligned} L(d)_{NLoS} &= 43.3\log_{10}(d) + 11.5 + 20\log_{10}(fc) \\ L(d)_{LoS} &= 16.9\log_{10}(d) + 32.8 + 20\log_{10}(fc) \end{aligned} \tag{21}$$

Based on (20), the supported propagation path also generated through CSGC distribution but multiplied with the LoS path-loss model. The rest of the default parameters are summarized in Table 1.

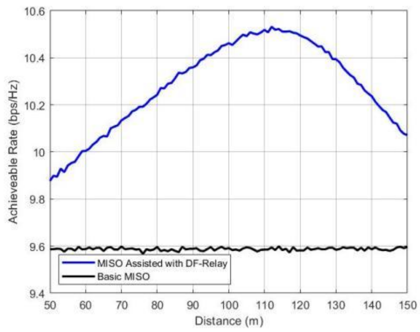
Table 1. Simulation Parameters

Parameters	Value
Channel iteration (i)	10000
Number of antenna (M)	5
Carrier frequency (fc)	2.4 GHz
Bandwidth (B)	180 Mbps
Noise (n)	$-174 + 10\log_{10}(B)$ dB
IRS/DF-Relay location	(120m,20m)
Transmit power	10dBm

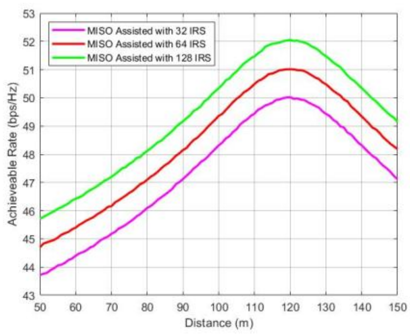
In addition, the simulation for all of the scenarios assumed operating under maximum transmit power and IRS working under random phase shift scenario.

4. NUMERICAL RESULT

Based on the simulation setup, several numerical results are investigated in this section. In Figure 3, we simulate the achievable rate performance with respect to IRS and DF-Relay location based on distance variables d in Figure 2.



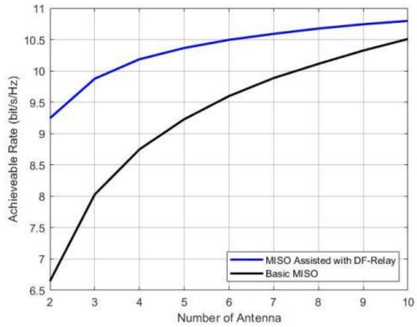
(a) Comparison between DF-Relay and Basic MISO Transmission



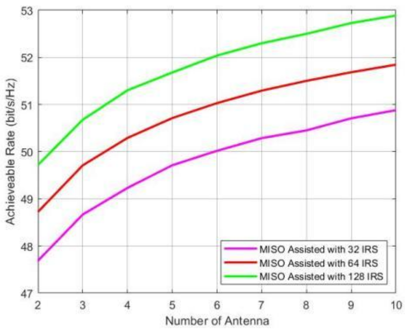
(b) Comparison between different IRS elements on MISO Transmission

Figure 3. IRS and DF-Relay distance vs achievable rate

In Figure 3 (a), the distance doesn't affect the ordinary MISO transmission rate. The flatness rate happens since we don't put any supporting device in that scheme. While the transmission gets assisted by IRS/DF-Relay, the achievable rate slowly increases as the supporting devices approach the user and start decreasing as it away. This phenomenon occurs because the supported propagation path starts dominating the direct propagation path. we also investigate that the achievable rate can be increased with the same trends by adding more IRS elements.



(a) Comparison between DF-Relay and Basic MISO Transmission

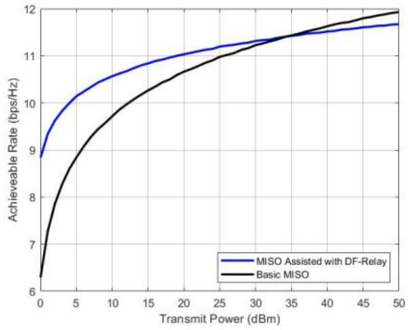


(b) Comparison between different IRS elements on MISO Transmission

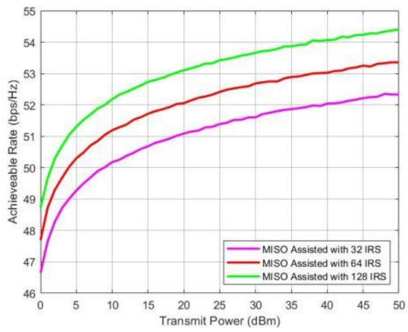
Figure 4. Number of antenna vs achievable rate

In Figure 4, we plot the achievable rate concerning the number of antennas and it ends with IRS-supported transmission outperforming the others. The number of antenna take a range from 2 antennas into 10 antennas deployment. From Figure 4 (a) and (b), all three schemes have similar trends. As the number of antennas increases, the achievable rate will go up. Interestingly, from Figures 4 (a), we can see that the elevation of DF-Relay achievable rate getting insignificant compared with basic MISO. In Figure 4 (b), an increasing number of IRS elements in different number antennas will also increase the achievable rate.

In Figure 5, simulated results of achievable rate are shown concerning transmit power with a range from 0 dBm until 50 dBm. From that figure, we can see that IRS-supported transmission still outperforms the others. The increase of



(a) Comparison between DF-Relay and Basic MISO Transmission



(b) Comparison between different IRS elements on MISO Transmission

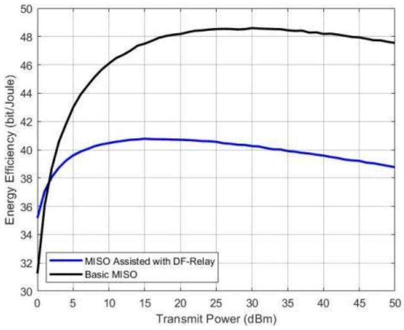
Figure 5. Transmit power vs achievable rate

transmit power will lead to escalation of the achievable rate. In Figure 4 (a), basic MISO transmission start overcomes the DF-Relay assisted transmission at $p = 35$ dBm. Based on that explanation, DF-Relay assisted transmission is optimally deployed with the low power transmit. It can be explained cause DF-Relaying protocols use the power for two-phase transmission, different from the ordinary MISO, which fully utilizes that power in a single transmission.

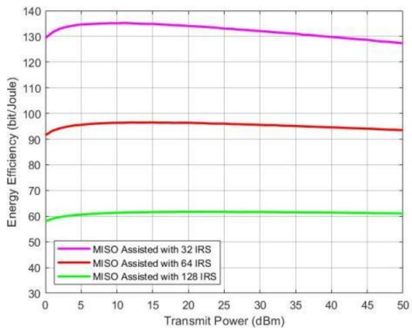
Finally, in Figure 6, we show the energy efficiency of the transmission system concerning transmitted power. While in Figure 6 (a), we compare the performance of the DF-Relay supported transmission and ordinary MIMO transmission, it shows that DF-Relay is efficient if operated below 2dBm increasing until a peak point and decrease after exceeding that value. The degradation of energy efficiency happens because the escalation of achievable rate can't compensate for the escalation of total power anymore. In Figure 6 (b), using more IRS elements may increase the energy efficiency but the power dissipation of the IRS will escalate, which results in steep degradation compared to a small number of IRS elements being deployed.

5. CONCLUSION

We studied the MIMO transmission supported by IRS with DF-Relaying and basic MIMO transmission as a comparison scheme. Achievable rate and energy efficiency are used to evaluate the performance of the system. The transmission system is operating under maximum power transmit, while IRS works under random phase shift scenarios. Simulation results demonstrated the effectiveness of IRS while deployed as a supported device in the MIMO transmission system with a higher achievable rate and energy efficiency. Based on the results, adding more IRS elements may also enhance the system's performance.



(a) Comparison between DF-Relay and Basic MISO Transmission



(b) Comparison between different IRS elements on MISO Transmission

Figure 6. Transmit power vs energy efficiency

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