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Joint Beamforming Design for IRS-Assisted Beyond 5G Wireless Networks

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***Abstract*— Intelligent reflecting surface (IRS) has emerged as a promising technology to enhance wireless communications by smartly shaping the radio propagation environment with reduced hardware and energy costs. In this paper, we integrate the IRS to a multiple-input single-output (MISO) fifth generation (5G) system via the joint optimization of the IRS reflecting coefficients and the transmit beamforming at the base station (BS) to maximize the spectral efficiency in an urban micro (UMi) propagation environment. Simulation results indicate that IRS successfully enhances the performance of the wireless network in terms of spectral and energy efficiencies compared with traditional transmit beamforming and relay-assisted systems.**

***Keywords*— Intelligent reflecting surface, beamforming, spectral efficiency, energy efficiency.**

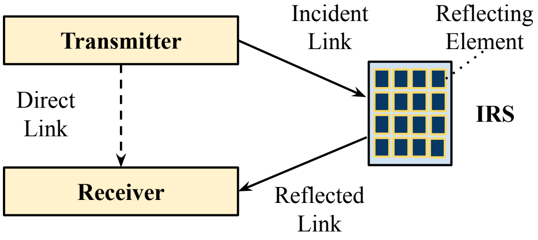

Fig. 1: Model of an IRS-assisted wireless network. The channel between the transmitter and receiver (direct link) is represented by the dashed arrow. The IRS-assisted links (incident and reflected) are indicated by solid arrows.

I. Introduction

Intelligent reflecting surface (IRS) is envisioned as a promising technology to meet the challenging design requirements of high spectral and energy efficiencies of beyond fifth generation (B5G) wireless networks [1]. IRS smartly modifies the wireless propagation environment, controlling the scattering, reflection, and refraction characteristics of electromagnetic waves to overcome the adverse effects of natural wireless propagation [1]. By the careful design of the reflection phase shift and/or amplitude of a large number of passive reflecting elements, IRS creates favorable signal paths between the transmitter and the receiver (incident and reflected links), as illustrated in Figure 1.

IRS differs significantly from the relaying technology. The relay assists the transmitter-receiver link by actively processing the received signal, then generating a new improved signal that is transmitted. In contrast, the IRS does not use a transmitter module since it only reflects the signals as a passive array. Consequently, IRS does not require active hardware elements, such as radio frequency (RF) chains, which implies reduced additional power consumption [2]. Therefore, IRS can provide performance enhancements to the wireless network without any new signal generation or amplification, which reduces the hardware cost and the power consumption [3]. The authors of [4] have compared the performance of an amplify-and-forward (AF) relay scheme with an IRS in a multiple-input single-output (MISO) network. They demonstrated that the IRS-assisted communication can provide large energy efficiency gains compared to the relay-assisted one. Bjornson et al. compared the ideal IRS with a decode-and-forward (DF) relay scheme to determine the conditions under which an IRS-assisted transmission to outweigh the conventional DF relaying in a single-input single-output (SISO) network in [5] and [6]. The authors demonstrated that, in a long term evolution advanced (LTE-A) propagation scenario, IRS can provide higher energy efficiency than DF according to the required data rates and the number of reflecting elements. The author of [7] extended this evaluation by considering a study in a fifth generation (5G) propagation scenario. The presented results supported the main conclusions of [5] and highlighted the differences in the performance of each scheme according to the path loss model, frequency operation, and geometric aspects of the network.

In this work, we evaluate the downlink performance of an IRS-assisted MISO communication system. Since the receiver takes the superposed signals from the direct and IRS-assisted links, it is necessary to jointly optimize the active beamforming at the transmitter and the passive beamforming (i.e, reflecting coefficients) at the IRS to maximize the received signal strength at the desired receiver. This problem was initially studied in [8] and extended by [9], in which the authors formulated a convex optimization problem to maximize the total received signal power at the receiver. They proposed a centralized algorithm based on the semidefinite relaxation (SDR) by assuming the availability of the channel state information (CSI) at the IRS. Since the centralized implementation requires excessive channel estimation and signal exchange overheads, they developed a low-complexity distributed algorithm, where the active and passive beamformers are adjusted in an alternating manner until convergence is reached.

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Motivated by the above discussion, we investigate the integration of an IRS in a MISO 5G network via the joint optimization of the IRS reflecting coefficients and the active beamforming to maximize the spectral efficiency in an urban microcell (UMi) propagation environment. The main contributions of this work can be summarized as follows:

1) Evaluation of a joint optimization of active and passive beamforming to maximize spectral efficiency;
2) Comparison of the IRS-assisted network with traditional transmit beamforming and DF relaying in a 5G-based propagation environment.

The remainder of this work is organized as follows. We present in Section II the main assumptions of our system model. Section III presents the joint active and passive beamforming design. Simulation parameters and numerical results are discussed in Section IV, and the main conclusions and research perspectives are drawn in Section V.

Notation: Bold lowercase and uppercase letters represent column vectors and matrices, respectively. $(\cdot)^*$, $(\cdot)^T$, and $(\cdot)^H$ stand for complex conjugate, transpose, and Hermitian of a matrix, respectively. $||\cdot||$ represents the Euclidean norm of a complex vector. $\mathbf{I}$ represents the identity matrix. $\Pi_{\mathbf{d}} = \mathbf{d}(\mathbf{d}^H\mathbf{d})^{-1}\mathbf{d}^H$ is the orthogonal projection onto a vector $\mathbf{d}$ and $\Pi_{\mathbf{d}}^{\perp} = \mathbf{I} - \Pi_{\mathbf{d}}$ represents the orthogonal projection onto the orthogonal complement of $\mathbf{d}$.

II. SYSTEM MODEL

We consider the downlink of a MISO wireless network, where a base station (BS) equipped with M antenna elements serves a single-antenna user equipment (UE). The communication link BS-UE is assisted by an IRS composed of N reflecting elements. The IRS is equipped with a smart controller, which dynamically adjusts the reflecting properties of each reflecting element. The BS determines the reflecting strategies performed by the IRS controller by a separated control link, as indicated in Figure 2. We assume a quasi-static flat-fading channel model for all channels involved in this network. The channels are assumed to be statistically independent. The channel corresponding to the BS-UE link, also referred to as direct link, is represented as $\mathbf{h}_{\text{BS-UE}} \in \mathbb{C}^{M\times 1}$. The equivalent channels of the IRS-assisted links, namely the BS-IRS link and IRS-UE link, are denoted as $\mathbf{H}_{\text{BS-IRS}} \in \mathbb{C}^{N\times M}$ and $\mathbf{h}_{\text{IRS-UE}} \in \mathbb{C}^{N\times 1}$, respectively. We consider that the CSI of all involved channels is perfectly known at the BS.

The properties of the IRS are represented by the reflecting matrix $\Theta = \text{diag}([e^{j\theta_1}, \cdots, e^{j\theta_N}]) \in \mathbb{C}^{N\times N}$, where $e^{j\theta_n}$ is the reflecting coefficient and $\theta_n \in [0, 2\pi]$ is the phase shift of the n-th reflecting element. The signal received at the UE is given by

$$y = \sqrt{P}(\mathbf{h}_{\text{BS-UE}}^H + \mathbf{h}_{\text{IRS-UE}}^H \Theta \mathbf{H}_{\text{BS-IRS}})\mathbf{w}x \; + \; z, \tag{1}$$

where P is the transmit power, $\mathbf{w} \in \mathbb{C}^{M\times 1}$ is the active beamforming vector at the BS, x is the transmitted signal, and $z \in \mathcal{CN}(0, \sigma^2)$ is the additive white Gaussian noise (AWGN) with zero mean and variance σ^2. The spectral efficiency, also known as achievable data rate, of the IRS-assisted network can be written as

$$\text{SE} = \log_2\left(1 + \frac{P|(\mathbf{h}_{\text{BS-UE}}^H + \mathbf{h}_{\text{IRS-UE}}^H \Theta \mathbf{H}_{\text{BS-IRS}})\mathbf{w}|^2}{\sigma^2}\right). \tag{2}$$

The energy efficiency of an IRS-assisted network can be written as

$$\text{EE} = \frac{B \cdot \text{SE}}{\eta \cdot P + P_{\text{BS}} + P_{\text{UE}} + N \cdot P_{\text{RE}}}, \tag{3}$$

where B is the bandwidth, η is the efficiency of the power amplifier, P is the transmit power, P_{BS} and P_{UE} are the hardware-dissipated power at the BS and UE, respectively. P_{RE} is the power dissipated per reflecting element due to the circuitry required to adapt dynamically the phase shift.

To capture the impact of 5G scenario, we assume an outdoor-to-outdoor radio propagation in an urban environment modeled according to UMi specifications [10]. The BS is mounted below the rooftop levels of surrounding buildings and UE is placed in a street flanked by buildings on both sides. The path loss models, defined in [10], for the line of sight (LOS) and non-line of sight (NLOS) are

$$\text{PL}_{\text{LOS}} = 32.4 + 21 \cdot \log_{10}(d) + 20 \cdot \log_{10}(f_c), \tag{4}$$

expression valid for for 10m $\leq d \leq d'_{BP}$, where $d'_{BP} = 4(L_{\text{BS}} - 1)(L_{\text{UE}} - 1)f_c/3 \times 10^8$, L_{BS} is the height of the BS and L_{UE} is the height of the UE.

$$\text{PL}_{\text{NLOS}} = \max\{\text{PL}_{\text{LOS}}, \text{PL}'_{\text{NLOS}}\}, \tag{5}$$

$$\text{PL}'_{\text{NLOS}} = 22.4 + 35.3 \cdot \log_{10}(d) + 21.3 \cdot \log_{10}(f_c) - 0.3(L_{\text{UE}} - 1.5)$$

where d is the distance (in meters) between the network elements, and f_c is the carrier frequency (in GHz). The channel gains are calculated according to the following expressions

$$G_{\text{LOS}} = G_{\text{BS}} + G_{\text{UE}} - \text{PL}_{\text{LOS}}, \tag{6}$$

$$G_{\text{NLOS}} = G_{\text{BS}} + G_{\text{UE}} - \text{PL}_{\text{NLOS}}, \tag{7}$$

where G_{BS} and G_{BS} denote the antenna gains at the BS and UE, respectively.

In the following, we detail how to perform the joint optimization of the active beamforming vector $\mathbf{w}$ and the IRS reflection matrix Θ to enhance the performance of the MISO system.

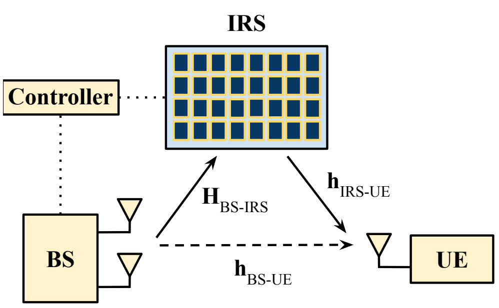


Fig. 2: IRS-assisted MISO wireless network.

III. JOINT BEAMFORMING DESIGN

A. IRS-Assisted Design

In this paper, we aim to maximize the spectral efficiency subject to the IRS phase shifts and transmit beamforming vector constraints. For this purpose, the following optimization problem can be formulated

$$\max_{\boldsymbol{\theta},\mathbf{w}} \quad P|(\mathbf{h}_{\text{BS-UE}}^H + \mathbf{h}_{\text{IRS-UE}}^H \Theta \mathbf{H}_{\text{BS-IRS}})\mathbf{w}|^2 \tag{8a}$$

$$\text{s. t.} \quad ||\mathbf{w}||^2 < 1, \tag{8b}$$

$$0 \leq \theta_n < 2\pi, \, \forall n = 1, \ldots, N. \tag{8c}$$

Despite the convexity of the constraints, this is a non-convex optimization problem due to the non-concave objective function with respect to $\mathbf{w}$ and Θ, as it can be seen in Eq. (8a). To overcome this issue, the authors of [8] proposed a low complexity solution based on an alternating optimization (AO). In this algorithm, the transmit beamforming vector $\mathbf{w}$ at the BS and the phase shifts θ_n at the IRS are optimized in an alternating manner with one being fixed and other updated at each iteration.

In the first iteration, the active beamforming vector $\mathbf{w}$ is initialized considering only the direct link BS-UE, that is

$$\mathbf{w}^{(1)} = \frac{\mathbf{h}_{\text{BS-UE}}}{||\mathbf{h}_{\text{BS-UE}}||}. \tag{9}$$

Next, we calculate the reflecting coefficients and update the beamforming vector. In other words, for a fixed transmit beamforming $\mathbf{w}^{(k-1)}$, the optimal phase shifts can be computed as

$$\theta_n^{(k)} = \angle[\mathbf{h}_{\text{BS-UE}}^H \mathbf{w}^{(k-1)}] - \angle[\mathbf{H}_{\text{BS-IRS}} \mathbf{w}^{(k-1)}]_n - \angle[\mathbf{h}_{\text{IRS-UE}}^H]_n,$$

where $\angle[\cdot]_n$ indicates the phase of the n-th element of a vector. Then, for a fixed set of phase shifts, $\{\theta_n^{(k)}\}$, we determine the optimal transmit beamforming vector using maximum ratio transmit (MRT). In this point, we include the IRS-assisted link. Making use of $\Theta^{(k)}$, the the active beamforming vector is updated at the k-th iteration as follows

$$\mathbf{w}^{(k)} = \frac{(\mathbf{h}_{\text{BS-UE}}^H + \mathbf{h}_{\text{IRS-UE}}^H \Theta^{(k)} \mathbf{H}_{\text{BS-IRS}})^H}{||\mathbf{h}_{\text{BS-UE}}^H + \mathbf{h}_{\text{IRS-UE}}^H \Theta^{(k)} \mathbf{H}_{\text{BS-IRS}}||}. \tag{10}$$

The process is iterated until $\mathbf{w}^{(k)}$ and $\Theta^{(k)}$ reach the convergence, or until maximum number of iterations is executed [9]. The main steps of IRS-assisted beamforming scheme are shown in Algorithm 1.

Algorithm 1: Alternating Optimization Design [8]

```
$k \leftarrow 1$
Initialize beamforming vector $\mathbf{w}^{(k)} = \frac{\mathbf{h}_{\text{BS-UE}}}{||\mathbf{h}_{\text{BS-UE}}||}$
while stopping criteria not reached do
    $k \leftarrow k+1$
    Calculate phase shifts $\theta_n^{(k)} = \angle[\mathbf{h}_{\text{BS-UE}}^H \mathbf{w}^{(k-1)}] -$
        $\angle[\mathbf{H}_{\text{BS-IRS}} \mathbf{w}^{(k-1)}]_n - \angle[\mathbf{h}_{\text{IRS-UE}}^H]_n$,
    Calculate beamforming vector
        $\mathbf{w}^{(k)} = \frac{(\mathbf{h}_{\text{BS-UE}}^H + \mathbf{h}_{\text{IRS-UE}}^H \Theta^{(k)} \mathbf{H}_{\text{BS-IRS}})^H}{||\mathbf{h}_{\text{BS-UE}}^H + \mathbf{h}_{\text{IRS-UE}}^H \Theta^{(k)} \mathbf{H}_{\text{BS-IRS}}||}$
end
```

B. Relay-Assisted Design

We consider the repetition-coded DF relaying protocol as a benchmark solution. It is divided into two transmission phases. In the first phase, the BS transmits and the signal is received at the UE and at the relay. Then, the relay uses the received signal to decode the information and then encodes it again to transmit to the UE in the second phase. The signals received at the UE in the first and the second transmission phases are combined to improve the achievable data rate. For this approach, the spectral efficiency is given by

$$\text{SE} = \frac{1}{2}\min(\text{SE}_{\text{R}}, \text{SE}_{\text{UE}}), \tag{11}$$

where SE_{R} and SE_{UE} are the the spectral efficiency at the relay and at the UE, respectively. These spectral efficiencies are calculated according to

$$\text{SE}_{\text{R}}(\mathbf{w}) = \log_2\left(1 + \frac{P_S|\mathbf{h}_{\text{BS-R}}^H \mathbf{w}|^2}{\sigma^2}\right), \tag{12}$$

$$\text{SE}_{\text{UE}}(\mathbf{w}) = \log_2\left(1 + \frac{P_s|\mathbf{h}_{\text{BS-UE}}^H \mathbf{w}|^2}{\sigma^2} + \frac{P_r|h_{\text{R-UE}}|^2}{\sigma^2}\right), \tag{13}$$

where P_s and P_r are the transmit power at the BS and at relay, respectively; the involved channels are $\mathbf{h}_{\text{BS-UE}} \in \mathbb{C}^{M\times 1}$, $\mathbf{h}_{\text{BS-R}} \in \mathbb{C}^{M\times 1}$, and $h_{\text{R-UE}} \in \mathbb{C}$. The spectral efficiency is maximized when there is a $\overline{\mathbf{w}} \in \mathbb{C}^{M\times 1}$ such that $\text{SE}_{\text{R}} = \text{SE}_{\text{UE}}$.

We consider the beamforming design proposed in [11], in which the authors developed an algorithm to balance direct and relay links to maximize the spectral efficiency of the overall system, as summarized in Algorithm 2.

The energy efficiency of a relay-assisted system is given by

$$\text{EE}_{\text{R}} = \frac{B \cdot \text{SE}_{\text{R}}}{\eta \cdot P + \frac{1}{2}P_{\text{BS}} + P_{\text{UE}} + \cdot P_{\text{R}}}, \tag{14}$$

where $P = \frac{P_s+P_r}{2}$, P_{R} is the power dissipated at relay. The $\frac{1}{2}$ factor is due to the duty cycle loss in the half-duplex relaying.

Algorithm 2: Vector Estimation Design [11]

```
$k \leftarrow 1$, $\delta = 10^{-7}$, $\epsilon_1^{(k)} = 1$, $\epsilon_2^{(k)} = 0$
Initialize beamforming vector $\mathbf{w}^{(k)} = \mathbf{h}_{\text{BS-R}}/||\mathbf{h}_{\text{BS-R}}||$
Define $D^{(k)} = \text{SE}_R(\mathbf{w}^{(k)}) - \text{SE}_{\text{UE}}(\mathbf{w}^{(k)})$
while $D^{(k)} < D^{(k-1)}$ do
    $k \leftarrow k+1$
    $\epsilon_1^{(k)} = \epsilon_1^{(k-1)} - \delta$
    $\epsilon_2^{(k)} = \sqrt{1 - \epsilon_1^{(k)}} e^{j\angle(\mathbf{h}_{\text{BS-UE}}^H \mathbf{h}_{\text{BS-R}})}$
    Update beamforming vector
        $\mathbf{w}^{(k)} = \epsilon_1^{(k)} \frac{\mathbf{h}_{\text{BS-R}}}{||\mathbf{h}_{\text{BS-R}}||} + \epsilon_2^{(k)} \frac{\Pi_{\mathbf{h}_{\text{BS-R}}}^{\perp} \mathbf{h}_{\text{BS-UE}}}{||\Pi_{\mathbf{h}_{\text{BS-R}}}^{\perp} \mathbf{h}_{\text{BS-UE}}||}$
end
$\epsilon_1^* = \epsilon_1^{(k-1)}$, $\epsilon_2^* = \epsilon_2^{(k-1)}$
Define $\alpha^*$ and $\beta^*$
$\alpha^* = \epsilon_1^* - \epsilon_2^* \frac{||\Pi_{\mathbf{h}_{\text{BS-R}}} \mathbf{h}_{\text{BS-UE}}||}{||\Pi_{\mathbf{h}_{\text{BS-R}}}^{\perp} \mathbf{h}_{\text{BS-UE}}||}$ , $\beta^* = \epsilon_2^* \frac{||\mathbf{h}_{\text{BS-UE}}||}{||\Pi_{\mathbf{h}_{\text{BS-R}}}^{\perp} \mathbf{h}_{\text{BS-UE}}||}$
Calculate optimal beamforming vector
$\overline{\mathbf{w}} = \alpha^* \frac{\mathbf{h}_{\text{BS-R}}}{||\mathbf{h}_{\text{BS-R}}||} + \beta^* \frac{\mathbf{h}_{\text{BS-UE}}}{||\mathbf{h}_{\text{BS-UE}}||}$
```

IV. SIMULATION RESULTS

We consider the downlink of a MISO wireless network, where the BS is equipped with $M = 8$ antenna elements and serves a single-antenna UE. The network is assisted by an IRS with a variable number of reflecting elements, namely $N = \{100, 200, 400\}$. The BS and IRS are deployed at fixed positions, separated by a distance $d_{\text{BS-IRS}} = 80$ m. The UE moves along a line parallel to the line connecting BS and IRS. These two lines are separated by a distance $d_V = 10$ m. The distance covered by the UE is denoted by d_{UE} which increases from 0 to 100 m. The BS has a height equal to $L_{\text{BS}} = 10$ m. The IRS is placed in front of BS, thus, have the same height $L_{\text{IRS}} = L_{\text{BS}}$. The height of the UE is $L_{\text{UE}} = 1.5$ m. The relay has the same coordinates as the IRS. Figure 3 depicts the spatial configuration of the evaluated network.

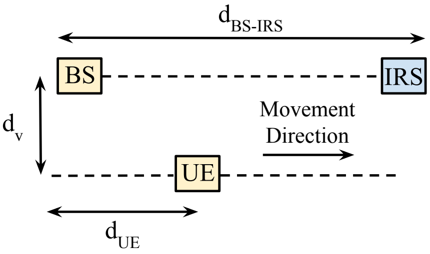
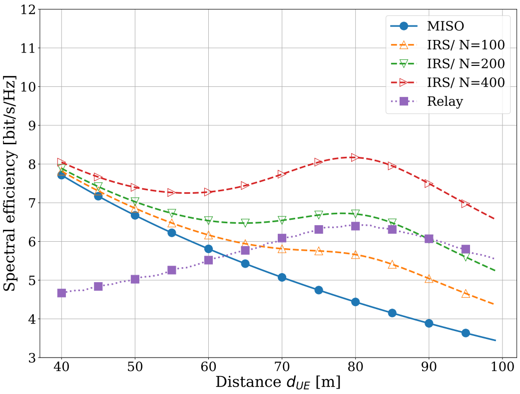


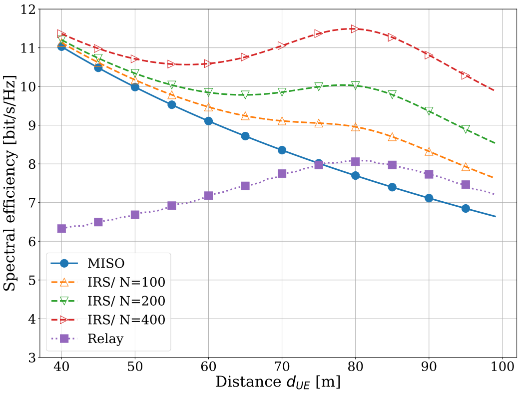
Fig. 3: Simulation setup.

The antenna gains have been set to 8 dBi at the BS and the IRS, and to 0 dBi at the UE. The propagation conditions are modeled as UMi according to the 3rd Generation Partnership Project (3GPP) specifications [10]. The BS-UE link is modeled as UMi NLOS to indicate the hard propagation conditions. The BS-IRS and IRS-UE links are modeled as UMi LOS. The carrier frequency is $f_c = 3$ GHz, the bandwidth is $B = 10$ MHz, and the noise power is -94 dBm.

Figure 4 presents the spectral efficiency *versus* the horizontal distance between the BS and UE for different values of the transmit power P. In a system without IRS, the beamforming is designed by considering only the direct link, as indicated in Eq. (9). In this scheme, as the UE moves away from the BS, the signal to noise ratio (SNR), and consequently the spectral efficiency, is reduced due to the increasing attenuation. This problem is alleviated with the deployment of an IRS to aid the communication. In our simulation setup, as the UE moves away from the BS, it approaches the IRS. Consequently, the signal reflected by the IRS becomes stronger. We observe that the spectral efficiency has its highest values when the UE is near to the BS or to the IRS. In our model, the highest spectral efficiency is observed when $d_{\text{BS-IRS}} = 80$m, i.e., when the UE is in front of the IRS. The increment of the spectral efficiency when $N = 400$ is 75% and 53% with transmit power $P = 2$ dBm and $P = 12$ dBm, respectively. The relay-assisted network also experiences an increment of the spectral efficiency as the UE is close to the relay. However, it has limited capability to reduce the attenuation of the signal. As we can observe in Fig. 4b, the IRS is more effective to enhance the propagation conditions with the increment of the transmit power. Consequently, the performance gap between IRS and relay at their best position ($d_{\text{UE}} = 80$) increases, from 2 bit/s/Hz to 4 bit/s/Hz.



(a) Transmit power $P = 2$ dBm.

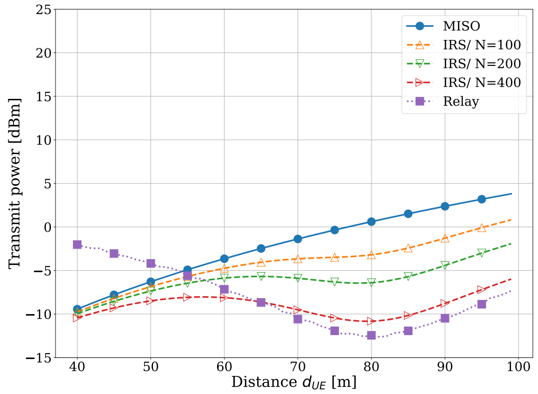


(b) Transmit power $P = 12$ dBm.

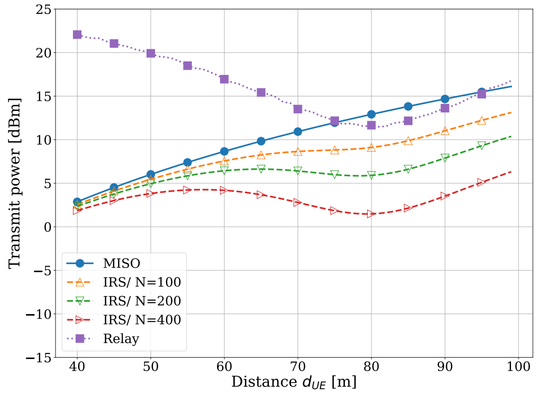
Fig. 4: Spectral efficiency versus distance d_{UE} with different transmit powers.

Figure 5 shows the transmit power P required to achieve a predefined spectral efficiency versus the horizontal distance d_{UE}. The required transmit power for the MISO scheme increases with the distance d_{UE} since the propagation conditions worsen and nothing is done to improve them. By its turn, the DF relaying case requires the least transmit power the UE gets closer to the relay. On the other hand, the required transmit power in the IRS-assisted scenario reduces when N increases. Moreover, the performance gap with respect to DF relaying case is smallest when the UE is located close to (in front of) the IRS. Note that higher spectral efficiency targets benefit the IRS, which becomes more competitive. In this case, the IRS reduces the required transmit power by approximately 12 dB in comparison with DF relaying.

Figure 6 indicates the energy efficiency versus the achievable data rate considering the UE located in front of the IRS, i.e., $d_{\text{UE}} = 80$ m. We consider $\eta = 0.5$, $P_{\text{BS}} = P_{\text{UE}} = P_{\text{R}} = 100$ mW and $P_{\text{RE}} = 5$ mW [5]. Although the relay has an improved spectral efficiency and requires less transmit



(a) Transmit power versus $\mathrm{d_{UE}}$ for SE $= 4$ bits/s/Hz



(b) Transmit power versus $\mathrm{d_{UE}}$ for SE $= 8$ bits/s/Hz

Fig. 5: Transmit power as a function of $\mathrm{d_{UE}}$ for different target spectral efficiencies (4 and 8 bits/s/Hz).

power for lower rates, it does not compensate the added dissipated power, making the MISO setup a better option regarding energy efficiency. It is important to notice that IRS has highest energy efficiency values when we consider higher achievable rates, which in this scenario occurs when SE $>$ 12.5 bit/s/Hz. For lower rates, the increase on the number of reflecting elements reduces the energy efficiency due to the power dissipated per reflecting element. However, when higher rates are required, increasing the number of reflecting elements increases the energy efficiency since the enhancement of the channel conditions compensates the increment on the power consumption.

V. CONCLUSIONS

In this paper, we evaluated the integration of the IRS to MISO wireless network exploring an alternating optimization algorithm to design the IRS reflection characteristics and the transmit beamforming vector. Simulation results indicated that IRS successfully enhanced the performance of the wireless network compared with traditional transmit beamforming and DF relaying. The IRS successfully improved the propagation conditions, providing an increment of the spectral efficiency of 75% compared with the system without IRS and 20% to the relay-assisted network when $N = 400$. In terms of energy efficiency, the impact of the IRS on the network performance is more pronounced under more restrictive spectral efficiency requirements. As perspectives, we include the extensions to the multiple-input multiple-output (MIMO) and multi-user (MU) scenarios, a performance evaluation under more realistic channel models, and the study of the impact of hardware models for the IRS.

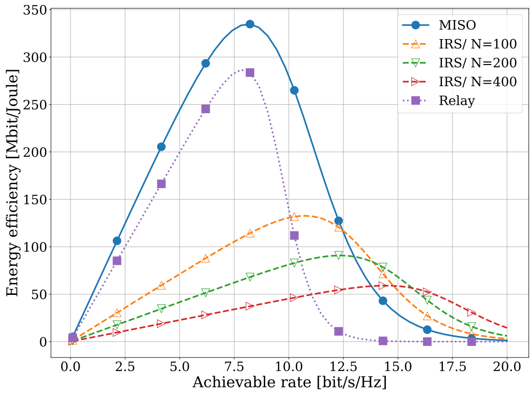


Fig. 6: Energy efficiency at $d_{\mathrm{UE}} = 80$ m.

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