Intelligent Reflecting Surfaces Versus Full-Duplex Relaying: Performance Comparison for Non-Ideal Transmitter Case

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***Abstract*—An intelligent reflecting surface (IRS) comprises of an array of discrete reflective elements (REs) possessing re-configurable scattering properties. IRS has the capability to beamform and relays the received radio signal from the transmitter to the desired receiver. This has made the IRS a promising candidate technology for the beyond fifth-generation (5G) cellular standards. In this work, the performance of an IRS-assisted wireless communication system is investigated and compared with the full-duplex (FD) relay-assisted system in the presence of non-ideal transmitters. Specifically, the performance is compared in terms of channel capacity and energy efficiency (EE). The results show that the IRS can never achieve more capacity than the ideal FD relaying, in the presence of a non-ideal transmitter, irrespective of the placement of IRS and relay. Further increasing the number of REs, the capacity saturates with an upper bound that equals to the capacity provided by the relay-assisted system. However, increasing the number of REs results in the reduction of the EE for IRS-assisted systems, which are otherwise known to be highly energy-efficient.**

***Index Terms*— Intelligent reflecting surface, energy efficiency, decode-and-forward, channel capacity, non-linearity, full-duplex, self-interference.**

I. Introduction

Over the last few decades, there has been a widespread proliferation of wireless services, catering for the diverse quality of service (QoS) applications. With the advent of the fifth-generation (5G) wireless standard, it is expected that data traffic volume will further increase. Further, the 5G standard has to support massive connectivity, i.e., serving a huge number of devices with seamless connectivity. This exponential growth of wireless services has significantly raised the energy requirement. Thus to have sustainable growth, the ambitious goals for the next generation (beyond 5G) wireless communication systems is to increase the system capacity by 1000-times and scale down the energy requirements up to 100 times [1]. Further, recently, wireless techniques have played a crucial role in connecting and communicating during this pandemic. The crisis has further surged the wireless data consumption; as an example, a 50% average increase in monthly mobile data usage in India has been reported [2].

Recently, intelligent reflecting surfaces (IRSs) has been proposed as a potential disruptive technology that could achieve both the aforementioned goals required for sustainable growth, i.e., high energy efficiency (EE) and high spectral efficiency (SE) [3], [4]. Specifically, IRSs are an array of sub-wavelength-sized scattering elements that can align the phase of a received signal in a particular desired direction. Thus, IRS has the potential to alter the wireless radio propagation environment to have a favorable channel between the transmitter and receiver. The real-time re-configurable property of IRS has recently sparked a new interest in mobile wireless communication research. With these aforementioned benefits, IRS has emerged as a strong contender and a key enabler for next-generation 6G wireless networks [5].

A performance comparison of IRS with an ideal amplify-and-forward (AF) relay was studied in [6], where the IRS is shown to have large energy efficiency (EE). Further, in [7], the performance IRS-assisted system is compared with ideal AF relay in terms of outage probability, SER and ergodic capacity. Here also, the IRS-assisted system outperforms the conventional AF relaying. Likewise, in [8], Bjornson et al. have compared the performance of IRS-assisted systems against decode-and-forward (DF) relaying. The authors have shown that the IRS-aided transmission does not always outweigh the conventional DF relaying, however, for a very large number of REs, the IRS can outperform the DF relaying. Moreover, in [9], the authors have considered some novel 5G channel models and revised the results for IRSs and DF relays, where they have shown that the IRS and DF relay can complement each other's strengths and can both have a place in 5G and beyond 5G architectures. Finally, Renzo et al. have summarized various the key differences and similarities between IRSs and the relays in [10].

As evident from above, the performance comparison for IRS and relaying have been studied in the literature considering the ideal hardware scenario. However, as shown in [11], the presence of non-ideal transmitter at the source severely restricts the performance of IRS-assisted wireless communication system. Motivated by the above, in this article, we investigate and compare the performance of IRS-supported transmission and relaying in the presence of non-ideal transmitter.

II. System Model

In this work, we have considered a system where a source is trying to communicate with the destination. The transmission

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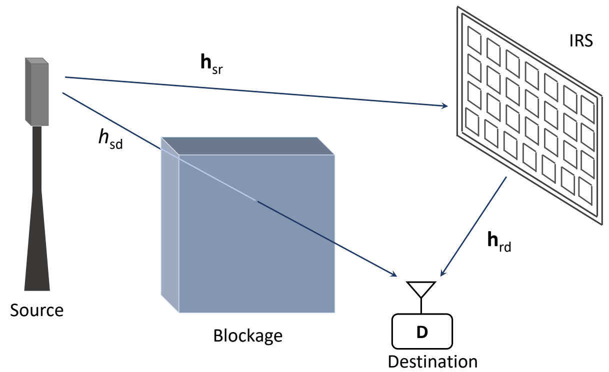
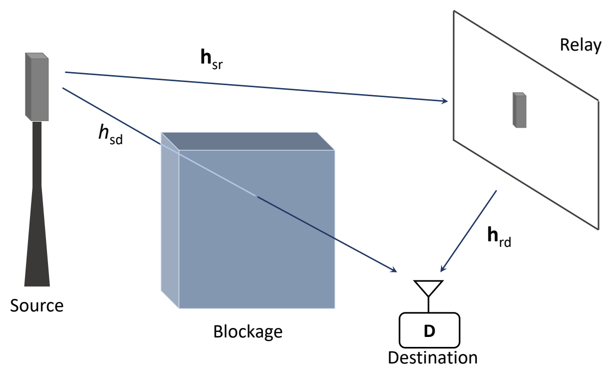


(a) IRS-assisted Wireless System



(b) Relay-assisted Wireless System

Fig. 1. Schematic for the considered scenario.

is aided either by an IRS or a DF relay, as shown in Fig. 1.

A. Channel Model

1) IRS-assisted Transmission: : As illustrated in Fig. 1(a), we have considered the scenario where a source is communicating with the destination via an IRS. The IRS, which consists of N discrete reflecting elements (REs), is facilitating the information transfer. The channel between the source and the IRS is denoted as $\mathbf{h}_{sr}$, and the one between the IRS and the destination is denoted as $\mathbf{h}_{rd}$. Further, the source-to-IRS distance and the IRS-to-destination distance are denoted as d_{sr} and d_{rd}, respectively, whereas d_{sd} denotes the source-to-destination distance. The sum distance of source-to-destination via relay link is D, i.e., $D = d_{sr} + d_{rd}$. Further, we considered the scenario where the direct link between source and destination is obstructed by a blockage, and the IRS is deployed for assisting the communication[1]. Since there is no direct line of sight link, $D > d_{sd}$, i.e., which implies that the IRS relay cannot be placed in between the source-to-destination link.

2) Relay-assisted Transmission: : For the relay-assisted system, we have considered a relay in place of IRS, as shown in Fig. 1(b). A full-duplex (FD) mode has been considered for the relay where the relay node is equipped with a pair of antenna, one each for transmitting and receiving. Furthermore, it is assumed that the relay have perfect knowledge of channel state information (CSI). The source and relay transmit data symbols are denoted by x_s and $\mathbf{x}_r$, assumed to be i.i.d. with zero mean and variance $P_s = \mathrm{E}\left\{s_x s_x^H\right\}$ and $P_r = \mathrm{tr}\left(\mathrm{E}\left\{\mathbf{r}_x \mathbf{r}_x^H\right\}\right)$ respectively. P_s and P_r represents the transmit power constraint at the source and the relay, respectively. The self-interference (SI) channel, h_{si}, is modeled as frequency non-selective Rayleigh flat fading channel having i.i.d. elements, $h_{si} \sim \mathcal{CN}(0,1)$ [12].

B. Transceiver Impairments

Conventionally it has been shown in the literature that the assumption of considering the ideal hardware is not practical as the transceiver architecture at the RF front-end is prone to various inevitable additive impairments such as I/Q imbalance, phase noise and nonlinearity of RF. A generic approach for modeling the joint impact of all these impairments considers that the resultant distortion noises are Gaussian distributed with their average power being proportional to the average transmit power of signal[2]. Consequently, at the source, the above imperfections will result into a mismatch between the actual transmitted signal and the desired signal, x, where $x \in \mathcal{CN}(0, \sigma_{in}^2)$. So the actual transmitted signal, $\tilde{x}$, can be rewritten as

$$\tilde{x} = x + w, \tag{1}$$

where w represents the distortion caused by the aggregated hardware imperfections, and it can be modeled as a zero-mean complex Gaussian process whose variance can be expressed as

$$\sigma_w^2 = \xi^2 \sigma_{in}^2, \tag{2}$$

where, ξ is a proportionality constant that characterize the level of residual impairment at the source.

C. Received Signal Model

1) IRS-assisted Transmission: The received signal at the destination, reflected signal from IRS can be denoted as

$$\begin{aligned} y &= \sum_{i=1}^{N} h_{sr} r_i h_{rd} \tilde{x}_t + n_d, \\ &= \mathcal{G} r_i \tilde{x}_t + n_d, \end{aligned} \tag{3}$$

where n_d denotes the additive white Gaussian noise (AWGN) with $\mathcal{CN}(0, \sigma^2)$. Further, with $\mathcal{G} = \sum_{i=1}^{N} \left[|h_{sr}|\right]_i \left[|h_{rd}|\right]_i$ being the gain provided by the IRS.

Moreover, $r_i = |r_i| \exp(j\varphi_i)$ represents the response of the ith RE where φ_i denotes the phase shift that is applied by the ith RE of the IRS. Without losing any generality, we assume that $|r_i| = 1$, as discussed in [7]. Further, the phase can be optimally set to reflect the incoming signal towards user. The optimal phase shift that can be adjusted is $\varphi_i = -\left(\varphi_{[h_{sr}]_i} + \varphi_{[h_{rd}]_i}\right)$, and so, with the optimal beamforming at IRS, r_i can be rewritten to as $r_i =$

[1]The above-considered scenario is one of the practical application of IRS that has been explored in literature [7].

[2]This Gaussian characterization has been experimentally validated as discussed in literature [13]

$\exp\left(-j\left(\varphi_{[h_{sr}]_i}+\varphi_{[h_{rd}]_i}\right)\right)$. Thus, utilizing (1), the received signal at the destination can now be expressed as

$$\begin{aligned} y &= \mathcal{G}\tilde{x}_t + n_d, \\ &= \mathcal{G}x_t + \mathcal{G}w_t + n_d. \end{aligned} \tag{4}$$

2) Relay-assisted Transmission: The received signal at the FD relay, y_R, can be expressed as

$$y_r = h_{sr}\tilde{x}_s + h_{si}\tilde{x}_r + n_r, \tag{5}$$

where n_r is the AWGN noise with $\mathcal{CN}(0,\sigma^2)$.

Now at the FD relay, the SI can be mitigated by estimating and subtracting it from the received signal. However, the presence of various imperfections results in some residual SI. Thus, after estimating $h_{si}\tilde{x}_r$, it can be subtracted from y_r, the received signal at the relay. Thus, in (5), the received signal can be now be written as:

$$y_r = h_{sr}\tilde{x}_s + d_r + n_r, \tag{6}$$

where d_r denotes the RSI with $d_R \sim \mathcal{CN}(0,\sigma^2_{rsi})$ and $\sigma^2_{rsi} = \alpha P_r^{\nu}$. Further, α and ν ($0 \leq \nu \leq 1$) are constants depending upon the efficacy of employed SI cancellation scheme.

Thus, the equivalent received signal in (6) can be rewritten by substituting (1) as

$$y_r = h_{sr}x_s + h_{sr}w_s + d_r + n_r, \tag{7}$$

Likewise the received signal y_d at the destination can be written as

$$y_d = h_{rd}\tilde{x}_r + n_d. \tag{8}$$

or equivalently, using (1) it can be re-written as

$$y_d = h_{rd}x_r + h_{rd}w_d + n_d. \tag{9}$$

III. Channel Capacity and EE Evaluation

In this section, we present the analytical formulation for the system capacity and EE.

The EE can be defined as the ratio of the rate over the total power consumed [14],

$$EE = \frac{Rate}{P_t + P_{cir}}. \tag{10}$$

where $P_t = P_s + P_r$ is the total transmitted power at the source and relay, and P_{cir} is the circuit power consumption.

A. Circuit Power Modeling

The source power consumption comprises the transmit power at source, P_s, circuit power consumption in HPA, P^S_{hpa}, and other circuitry[3], P^S_c. Now, the HPA power consumption can be modeled as $P^S_{hpa} = \beta P_s$, where $\beta = \frac{1}{\omega}$ and ω is the drain efficiency of HPA. Thus the total power consumed at source can be written as

$$P^S_{tot} = (1+\beta)P_s + P^S_c. \tag{11}$$

[3]This accounts the power consumed in other blocks apart from HPA such as mixer, a digital-to-analog converter, frequency synthesizer.

Likewise the total power consumption at the FD relay can be expressed as:

$$P^R_{tot} = (1+\beta)P_r + P^R_c, \tag{12}$$

where P^R_c is the circuit power consumption (excluding the HPA power consumption) at the FD relay. Similarly the power consumed at the destination is $P^D_{tot} = P^D_c$, where P^D_c is the power consumed in the destination circuitry.

Since the IRS is equipped with multiple REs, for the ease of exposition and without losing any generality, we assume that the power consumed by each of the RE is identical [6]. So, the power consumed at the IRS can be expressed as

$$P^{IRS} = NP_{RE}, \tag{13}$$

where P_{RE} is the circuit power consumption at each of the RE in the IRS.

B. IRS-assisted Transmission

In this subsection, we will formulate the channel capacity expression for IRS-assisted transmission and then evaluate the EE of the system. The signal-to-distortion-plus-noise-ratio (SDNR) for the can be obtained from (2) and (4) as

$$\Gamma_{IRS} = \frac{\mathcal{G}^2 P_t}{\mathcal{G}^2\xi_t^2 P_t + \sigma^2} = \frac{\mathcal{G}^2}{\xi_t^2\mathcal{G}^2 + \frac{1}{\Gamma_t}}, \tag{14}$$

where, $\Gamma_t = \frac{P_t}{\sigma^2}$, denotes the transmit signal-to-noise ratio (SNR). So, the channel capacity of the IRS-assisted network can be expressed as:

$$R_{IRS} = \log_2\left(1 + \Gamma_{IRS}\right). \tag{15}$$

After taking into account the circuit power consumption as discussed above, the EE in (10) and (15) can be expressed as

$$EE = \frac{R_{IRS}}{(1+\beta)P_t + P^S_c + NP_{RE} + P^D_c} \tag{16}$$

From (16), it can be observed that increasing N increases the power consumption linearly, whereas the SE increases logarithmically with respect to N. Thus, the overall impact will be a compound effect of both, where the EE increases initially with increasing M, but later, the EE decreases. This has also been verified through simulation results in the next section.

C. Relay-assisted Transmission

In this subsection, we formulate the channel capacity relay-assisted transmission and then evaluate the EE of the system. The SDNR for the source-to-relay link can be obtained from (2) and (7) and is represented as

$$\begin{aligned} \Gamma_{SR} &= \frac{|h_{sr}|^2 P_s}{|h_{sr}|^2\xi_s^2 P_s + \sigma^2_{rsi} + \sigma^2}, \\ &= \frac{\Gamma_s}{\xi_s^2\Gamma_s + \Gamma_{rsi} + 1}, \end{aligned} \tag{17}$$

where $\Gamma_s = P_s|h_{sr}|^2/\sigma^2$ and $\Gamma_{rsi} = \sigma^2_{rsi}/\sigma^2$.

TABLE I
SIMULATION PARAMETERS

Parameter	Simulation Values
σ^2	0 dB
ν	1
α	80 dB
ξ_t, ξ_s, ξ_r	0.1
β	0.8
P_c^S, P_c^R, P_c^D	10 dBm [6]
P_{RE}	10 dBm [6]
G_t, G_r	0 dBi

Likewise, the SDNR for the relay-to-destination link can be obtained from (2) and (9) as:

$$\Gamma_{RD} = \frac{|h_{rd}|^2 P_r}{|h_{rd}|^2 \xi_r^2 P_r + \sigma^2}, = \frac{\Gamma_r}{\xi_r^2 \Gamma_r + 1}, \tag{18}$$

where $\Gamma_r = P_r |h_{rd}|^2 / \sigma^2$.

Thus the end-to-end SDNR of the source-to-destination via relay link can be expressed from (17) and (18) as

$$\Gamma_{FD} = \min\{\Gamma_{SR}, \Gamma_{RD}\}. \tag{19}$$

Therefore, the channel capacity for the relay-assisted system can be expressed as:

$$R_{FD} = \log_2(1 + \Gamma_{FD}), = \log_2(1 + \min\{\Gamma_{SR}, \Gamma_{RD}\}) \tag{20}$$

The EE for FD relay-assisted transmission can be evaluated from (10) and (20) as

$$EE = \frac{R_{FD}}{(1+\beta)P_t + P_c^R + P_c^S + +P_{SIC} + P_c^D} \tag{21}$$

Special Case (Half-Duplex): For the half-duplex mode of operation at the relay, each of the source and the relay would transmit for half of the time interval. Additionally, the SI term would no longer be valid. So, the channel capacity would be as below:

$$R_{HD} = \frac{1}{2}\log_2(1 + \Gamma_{HD}), \tag{22}$$

where, Γ_{HD} can be defined from (17) and (18) as

$$\Gamma_{HD} = \min\left\{\frac{\Gamma_s}{\xi_s^2\Gamma_s + 1}, \frac{\Gamma_r}{\xi_r^2\Gamma_r + 1}\right\}. \tag{23}$$

Therefore, the corresponding EE can be expressed as

$$EE = \frac{R_{HD}}{(1/2)(1+\beta)P_t + P_c^S + P_c^R + P_c^D} \tag{24}$$

where the factor (1/2) indicates that the source and relay transmit only during half of the entire time slot which makes the EE of the half-duplex system is better than its FD counterpart.

IV. SIMULATION RESULTS

In this section, we discuss and present the simulation results for the performance of both IRS-assisted and relay-assisted transmission systems. The major simulation parameters are listed in Table I. Further, we specify the placement parameter as ρ, which defines the IRS/relay localization as $d_{sr} = \rho D$ and $d_{rd} = (1-\rho) D$. Also, to have a better performance benchmark, the total transmit power is kept constant for both IRS and relay-assisted system such that $P_s + P_r = P_t$ and for ease of exposition $P_s = P_r$.

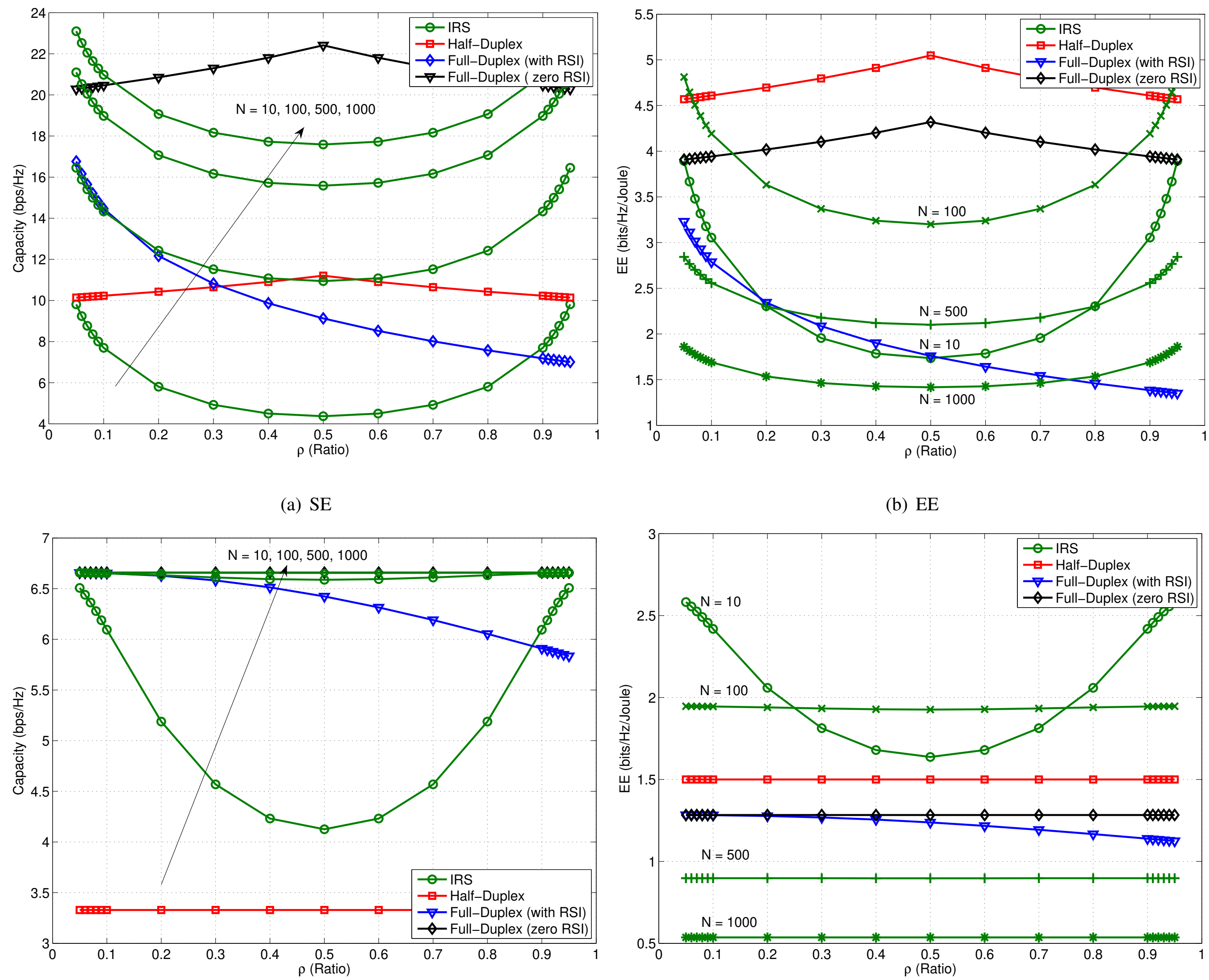
The channel gain is modeled using the 3GPP Urban Micro (UMi) as described and discussed in [8]. Similar to [8], [9], we neglected the shadow fading to have a deterministic channel gain, $\beta(d)$ (i.e., $h_i = \sqrt{\beta(d)}, i \in sr, rd$). At the carrier frequency of 3 GHz, $\beta(d)$ can be expressed as:

$$\beta(d) \text{ [dB]} = G_{\mathrm{t}} \text{ [dBi]} + G_{\mathrm{r}} \text{ [dBi]} + \begin{cases} -37.5 - 22\log_{10}(d/1\,\mathrm{m}) & \text{if LOS,} \\ -35.1 - 36.7\log_{10}(d/1\,\mathrm{m}) & \text{if NLOS,} \end{cases} \tag{25}$$

where G_{t} and G_{r} denote the transmit and receive antenna gain at the source/relay and relay/destination, respectively.

Fig. 2 shows the SE and the EE for both ideal and non-ideal transmitter considering the total distance to be $D = 110$ m. Specifically, Figs. 2(a) and 2(c) show the capacity for both IRS-assisted and relay-assisted transmission system for ideal and non-ideal transmitter, respectively. The following observations can be made from Fig. 2(a): a) the performance of IRS improves when the number of REs are increased, b) while increasing the number of REs, the IRS-assisted system is able to outperform DF relaying for very large N, c) the performance IRS-assisted system is significantly improved when the IRS is in close proximity of the source or when the destination is very close to IRS, d) ideal FD relay-assisted system provides the exact double capacity, however, the practical performance is affected by the RSI, and e) practical FD-DF-relaying is significantly impacted by RSI when the relay is far away from the source, this is because of the fact that when the relay is moving farther from source, the received signal strength falls off and so the RSI's impact dominates the overall performance[4]. In addition to these, the following insights can be gained from Fig. 2(c), f) in the non-ideal hardware transmitter based IRS-assisted system can never outperform the ideal FD-DF relaying in terms of capacity, g) the capacity saturates with increasing the number of REs and after $N = 100$, the capacity saturates, h) after $N = 100$, there is hardly any measurable gain in the capacity even by changing the location of IRS, and i) the capacity of relay-assisted transmission is also influenced by the location as the capacity is dominated by the distortion noise and so by altering the location of relay, the capacity can be increased, this is in contrast to the ideal hardware transmitter case, where the capacity is maximum when the relay is placed at $\rho = 0.5$.

[4]The performance of practical FD-DF-relaying can be improved further through optimal power allocation, which is out of scope for the current work, however, it can be considered for the future extension of this work.



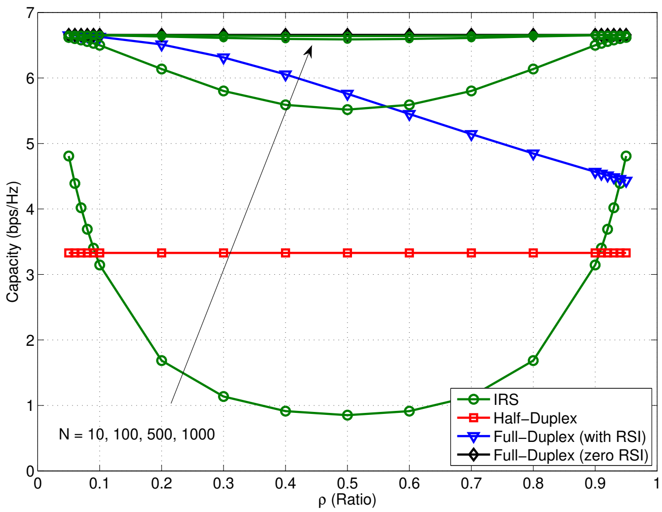
(a) SE (b) EE

(c) SE (d) EE

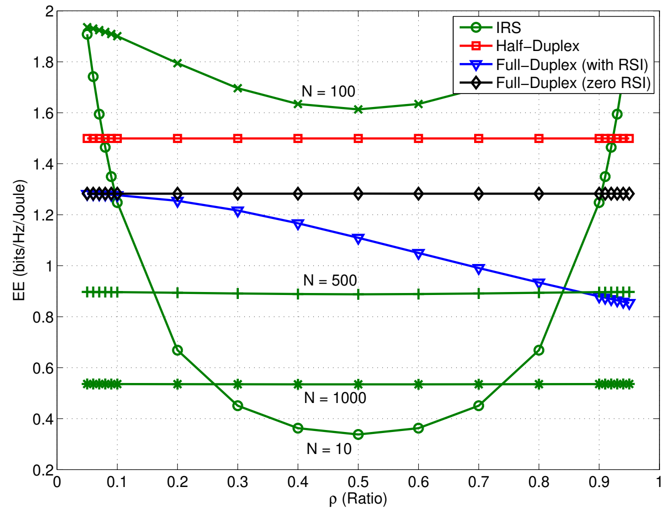
Fig. 2. SE and EE with respect to placement parameter for both the ideal and non-ideal hardware transmitter case for $D = 110$ m.

Figs. 2(b) and 2(d) show the EE of the ideal and non-ideal transmitter, respectively. Also, the Fig. 2(b) shows the EE for different M, i.e., the number of REs in the IRS, where it is evident that the EE initially increases with increasing M, however afterwards it decreases. Further, Fig. 2(d) shows that for the non-ideal hardware transmitter case, the EE decreases considerably with increasing M. This is due to the fact that the capacity saturates with increasing M, however the energy consumption increases linearly. Consequently, it results in an overall reduction in the EE of the IRS-assisted transmission system, this can also be verified from (16). Further, it can also be verified that the half-duplex relay-assisted system is the most energy-efficient, this is because of the fact that, in contrast to FD relaying, the source and the relay transmits only for half the time interval, this can also be viewed from (24). Further, in the FD-relaying there is an additional power consumption in the SI cancellation circuitry as can be viewed in (21).

Fig. 3 shows the another set of capacity and EE results for both the non-ideal transmitter case when the total distance is increased to $D = 220$ m. The following points are worth noting while comparing Fig. 2 and Fig. 3. a) For large M, the impact of distortion noise is more severe, the capacity is saturated and not impacted by the placement of IRS, however when M is small, the capacity is impacted by the placement of IRS. Further, the capacity decreases when the total distance is increased, this is due to the fact the path-loss increases with increasing distance, and b) The EE of the IRS-assisted system is impacted more severely when the distance is increased and even the FD relaying is more energy-efficient than the IRS-assisted transmission system. So, it can be inferred here that, the IRS-assisted system can only outperform the capacity of relay-assisted system only for shorter distances and ideal-hardware transmitter case. Moreover, the capacity of ideal-hardware based IRS-assisted can be further enhanced by placing it near the source or destination. Further, for the non-



(a) SE



(b) EE

Fig. 3. SE and EE with respect to placement parameter considering both ideal and non-ideal transmitter for $D = 220$ m.

ideal hardware system, the FD-relaying always outperform the IRS-assisted system irrespective of the placement of IRS and its size, i.e., M. Similar argument can be provided for the EE of the IRS-assisted system and the FD based DF-relaying.

V. Conclusion

In this work, the performance of an intelligent reflecting surface (IRS)-assisted wireless system is investigated and compared with the traditional relay-assisted wireless system in the presence of a non-ideal transmitter. Specifically, the performance is compared in terms of channel capacity and EE. The main observation is that the IRS-assisted system can never outperform the capacity achieved by ideal full-duplex relaying for the non-ideal hardware scenario. Further, by increasing the number of REs, the capacity of IRS-assisted system saturates to the capacity achieved by the ideal FD relay-assisted system. However, this also results in the reduction of the EE of the IRS-assisted system, thus, there is a trade-off with respect to increasing the number of REs, that can be observed in the capacity and EE of the IRS-assisted system. Apart from this, several other insights have also been provided while discussing the results.

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