Performance Analysis of Intelligent Reflecting Surfaces in comparison to MIMO

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***Abstract*—Intelligent Reflecting Surfaces(IRS) provide improved energy efficiency and consumes less transmit power in wireless communication systems, when the direct path between source to destination is weak. IRS surfaces contain an array of elements that reflect the incoming signal to the destination with beamforming. The new IRS technology is compared with MIMO technology and simulation results are plotted for transmit power, energy efficiency, and Bit Error Probability. It is seen that the for different performance metrics IRS performs better than MIMO.**

keywords —Intelligent reflecting surface, MIMO.

I. INTRODUCTION

An IRS is a flat surface that consists of an array of elements or IRS units such that each element incurs some changes to the incoming signal by phase shifting the waves differently. The direction of reflection is determined by the phase shift pattern of the elements. Intelligent Reflecting Surface(IRS) is also named Reconfigurable Intelligent Surface (RIS), Software Controlled Metasurface which has real-time reconfigurable properties and recently IRS is considered a prominent technology for people working in the communication field. The main idea of IRS is, that communication is done from source to target by adapting the propagation environment, that beamforms the signal towards the target. The architecture of the IRS resembles a relay but the main difference is a relay actively processes and amplifies the received signal before transmitting but an IRS passively reflects the signal with beamforming. The 5G technology provided massive connectivity, ultra-low latency services, enhanced mobile broadband services, network densification, and multiple input multiple output (MIMO). But a lot of power is consumed by these technologies and in harsh environments, these technologies struggle to provide quality services. So, there is a need for green and sustainable future technologies, and this can be fulfilled by IRS. The passive elements of IRS and its beamforming property helps to achieve better communication capacity. In this paper, a fair comparison is made between IRS and MIMO with the purpose to determine how large an IRS is and how many elements in IRS are needed to beat MIMO.

II. SYSTEM MODEL

A. *Transmission using IRS*

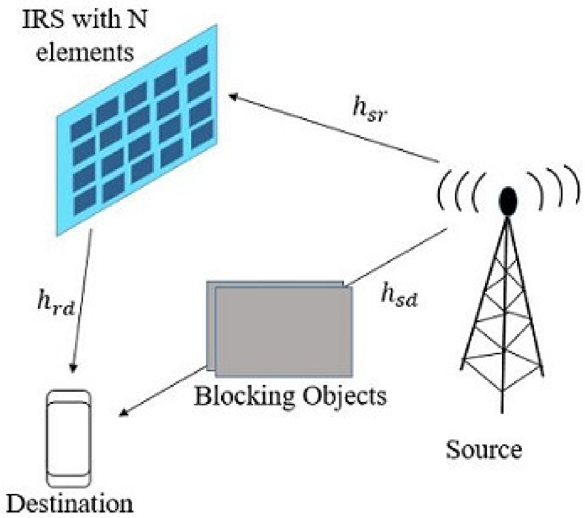

Fig. 1. Transmission model using IRS.

In this framework, an IRS having N discrete elements is considered, as represented in Fig. 1. The source to the IRS channel is given as $h_{sr} \in C^N$, where $[h_{sr}]_n$ indicates the n^{th} element of IRS . The channel from IRS to destination is represented as $h_{rd} \in C^N$. Each element of IRS reflects the incoming signal with constant gain towards the destination and each element of IRS has a smaller size than the wavelength of the signal [13]. The elements of IRS is represented by a diagonal matrix

$$\phi = \alpha \text{diag}\left(e^{j\theta_1}, \ldots, e^{j\theta_N}\right), \tag{1}$$

where $\alpha \in (0, 1)$ is the fixed amplitude reflection coefficient and ϕ_1..........ϕ_N are the phase-shift of IRS which can be optimized by the IRS. From the system model represented in fig.1, the signal received at the destination is

$$y = (h_{sd} + h_{sr}^T \phi h_{rd})\sqrt{p}x + n, \tag{2}$$

where p , x , and n are transmit power, unit-power information signal and receiver noise respectively. Here it is assumed that the channel is assumed to be deterministic. The achievable rate of the network assisted by IRS is given as

$$R_{\mathrm{IRS}}(N) = \max_{\phi_1,\ldots,\phi_N} \log_2\left(1+\frac{p|h_{\mathrm{sd}}+\mathbf{h}_{\mathrm{sr}}^{\mathrm{T}}\theta\mathbf{h}_{\mathrm{rd}}|^2}{\sigma^2}\right)$$
$$=\log_2\left(1+\frac{p\left(|h_{\mathrm{sd}}|+\alpha\sum_{n=1}^{N}|[\mathbf{h}_{\mathrm{sr}}]_n\,[\mathbf{h}_{\mathrm{rd}}]_n|\right)^2}{\sigma^2}\right). \tag{3}$$

B. MIMO Supported TRansmission

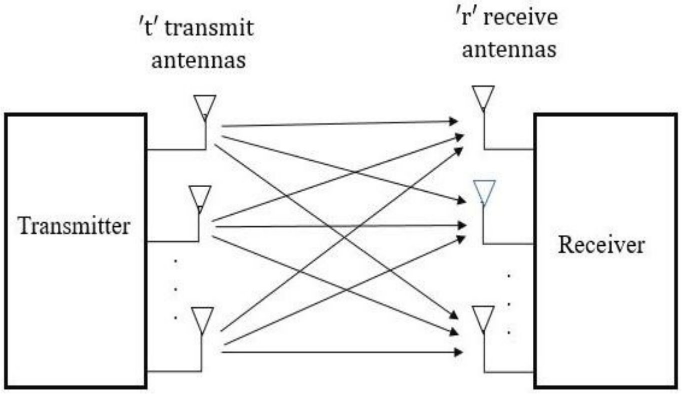

Fig. 2. Transmission model using MIMO.

In this setup, a MIMO wireless system with t transmit antennas and r receive antennas is considered as in fig 2. Let x_1,x_2,.....x_t denote the t symbol transmitted from the t antennas in the MIMO system i.e. x_i denote the symbol transmitted from the i^{th} transmit antenna, $1 \leq i \leq$. These transmit symbols can be stacked to form the t-dimensional vector, also termed the transmit vector as x= $\left[\mathrm{x}_1, x_2, ...x_t\right]$ Let y_1,y_2, ... y_r denote the r received symbols across the r receive antennas in the MIMO system, which can be stacked as r-dimensional receive symbol vector as y= $\left[\mathrm{y}_1, y_2, ...y_r\right]$ Let the complex coefficient h_{ij} represent the coefficient of the fading channel between i^{th} receive antenna and the j^{th} transmit antenna. Thus there are a net of rt channel coefficients to all possible combinations of the r recieve antennas and t transmit antennas. This can be written as

$$\mathrm{H}=\begin{bmatrix} \mathrm{h}_{11} & \mathrm{h}_{12} & \ldots & \mathrm{h}_{1t} \\ \mathrm{h}_{21} & \mathrm{h}_{22} & \ldots & \mathrm{h}_{2t} \\ . & . & \ldots & . \\ . & . & & . \\ . & . & & . \\ \mathrm{h}_{r1} & \mathrm{h}_{r2} & \ldots & \mathrm{h}_{rt} \end{bmatrix}$$

where, the r x t dimensional matrix H is termed as MIMO channel matrix. Let the additive noise at the receive antenna i is denoted by n_i, that is n_1,n_2,..... n_r denote the additive noise at the r receive antennas. Thus the net MIMO input output system model can be represented in vecor form as

$$y = Hx + n \tag{4}$$

where y, H and n are the received signal vector, channel matrix in vector form and noise respectively. The noise n is considered as additive white gaussian noise with $n \sim N(0, \sigma^2)$.
Considering the i^{th} parallel MIMO channel, the above equation can be written as

$$\tilde{y_i} = \sigma_i \tilde{x_i} + \tilde{n_i} \tag{5}$$

The channel Capacity for i^{th} channel in the MIMO supported network is

$$c_i = \log_2 (1 + \frac{P_i {\sigma_i}^2}{{\sigma_n}^2}) \tag{6}$$

The net MIMO capacity is given as the sum of individual capacities of all the t channels

$$c = \sum_{i=1}^{t} \log_2 (1 + \frac{P_i {\sigma_i}^2}{{\sigma_n}^2}) \tag{7}$$

where, P_i is the totat power of the i^{th} channel which is allocated by optimal power allocation, σ_i is the signal attenuation power of i^{th} channel, and σ_n is the noise power.

III. Transmit power, Total power, Energy efficiency and Bit Error Probability

In this section expression for transmit power,energy efficiency, spectral efficiency and Bit Error Probability is found out. For conciseness, the notations introduced are $|h_{sd}| = \sqrt{\beta_{sd}}$ is the channel from source to destination, $|h_{sr}| = \sqrt{\beta_{sr}}$ is the channel from source to IRS, $|h_{rd}| = \sqrt{\beta_{rd}}$ is the channel from IRS to destination, $\frac{1}{N}\sum_{n=1}^{N} e^{j\theta}[h_{sr}]_n[h_{rd}]_n$=$\sqrt{\beta_{IRS}}$.

A. Transmit power and Total power

For any value of $N \geq 1$ the IRS transmission model provides the maximum rate for any if $\beta_{sd} > \beta_{sr}$. But when $\beta_{sd} \leq \beta_{sr}$, the system provides the maximum rate if and only if

$$N > \frac{\sqrt{\left(\sqrt{1+\frac{2p\beta_{\mathrm{rd}}\beta_{\mathrm{sr}}}{(\beta_{\mathrm{sr}}+\beta_{\mathrm{rd}}-\beta_{\mathrm{sd}})\sigma^2}}-1\right)\frac{\sigma^2}{p}}-\sqrt{\beta_{\mathrm{sd}}}}{\alpha\sqrt{\beta_{\mathrm{IRS}}}}. \tag{8}$$

The right hand side of (8) relies on the amplitude reflection coefficient α, the transmit SNR $\frac{p}{2}$, and the gains of the channel β_{sd}, β_{sr}, β_{rd} and $\beta_{IRS} = \beta_{sr}\beta_{rd}$. It is seen that the right section in (13) approaches -$\frac{\sqrt{\beta_{sd}}}{\alpha\sqrt{\beta_{sr}\beta_{rd}}}$ as $p \to \infty$, which indicates that the transmission using IRS attains the highest rate at high SNR for any value of N . When $p \to \infty$, which is a large number, and if $\beta_{sd} \ll \beta_{sr}$ equation (13) becomes,

$$N > \frac{\sqrt{\frac{1}{(\beta_{\mathrm{sr}}+\beta_{\mathrm{rd}}-\beta_{\mathrm{sd}})}}-\frac{\sqrt{\beta_{\mathrm{sd}}}}{\sqrt{\beta_{\mathrm{sr}}\beta_{\mathrm{rd}}}}}{\alpha}. \tag{9}$$

The transmit power equations for the system models (IRS and MIMO) are : For the IRS supported transmission, to achieve a data rate $\bar{R}$ the power required is

$$p_{\mathrm{IRS}}(N) = \left(2^{\bar{R}}-1\right)\frac{\sigma^2}{(\sqrt{\beta_{\mathrm{sd}}}+N\alpha\sqrt{\beta_{\mathrm{IRS}}})^2}, \tag{10}$$

P_{total} is denoted as the total power consumption of a system which consists of the power loss by the hardware components and the transmit power. For the IRS case the total power consumption is given as

$$P_{\text{total}}^{\text{IRS}}(N) = \frac{p_{\text{IRS}}(N)}{\nu} + P_{\text{s}} + P_{\text{d}} + NP_{\text{e}}, \tag{11}$$

where p_e denotes the power loss per element, due to the hardware components used for phase shifting and $\nu \in (0,1)$ is the efficiency of the power amplifier.
Considering β_{IRS} is a constant value which is independent of number of elements. The optimum value of N is minimized by optimizing the total power $P_{IRS}^{total}(N)$.

$$N^{\text{opt}} = \sqrt[3]{\frac{\left(2^{\bar{R}}-1\right)\sigma^2}{\alpha^2 \beta_{\text{IRS}} P_{\text{e}}}} - \frac{1}{\alpha}\sqrt{\frac{\beta_{\text{sd}}}{\beta_{\text{IRS}}}}. \tag{12}$$

For MIMO case, to attain a data rate R, the power required for MIMO supported transmission is

$$p_{MIMO} = \frac{(2^R - 1){\sigma_n}^2}{(M-1){\sigma_i}^2} \tag{13}$$

The total power of the system in MIMO case is

$$P_{\text{total}}^{\text{MIMO}} = \frac{p_{\text{MIMO}}}{\nu} + P_{\text{FIX}}, \tag{14}$$

Where P_{FIX} circuit power of receiver consists of only fixed power.

B. Energy Efficiency

The energy efficiency is defined as $B * \bar{R}/P_{total}$[11]. Implementing equations (11) and (14), energy efficiency is found out.

C. Bit error probability

From the system model represented in fig 1., the signal received at the receiver reflected by IRS(assuming the direct channel is blocked) is given by

$$y1 = \left[\sum_{i=1}^{N} h_{sr} e^{j\phi_i} h_{rd}\right] x + n \tag{15}$$

where ϕ_i is the phase shift induced by the i^{th} reflecting element of the IRS, x is the information symbol and $n \in CN(0,N)$ is the AWGN term. Here $h_{sr} = a_i e^{-j\theta_i}$ and $h_{rd} = b_i e^{-j\psi_i}$. The instantaneous SNR is

$$\gamma = \frac{\left|\sum_{i=1}^{N} \alpha_i \beta_i e^{j(\phi_i - \theta_i - \psi_i)}\right|^2 E_s}{N_0} \tag{16}$$

where Es is the average transmitted energy per symbol. By eliminating the channel phases can be maximized, $\phi_i = \theta_i + \psi_i$ for i = 1,..., N.

$$\gamma = \frac{\left(\sum_{i=1}^{N} a_i b_i\right)^2 E_s}{N_0} = \frac{A^2 E_s}{N_0}. \tag{17}$$

Considering a_i and b_i are independently Nakagami distributed random variables (RVs) and $E[a_i b_{i]} = 9\pi$ and $VAR[a_i b_i] = 64 - 81\pi^2$. So for a large number of elements, the CLT(Central Limit Theorem) is invoked. Now A follows a gaussian distribution with $E[a_i b_i] = N9\pi$ and $VAR[a_i b_i] = N(64 - 81\pi^2)$. Now it is seen that γ follows a non-central chi-square RV with one degree of freedom and the moment generating function (MGF) is given as

$$M_\gamma(s) = \left(\frac{1}{1 - \frac{s2N(64-81\pi^2)E_s}{N_0}}\right)^{\frac{1}{2}} \exp\left(\frac{\frac{sN^2 81\pi^2 E_s}{N_0}}{1 - \frac{s2N(64-81\pi^2)E_s}{N_0}}\right). \tag{18}$$

The average Symbol Error Probability(SEP) for M-PSK signaling can be obtained from the above equation as

$$P_e = \frac{1}{\pi}\int_0^{(M-1)\pi/M} M_\gamma\left(\frac{-\sin^2(\pi/M)}{\sin^2\eta}\right) d\eta \tag{19}$$

The above equation can be simplified for binary PSK (BPSK) as

$$P_e = \frac{1}{\pi}\int_0^{\pi/2} \left(\frac{1}{1 + \frac{2N(64-81\pi^2)E_s}{\sin^2\eta N_0}}\right)^{\frac{1}{2}} \exp\left(\frac{-\frac{N^2 81\pi^2 E_s}{\sin^2\eta N_0}}{1 + \frac{2N(64-81\pi^2)E_s}{\sin^2\eta N_0}}\right) d\eta. \tag{20}$$

The above equation (6) can be upper bounded by letting $\eta = \pi/2$ as

$$P_e \leq \frac{1}{2}\left(\frac{1}{1 + \frac{2N(64-81\pi^2)E_s}{N_0}}\right)^{\frac{1}{2}} \exp\left(\frac{-\frac{N^2 81\pi^2 E_s}{N_0}}{1 + \frac{2N(64-81\pi^2)E_s}{N_0}}\right). \tag{21}$$

IV. RESULTS AND DISCUSSION

In this segment, the system models of these two systems are compared. By using the 3GPP Urban Micro(Umi)[17, Table B.1.2.1-1] having carrier frequency of 3GHz, the channel gains are modelled. The non line of sight(NLOS) and line of sight(LOS) categories are considered for a distance of $\geq$ 10m. The antenna gains in dBi at source and destination are defined as G_t and G_r respectively. The channel gain B is taken as a function of distance d, and to get a deterministic model,the shadow fading is neglected here.

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

In the simulation setup, the transmitter and IRS are installed at permanent locations, but the location of the receiver is varied, which is taken maximum up to 100 metres. The channel gains are computed based on the distance by using equation (22) and assuming the source, IRS are having identical 5 dBi antennas while the receiver is assumed to have an omnidirectional antenna with 0 dBi. The IRS is installed at heights. The importance of IRS is realized when there exist a NLOS(Non Line of Sight) channel between transmitter and

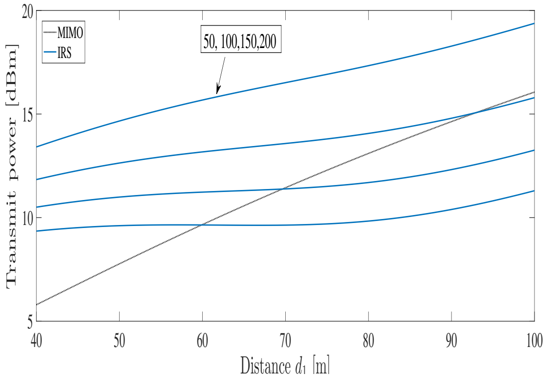

Fig. 3. Transmit power for different number of reflecting elements of IRS and MIMO.

receiver, as without use of IRS in NLOS environment results in a weaker channel gain.

To achieve a rate of r= 5 bits/Hz , the transmit power required is shown in Fig(3). For simulation the bandwidth is taken as 20 MHz(for LTE). The noise power is taken as 94 dBm, $\alpha = 1$, and the number of antennas is taken as 10. The transmit power comparison for MIMO and an IRS with N having different values of $50, 100, 150, 200$, is shown in figure 3. Considering the case when $\bar{R} = 5$ bit/s/Hz, the MIMO approaches the power nearly equal to the power for $N = 100$ elements. The transmit power required decreases with the increase in number of elements(N) in IRS. The slight bending of the curve states that the receiver is close to destination or IRS. It can be also stated that by using more number of reflecting elements, the transmit power can be reduced. As MIMO contains active antennas which can transmit and process the signals but IRS has passive elements which can neither transmit nor process the signals, so to outperform MIMO, a large number od IRS elemnts are required. When d1= 80m, the number of IRS elements needed is $N > 100$

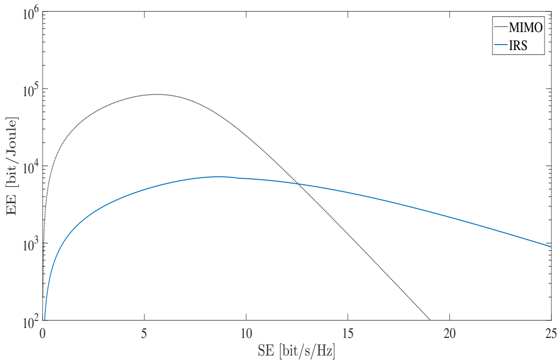

Fig. 4. Energy efficiency versus rate R for MIMO and IRS communication when M=10 for MIMO.

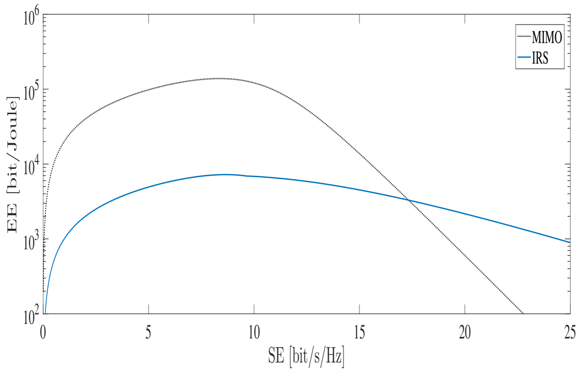

Fig. 5. Energy efficiency versus rate R for MIMO and IRS communication when M=100 for MIMO.

Figure 4 and 5 shows energy efficiency as a function of R for different M values of MIMO and IRS. For simulation setup, different values are defined as $\nu = 0.5$, $P_s = P_d = P_r = 100mW$, $p_e = 5mW$, and $d_1 = 80m$. For number of elements in IRS, N is optimized using equation(12). It is seen that when M value was 100, the MIMO case provided the highest energy efficiency at $\bar{R} = (0, 10)$ bit/s/Hz, But at higher rates, the IRS outperforms MIMO . It is found that only for $\bar{R} > 11$ bit/s/Hz that the IRS has $N^{opt} > 0$ and it is only for $\bar{R} > 17.5$ bit/s/Hz that it provides higher energy efficiency than MIMO.

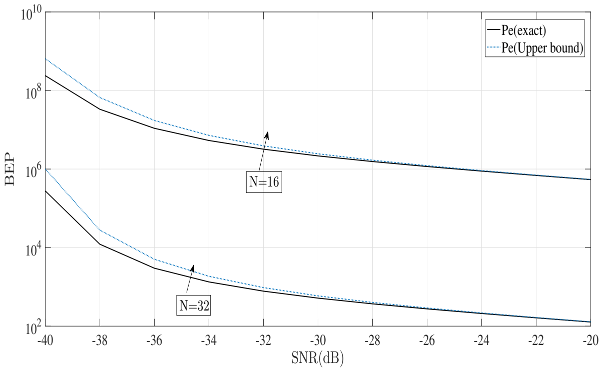

Fig. 6. Theoritical result of BEP under Nakagami fading for N=16 and N=32

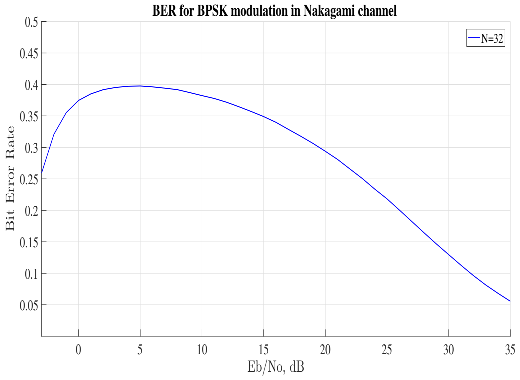

Fig. 7. simulated BER for N=32 elements of IRS

Fig. 6. shows the exact and upper bound theorical result of

Bit Error Probability under Nakagami fading for N=16 and N=32 number of reflecting elements. It is seen that increasing the number of reflecting elements can decrease the Bit Error Probability. For calculation of BEP m=2, omega=1, BPSK modulation is considered and theoritical result is plotted. Fig. 7. shows the simulated BER for N=32 number of elements of IRS.

V. Conclusion

In this paper the performance of IRS is compared with MIMO. Even if frequency-flat fading channels and ideal phase shifting is considered, it is observed that to obtain minimum transmit power and higher energy efficiency a large number of reflecting elements are required to overcome MIMO. The reason is that to reach the destination, source transmit power must travel over two channels leading to a small channel gain of $\beta_{sr}\beta_{rd}$ per element in the IRS. Hence there arises a need for large number of reflecting elements to compensate for the low channel gain. Having a disadvantage of large number of elements in IRS communication, the main advantage is it does not require power amplifiers. At higher rates an IRS achieves higher Energy Efficiency than MIMO. This IRS communication is very helpful in places where there is NLOS(no line of sight) communication. High rise buildings, mountain and hilly areas where LOS communication is a hindrance, IRS proves to be a boon at that places. When we go for higher frequency range communication like millimeter wave communication, terahertz communication, where there is a large attenuation, IRS is helpful in these environments to overcome the challenges.

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