“Performance of a IRS assisted Wireless model”

A Project Report Submitted
in Partial Fulfilment of the
Requirements for the
Degree of

B.TECH

ELECTRONICS AND COMMUNICATION ENGINEERING

By

Manan Sanson

(2020BECE039)

Student Declaration

I, Manan Sanson, hereby declare that the presented report of internship titled "**Performance of a IRS assisted Wireless model**" is uniquely prepared by me after the completion of 8 weeks internship at BITS Pilani, Rajasthan. I also confirm that the report is only for my academic requirement, not for any other purpose.

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Date: 15-12-2022

Dr. Sandeep Joshi,
Assistant professor, BITS PILANI

Subject: **Permission of Internship online/offline for student of NIT Srinagar.**

In – Plant/on–the –project internship/Practical Training is an important part of our engineering curriculum. This internship/training is regarded as a vital component of engineering education and is an indicator of extent of field experience, which is very essential for attaining excellence in the technical education. In this context, **Mr. /Ms. Manan Sanson,** Enrolment No: **2020BECE039** pursuing B. Tech in ELECTRONICS & COMMUNICATIONS ENGINEERING DEPARTMENT (2020-2024) in this Institute has completed his/her 4th semester of the degree (pursuing in 5th semester) and is interested in 45 days internship in your esteemed organization.

It will be highly appreciated if your organization provides him/her a chance to get an exposure to some project related to him/her branch of engineering online/offline that is being carried out by your organization during winter vacation from 20th December 2022 to 15th February 2023.

We fervently hope that you will accede to our request and allow him/her to pursue him/her internship in your esteemed organization. The student has been advised to abide by the rules and regulation of your organization. Also, the student has to submit completion report and certificate in the training & placement department after completion of the internship, failing this his/her internship will be deemed incomplete.

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Dr. Sandeep Joshi, Assistant Professor, Department of Electrical and Electronics Engineering

To whomsoever it may concern

This is to certify that **Manan Sanson**, ID no. 2020BECE039, a student of B. Tech in Electronics and Communication Engineering, NIT Srinagar has successfully completed the internship under my supervision. The details of the internship are as follows.

Title: ***Performance of Intelligent Reflecting Surface (IRS) Assisted Wireless Communications System***

Duration: ***25th December 2022 to 25th February 2023***

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Lastly, we thank Almighty, our parents, and our accompanying friends for their constant encouragement without whom this training would not have been possible.

Abstract

Intelligent Reflecting Surfaces (IRS) have emerged as a promising technology for improving wireless communication systems. An IRS is a planar array of passive reflecting elements that can intelligently manipulate the signal propagation environment, enabling better coverage, higher data rates, and improved energy efficiency. In this paper, we present an introduction to IRS technology and discuss its potential benefits in a NxM Multiple-Input Multiple-Output (MIMO) system model. We also provide a detailed performance analysis of the IRS in the MIMO system model, considering the impact of various system parameters, such as the number of reflecting elements, the path loss, fading, placement of IRS. Our analysis demonstrates that the use of an IRS can significantly improve the system performance, achieving higher signal-to-noise ratio and coverage compared to traditional MIMO systems. Our findings highlight the potential of IRS technology for next-generation wireless communication systems

CONTENT

Introduction to IRS

● IRS is a planar surface with many passive reflecting elements that can change amplitude and/or phase of incident signals independently.

● IRSs are made of small, passive elements, such as patch antennas, resonators, or metamaterials, that can be electronically controlled to reflect and manipulate electromagnetic waves

● IRS uses constructive and destructive interference of the reflected waves to create a desired spatial distribution of the electromagnetic field by adjusting the phase shifts of individual elements

● IRS can steer reflected waves in a particular direction, amplify or attenuate specific frequency components, or create a specific polarisation pattern

● IRS can dynamically adjust reflection properties based on changing environment or user requirements

● IRS has low power consumption and cost compared to other active radio frequency components, making them suitable for use in energy-constrained or remote locations

● IRS technology has the potential to revolutionise wireless communication by providing a low-cost, energy-efficient, and flexible solution for enhancing signal quality and coverage.

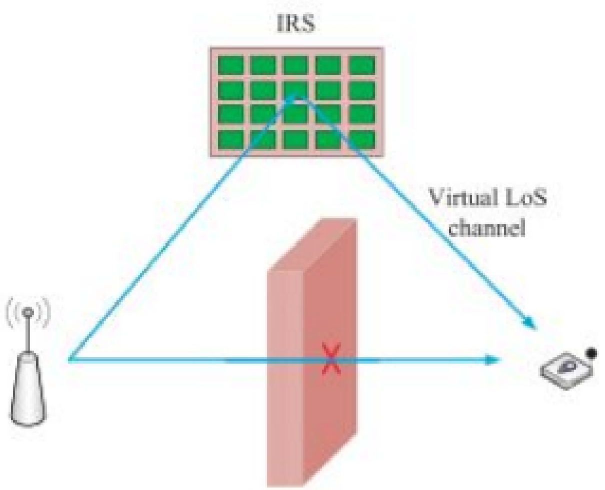
● Reflecting elements passively reflect signals without requiring any transmit RF chains, leading to lower hardware/energy cost than traditional active antenna arrays or active surfaces.

● IRS operates in full-duplex mode and is free of any antenna noise amplification or self-interference, offering advantages over traditional active relays.

● IRS is generally of low profile, light weight, and conformal geometry, making it easily mountable on environment Objects for deployment/replacement .

● IRS is an auxiliary device in wireless networks and can be integrated into them transparently, providing flexibility and compatibility with existing wireless systems such as cellular or WiFi.

● Due to these advantages, IRS is suitable for massive deployment in wireless networks to significantly enhance their spectral and energy efficiency cost-effectively.



(a) IRS for coverage extension

Why do we need the IRS?

The requirements for 5G services, such as enhanced mobile broadband, ultra-reliable and low latency communication, and massive machine-type communication, may not be fully achieved with existing technology trends.

- Increasingly more active nodes such as base stations, access points, relays, and distributed antennas/remote radio heads are being deployed to achieve enhanced network coverage and capacity, which incurs higher energy consumption and deployment/backhaul/maintenance cost.

- Substantially more antennas are being packed at the BSs/APs/relays to harness the enormous massive multiple-input-multiple-output (M-MIMO) gains, which requires increased hardware and energy cost as well as signal processing complexity.

- Higher frequency bands such as millimetre wave and even terahertz frequencies are being utilised to utilise their large and available bandwidth, which results in deploying even more active nodes and mounting them even more antennas (i.e., super MIMO) so as to compensate for their higher propagation loss over distance.

IRS can be used in various wireless communication scenarios, including indoor and outdoor environments, cellular networks, satellite communications, and Internet of Things (IoT) systems. By strategically placing an IRS in the communication path, it is possible to enhance the signal quality, extend the coverage, and reduce the power consumption of the system.

Fundamentals of IRS

● The article explains a scenario where an IRS (Intelligent Reflecting Surface) is used to assist in communication from a transmitter to a receiver.

● The IRS consists of N passive reflecting elements on a planar surface, which can induce a controllable amplitude and/or phase change to the incident signal independently.

● The system assumes a single antenna at both the transmitter and receiver, and the communication system operates in a narrow band at a particular carrier frequency.

● The carrier frequency and system bandwidth are denoted by fc and B in hertz (Hz), respectively, with B equal to fc.

● The signal propagation from the transmitter to the receiver through a particular reflecting element of the IRS is illustrated using the example of an equivalent baseband complex channel coefficient.

● The passband signal received by the IRS element n is given by yin,n(t) = Re(α1,ne−jξ1,n x(t)ej2πfct).

● The amplitude attenuation and time delay induced by IRS element n are denoted by βn and tn, respectively.

● The reflected signal by IRS element n is expressed as Re βne−jθ n α1,ne−jξ1,n x(t) ej2πfct, ignoring hardware imperfections such as circuit nonlinearity and phase noise.

● The received signal from all IRS elements is a superposition of their respective reflected signals.

● The baseband signal model accounting for all N IRS elements is given by an equation:

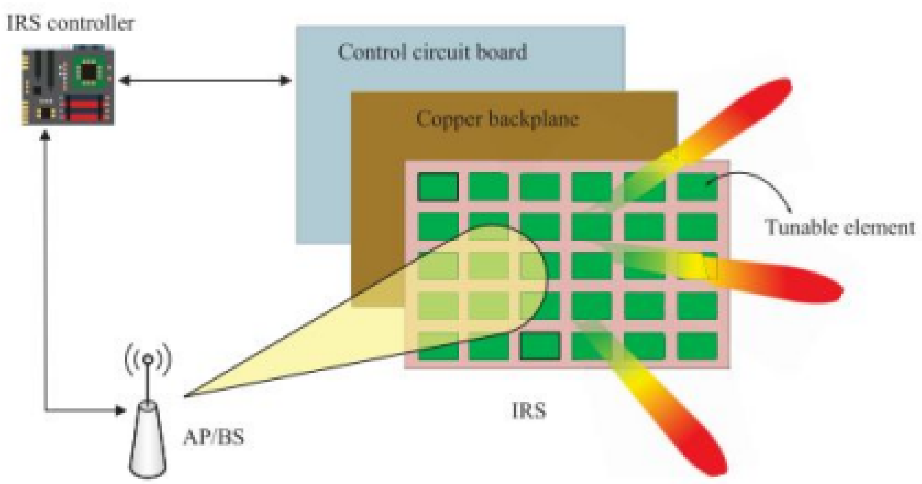
$$y(t) = \left(\sum_{n=1}^{N} \beta_n e^{j\theta_n} h_{r,n}^{*} g_n \right) x(t) = \boldsymbol{h}_r^H \boldsymbol{\Theta} \boldsymbol{g} x(t),$$

● The equation involves hHr, g, and Θ, where hHr is the conjugate transpose of the channel coefficient vector from the transmitter to the receiver, g is the N-element complex-valued reflection coefficient vector of the IRS, and Θ is an N × N diagonal complex-valued reflecting matrix.

● The IRS performs a linear mapping from the incident (input) signal vector to a reflected (output) signal vector using Θ.

IRS Architecture & Hardware

The IRS's controllable reflection is achieved through a planar array of digitally reconfigurable metasurfaces. These metasurfaces consist of properly designed reflecting elements/meta-atoms with an electrical thickness that is typically subwavelength in size. By adjusting the geometry, size, orientation, and arrangement of each element, desired signal response can be realised in terms of reflection amplitude and/or phase shift. However, wireless channels are generally time-varying due to the mobility of the transmitter/receiver and surrounding objects, requiring real-time tunable response of the IRS. To accomplish this, the IRS elements need to be manufactured with dynamically adjustable reflection coefficients and connected to the wireless system.



● An IRS (Intelligent Reflecting Surface) typically consists of three layers and a smart controller.

● The first layer is located on the outside and is composed of a large number of tunable/reconfigurable metallic patches that are printed on a dielectric substrate.

● The second layer, located in the middle, is usually made of copper and is used to minimise signal energy leakage during reflection.

● The third layer, located on the inside, is a control circuit board that excites the reflecting elements and tunes their reflection amplitudes and phase-shifts in real-time.

● The smart controller, attached to each IRS, triggers and determines the reflection adaptation.

● The smart controller is implemented via a field-programmable gate array (FPGA) and acts as a gateway to communicate with other network components through wired or wireless backhaul/control links.

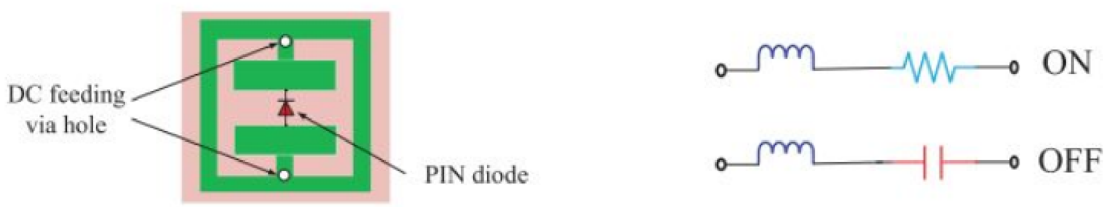
● Dedicated sensors can also be deployed in the first layer to sense the surrounding radio signals of interest and facilitate the smart controller in designing the reflection coefficients.

● There are three main approaches for achieving reflection in IRS: mechanical actuation, functional materials, and electronic devices.

● The electronic device approach, specifically using PIN diodes, is widely adopted due to its fast response time, low reflection loss, low energy consumption, and hardware cost.

● Applying different biassing voltages to the PIN diode allows the element to switch between "ON" and "OFF" state, leading to a phase-shift difference of π in the incident signal.

● Amplitude adjustment is achieved by changing the resistance of each element, enabling a dynamic range of reflection amplitude in [0, 1].



(a) Tunable reflecting element (b) Equivalent circuit of PIN diode

Challenges in Designing

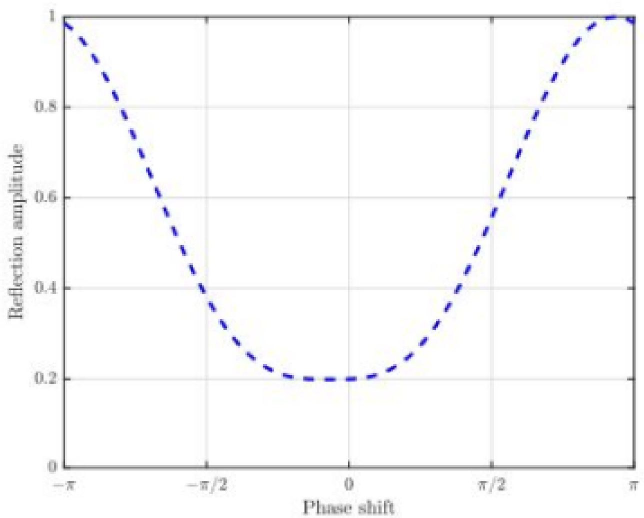
● In designing IRS, achieving independent control of reflection amplitude and phase shift simultaneously is challenging in element design.

● A practical reflection model for IRS was proposed by modelling each reflecting element as a resonant circuit with inductance, capacitance, and resistance.

● The reflection model revealed that reflection amplitude and phase shift are not independently adjustable due to the non-linear coupling between them.

● The reflection amplitude typically reaches its minimum value at zero phase shift and monotonically increases towards the maximum value of one as the phase shift approaches pi or -pi.

● This coupling has a significant impact on the optimal reflection coefficient design of IRS.



Channel Model

● Channel coefficients h and g depend on path loss, shadowing, and fading.

● Path loss of IRS-reflected channel captures its average power and is essential for performance evaluation.

● Assume IRS element n is located far from both transmitter and receiver with distances d1and d2.

● Under far-field propagation conditions, d1,n = d1 and d2,n = d2 for all n.

● E(|hr,n|2) and E(|gn|2) are proportional to path loss at reference distance d0 and path loss exponents a1 and a2, respectively.

● Average received signal power via reflection by IRS element n, Pr,n, is inversely proportional to da1/d1 and da2/d2. i.e.,

$$P_{r,n} \propto \frac{1}{d_1^{a_1} d_2^{a_2}}.$$

● IRS reflected channel via element n suffers from double path loss, referred to as product-distance path loss model.

● Large number of IRS reflecting elements needed to compensate for severe power loss by designing their reflection amplitudes and/or phases to achieve high passive beamforming gains.

We have used Rician fading which is a model for radio propagation abnormally caused by partial cancellation of the signal itself. The signal arrives by several different paths. It occurs when one of the parts is typically much stronger than the others. (No direct LOS between tx and rx considered)

given a K factor, the samples for the Rician flat-fading samples are drawn from the following random variable

$$h = |X + jY|$$

where X,Y ~ N(μ,σ2) are Gaussian random variables with non-zero mean μ and standard deviation σ

$$\mu = g_1 = \sqrt{\frac{K}{2(K+1)}} \qquad \sigma = g_2 = \sqrt{\frac{1}{2(K+1)}}$$

where, K represents the Rician K factor given as the ratio of power of the LOS component A2 to the power of the scattered components (S2) marked in the equation above.

$$K = \frac{A^2}{S^2}$$

At last we added AWGN noise to the faded signal with mean 0 and variance 1.

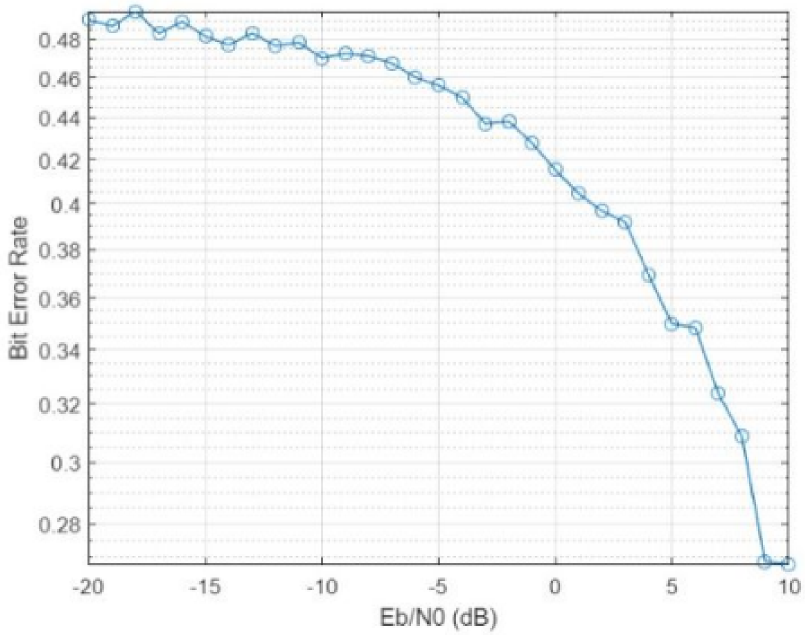
SNR vs BER PLOT

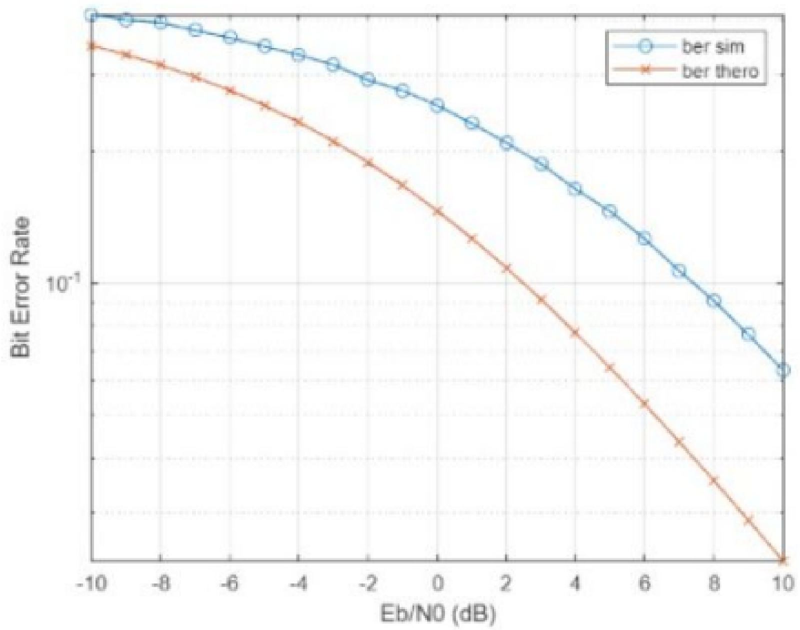
SNR (Signal-to-Noise Ratio) and BER (Bit Error Rate) are two important parameters that are used to measure the performance of a communication system. The SNR is a measure of the signal strength relative to the noise level in the channel, while the BER is a measure of the probability of bit errors in the received signal.

BER expression is typically a function of the SNR and the channel characteristics, such as noise, interference, and fading.

In general, as the SNR increases, the BER decreases, and the system performance improves. This is because a higher SNR means that the signal is stronger relative to the noise, and the receiver is able to better distinguish between the signal and the noise. As a result, the probability of bit errors decreases.

However, there is a limit to how much the SNR can be increased to improve the system performance. At very high SNR values, the improvement in the system performance becomes less significant, and the cost and complexity of the system may increase. In addition, the channel characteristics, such as fading and interference, may become more significant at high SNR values, which can limit the performance improvement.





In summary, as the SNR increases, the BER decreases, and the system performance improves. However, the relationship between SNR and BER is not linear, and the actual BER vs SNR curve may differ from the theoretical curve due to various factors.

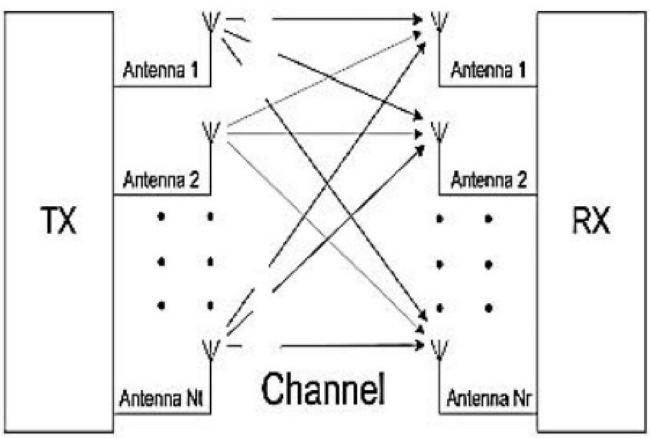
NxM MIMO SYSTEM

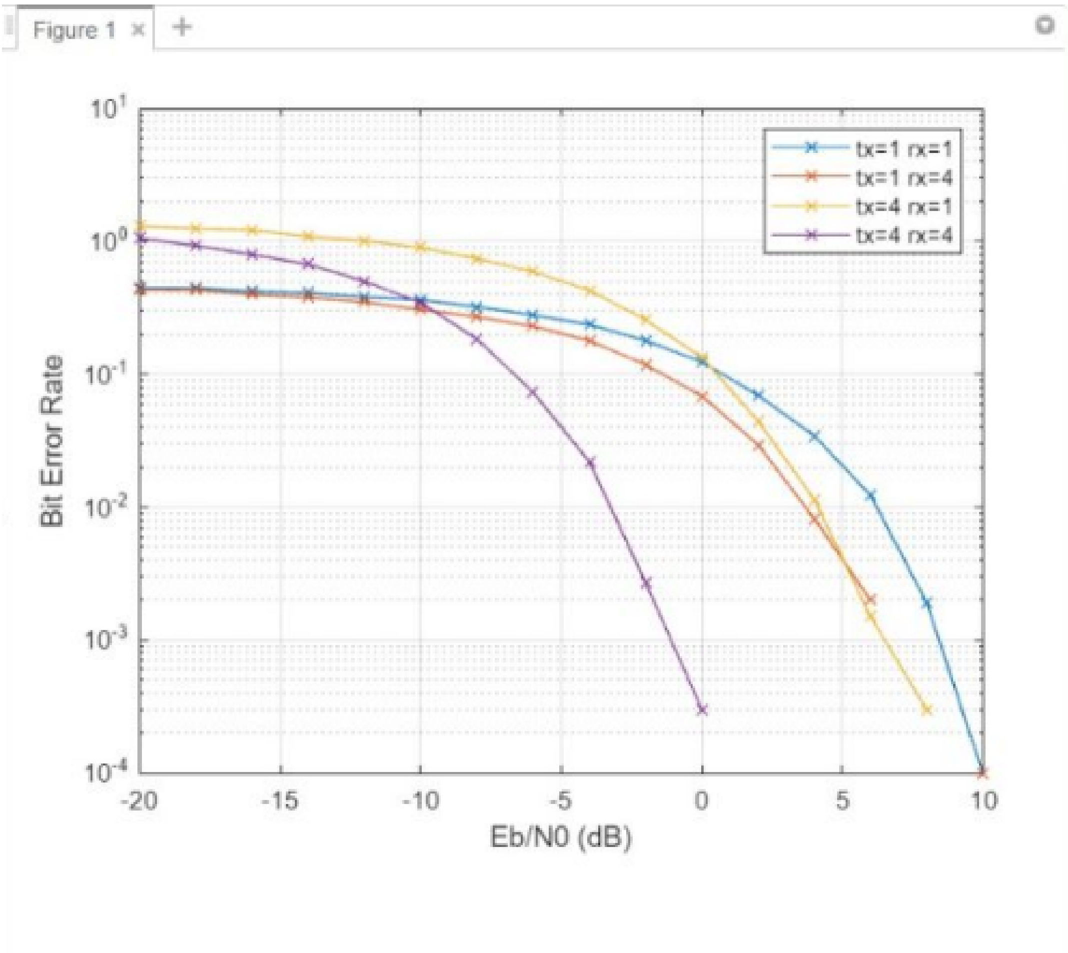
In a NxM MIMO (Multiple Input Multiple Output) system, spatial diversity can be used to improve the system performance. Spatial diversity refers to the use of multiple antennas to provide redundant copies of the transmitted signal, which can be used to combat the effects of fading and other types of channel impairments.

1. Transmit diversity: In this technique, multiple antennas are used to transmit the same signal.. This creates multiple copies of the transmitted signal that can be combined at the receiver to improve the signal quality.

2. Receive diversity: In this technique, multiple antennas are used to receive the same signal, and the received signals are combined to improve the signal quality.

In summary, the use of spatial diversity in a NxM MIMO system can improve the system performance by combating the effects of fading and other types of channel impairments.





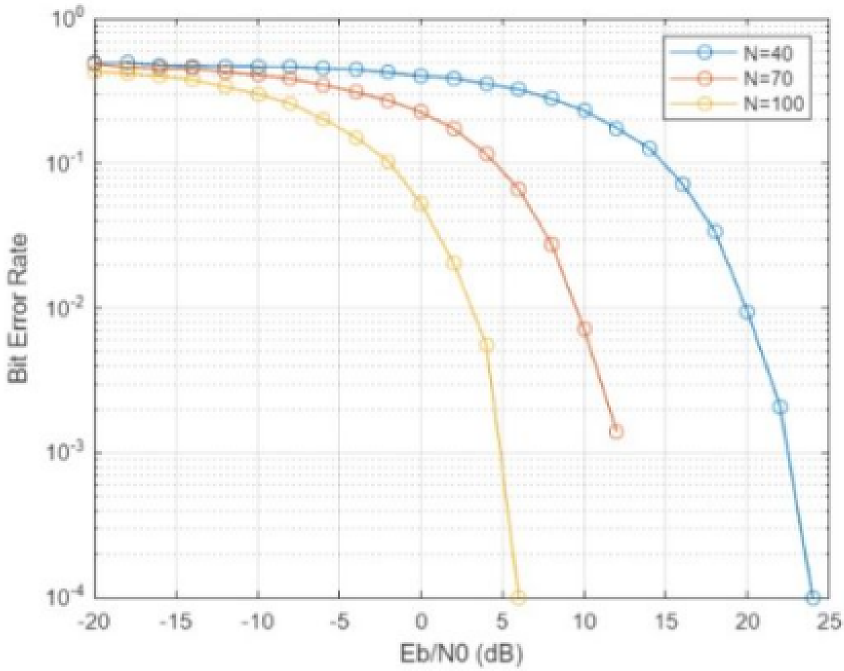
We can analyse that with an increase in the number of transmitters and receivers we achieve better performance (less bit errors) at lower SNR values.

Performance Analysis of IRS (Effect of N)

As we increase the number of elements (N) in the IRS, the BER of the communication system can be improved. This is because the IRS can be used to enhance the received signal power and reduce the interference and noise in the channel.

In a typical simulation setup, we can model the channel as a Rician fading channel, where the channel coefficients are modelled as complex Gaussian random variables.

Hence, we can analyse that with an increase in N (number of elements In IRS) we get improved performance.



Effect of Position of IRS

● IRS placed close to Tx or Rx can cause near-field effects.

● Reflected signals from IRS interfere with direct LOS signal, reducing received signal quality.

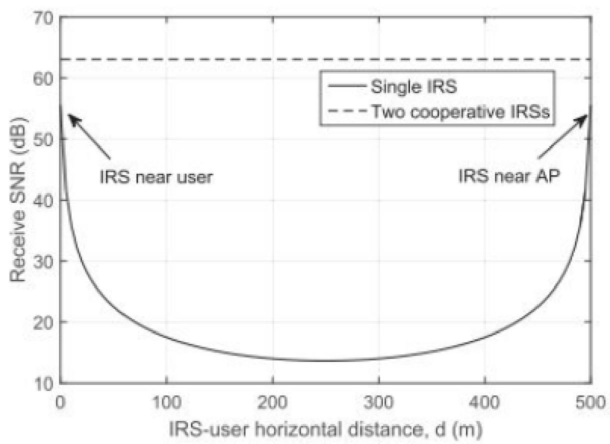
● IRS placed in between Tx and Rx can cause far-field effects.

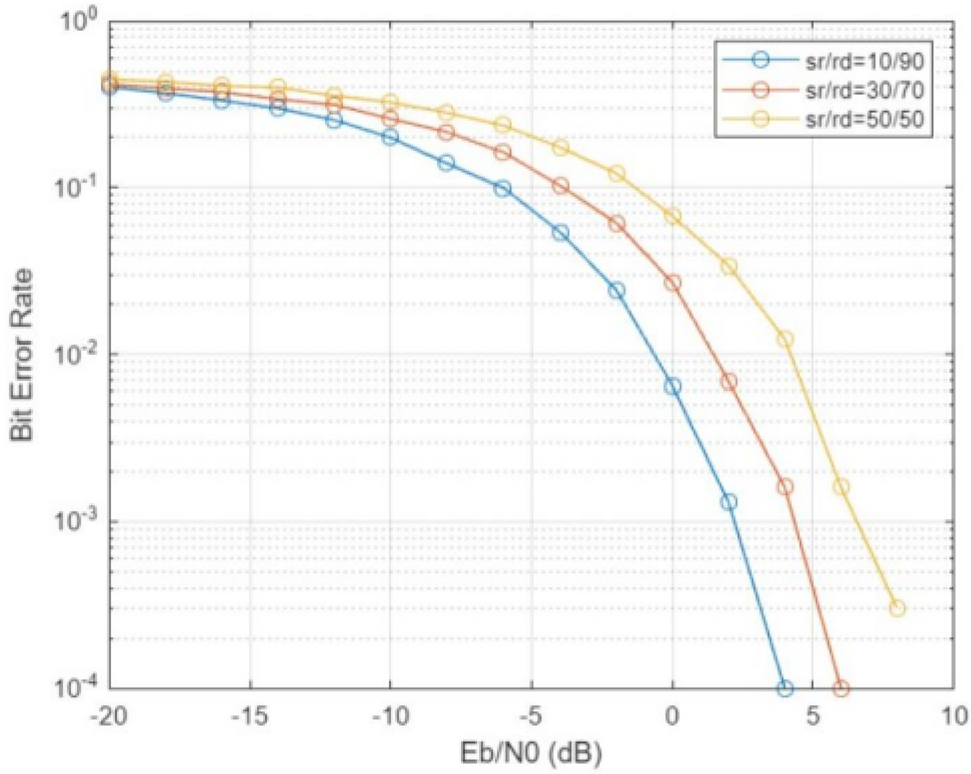
● Optimal position for IRS is at a distance much larger than its size, but still close to Tx or Rx.

● This allows reflected signals to reinforce direct signals without causing interference.

● Optimal placement of IRS depends on system parameters such as distance between Tx and Rx, size of IRS, and frequency of operation.

● IRS should be placed at a distance of at least 2-3 times the maximum dimension of IRS from Tx or Rx.





Where in sr/rd

sr = Source-IRS distance

rd = IRS-destination distance.

Hence, We can conclude that when the IRS is close to either source or user the performance is better.

MATLAB Code

```
clear;
close all;
clc;
%  number of transmitters and receivers
XY = [1 1; 1 3; 3 1; 3 3];
for i = 1:size(XY,1)
    tx = XY(i,1);
    rx = XY(i,2);
%Define the antenna gains at the source, IRS, and destination. The
%numbers are in linear scale
antennaGainS = db2pow(3);
antennaGainR = db2pow(3);
antennaGainD = db2pow(0);
Eb_N0_dB = -20:2:30; % SNR range in dB
ber = zeros(1, length(Eb_N0_dB)); % pre-allocate the BER array
%number of bits to transmit
n=10000;
% Generate binary data
data = randi([0 1], 1, n);
data1=repmat(data,tx,1);
% BPSK modulation
mod_data = 2*data1-1;
%distance between transmitter and receiver
f=1e8;
c=3e8;
d_sr=10;
d_rd=90;
alpha=0.5;
pathloss1=((d_sr)^alpha)*antennaGainS*antennaGainR;
pathloss2=((d_rd)^alpha)*antennaGainR*antennaGainD;
N=60;
% End-to-end channel gain
   A=(c/f)/8;
%   gain=(Nrange^2*A^2)/(4*pi*d_sr*d_rd)^2;
   gain1=N*A/(4*pi*d_sr);
   gain2=N*A/(4*pi*d_rd);
% Rayleigh fading channel coefficients
k=10^(12/10); %rician factor
```

```
sigma=sqrt(1/(2*(k+1)));
mew=sqrt(k/(2*(k+1)));
g1=gain1*((sigma*randn(rx,tx)+mew)+1i*(sigma*randn(rx,tx)+mew))*pathloss1;
h1=gain2*((sigma*randn(rx,tx)+mew)+1i*(sigma*randn(rx,tx)+mew))*pathloss2;
%  g2=repmat(g1,1,1,floor(n/tx));
%  h2=repmat(h1,1,1,floor(n/tx));
%  for m = 1:size(h2,3)
%      h22(:,:,m)=conv2(h2(:,:,m),g2(:,:,m));
%  end
h22=h1.*g1;
% Received signal
   rx_data1 = h22 * mod_data;
for i = 1:length(Eb_N0_dB)
   % Add white Gaussian noise
   Eb_N0 = 10^(Eb_N0_dB(i)/10);
   noise = sqrt(1/(Eb_N0))*(randn(rx,n)+1i*randn(rx,n));
      rx_data11 = rx_data1 + noise ;

   % BPSK demodulation
       demod_data1= (pinv(h22)*rx_data11);
       demod_data1=real(sum(demod_data1,1)/rx)>0;
   % Count the number of errors
       error_count11= sum(xor(data1, demod_data1));
   error_count1=sum(error_count11);
   % Calculate the BER for this value of SNR
   ber(i) = error_count1/length(data);

   EbN0Lin = 10.^(Eb_N0_dB/10);
%     BER=0.5.*(1-sqrt(EbN0Lin./(EbN0Lin+1)));
   end
% Plot the BER vs SNR
semilogy(Eb_N0_dB, ber, '-x');
legend('tx=1 rx=1','tx=1 rx=4', 'tx=4 rx=1','tx=4 rx=4' );
hold on;
end
xlabel('Eb/N0 (dB)');
ylabel('Bit Error Rate');
grid on;
```

Advantages of using IRS

Intelligent reflecting surfaces (IRS) are a type of wireless communication technology that uses a large number of passive reflecting elements to enhance wireless signal propagation. Some potential advantages of using IRS include:

Improved Signal Strength: IRS can significantly improve the signal strength of wireless transmissions by reflecting and redirecting signals in specific directions. This can lead to higher data rates, better network coverage, and reduced interference.

Cost-Effective: Compared to traditional wireless communication technologies, IRS can be a cost-effective solution. They use low-cost and passive reflecting elements that require minimal maintenance and energy consumption.

Privacy: IRS can help enhance privacy in wireless communications by limiting the propagation of signals beyond a specific area. This can prevent eavesdropping and unauthorised access to wireless networks.

Flexibility: IRS can be customised and reconfigured to adapt to changing network requirements and environmental conditions. They can be used in a wide range of applications, including indoor and outdoor environments.

Channel capacity: The channel capacity is a measure of the maximum data rate that can be transmitted over the channel. With an IRS, the channel capacity can be increased by optimising the phase shifts of the reflected signals.

Received signal power: The use of an IRS can increase the received signal power at the receiver. The received signal power can be calculated by taking into account the path loss, the power of the transmitted signal, and the reflection coefficient of the IRS.

Bit error rate (BER): With an IRS, the BER can be reduced by optimising the phase shifts of the reflected signals to maximise the signal power at the receiver. The BER can be calculated using the error function, which depends on the signal power, the noise power, and the modulation scheme.

Conclusion

In conclusion, the IRS technology is a promising enabler for smart and reconfigurable wireless communication environments. In this basic fundamentals presentation, we have provided an overview of the IRS technology and its potential advantages, including improved signal strength, cost-effectiveness, privacy, flexibility, and lower latency. We have also highlighted the paradigm shift in wireless system design from a traditional one with active components only to a new hybrid architecture comprising both active and passive components that co-work in an intelligent way. Overall, this basic fundamentals presentation serves as a useful starting point for individuals who want to gain a fundamental understanding of the IRS technology and its potential in future-generation wireless communications.

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- Ms. Neha Choudhary Mam
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- Intelligent Reflecting Surface Aided Multigroup Multicast MISO Communication System
- YouTube (@iain explains, IEEE seminar by Dr Ganesan Thiagarajan)
- @DSP Logs
- @GuassianWaves
- @Sci-Hub