JNEST EISSN: 2961-8738 ● PISSN: 2961-8916 ● DOI: 10.56741/jnest.v4i02.804
Article Received 4 January 2025. Revised 14 April 2025.

Physical Characteristics Analysis on Intelligent Reflecting Surface for High Speed Telecommunication Networks

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***Abstract*—The paper mainly focuses on the physical characteristics analysis of an intelligent reflecting surface for high-speed telecommunication networks. The research problem in this study are (i) To overcome the bottleneck, a novel transmission scheme, named hybrid reflection modulation (HRM) must be considered, exploiting both active and passive reflecting elements at the RIS and their combinations, which enables to convey information without using any radio frequency (RF) chains, (ii) In the HRM scheme, the active reflecting elements using additional power amplifiers can be able to amplify and reflect the incoming signal, while the remaining passive elements can reflect the signals with appropriate phase shifts, (iii) Based on this novel transmission model, we will observe an upper bound for the average bit error probability (ABEP), and derive achievable rate of the system using an information theoretic approach, and (iv) Moreover, comprehensive computer simulations could be performed to prove the superiority of the proposed HRM scheme over existing fully passive, fully active and reflection modulation (RM) systems. The research directions are as follows: (i) Implementing the Intelligent Reflecting Surfaces (IRS) and Hybrid Reflection Modulation Technologies for 6G Wireless Communication, (ii) Implementing the Intelligent Reflecting Surfaces (IRS) and Hybrid Reflection Modulation Technologies with physical layer security techniques, and (iii) Modelling the mathematical equation for optimization design of IRS system. There are two portions in this study. The first is designing the signal model in the IRS surface with specific physical parameters. The second one is an analysis of the capacity of point-to-point MIMO channels. The analyses are conducted using by MATLAB language. The results confirm the performance specification of the IRS system for high-speed telecommunication applications.**

***Index Terms*—Intelligent Reflecting Surface, High Speed Telecommunication System, Numerical Analysis, Physical Layer Security, Wireless Communication.**

I. INTRODUCTION

THE rudimentary scenario in wireless communications is that of a transmit antenna that radiates an electromagnetic waveform that spreads out and ultimately is measured by a receive antenna positioned at another geographical location. The transmitted waveform is planned to carry information that can be mined by the receiver from its received signal. A combination of digital modulation and channel coding is used to create the waveform and encode information into it, which is done in such a way that the receiver can extract it even if the signal is attenuated and distorted [1-5].

A key motivation for us is that with the advent of fifth-generation (5G) mobile networks, MIMO technology is everywhere: each base station and mobile phone is fitted out with antenna arrays accomplished of transmitting/receiving signals with controllable directivity. This feature leads to stronger signals, robustness against channel fading, and spatial multiplexing that can significantly advance data rates. This is only the beginning of the MIMO saga because larger antenna arrays and higher frequency bands that can put up more antennas in the same arena are anticipated for imminent network generations. The MIMO technology touches the physical-layer transmissions and deviations in how resource allocation and network optimization are completed. The equivalent practice also underpins emerging technologies such as reconfigurable intelligent surfaces (RIS) and integrated sensing and communication (ISAC) [6-10].

The bandwidths available on today's networks are increasing at a dramatic rate, and there is eternal optimism. This causes network designers to start thinking about what happens in the limit. Although high-speed networks bring a dramatic change in the bandwidth available to applications.

IRS emerges as a novel concept for customizing future wireless environments in a cost- and energy-efficient way. It reflects the incident signals into preferred directions and achieves an unsatisfactory performance improvement over the traditional wireless networks in certain conditions.

The research highlights in this study are based on the following concepts such as (i) Physical layer is very important and security is vital role to enhance the performance of the communication system, (ii) Performance accuracy and latency reduction process are the fundamental risk on this research works, (iii) Implementation of the Intelligent Reflecting Surfaces (IRS) and Hybrid Reflection Modulation Technologies for 6G Wireless Communication, (iv) Analyzing the mathematical modelling and physical parameters for Intelligent Reflecting Surface, Designing the Hybrid Modulation Scheme based on 6G Telecommunication System, and (v) Enhancing the high speed data rate and high performance of the physical layer components, the implementation of IRS and hybrid modulation [11-15].

The research objectives in this study are (i) Instead of exploiting whole of active reflecting elements in each time

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instant, more energy-efficient communication systems with high data rate can be constructed using HRM transmission concepts that limit the overall power consumption, and (ii) The results that the HRM scheme offers an intermediate solution between a fully passive and fully active RIS-aided transmission scheme, and achieves noticeable performance gains with a high data rate in a more energy-efficient manner.

The main contribution of this paper is to emphasize the appropriate optimal IRS model in numerical analyses and the performance evaluation of the combination of hybrid modulation and active IRS model based on an ideal channel model. The results are based on the probability distribution function of circularly symmetric complex Gaussian distribution, PDFs of the Rayleigh distribution, exponential distribution, and χ^2-distribution, sinusoidal wave propagates, two sinusoidal waves propagating in the xy-plane, and beamforming gain observed in different 3D directions. The implementation step is based on the system design and important mathematical approaches.

The paper is organized as follows. Section II presents the design of the Signal Model in the IRS surface with Specific Physical Parameters. Section III mentions the Analysis on Capacity of Point-to-Point MIMO Channels. Section IV expresses the implementation and analysis. Section V shows the research outcomes and results of the analyses. Section VI concludes the study.

II. Designing the Signal Model in the IRS surface with Specific Physical Parameters

The Complex Gaussian Distribution could be evaluated by using the following mathematical expressions.

$$f_x(x) = \frac{1}{\pi\sigma^2} e^{-\frac{|x|^2}{\sigma^2}} \quad (1)$$

where $x \sim N_C\left(0, \sigma^2\right)$. The mean value is $E\{x\} = 0$ and the variance is $Var\{x\} = E\left\{|x|^2\right\} = E\left\{a^2 + b^2\right\} = \sigma^2$.

The PDF of the complex Gaussian distribution as a function of the magnitude and argument

$$f_{y,\psi}(y,\psi) = \frac{y}{\pi\sigma^2} e^{-\frac{y^2}{\sigma^2}} \quad (2)$$

$$f_y(y) = \int_{-\pi}^{\pi} f_{y,\psi}(y,\psi)\partial\psi = \frac{2y}{\sigma^2} e^{\frac{-y^2}{\sigma^2}} \text{ for } y \geq 0 \quad (3)$$

It matches what is known as the Rayleigh distribution.

$$y \sim \text{Rayleigh}\left(\sigma/\sqrt{2}\right) \quad (4)$$

The capacity in the MIMO, SIMO/MISO, and SISO cases over an ideal channel where all entries have unit magnitude and all singular values of H are equal.

The MIMO capacity is M log2(1 + SNR), the SIMO/MISO capacity is log2(1 +MSNR), and the SISO capacity is log2(1 + SNR).

The MIMO capacity is

$$C = \sum_{k=1}^{r} \log_2\left(1 + \frac{q_k^{opt} s_k^2}{N_0}\right) = M \log_2\left(1 + \frac{q}{N_0}\right) \quad (5)$$

III. Analysis on the Capacity of Point-to-Point MIMO Channels

Single-input single-output (SISO) channel: The transmitter and receiver have one antenna each. Single-input multiple-output (SIMO) channel: The transmitter has one antenna, and the receiver has multiple antennas. Multiple-input single-output (MISO) channel: The transmitter has multiple antennas, and the receiver has one antenna. Multiple-input multiple-output (MIMO) channel: Both the transmitter and receiver have multiple antennas. The four kinds of point-to-point communication channels are where the transmitter and receiver have either one or multiple antennas.

IV. Implementation

The system diagram is illustrated in Fig. 1. There are eight portions to implement the study in this paper. The channel model design, reflecting coefficient model, is analyzed in the previous works [2]. The signal model, physical properties, the mathematical model for optimization, and the IRS model are analyzed in this paper. The performance analysis and optimized design of the IRS is the future works for the main study.

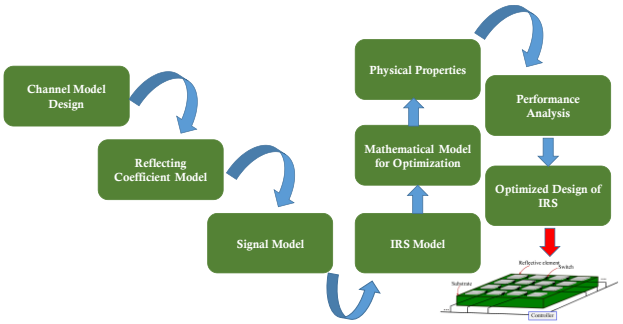


Fig. 1. System Diagram.

A. Design of Aperture Length and IRS Patch Spacing

The beamwidth analysis shows how the directivity of the radiation pattern can be controlled under the assumption of a ULA with IRS Patch spacing $\Delta = \lambda/2$. If the IRS Patch array has a different geometry, the radiation patterns that beamforming creates will be different—a more irregular geometry will result in a more irregular pattern. The beamforming gain can be expressed as a function of Φ as [16-17]

$$A(\phi) = \frac{1}{M} \frac{\sin^2\left(M \frac{\pi\Delta\Phi}{\lambda}\right)}{\sin^2\left(\frac{\pi\Delta\Phi}{\lambda}\right)} = \frac{1}{M} \frac{\sin^2\left(\pi D_\lambda \Phi\right)}{\sin^2\left(\pi\Delta_\lambda\Phi\right)} \quad (6)$$

B. Beamforming Gain with UPA and ULA for IRS Model

The comparison of the beamforming gain with a UPA ($M_H = 10$, $M_V = 4$) and a ULA ($M = M_H = 10$, $M_V = 1$) in the horizontal plane where $\theta = 0$ can be calculated. The arrays transmit in the broadside direction $\varphi_{beam} = 0$ and $\theta_{beam} = 0$ [18-19].

$$A_{M_H}(\Phi) A_{M_V}(\Omega) = \frac{1}{M} \frac{\sin^2\left(\pi L_{H,\lambda}\Phi\right)}{\sin^2\left(\pi\Delta_\lambda\Phi\right)} \frac{\sin^2\left(\pi L_{V,\lambda}\Phi\right)}{\sin^2\left(\pi\Delta_\lambda\Phi\right)} \quad (7)$$

V. Results and Discussions

A. *Probability Distribution Function of Circularly Symmetric Complex Gaussian Distribution*

Fig. 2 shows the classical shape of a Gaussian distribution, but in two dimensions. There are other types of complex Gaussian distributions than the one described above. To be precise, it should be defined what is known as the circularly symmetric complex Gaussian distribution.

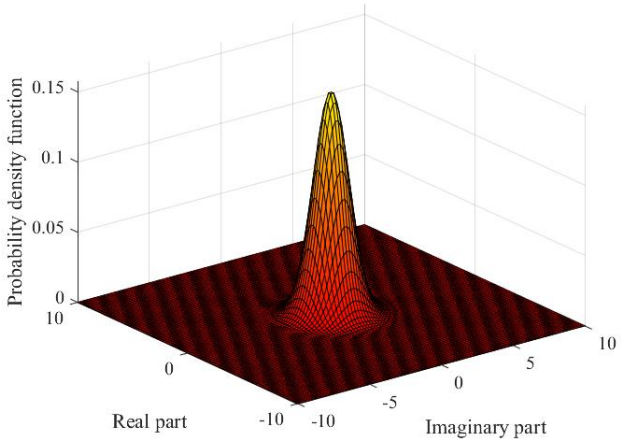


Fig. 2. PDF Result for Circularly Symmetric Complex Gaussian Distribution.

B. *PDFs of the Rayleigh distribution, exponential distribution, and χ^2-distribution*

The PDF with σ = 1 is illustrated in Fig. 3. When a communication channel is complex Gaussian distributed, it is referred to as Rayleigh fading since the magnitude is Rayleigh distributed. This PDF characterizes the variations in the squared magnitude of a complex Gaussian random variable. It matches what is known as the exponential distribution.

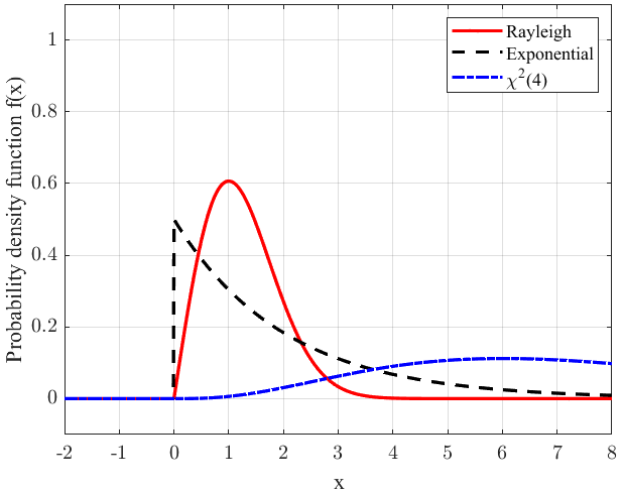


Fig. 3. PDF in Three Channels.

C. *Sinusoidal Wave Propagates*

The focus in this study is based on the complex numbers and detection theory, and many other statistical signal analysis approaches when developing concise models of communication systems with the IRS channel. The IRS channel is one of the outstanding approaches for solving the signal modelling and signal reconstruction for real-world applications.

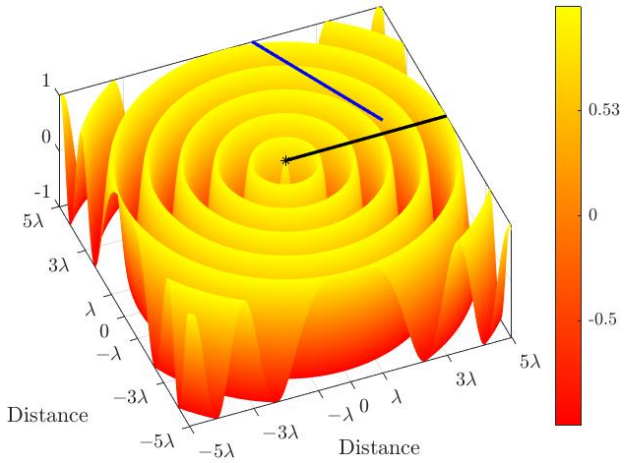


Fig. 4. Wave Propagations.

D. *Two sinusoidal waves propagating in the xy-plane*

The shape of the wavefront is seen by inspecting the points that attain the maximum value at the same time: these points lie on circular curves in Fig. 5(a) and on straight lines in Fig. 5(b). When this example is extended to wave propagation in three dimensions, the circular curves become spherical, while the straight lines become planes. The wave in Fig. 5(b) propagates along the x-axis. The spatial frequency is zero along the wavefront (i.e., no phase difference along the y-axis).

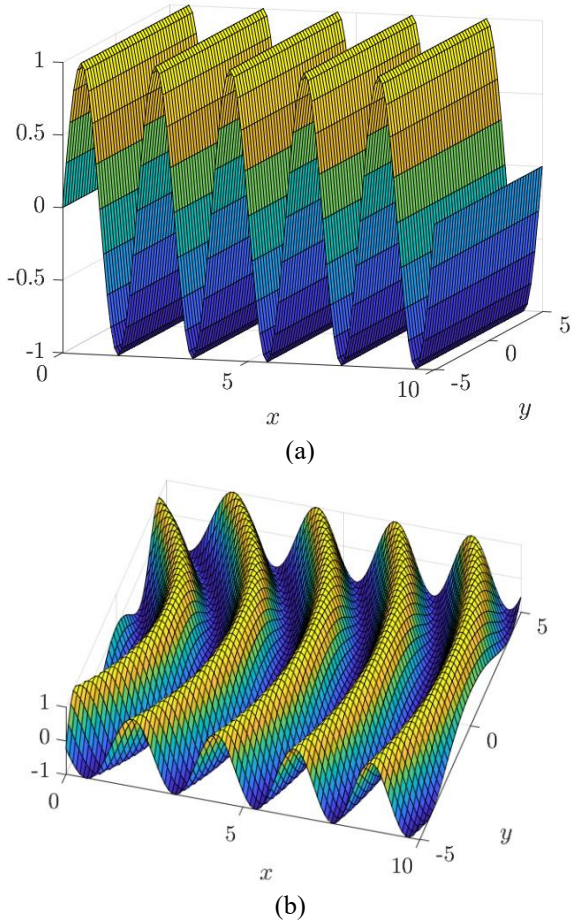
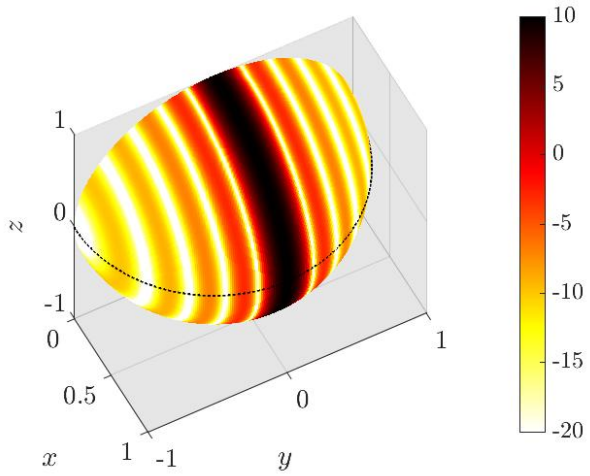


Fig. 5. Two Sinusoidal Waves Propagations.

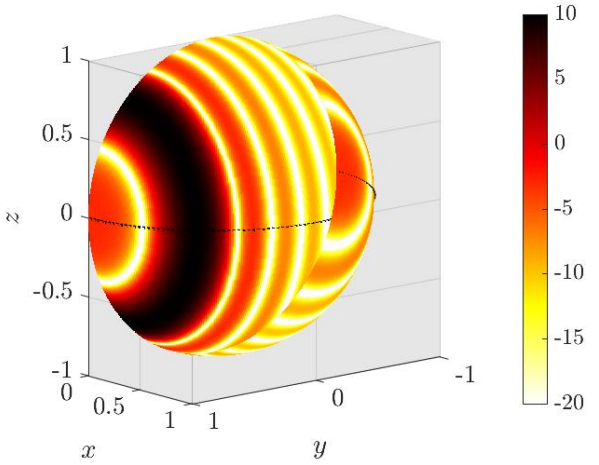
E. *Beamforming Gain observed in different 3D directions*

The ULA is deployed along the y-axis, and the xy-plane is the horizontal plane; thus, it is the beam patterns

along the dotted curves shown in Fig. 6. Note that the beam patterns are invariant if we rotate them around the y-axis; thus, the beam points in the desired direction in the azimuth plane and many other directions with non-zero elevation angles. The beamwidth in the horizontal plane is indeed smaller with $\varphi_{beam} = 0$ than with $\varphi_{beam} = \pi/4$, but this is compensated for since the beam covers more area in the elevation dimension in the former case. The average beamforming gain over the sphere is 1 in both cases. Since the beamwidth in the elevation dimension is broad, covering all elevation angles, the beams created by a ULA have roughly the same shape as orange slices.



(a)



(b)

Fig. 6. Beamforming Gain Results.

The beamspace representation for a half-wavelength-spaced 9 × 9 UPA is illustrated in Fig. 7. We begin by revisiting the NLOS setup with four propagation paths having distinct azimuth and elevation angles. The real part of the wave impinging on the array is considered. The UPA samples the wave at the marked antenna locations. The resulting channel can be turned into the beamspace by taking a 2D-DFT of the channel coefficients, which results in the 2D spatial frequency spectrum shown in Fig. 7. There are four peaks, which match the number of paths. It was implicitly assumed in this study that the paths gave rise to plane waves. However, the beamspace analysis can be applied regardless of the wavefront. The real part of the impinging wave emitted from a transmitter at a short distance of 8λ in the broadside direction is also considered. There are large circle-shaped phase variations over the array, which is typical for spherical waves. When turning this near-field channel into the beamspace, we obtain the 2D spatial frequency spectrum shown in Fig. 7.

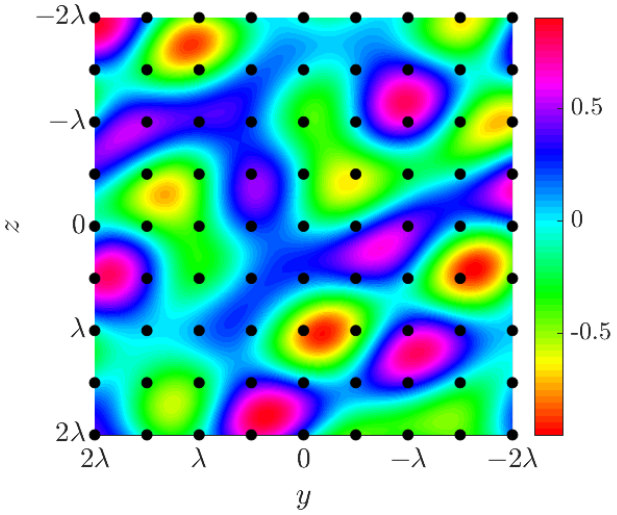


Fig. 7. IRS with Optimized Design.

VI. Performance Evaluation

The spectrum sensing for hybrid modulation with different IRSs and adaptive thresholds is based on the detection probability concerning SNR is an important analysis for performance evaluation of the hybrid modulation with IRS technology for the high-speed telecommunication system. Fig. 8 illustrates the Detection Probability Analysis with Hybrid Modulation. In that evaluation, the red color represents the evaluation based on without IRS method. The dash-blue color refers to the active IRS in the near position from the source of the user position. The dot-black color means the active IRS is far from the source of the user position. In the performance evaluation, we could conclude that the detection probability could be accepted after using hybrid modulation with different positions of IRSs from the various locations of different users for the adaptive threshold value of noise figure of 10 in reality [20].

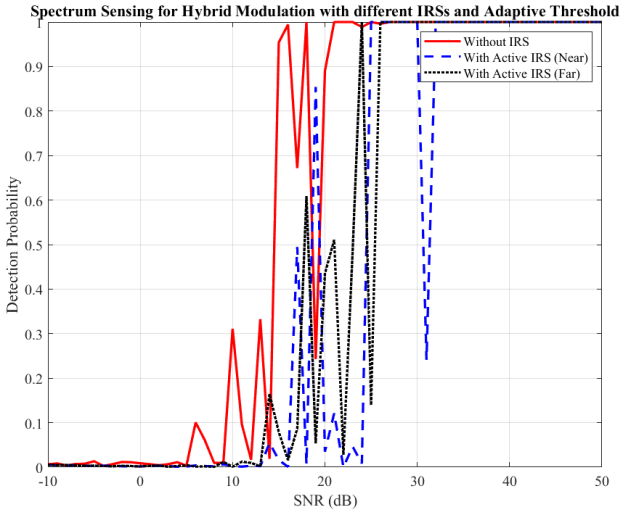


Fig. 8. Detection Probability Analysis with Hybrid Modulation

The theoretical BER Vs SNR for the IRS Model with N=64 and N=128 with various numbers of patch n_R=2, 4, 8, and 16, respectively. Therefore, RIS-based schemes may have higher signaling overhead due to the training of RISs, while traditional schemes have a much higher transmitter complexity. The effective use of RIS-assisted communication schemes may be a game-changing paradigm for next-generation communication networks by eliminating the need for sophisticated massive MIMO schemes that require expensive and power-hungry components [21].

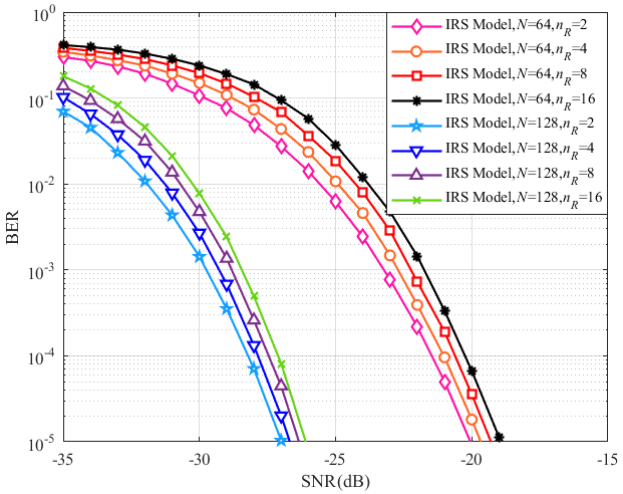


Fig. 9. Bit Error Rate concerning SNR (dB) for the IRS Model with Hybrid Modulation

VII. Hardware Testing

The 16-element IRS design is developed, but the bandwidth is narrower than the simulation results in [16]. However, good results could be obtained when measuring the mutual coupling. Table I gives the measurement results on a 16-element IRS design. The measurement results could be accepted for real-world applications.

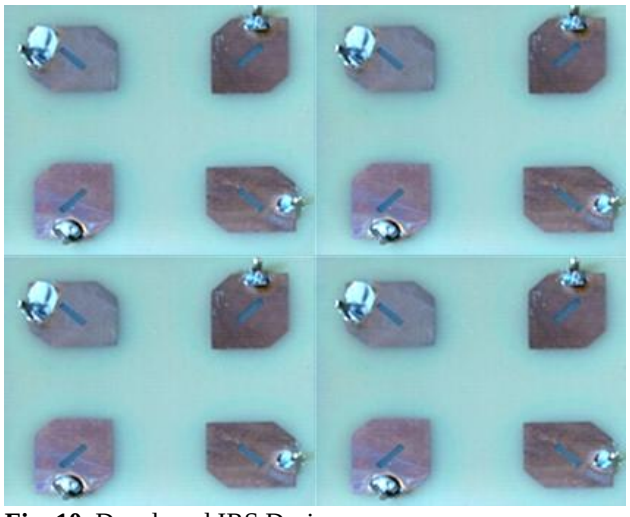


Fig. 10. Developed IRS Design

VIII. Conclusion

The statistical model for MIMO channels is extended and obtains what is known as independent and identically distributed Rayleigh fading. Depending on how quickly the channels vary over time, different ways of extending the capacity concept to handle fading channels were considered. The focus in this study is based on complex numbers and detection theory, and many other statistical signal analysis approaches, when developing concise models of communication systems with the IRS channel. The IRS channel is one of the outstanding approaches for solving the signal modelling and signal reconstruction for real-world applications.

TABLE I. Measurement Results

Sr. No	Measurement Parameters	Results
1.	Bandwidth (Port 1 to Port 1)	0.39 GHz
2.	Bandwidth (Port 2 to Port 2)	0.57 GHz
3.	Bandwidth (Port 3 to Port 3)	2.04 GHz
4.	Bandwidth (Port 4 to Port 4)	0.12 GHz
5.	From other ports	< -20 dB
6.	At 5.9 GHz Minimum (Port 1 to Port 1), (Port 2 to Port 2), (Port 3 to Port 3), (Port 4 to Port 4)	-10.86 dB, -10 dB, -11.27 dB, -10.9 dB

The sixth-generation (6G) remote environment will be fundamental for a horde of new applications dependent on precise area mindfulness and other logical data. Such a remote environment has been empowered by cutting-edge 6G remote innovations coordinated with existing advancements for the Internet-of-things (IoT) and the worldwide route satellite framework. With immense mm-Wave range and tight shaft reception apparatus innovation, exact position area is currently conceivable in 6G and future portable communication frameworks. The further research directions could be expanded to include specific aspects such as material challenges and the integration with AI-driven network optimizations for the next advanced technology.

Acknowledgment

The authors acknowledge the colleagues from the Telecommunication Engineering Research Group of the Department of Electronic Engineering at Yangon Technological University for completing this study.

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