Chapter 7

Conclusion and Future Scope

7.1 Conclusion

The current thesis concentrates on performance analysis to enhance the extensive connectivity, spectrum efficiency, and energy conservation of a proposed multiple RIS-assisted wireless system for next-generation communications. RIS holds the capability to transform a rapidly fluctuating channel into a more stable one by reconfiguring the wireless channel environment and adjusting the phase of reflected signals in a constructive manner. Through the implementation of IRS panel selection in various scenarios involving multiple IRS, system performance can be enhanced significantly while maintaining low computational complexity. Additionally, the integration of IRS into NOMA allows for accommodating a greater number of users using the same time and frequency resources.

This thesis is presented across some key aspects such as: Introduction of fundamental concepts pertaining to RIS, NOMA, UWB and other contemporary Physical layer approaches. Introduction of IRS panel selection methodologies along with their detailed analytical representation by considering various wireless system fading channel models such as Rayleigh, Rician, Nakagami-m, and $\alpha-\mu$, specifically in the context of IRS-assisted systems. Further, theoretical analysis is considered of RIS and NOMA transmission models for downlink scenario. Exploration of the combination of RIS with NOMA to enhance connectivity, spectrum efficiency, and energy conservation. Additionally, the thesis delves into the introduction of an RIS-assisted UWB system, where combined optimization of beamforming and phase adjustments of reflecting elements at the RIS are implemented. Below is an overview highlighting the key contributions and insights.

In Chapter 2, an extensive investigation into the performance of a multiple-IRS-assisted SISO communication system employing optimal IRS panel selection over independent and identically distributed (i.i.d.) Rician fading channels is considered. We have derived closed-form approximate OP expressions using both CLT-based and LSE-based methods, along with an asymptotic OP expression providing diversity gain and coding gain insights. Our analysis showcased the system's performance, observing the precision of the LSE-based approximation for low IRS element values and its close alignment with the CLT-based approximation for high IRS element values. Impact of various factors, including the number of IRS elements, IRS panel count, panel location, and fading parameter is considered. Monte-Carlo simulations were conducted to validate our theoretical analysis. Results demonstrated the considerable enhancement in system performance with multiple IRS compared to a single IRS-assisted system.

In Chapter 3, a comprehensive study of a multiple-IRS-assisted SISO communication system employing SSC and SEC selection schemes in Rician fading channels has been conducted. Closed-form expressions for accurate OP were derived for scenarios with a large number of IRS elements. Additionally, asymptotic OP expressions, providing diversity gain and coding gain insights, were obtained. The analytical expressions were thoroughly assessed to demonstrate system performance, considering factors such as the number of IRS elements, IRS panels, fading parameters, and IRS panel placement. Monte Carlo simulations were conducted to validate the theoretical analysis, confirming its accuracy.

In Chapter 4, an extensive analysis focused on SISO communication systems employing multiple IRS (MIRS) panels over independent and identically distributed (i.n.d.) Nakagami-m fading channels is considered. Our approach involved deriving accurate OP expressions using both CLT and LSE methodologies. Additionally, we derived a novel asymptotic OP and established a closed-form expression for diversity order. Notably, this diversity order expression relies on the minimum fading parameter between the transmitter-IRS panel and the IRS panel-receiver links, as well as the number of IRS panels. The simulation results corroborated our theoretical analysis, providing consistent outcomes. Our investigation further scrutinized how various system parameters, such as the fading parameter (m) and the number of IRS panels, impact the system's OP performance. The findings underscored that apart from the number of IRS elements, both IRS panel selection strategies and fading parameters significantly influence system performance.

In Chapter 5, an extensive study evaluating the BER performance within an IRS-assisted downlink power domain NOMA system has conducted. Our investigation encompasses i.n.i.d. (independent and identically distributed) Rician fading channels while considering errors in SIC. The study resulted in closed-form BER expressions for both near and far users, accounting for a significant quantity of IRS elements. Additionally, we have derived asymptotic BER expressions for each user. Moreover, we have analyzed influence of several factors such as fading parameters, the number of IRS elements, power coefficients of near users, and the placement of

IRS panels on the BER performance of both near and far users. To validate the accuracy of our theoretical analysis, we have conducted extensive Monte Carlo simulations. The outcomes demonstrated a marked improvement in BER performance with an increase in the number of reflecting elements, confirming the precision of our theoretical findings.

In Chapter 6, UWB system integrates an IRS (IUWB) to optimize energy efficiency within the system design is proposed and analyzed. The analysis primarily emphasizes the BER and total throughput performance of IUWB. A unique phase optimization approach, grounded in the strongest path concept, is introduced and contrasted against coherent and random phase shift methods. Results demonstrate that the proposed strongest path-based phase optimization method exhibits BER performance similar to that of the coherent phase method. Furthermore, the study investigates the influence of diverse UWB channels and the quantity of reflecting elements on IUWB performance, comparing it with a conventional UWB system lacking an IRS. Findings highlight that augmenting the number of reflecting elements notably enhances both the sum-rate and BER performance of IUWB. Additionally, positioning the IRS in proximity to either the BS or UE yields superior performance compared to alternative placements.

7.2 Future Scope

In the previous research, the assumption was that both the BS and users had access to ideal CSI. However, our future focus will involve utilizing artificial intelligence (AI) and deep learning techniques to address imperfect CSI scenarios. Consequently, implementing the current RIS-assisted NOMA system with flawed CSI becomes a more intriguing prospect. Moreover, there's ongoing exploration of Terahertz frequencies due to their high data rates, despite challenges like obstacles causing spreading loss and molecular absorption between transmitters and receivers. Addressing this issue, my ongoing research on RIS-assisted NOMA aims to alleviate these obstacles.

Furthermore, RIS-NOMA research emphasizes wireless power transfer, an exciting technology with the potential to enhance the battery life of IoT devices in upcoming wireless networks.

In the forthcoming era, RIS-assisted orthogonal time-frequency space (OTFS) modulation is poised to support high Doppler shifts. Channel-induced Doppler shifts commonly diminish data rates and communication reliability, particularly in scenarios with high mobility, such as high-speed trains or IoT devices transitioning from static to high-mobility channels. In OTFS modulation, information bits are initially embedded within the delay-Doppler domain, followed by transformation into time-domain transmit signals. Upon reception, the received time domain is restored to the delay-Doppler domain, allowing for the extraction of the original information bits. This approach effectively addresses issues related to inter-symbol interference (ISI) and inter-carrier interference (ICI). As a result, RIS-assisted OTFS modulation emerges as an exceedingly intriguing area for further exploration and study.

Appendix A

In [78], authors present a method to find the product $Z = XY$ of two independent complex Gaussian RVs $X \sim \mathcal{CN}\left(v_x^2 e^{j\phi_x}, \sigma_x^2\right)$ and $Y \sim \mathcal{CN}\left(v_y^2 e^{j\phi_y}, \sigma_y^2\right)$. Note that Z will be a double variables distribution in amplitude $R_z = |Z|$ and phase $\Theta = \text{Arg}(Z) \in [0, 2\pi) : f_{R_z,\Theta}(r_z, \theta)$. It is well-known that the RV X is a complex Gaussian with $\mathbb{E}[X] \neq 0$, the amplitude $R_x = |X|$ models as a Rician distribution. For other details, the interested reader can refer to the reference paper [78]. (22) of [78] is given as

$$f_{R_z,T}(r_z, t) = \frac{4r_z}{t\,\sigma_x^2 \sigma_y^2} \exp\left(-\left(\frac{r_z^2}{t^2\sigma_x^2} + \frac{t^2}{\sigma_y^2} + k_x^2 + k_y^2\right)\right) I_0\left(\frac{2r_z v_x}{t\sigma_x^2}\right) I_0\left(\frac{2tv_y}{\sigma_x^2}\right) \tag{A.1}$$

Using $\Omega_x = \mathbb{E}[|X|^2]$, $\Omega_y = \mathbb{E}[|Y|^2]$, $K_x = k_x^2 = \frac{v_x^2}{\sigma_x^2}$, $K_y = k_y^2 = \frac{v_y^2}{\sigma_y^2}$, $\sigma_x^2 = \frac{\Omega_x}{(1+K_x)}$, and $\sigma_y^2 = \frac{\Omega_y}{(1+K_y)}$ in (2.1), we can rewrite (A.1) as

$$\begin{aligned} f_{R_z,T}(r_z, t) = {} & \frac{4(1+K_x)(1+K_y)r_z}{t\,\Omega_x\,\Omega_y\,\exp\left(K_x + K_y\right)} \exp\left(-\left(\frac{(1+K_x)r_z^2}{t^2\Omega_x} + \frac{(1+K_y)t^2}{\Omega_y}\right)\right) \\ & \times I_0\left(\frac{2\,r_z\sqrt{K_x(1+K_x)}}{t\sqrt{\Omega_x}}\right) I_0\left(\frac{2\,t\sqrt{K_y(1+K_y)}}{\sqrt{\Omega_y}}\right). \end{aligned} \tag{A.2}$$

In asymptotic analysis, we assume that $\bar{\gamma}_m \to \infty$. It implies that $\Omega_x \to \infty$ and $\Omega_y \to \infty$. For small arguments of the Bessel function, the relation holds $\lim_{z\to 0} I_0(z) \approx 1$ [75, (9.6.7)]. Using this relation in (A.2), the asymptotic joint PDF expression $f^{\infty}_{R_z,T}(r_z,t)$ can be given as

$$f^{\infty}_{R_z,T}(r_z,t) \approx \frac{4(1+K_x)(1+K_y)r_z}{t\,\Omega_x\,\Omega_y\,\exp\left(K_x+K_y\right)}\exp\left(-\left(\frac{(1+K_x)r_z^2}{t^2\Omega_x}+\frac{(1+K_y)t^2}{\Omega_y}\right)\right). \tag{A.3}$$

Now, one will integrate this asymptotic joint PDF expression $f^{\infty}_{R_z,T}(r_z,t)$ over $t \in [0,\infty)$, then, with aid of [79, (2.3.16.1)], one can get the asymptotic marginal PDF $f^{\infty}_{R_z}(r_z)$

$$\begin{aligned} f^{\infty}_{R_z}(r_z) &= \int_0^{\infty} f^{\infty}_{R_z,T}(r_z,t)dt \\ &= \frac{4(1+K_x)(1+K_y)r_z}{\Omega_x\Omega_y\,\exp\left(K_x+K_y\right)}K_0\left(2\,r_z\sqrt{\frac{(1+K_x)(1+K_y)}{\Omega_x\,\Omega_y}}\right) \end{aligned} \tag{A.4}$$

where $K_0(\cdot)$ is the zeroth order modified second kind Bessel function. Again, for the small argument of modified second kind Bessel function $K_0(\cdot)$, the relation holds $\lim_{z\to 0} K_0(z) \approx -\ln z$ [75, (9.6.8)][1], we can further approximate the asymptotic PDF expression $f^{\infty}_{R_z}(r_z)$ in (A.4) as [2]

$$f^{\infty}_{R_z}(r_z) \approx \frac{4\,\Delta(1+K_x)(1+K_y)r_z}{\Omega_x\Omega_y\,\exp\left(K_x+K_y\right)}. \tag{A.5}$$

where $\Delta = -\lim_{\Omega_x,\Omega_y\to\infty}\ln\left(2\sqrt{\frac{(1+K_x)(1+K_y)}{\Omega_x\,\Omega_y}}\right)$ and $\ln(\cdot)$ denotes the natural logarithm. To write the PDF expression $f^{\infty}_{z_{mi}}(x)$ of (2.16), one can consider $R_z = z_{mi}$, $r_z = x$, $|X| = |h_{mi}|$, $|Y| = |\mathrm{g}_{mi}|$, $\Omega_x = d_{h_m}^{-\alpha_{h_m}}$ and $\Omega_y = d_{\mathrm{g}_m}^{-\alpha_{\mathrm{g}_m}}$ in (A.5).

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[1] Note that we have neglected $-\ln r_z$ term in approximation.

[2] For $\Omega \to \infty$, $K_0(\cdot)$ can be approximate a constant value Δ which can be computed numerically by MATHEMATICA/MATLAB software.

Appendix B

In [78], authors have derived a method to find the product $Z = XY$ of two nonzero-mean complex Gaussian independent random variables $X \sim \mathcal{CN}\left(v_x^2 e^{j\phi_x}, \sigma_x^2\right)$ and $Y \sim \mathcal{CN}\left(v_y^2 e^{j\phi_y}, \sigma_y^2\right)$. Since Z is complex, its amplitude follows a bivariate distribution, i.e., $R_z = |Z|$ and phase $\Theta = \mathrm{Arg}(Z) \in [0, 2\pi) : f_{R_z,\Theta}(r_z, \theta)$. For a complex Gaussian random variable X, with non-zero expectation, the amplitude $R_x = |X|$ follows a marginal Rician distribution. For more details, the interested reader can refer [78]. Eq. (22) of [78] is given as

$$f_{R_z,T}(r_z,t) = \frac{4r_z}{t\,\sigma_x^2\sigma_y^2} \exp\left(-\left(\frac{r_z^2}{t^2\sigma_x^2} + \frac{t^2}{\sigma_y^2} + k_x^2 + k_y^2\right)\right) I_0\left(\frac{2r_z v_x}{t\sigma_x^2}\right) I_0\left(\frac{2tv_y}{\sigma_x^2}\right) \tag{B.1}$$

Using $\Omega_x = \mathbb{E}[|X|^2]$, $\Omega_y = \mathbb{E}[|Y|^2]$, $K_x = k_x^2 = \frac{v_x^2}{\sigma_x^2}$, $K_y = k_y^2 = \frac{v_y^2}{\sigma_y^2}$, $\sigma_x^2 = \frac{\Omega_x}{(1+K_x)}$, and $\sigma_y^2 = \frac{\Omega_y}{(1+K_y)}$ in (3.1), we can rewrite (3.1) as

$$\begin{aligned} f_{R_z,T}(r_z,t) = {} & \frac{4(1+K_x)(1+K_y)r_z}{t\,\Omega_x\,\Omega_y\,\exp\left(K_x+K_y\right)} \exp\left(-\left(\frac{(1+K_x)r_z^2}{t^2\Omega_x} + \frac{(1+K_y)t^2}{\Omega_y}\right)\right) \\ & \times I_0\left(\frac{2\,r_z\,\sqrt{K_x(1+K_x)}}{t\,\sqrt{\Omega_x}}\right) I_0\left(\frac{2\,t\,\sqrt{K_y(1+K_y)}}{\sqrt{\Omega_y}}\right). \end{aligned} \tag{B.2}$$

For asymptotic analysis, we assume that $\bar{\gamma}_m \to \infty$, which implies that $\Omega_x \to \infty$ and $\Omega_y \to \infty$. For small arguments of the Bessel function, the relation holds $\lim_{z\to 0} I_0(z) \approx 1$ [75, (9.6.7)]. Therefore, (B.1) for asymptotic joint PDF expression $f^{\infty}_{R_z,T}(r_z,t)$ can be given as

$$f^{\infty}_{R_z,T}(r_z,t) \approx \frac{4(1+K_x)(1+K_y)r_z}{t\,\Omega_x\,\Omega_y\,\exp\left(K_x+K_y\right)} \exp\left(-\left(\frac{(1+K_x)r_z^2}{t^2\Omega_x} + \frac{(1+K_y)t^2}{\Omega_y}\right)\right). \quad \text{(B.3)}$$

Now, we integrate above asymptotic joint PDF expression $f^{\infty}_{R_z,T}(r_z,t)$ over $t \in [0,\infty)$, then with the help of [79, (2.3.16.1)], one can get the asymptotic marginal PDF $f^{\infty}_{R_z}(r_z)$ as

$$f^{\infty}_{R_z}(r_z) = \int_0^{\infty} f^{\infty}_{R_z,T}(r_z,t)dt = \tfrac{4(1+K_x)(1+K_y)r_z}{\Omega_x\Omega_y\,\exp(K_x+K_y)} K_0\left(2\,r_z\sqrt{\tfrac{(1+K_x)(1+K_y)}{\Omega_x\,\Omega_y}}\right) \quad \text{(B.4)}$$

where $K_0(\cdot)$ denotes the modified zeroth order second type Bessel function. Again, for a small argument of modified second kind Bessel function $K_0(\cdot)$, the relation holds $\lim_{z\to 0} K_0(z) \approx -\ln z$ [75, (9.6.8)][1], we can further approximate the asymptotic PDF expression $f^{\infty}_{R_z}(r_z)$ in (3.4) as [2]

$$f^{\infty}_{R_z}(r_z) \approx \frac{4\,\Delta(1+K_x)(1+K_y)r_z}{\Omega_x\Omega_y\,\exp\left(K_x+K_y\right)}. \quad \text{(B.5)}$$

where $\Delta = -\lim_{\Omega_x,\Omega_y\to\infty} \ln\left(2\sqrt{\tfrac{(1+K_x)(1+K_y)}{\Omega_x\,\Omega_y}}\right)$ and $\ln(\cdot)$ denotes the natural logarithm. To write the PDF expression $f^{\infty}_{z_{mi}}(x)$ of (3.17), one can consider $R_z = z_{mi}$, $r_z = x$, $|X| = |h_{mi}|$, $|Y| = |\mathrm{g}_{mi}|$, $\Omega_x = d_{h_m}^{-\alpha_{h_m}}$ and $\Omega_y = d_{\mathrm{g}_m}^{-\alpha_{\mathrm{g}_m}}$ in (B.5).

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[1] Note that we have neglected $-\ln r_z$ term in approximation.

[2] For $\Omega \to \infty$, $K_0(\cdot)$ can be approximate a constant value Δ which can be computed numerically by MATHEMATICA/MATLAB software.

Appendix C

In this appendix, we provide expressions for the integrals $\mathcal{I}_u^{(j)}\left(\frac{\pi}{2}\right)$ and $\mathcal{I}_{u,\infty}^{(j)}\left(\frac{\pi}{2}\right)$, where u takes values from the set $\{n, f\}$, respectively.

$\mathcal{I}_u^{(j)}\left(\frac{\pi}{2}\right)$:

After substituting (5.6) into (5.10) and using the transformations $t = \frac{2\Delta_{u1}\Delta_{u2}\sin^2\phi}{2\Delta_{u1}\sin^2\phi + \epsilon_u\gamma_0}$ and $w = \left(\frac{2\Delta_{u1}+\gamma_0}{2\Delta_{u1}\Delta_{u2}}\right)t$, a new expression for the integral $\mathcal{I}_u^{(j)}\left(\frac{\pi}{2}\right)$ can be provided as

$$\begin{aligned}\mathcal{I}_u^{(j)}\left(\frac{\pi}{2}\right) &= \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \mathcal{M}_{\gamma_u^{(j)}}\left(\frac{1}{2\sin^2\varphi}\right)d\varphi = \frac{\sqrt{2\Delta_{u1}\epsilon_u\gamma_0}}{\pi(\epsilon_u\gamma_0 + 2\Delta_{u1})}\\ &\times \exp\left(-\Delta_{u2}\right)\psi_1\left(1; 1; 1.5; \frac{2\Delta_{u1}}{\epsilon_u\gamma_0 + 2\Delta_{u1}}, \frac{2\Delta_{u1}\Delta_{u2}}{\epsilon_u\gamma_0 + 2\Delta_{u1}}\right)\end{aligned} \tag{C.1}$$

where $\psi_1(\cdot, \cdot; \cdot; \cdot, \cdot)$ is the confluent Appell's hypergeometric function which can be expressed as [111]

$$\psi_1(a, b; c; w_1, w_2) = \tfrac{\Gamma(c)}{\Gamma(c-a)\ \Gamma(a)}\int_0^1 \tfrac{v^{a-1}(1-v)^{c-a-1}}{(1-vw_1)^b\exp(-vw_2)}dv, \tag{C.2}$$

where $\Gamma(\cdot)$ denotes the Gamma function.

$\mathcal{I}_{u,\infty}^{(j)}\left(\frac{\pi}{2}\right)$:

After substituting (5.21) into (5.23) and performing mathematical simplification, a new expression for the integral $\mathcal{I}_{u,\infty}^{(j)}\left(\frac{\pi}{2}\right)$ can be given as

$$\begin{aligned}\mathcal{I}_{u,\infty}^{(j)}\left(\frac{\pi}{2}\right) &= \frac{1}{\pi}\int_{0}^{\frac{\pi}{2}} \mathcal{M}_{\gamma_u^{(j)}}^{\infty}\left(\frac{1}{2\sin^2\varphi}\right) d\varphi \\ &= \left(\prod_{i=1}^{N_\mathrm{u}} \Delta\, \mathcal{A}_{h_{ui}}\mathcal{A}_{g_{ui}}\right) \frac{2^{N_\mathrm{u}-2}\Gamma(0.5+N_\mathrm{u})}{\sqrt{\pi}\Gamma(2N_\mathrm{u})\left(0.5\bar{\gamma}\right)^{N_\mathrm{u}} N_\mathrm{u}}\end{aligned} \tag{C.3}$$

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Author's Publications

- R.K. Hindustani, D. Dixit, and S. Sharma "Outage Probability Analysis of Multiple Intelligent Reflecting Surface-assisted Single-Input Single-Output System with Switched Diversity," *International Journal of Communication Systems*, Vol.36, No. 14, pp. e5550, 2023.
- R.K. Hindustani, D. Dixit, S. Sharma, and V. Bhatia "Outage Probability of Multiple-IRS-Assisted SISO Wireless Communications over Rician Fading," *Elsevier, Physical Communication*, Vol. 59, pp. 102102, 2023.
- R.K. Hindustani, S. Sharma, and D. Dixit, "Joint Symbol and ToA Estimation in RIS-assisted UWB Indoor Localization," *IEEE International Conference on IoT, Communication and Automation Technology*, 2023.
- R.K. Hindustani, S. Sharma, D. Dixit, and M. Sharma, "Intelligent Reflecting Surface-Assisted Downlink UWB System," *IEEE Global Conference on Artificial Intelligence and Internet of Things (GCAIoT)* 2023.
- S. Kumar, S. Sharma, S. Bhattacharyya, and R.K. Hindustani, "Multiuser Precoded OFDM System over Nonlinear Power Amplifier," *IEEE Wireless Antenna Microwave Symposium (WAMS)* 2024 (accepted).
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