Chapter 1

Introduction

Wireless technology has revolutionized mobile communications to facilitate seamless connectivity across vast distances. Through the deployment of cellular networks, wireless signals can be transmitted and received between mobile devices and base stations, enabling users to stay connected virtually anywhere. This connectivity has transcended geographical boundaries, enabling individuals to communicate and access information on the go, whether they are in bustling urban centers or remote rural areas. Devices leverage wireless communication protocols such as Wi-Fi, Bluetooth, and LTE (Long-Term Evolution) to access the internet, send messages, make voice calls, and run a myriad of applications.

Wireless technology has also transformed industries ranging from healthcare and transportation to finance and entertainment. For example, in healthcare, wireless-enabled medical devices and telemedicine solutions allow for remote patient monitoring and real-time health data transmission, improving patient outcomes and reducing healthcare costs. The rollout of 5G networks promises to deliver unprecedented speed, capacity, and low latency, unlocking new possibilities for connected devices, autonomous vehicles, augmented reality.

1.1 Evolution of Wireless Standards

First Generation (1G): The first generation of wireless standards introduced analog cellular networks, enabling basic voice communication. These networks, with their limited capacity and low data transfer rates, marked the beginning of the wireless revolution. However, the analog nature of 1G posed limitations in terms of clarity and security.

Second Generation (2G): The advent of 2G brought significant improvements over its predecessor. Digital cellular networks replaced analog systems, enabling clearer voice calls, text messaging, and the introduction of basic data services. 2G networks, using technologies like GSM (Global System for Mobile Communications), revolutionized wireless communication and laid the foundation for future innovations.

Third Generation (3G): The third generation of wireless standards, 3G, marked a major milestone in wireless communication by introducing high-speed mobile internet access. With improved data transfer rates, users could now enjoy web browsing, video streaming, and advanced multimedia services on their mobile devices. 3G technologies like UMTS (Universal Mobile Telecommunications System) and CDMA (Code-division Multiple Access) played key roles in this transformation.

Fourth Generation (4G): The roll-out of 4G networks introduced true broadband connectivity, enabling faster data transfer speeds, low latency, and enhanced multimedia capabilities. With 4G, users could experience seamless video conferencing, high-quality video streaming, and faster downloads. LTE emerged as the dominant technology, revolutionizing wireless communication and paving the way for modern-day applications.

Fifth Generation (5G): The latest milestone in wireless standards is the much-anticipated arrival of 5G. 5G networks promise unprecedented speeds, ultra-low latency, and massive device connectivity. This technology opens doors to transformative applications such as autonomous vehicles, smart cities, virtual reality, and Internet of Things (IoT) devices. With its faster and more reliable connectivity, 5G is set to revolutionize industries and empower the next generation of communication. *Sixth Generation (6G)*: While 5G is still being deployed worldwide, researchers and industry experts are already envisioning the potential of 6G wireless standards [1]. A summary of evolution of wireless standards is given in Figure 1.1.

Key technologies for 5G and beyond wireless communications encompass a diverse array of innovations poised to transform connectivity and enable new applications in the digital era. Terahertz communication promises to leverage frequencies beyond traditional bands, offering ultra-high data rates and unlocking unprecedented bandwidth for bandwidth-intensive applications. Massive MIMO (Multiple Input Multiple Output) systems harness the power of numerous antennas to enhance spectral efficiency and network capacity, enabling simultaneous connections to multiple users. Integrated terrestrial and non-terrestrial networks combine terrestrial infrastructure with satellite communication to extend coverage to remote areas and support ubiquitous connectivity. Here are a few key concepts being explored:
a. Intelligent Reflecting Surfaces (IRS): The IRS utilizes smart surfaces embedded with tiny reconfigurable elements to control and manipulate wireless signals [2, 3]. These surfaces reflect and redirect the signal, enhancing coverage, improving signal strength, and reducing interference. IRS is expected to play a crucial role in achieving higher data rates and more reliable connections in 6G networks.
b. IRS-aided Non-Orthogonal Multiple Access (NOMA): IRS-aided NOMA allows multiple users to share the same time-frequency resources, boosting spectral efficiency and increasing the number of connected devices with higher spectral efficiency

[2]. This technology ensures higher capacity and improved network performance, enabling seamless connectivity in densely populated areas.

c. Orthogonal Time Frequency Space (OTFS): OTFS is an innovative modulation and coding scheme that aims to overcome the limitations of traditional wireless communication system in high mobility scenarios. By leveraging time-frequency space, OTFS provides better resilience to fading and interference, resulting in improved signal quality and increased coverage.

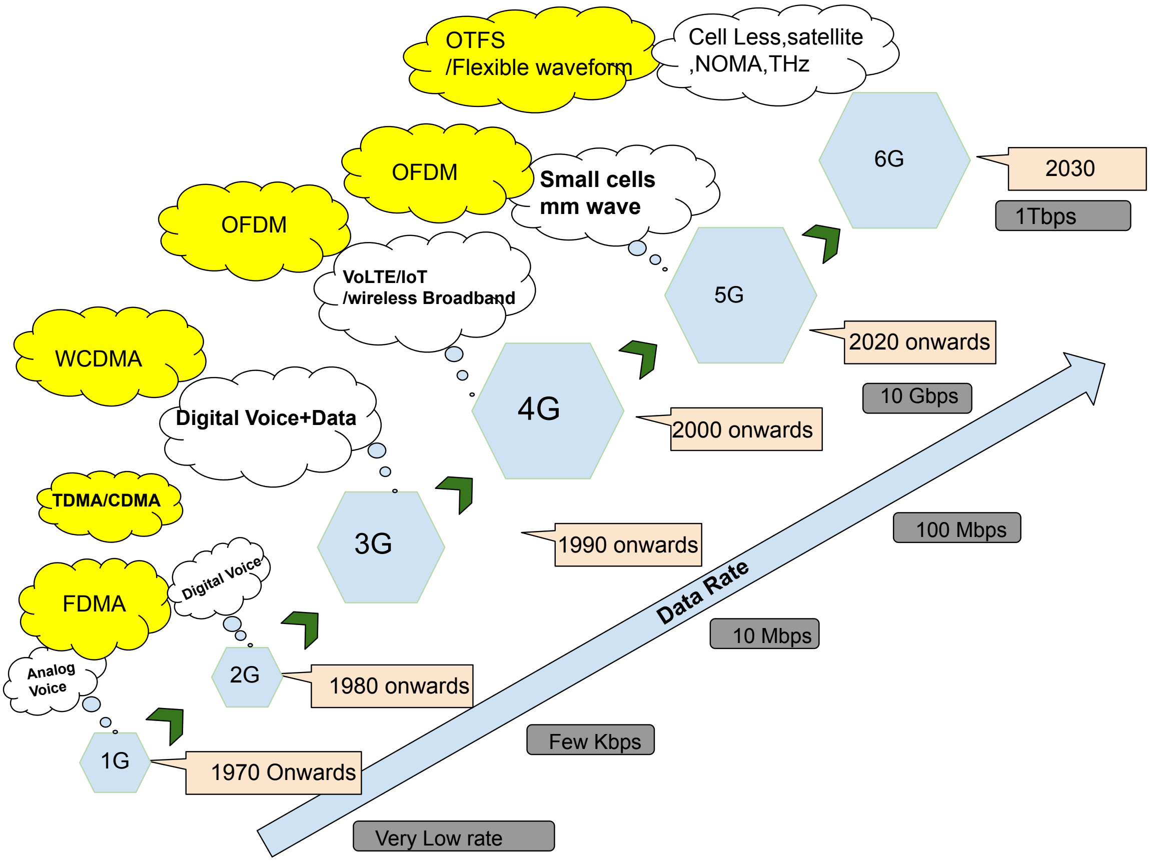

FIGURE 1.1: Evolution of Wireless Standards

1.2 Motivation for the Thesis

The motivation behind this thesis lies in the pursuit of overcoming the limitations of 5G and improving energy and spectral efficiencies of next-generation wireless networks. With the increasing demands for higher capacity, improved coverage, and reliable connectivity, novel technologies like IRS have emerged as promising solutions. By intelligently manipulating the wireless channels, the IRS can enhance signal strength, coverage, and overall network performance [4]. Therefore, this thesis aims to analyze the impact of the IRS on various performance metrics to gain insights and provide valuable contributions to the field. Selection combining and switched diversity techniques in IRS-assisted networks aim to enhance signal quality by intelligently selecting the best available signals from multiple IRS. The IRS-assisted non-orthogonal multiple access (NOMA) technique has the potential to significantly enhance spectral and energy efficiencies in wireless communication systems [5]. The BER performance analysis of the IRS-assisted NOMA system is an important research problem for investigation.

IRS-assisted ultra-wideband (UWB) system has the potential for coverage enhancement, interference suppression, signal focusing, localization and channel capacity improvement for short range communication. With the assistance of IRS, UWB signals can be accurately focused and directed towards specific locations, enabling enhanced localization accuracy. By strategically deploying IRS to improve signal coverage, suppress interference, focus signals, and increase channel capacity, IRS-aided UWB systems can achieve improved performance in terms of coverage, reliability, positioning accuracy, and data rates. This research aims to explore these opportunities and contribute to the advancement of IRS-aided UWB technology, enabling novel applications and addressing the evolving needs of wireless communication systems.

1.3 Intelligent Reflecting Surfaces

IRS[1] is an emerging technology that has gained significant attention in the field of wireless communication [6, 7]. With the ever-increasing demand for faster and more reliable wireless networks, researchers have been exploring innovative solutions, and IRS has emerged as a promising candidate [2].

IRS consists of a large number of tiny passive reflecting elements, as shown in FIGURE 1.2, such as meta-surfaces or metamaterials, that are strategically deployed in the environment. These elements have the ability to manipulate the incoming signals by reflecting, refracting, or diffracting them according to a predefined pattern. By doing so, the IRS can intelligently adjust the propagation environment, leading to significant improvements in wireless communication performance.

The primary goal of the IRS is to enhance signal quality and coverage, mitigate interference, and improve the overall system capacity. Unlike traditional wireless communication methods that rely on direct communication between the transmitter and receiver, IRS introduces an additional layer of signal manipulation, enabling more efficient use of the available resources.

The key advantage of IRS lies in its ability to achieve beamforming and signal focusing without the need for active radio frequency (RF) components or power-hungry amplifiers. By intelligently reflecting the incident signals toward the desired receiver, IRS can amplify the received power, improve the signal-to-noise ratio, and extend the communication range.

Moreover, the IRS can be dynamically reconfigured to adapt to changing wireless channel conditions, user locations, or network requirements. This flexibility allows

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[1] IRS is also known as reflecting intelligent surfaces (RIS) in the literature

for optimization and fine-tuning of the wireless communication system, resulting in improved performance and increased spectral efficiency.

IRS has the potential to revolutionize various wireless communication applications, including 5G and beyond, the IoT, smart cities, and wireless sensor networks. It opens up new possibilities for designing cost-effective, energy-efficient, and high-capacity wireless networks.

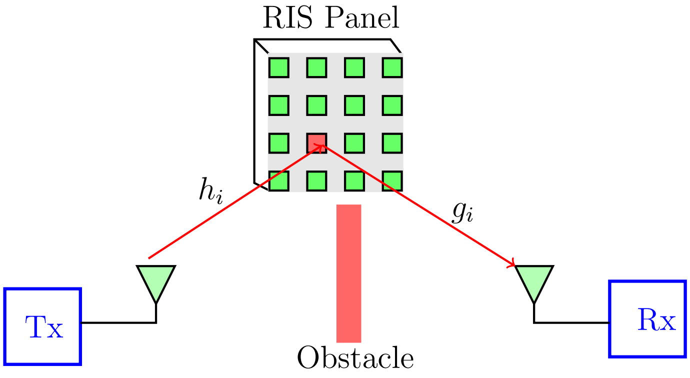

FIGURE 1.2: RIS-assisted SISO system.

In Figure 1.2, visualize each transmitter (Tx) and receiver (Rx) possessing a single antenna without any direct path between them due to blockages. The reflecting intelligent surface (RIS) comprises N passive reflecting elements. The distance between Tx and RIS is denoted as d_1, and the distance between RIS and Rx is denoted as d_2. According to the free propagation theory, the maximized received power P_r is proportional to $P_\mathrm{t}\frac{N^2\lambda^4}{(4\pi)^2{d_1}^2{d_2}^2}$ [4], where P_t represents the transmit power, and λ represents the wavelength.

The received signal power depends on the reflective elements N^2, distances d_1 and d_2, and the Rayleigh flat fading channels h_i and g_i between Tx to RIS and RIS to Rx of the ith reflective element, respectively. Consider the channel phase information known at the RIS. Therefore, the Rx received signal can be expressed as:

$$y = \left[\sum_{i=1}^{N} h_i e^{j\phi_i} g_i \right] x + n. \tag{1.1}$$

Here, x represents modulation symbols selected from the constellation points of M-ary phase shift keying (PSK) or M-ary quadrature amplitude modulation (QAM), and n is the additive white Gaussian noise (AWGN) following a distribution $\sim \mathcal{CN}(0, N_0)$. Consequently, the maximized signal-to-noise ratio (SNR) is given by

$$\gamma_{\max} \leq \frac{\left| \sum_{i=1}^{N} h_i g_i \right|^2 E_s}{N_0}. \tag{1.2}$$

Here, E_s represents the average transmitted energy of each modulation symbol. Therefore, the RIS has the potential to enhance bit error rate (BER), sum-rate, spectral, and energy efficiencies in next-generation wireless communications.

1.4 Fading Channel Models

During wireless communication, a transmitted signal encounters random reflectors, scatterers, and attenuators, resulting in the signal arriving at the receiver via multiple paths [8]. This scenario, where multiple copies of the signal reach the receiver through different paths, is known as a multipath channel [9]. These diverse signal copies, characterized by varying amplitudes, phases, and delays, converge at the receiver, leading to either constructive or destructive interference. Consequently, the received signal undergoes changes in its shape over time, a phenomenon referred to as multipath fading [8].

Multipath fading, also termed small-scale fading, emerges due to the signal's propagation across multiple paths within a wireless channel. Depending on the signal and channel properties, fading can be categorized as flat or frequency non-selective, frequency-selective, fast, or slow fading. Frequency selectivity aligns with the multipath time delay spread, while the distinction between fast or slow fading relates to the channel's Doppler spread. Accurately modeling fading presents challenges due to its inherent complexity. Nonetheless, substantial research has focused on statistically modeling these intricate effects, leading to the introduction of numerous mathematical models to characterize fading channels [9]. Various statistical distributions are utilized to model multipath fading in different environments. Several standard fading models include the following:

- **Rayleigh Fading**: The Rayleigh distribution is employed for modeling multipath fading in scenarios where independent scatterers are adequately large, possessing nearly identical energy, and where no line-of-sight (LoS) component reaches the receiver. Under these conditions, the probability density function (PDF) of the channel fading amplitude $|h|$ can be expressed [9] as follows:

  $$f_{|h|}(x) = \frac{2x}{\Omega} e^{-x^2/\Omega}, \quad x \geq 0 \tag{1.3}$$

  where $\Omega = \mathbb{E}[|h|^2]$ and $\mathbb{E}[\cdot]$ is the expectation operator. A Rayleigh RV $|h|$ can be modeled as $|h| = |X + jY|$, where X and Y are independent Gaussian RVs with zero mean and equal variances.

- **Rician Fading**: The Rician fading distribution, alternatively recognized as the Rice distribution, serves to model propagation paths characterized by a prominent direct LoS component alongside numerous multipath components.

The PDF for $|h|$ is expressed as [8]

$$f_{|h|}(x) = \frac{x}{\sigma^2} e^{-(x^2+v^2)/2\sigma^2} I_0(\frac{xv}{\sigma^2}), \quad x \geq 0. \tag{1.4}$$

The function $I_0(\cdot)$ represents the modified Bessel function of the first kind with order zero. In the Rician fading, this distribution is frequently reformulated utilizing the shape parameter $K = \frac{v^2}{2\sigma^2}$, which signifies the ratio between the power attributed to the LoS path and the cumulative power contributed by the remaining multipaths. Additionally, the scale parameter $\Omega = v^2 + 2\sigma^2$ is defined as the aggregate power received across all paths [8]. It represents scenarios where there's a strong direct signal component along with weaker scattered signals. Rician fading is often observed in open spaces with fewer obstacles.

- **Nakagami-m Fading**: The Nakagami-m distribution frequently provides the most suitable fit for land-mobile and indoor-mobile multipath propagation, along with the scintillation observed in ionospheric radio links [8]. Moreover, it is extensively employed to characterize the urban environment, offering a PDF for the envelope given by

$$f_{|h|}(x) = \frac{2m^m x^{2m-1}}{\Omega^m \Gamma(m)} e^{-mx^2/\Omega}, \quad x \geq 0. \tag{1.5}$$

The parameter m is greater than or equal to 0.5, representing the severity of fading, while $\Gamma(\cdot)$ denotes the gamma function. This function caters to specific scenarios: Rayleigh fading ($m = 1$) and one-sided Gaussian fading ($m = 0.5$) are included as special cases.

- **κ-μ Fading**: The κ-μ models have proven effective in modeling small-scale fading within mobile radio channels, particularly those featuring LoS components [10]. Incorporating non-homogeneous physical modeling, these models offer optimal fits to real-world scenarios and experimental data. The PDF for the κ-μ distribution is provided as follows [8]

$$f_{|h|}\left(x\right)=\frac{2\mu\left(1+\kappa\right)^{\frac{\mu+1}{2}}x^{\mu}\exp\left(-\frac{\mu(1+\kappa)}{\Omega}x^{2}\right)}{\kappa^{\frac{\mu-1}{2}}\exp\left(\mu\kappa\right)\Omega^{\frac{\mu+1}{2}}}I_{\mu-1}\left(2\mu\sqrt{\frac{\kappa\left(1+\kappa\right)}{\Omega}}x\right),\qquad x\geq 0 \tag{1.6}$$

The parameter κ represents the ratio between the overall power of the dominant component and the combined power of the scattered waves. Additionally, the parameter μ is given by the formula $\mu=\frac{1}{\mathrm{Var}[|h|^{2}]}\frac{1+2\kappa}{(1+\kappa)^{2}}$, and denotes the count of multipath clusters within the scenario. Several fading models such as Nakagami-m ($\kappa\rightarrow 0$, $\mu=m$), Nakagami-n (Rice) ($\kappa=K$, $\mu=1$), and Rayleigh ($\kappa\rightarrow 0$, $\mu=1$) can be realized as special cases of κ-μ fading model.

The κ-μ fading channel is a mathematical model used to describe wireless communication channels that exhibit both small-scale and large-scale fading effects. It provides a flexible representation of real-world fading conditions. In the κ-μ fading model, the small-scale fading is characterized by the κ-μ distribution, which takes into account two parameters: κ and μ. κ represents the severity of fading, where higher values indicate more severe fading conditions, and μ represents the degree of non-centrality, which affects the shape of the fading distribution.

1.5 Diversity Techniques

Numerous contemporary and upcoming wireless systems implement various forms of diversity. Diversity combining, a technique where two or more independent copies of a signal carrying the same message are appropriately merged, serves to enhance the overall SNR. In essence, diversity combining stands as a practical strategy aimed at alleviating the impact of fading in wireless channels.

The fundamental concept revolves around leveraging the low likelihood of simultaneous occurrence of significant signal fades across all diversity channels. This strategy aims to diminish the probability of errors or outage occurrences [11]. Below is a compilation of potential methods through which independent faded signals can be acquired as

- **Frequency Diversity:** The transmission of signals through different modulation frequencies, adequately spaced apart, can result in distinct fading channels. It's crucial that the minimum frequency separation meets or exceeds the coherence bandwidth of the channel [12].
- **Time Diversity:** Sending identical information signals at different time intervals allows the reception of independent faded signals. For this method to be effective, the minimum time interval needs to surpass the coherence time of the channel [13].
- **Spatial Diversity:** Utilizing multiple transmit or receiver antennas facilitates spatial diversity, wherein the diversity branches encounter uncorrelated fading, primarily dictated by the spatial separation among the antennas [14]. By capturing signals through distinct antennas positioned at adequate distances, statistically independent faded signals can be obtained.

For mobile units, the minimum antenna spacing is typically recommended to be at least half a wavelength [13]. In contrast, for stationary base stations equipped with elevated antennas, the requisite spacing to attain independent faded signals can be wider than that of mobile unit antennas [13]. As per experimentation, a range of 30 to 50 wavelengths for stationary receivers has been suggested, effectively limiting the correlation between faded signals to below 0.3, as also suggested in [13].

- **Polarization Diversity:** Achieving independent fading paths can be accomplished through the simultaneous transmission of signals employing both horizontal and vertical polarizations [13].
- **Multipath Diversity:** Another approach to achieve independent fading paths involves resolving multipath components with varying delays through the utilization of direct sequence spread spectrum signaling coupled with a RAKE receiver [13].

1.5.1 Diversity Combining Receiver

FIGURE 1.3 illustrates a block diagram of a diversity combining receiver. The combiner, which can be either selection combining (SC), equal gain combining (EGC), or maximum ratio combining (MRC), incorporates total L receiving antennas. Adequate antenna spacing is crucial to receive independent fading signals.

During multipath propagation of a modulated signal $x(t)$ within an AWGN channel, the received faded signals are denoted as $y_l(t)$ for $l = 1, \cdots, L$. The combiner can operate as either a predetection or a post-detection type [8]. Following the combiner, a detector is employed, utilizing detection rules based on the modulation scheme utilized in signal $x(t)$. In a typical receiver operation, a demodulated signal is fed to the detector [8]. To satisfy this prerequisite, it is assumed that the demodulation process occurs within the combiner itself.

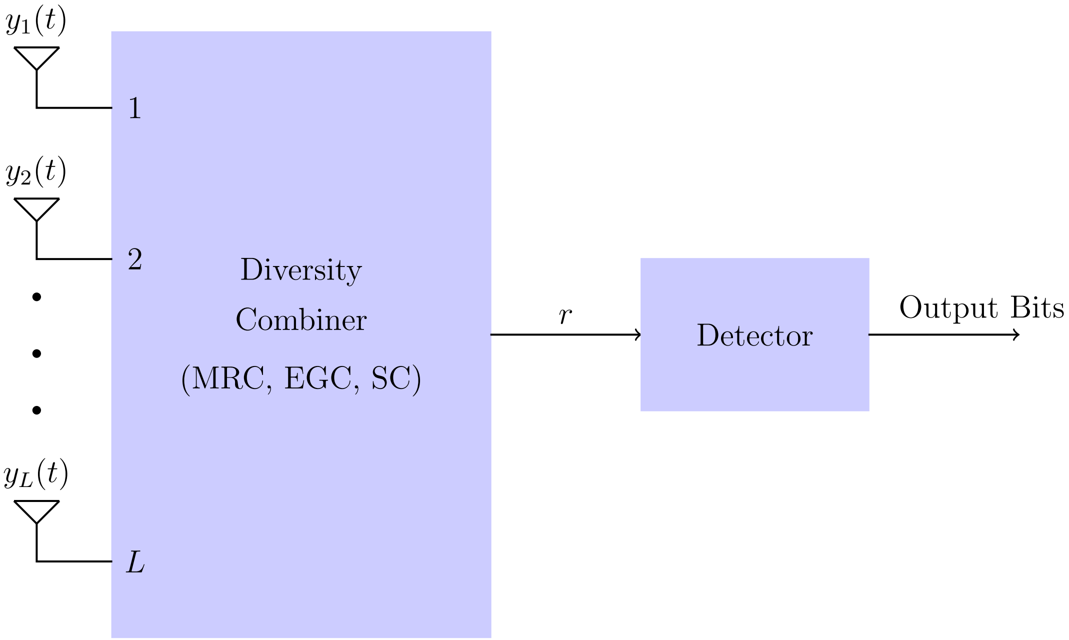

FIGURE 1.3: Block diagram of diversity receiver system.

The mathematical expression for the output of the combiner, denoted as r, can be derived based on the operating principle of the combiner such as MRC, EGC or SC. In the case of linear diversity combining, a generalized expression for r can be provided as

$$r = \sum_{l=1}^{L} c_l y_l, \tag{1.7}$$

where the combining coefficients c_ls, take values according to the combining rule employed, and y_l is the l^{th} path received signal.

Several diversity techniques have been developed, including SC, EGC, MRC, switch and stay combining (SSC), and switch and examine combining (SEC), and these are described as

1. **Selection Combining:**

SC is a diversity technique that selects the best signal among multiple received signals. It operates by comparing the received signals' quality and selecting the one with the highest SNR path. By choosing the best signal, selection combining mitigates the impact of fading and improves the overall system performance. For a SC combiner, c_ls can be given as [8]

$$c_l = \begin{cases} 1, & \text{for } l = k \\ 0, & \text{for } l \neq k \end{cases} . \tag{1.8}$$

Here k^{th} path has maximum SNR. Hence, at any given instance, only a single signal from the available L signals is chosen for processing, specifically the one displaying the highest SNR among the entire set. This method stands as the simplest implementation among all diversity combiners.

2. **Equal Gain Combining:**

EGC is a diversity technique combining the received signals with equal weights. EGC helps reduce fading impact and improves the received signal quality. In an EGC configuration, the signals received from all L receiving antennas are aligned in phase and then multiplied by a unity weight factor before being summed together to generate the output signal of the combiner. The combining coefficients c_ls for an EGC combiner can be expressed as [8]

$$c_l = \exp(-j\varphi_l), \qquad \forall l = 1, 2, \ldots, L. \tag{1.9}$$

Here φ_l denotes the phase of the l^{th} path. EGC demonstrates performance closely comparable to MRC, albeit with lower complexity. Hence, in communication systems, EGC finds widespread usage due to its favorable balance between performance and complexity.

3. **Maximum Ratio Combining:**

Within the MRC combiner, all received signals are aligned in phase and subsequently multiplied by a weight factor proportional to the branch SNR. These weighted signals are then summed up to generate the output of the combiner, represented as [8]

$$c_l = |\alpha_l| \exp(-j\varphi_l), \qquad \forall l = 1, 2, \ldots, L. \tag{1.10}$$

Weights c_l to be the conjugate of channel gain must be estimated. The combiner output is given by

$$r = \sum_{l=1}^{L} |\alpha_l| \exp(-j\varphi_l) y_l. \tag{1.11}$$

The MRC is a diversity technique that combines the received signals with weights proportional to their SNR. MRC utilizes the knowledge of the channel conditions to assign appropriate weights for each received signal. By doing so, MRC optimally combines the signals to maximize the received signal power, thus improving overall system performance.

4. **Switch and Stay Combining:**

The SSC is a diversity technique that involves using multiple antennas or multiple IRS panels. In this technique, when the received signal power from the selected IRS panel (or antenna) goes below a predetermined threshold, then the received signal branch becomes undesirable and an IRS panel (or antenna) switching is required [8].

5. **Switch and Examine Combining:**

The SEC is a diversity technique similar to switch and stay combining. However, instead of switching directly, switch and examine combining periodically evaluates the received signal quality and switches between antennas or IRS panels when a significant degradation in signal quality is detected [8].

Diversity techniques are valuable tools for improving the reliability and performance of wireless communication systems. By effectively combating fading and interference, diversity techniques contribute to achieving higher data rates, increased coverage, enhanced outage, and enhanced overall system capacity.

1.6 Non-Orthogonal Multiple Access

Power domain NOMA is a technique used in wireless communication systems to improve spectral efficiency and accommodate multiple users in the same frequency and time resources [15]. In the power domain NOMA, multiple users are assigned different power levels to share the same resource blocks simultaneously. Additionally, the utilization of successive interference cancellation (SIC) at receivers serves to alleviate interference caused by strong users for the benefit of high channel gain users [16].

In the two user NOMA system, two users are categorized as the near user (NU) or strong user and the far user (FU) or weak user. The NU typically utilizes less transmitting power compared to the FU, and the total power is apportioned between the NU and FU at the base station (BS) in the downlink NOMA system. Additionally, the NU employs SIC for signal detection, as illustrated in FIGURE 1.4. The FU decodes its signal directly while considering the NU's transmission as interference [17, 18].

Features of the power domain NOMA [18–21]:

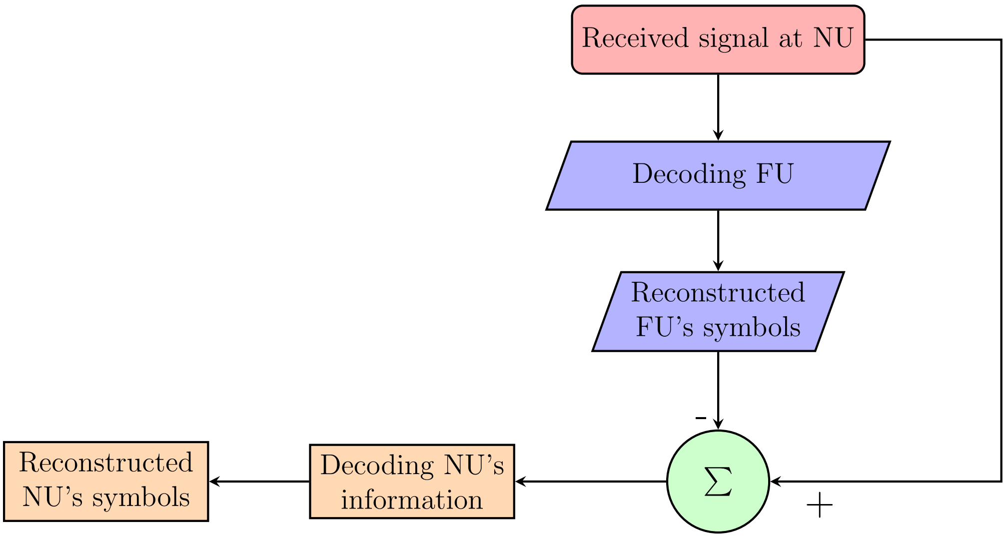

FIGURE 1.4: SIC implemented at NU.

- *User Multiplexing:* In the NOMA, multiple users are multiplexed together in the power domain. Unlike traditional orthogonal multiple access (OMA) schemes where users are assigned orthogonal resources, NOMA allows users to share the same resources.

- *Power Allocation:* Each user in the NOMA is assigned a specific power level based on their channel conditions. Users with weaker channel conditions are allocated higher power levels, while users with stronger channel conditions are allocated lower power levels. This power allocation is crucial to ensure that users with poorer channel conditions can still achieve acceptable signal quality.

- *Superposition Coding:* At the transmitter, superposition coding is used to combine the signals intended for different users. The signals are weighted according to the power allocation and then superimposed before transmission.

- *Successive Interference Cancellation:* At the receiver, SIC is performed to separate the signals of different users. The receiver initially decodes the signal of the user with the strongest power level and removes it from the received signal.

Then, it proceeds to decode the signal of the user with the next strongest power level, taking into account the interference caused by the previously decoded user. This process continues until all users' signals are decoded.

1.7 Ultra-Wideband

UWB technology harnesses very large bandwidth for information transmission. According to the Federal Communications Commission (FCC), UWB communication is characterized by a signal bandwidth of no less than 500 MHz or a fractional bandwidth surpassing 20% [22]. The extensive signaling bandwidth and low power characteristics of UWB signals unveil numerous promising attributes. These include high-data-rate communications, precise ranging and localization, and the potential for simplified device complexity. These merits have sparked significant interest in UWB communications as a facilitating technology, offering low-power and simplified UWB transmissions. This interest primarily aims to interconnect diverse devices in IoT applications within unlicensed spectrum environments. Here are some key aspects of UWB technology in wireless communication [23–25]:

- *Wide Bandwidth:* UWB uses a wide frequency spectrum, typically exceeding 500 MHz or even multiple GHz. This allows for high data rates and enables the transmission of large amounts of information in a short amount of time.
- *Low Power Spectral Density:* UWB signals are transmitted at a very low power spectral density limited by FCC, which helps mitigate interference with other existing narrowband wireless systems operating in the same frequency band.
- *Impulse-Based Transmission:* UWB often employs impulse-based transmission, where very short-duration pulses are used to carry data. These pulses

can be transmitted in a variety of modulation schemes, including pulse position modulation (PPM) and binary phase-shift keying (BPSK).

- *Short-Range Communication:* UWB is primarily designed for short-range communication applications, typically within a range of a few meters up to tens of meters. It's commonly used in applications like wireless personal area networks (WPANs), wireless sensor networks, and short-range data transfer between devices.
- *High Data Rates:* UWB technology enables high-speed data transmission due to its wide bandwidth. It can support data rates ranging from several hundred Mbps to several Gbps, depending on the implementation and channel conditions.
- *Positioning and Imaging:* UWB signals have unique characteristics that make them suitable for positioning and imaging applications. UWB-based systems can accurately measure distances and locate objects with high precision, making them useful in applications like indoor localization and radar imaging.

The performance of communication systems is significantly influenced by the prevailing channel conditions. Therefore, precise modeling of channel characteristics stands as a crucial aspect for wireless communication setups. In literature, channel modeling employs two main approaches: deterministic and statistical methods [13]. Deterministic channel modeling involves the utilization of ray-tracing techniques, incorporating factors such as the geometric shapes of obstacles, their types, and electromagnetic properties within the propagation environment. However, deterministic models may not be suitable in scenarios where the operational environment undergoes changes.

To account for changes in the operational environment, statistical channel modeling comes into play. These models rely on extensive measurement campaigns, providing information on the received envelope and path arrival time distribution. Many prevalent IEEE UWB standards adopt this statistical channel modeling approach. For instance, the key parameters of the UWB channel model cater to various scenarios, including indoor residential transmission in both LoS (called CM1 channel) and non-LoS (NLoS) (called CM2 channel) conditions, as well as indoor office environments in LoS (called CM3 channel) and NLoS (called CM4 channel) conditions [23].

1.8 Performance Measures and Evaluation

Literature offers established performance metrics to assess the performance of wireless systems at the physical layer. Various standard methodologies are commonly utilized to derive and analyze these measures, as outlined below [8].

Average output SNR: Average output SNR can be calculated by averaging the instantaneous output SNR γ_o across its PDF. Mathematically, it can be expressed as:

$$\bar{\gamma}_o = \int\limits_0^\infty \gamma f_{\gamma_o}(\gamma) d\gamma, \tag{1.12}$$

where $\bar{\gamma}_o$ is the average SNR and $f_{\gamma_o}(\gamma)$ is the PDF of γ_o.

Outage Probability: Outage probability (OP) is a crucial metric in evaluating communication receiver performance. Specifically for the output SNR, it represents the probability that the output SNR γ_0 is below a predetermined threshold value

γ_{th} [8]. Mathematically, it can be expressed as:

$$P_{\text{out}} = \Pr\{\gamma_o \leq \gamma_{th}\} = \int_{0}^{\gamma_{th}} f_{\gamma_o}(\gamma) d\gamma = F_{\gamma_0}(\gamma_{th}), \tag{1.13}$$

where $\Pr\{\cdot\}$ is the probability operator and $F_{\gamma_0}(\cdot)$ denotes the cumulative distribution function (CDF) of γ_0.

Average Bit/Symbol Error Rate: The average bit/symbol error rate (ABER/ASER) for a digital communication system employing various modulations can be derived by averaging the conditional bit/symbol error rate (BER/SER) conditioned on SNR associated with the modulation scheme over the PDF of the receiver's output SNR γ_o [8]. This can be mathematically represented as

$$P(e) = \int_{0}^{\infty} P(e|\gamma) f_{\gamma_o}(\gamma) d\gamma, \tag{1.14}$$

where $P(e\,|\gamma)$ is the conditional BER/SER corresponding to the modulation scheme employed.

Moment Generating Function: The moment generating function (MGF) necessitates an expression for the MGF of the receiver's output SNR γ_o. The MGF of a random variable (RV) γ_o is defined as:

$$\mathcal{M}_{\gamma_o}(s) = \mathcal{L}[f_{\gamma_o}(\gamma)] = \int_{0}^{\infty} \exp\left(-s\gamma\right) f_{\gamma_o}(\gamma) d\gamma, \tag{1.15}$$

where s is a complex variable with nonnegative real part and $\mathcal{L}[\cdot]$ is the Laplace transform operator.

Asymptotic Performance Measures: In asymptotic analysis, the assumption is made that the SNR γ_s is significantly high ($\gamma_s \to \infty$). Within the high SNR regime, the expressions for the ASER and the outage probability can be articulated as [8]

$$P_{\infty}(e) = \lim_{\gamma_s \to \infty} P(e) = \left(G_c\, \gamma_s\right)^{-G_d}, \tag{1.16}$$

and

$$P_{\text{out}}^{\infty} = \lim_{\gamma_s \to \infty} P_{out} = \left(G_c\, \gamma_s\right)^{-G_d}. \tag{1.17}$$

G_d and G_c represent the diversity order and coding gain of the system, respectively. The diversity order G_d signifies the count of independently fading channels inherent in the system or scheme. On the other hand, the coding gain relies on various system parameters such as code and fading parameters, as well as the SNR γ_s.

Signal-to-Interference-plus-Noise Ratio: The signal-to-interference-plus-noise ratio (SINR) quantifies the ratio of the power of a specific desired signal to the combined power of both interfering signals and background noise. Mathematically, it is expressed as

$$\text{SINR} = \frac{P_{\text{signal}}}{P_{\text{interference}} + P_{\text{noise}}} \tag{1.18}$$

Here, $P_{\text{interference}}$ represents the interference power within the system. P_{signal} and P_{noise} denote the signal and noise power, respectively. If the interference power is negligible (i.e., zero), the SINR equals the SNR in the system. For optimal communication performance, minimizing $P_{\text{interference}}$ and P_{noise} are essential.

1.9 Literature Review

In this section, IRS, NOMA, UWB and other emerging physical layer techniques related works are discussed.

Works related to IRS: In [26], authors explore the performance of a single-IRS system over Rician channels, focusing on metrics like OP, ASER, and ergodic capacity. Samuh et al [27] have also presented the performance of a single IRS system over Nakagami-m fading channels in terms of OP, ASER, and channel capacity. In [28], the ASER expression for several modulation schemes for a single IRS system is obtained over double-Nakagami-m fading channels. In [29], ASER performance of quadrature amplitude modulation schemes in a single-IRS-aided wireless communication system is studied for Rayleigh fading channels. In [30], a downlink multiple-user scenario with IRS is studied for energy-efficient designs. In [31], authors have studied the achievable capacity limit of IRS-aided multiple-input-multiple-output communication systems. Basar et al., [32] have presented analytical performance limits of IRS-based communications in Rayleigh fading channels. Further, a summary of IRS related works are given in Table 1.1.

Table 1.1: A summary of IRS related works

Ref.	**Performance Metrics**	**System Model**	**Fading Model**
[32]	ABER	IRS+SISO	Rayleigh
[33]	OP	Multi-IRS+SISO	Rician
[15]	Joint transmit power and phase shift optimization	IRS+NOMA	Rician
[34]	Ergodic Rate	Multi-IRS+DF	Nakagami-m
[26]	OP, ABER, Channel Capacity	IRS+SISO	Rician
[35]	Ergodic capacity, OP	IRS+SISO	Rician
[36]	ABER	IRS+SISO	Hoyt

Works related to NOMA: The performance analysis of wireless communication systems incorporating NOMA or/and IRS has been done in [5, 20, 21, 29, 37–44]. The BER performance of NOMA has been studied assuming imperfect SIC in [18, 37]. Additionally, a simplified design of IRS-assisted NOMA (INOMA) has been proposed and analyzed in [5, 45]. The power-efficient aspects of INOMA have been explored in [21, 38], where joint optimization of beamforming vectors and IRS phase shift matrices aims to enhance the sum-rate performance. The OP analysis of INOMA under perfect and imperfect SIC is studied in [39]. Furthermore, the OP analysis of IRS-assisted uplink NOMA under Nakagami-m fading, utilizing moments matching, has been investigated in [40]. Summary of NOMA related works are given Table 1.2.

Table 1.2: A summary of NOMA related works

Ref.	**Performance Metrics**	**System Model**	**Fading Model**
[40]	OP	IRS-aided NOMA	Nakagami-m
[41]	OP	Multi-IRS-aided NOMA	Rician
[15]	Joint transmit power and phase shift optimization	IRS-aided NOMA	Rayleigh
[44]	BER	IRS-aided NOMA	Rayleigh
[37]	BER	NOMA	Rayleigh
[46]	ABER	IRS-aided NOMA	Nakagami-m
[47]	OP, Sum-rate	IRS-aided NOMA	Nakagami-m

Works related to UWB: BER, sum-rate, and outage probability are analyzed for UWB without IRS [48–50]. A supervised learning-based UWB ranging error mitigation [24, 51], UWB channel models [23], and order statistic-based non-coherent UWB receiver [52] are analyzed. Further, IRS-assisted localization system analysis is also considered in literature [53–55].

1.10 Research Objective

The aim of this thesis research is to improve the spectral and energy efficiency in next-generation communications to provide the close form analysis of IRS-aided wireless system.

Through an extensive literature survey, notable researchers have primarily concentrated on deriving OP and maximizing SNR to enhance the sum-rate performance, particularly under low transmit power conditions. Additionally, there is a focus on addressing joint optimization problems involving both active and passive beamforming techniques in the IRS-aided systems.

Drawing from the preceding section's discussion, examining the performance of IRS-aided communication systems emerges as a promising avenue for research. Consequently, this thesis addresses the analysis of the following problems:

- Performance analysis of IRS-aided communication systems over different fading channels.
- Performance analysis of IRS-aided communication systems using best IRS panel selection among multiple IRS scenario to improve performance with low complexity.

Regarding the aforementioned issue, our emphasis is on deriving closed-form mathematical expressions for diverse performance metrics in IRS-aided communication systems.

1.11 Organization of Thesis

The thesis is organized as follows.

- **Chapter 2** presents the multiple IRS-assisted SISO system over Rician fading.

  The OP performance of multiple-IRS-assisted SISO wireless communication systems over Rician fading channels, focusing on IRS panel selection is analyzed. The investigation concerns a SISO wireless communication scenario where a single transmitting antenna communicates with a receiving node utilizing the best IRS panel selection. Using the central limit theorem (CLT) and Laguerre series expansion (LSE), approximate closed-form expressions for OP are derived. Additionally, a straightforward asymptotic OP is derived to determine diversity order and coding gain. Each system parameter's impact on OP performance is thoroughly examined.

- **Chapter 3** presents the multiple IRS-assisted system with switched diversity techniques.

  The OP analysis of multiple IRS-assisted SISO systems with switched diversity schemes is presented. The focus is on a SISO wireless scenario where a single transmitting antenna sends its message to a receiving antenna aided by multiple IRS panels. OP expressions for the dual-IRS-panel-aided SSC system and multiple-IRS-panel-aided SEC system are analyzed over Rician fading channels. Tight approximate OP expressions in closed form are derived for a large number of IRS elements, along with a simple asymptotic OP to study diversity order and coding gain. Numerical OP results are provided, accompanied by simulated OP results to validate the accuracy of the analytical analysis.

- **Chapter 4** presents the multiple-IRS-aided wireless networks over Nakagami-m fading channels.

  The OP for wireless systems aided by multiple IRS panels operating over Nakagami-m fading channels is analyzed. The focus lies in selecting the optimal IRS panel to maintain service quality and elevate user experience. Two closed-form expressions for OP utilizing the CLT and LSE are derived. Moreover, a novel asymptotic OP expression is developed, leading to the discovery of a unique diversity order. The diversity order of the system model in question is contingent on the minimum fading parameter (m) existing between the transmitter-IRS panel and IRS panel-receiver links, alongside the count of IRS panels. A thorough investigation into the impact of system parameters is conducted, and the validity of our analytical findings is confirmed through comprehensive simulations. The results demonstrate the significance of the diversity order, which is closely tied to the minimum fading parameter (m) between the transmitter-IRS panel and IRS panel-receiver links, the number of elements within each IRS panel, and the total number of IRS panels.

- **Chapter 5** presents the IRS-assisted downlink NOMA system.

  BER performance of an IRS-assisted downlink power domain NOMA system is analyzed by considering SIC errors. In this setup, direct links between the BS and users are obstructed by deep shadowing in IRS-NOMA. The IRS-assisted NOMA system is assumed to experience independent and non-identically distributed (i.n.i.d.) Rician fading channels. Closed-form BER expressions for each user in the IRS-assisted NOMA system are derived. The study investigates the impact of varying IRS element count, IRS-to-BS distance, Rician factor, and power coefficient fluctuations of users on BER performance, validated through simulations.

- **Chapter 6** presents the IRS-assisted UWB system.

  IRS-assisted UWB communication system, referred to as IUWB, is studied with the objective of enhancing energy efficiency. To address the limitations of coherent phase shift schemes at IRS, a novel strongest-path-based phase optimization method is proposed, leveraging time-resolved UWB multipath characteristics. Analysis encompasses the evaluation of BER and sum-rate performance of IUWB, comparing it against a standard UWB system without IRS. Impact of various parameters including the number of reflecting elements, diverse UWB channel models, and IRS positioning on the performance of IUWB is considered. Simulation outcomes highlight the advantageous attributes of IUWB, particularly in terms of energy efficiency and sum-rate.

- **Chapter 7** presents the conclusion of the thesis and future directions.

  This chapter provides a recap of the contributions made in the thesis and some research directions for future work.