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Wireless Communication over Rayleigh and Rician Channels: BER Behavior and System Impact

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Abstract: A thorough assessment of diversity combining methods, including Equal Gain Combining (EGC), Selection Combining (SC), and Maximal Ratio Combining (MRC), in wireless communication systems exposed to independent Rayleigh and Rician fading channels is presented in this work. Using Quadrature Phase Shift Keying (QPSK) modulation, the performance is examined. Rayleigh and Rician fading environments are generated as part of a comprehensive system model that is designed and simulated to represent realistic multipath propagation conditions. Every diversity plan is put into place to lessen the effect that fading has on signal integrity. The performance of each method is then evaluated by computing the Bit Error Rate (BER) at different Signal-to-Noise Ratio (SNR) levels. According to simulation results, EGC provides a performance that is comparable to MRC with less complexity, whereas MRC consistently achieves the lowest BER thanks to its ideal signal-to-noise ratio gain. Even though SC is the most straightforward, its inferior branch selection results in a higher BER. The study underscores the trade-offs between complexity and performance in diversity combining techniques and affirms the superiority of MRC in enhancing QPSK signal robustness under both Rayleigh and Rician fading conditions.

Keywords: Diversity Combining, Fading, Modulation, Bit Error Rate.

INTRODUCTION

Multipath fading-induced signal deterioration is a major problem in wireless communication systems that has an immediate impact on data transmission quality and dependability [1]. Fading phenomena like Rayleigh and Rician fading are caused by multipath propagation, which is the result of radio signals being reflected, diffraction, and scattered. Particularly in mobile situations, these impairments result in changes in signal amplitude and phase, which raise Bit Error Rates (BER) and degrade performance [2]. Diversity approaches have become viable ways to counteract the negative impacts of fading. The system can take use of the various broadcast signal versions that arrive via various paths by using diversity combining at the receiver side, which enhances the overall signal quality. By weighting each received signal branch based on its SNR, Maximal Ratio Combining (MRC), one of the popular combining approaches, offers the best performance [3]. While identical Gain Combining (EGC) combines all branches with identical amplitude but altered phases, Selection Combining (SC) (figure 1), despite being easier, only chooses the strongest branch for detection [4].

These diversity techniques are used in contemporary wireless standards and technologies, such LTE and 5G, to guarantee signal resilience. Understanding the practical efficacy of these techniques requires evaluating them under various channel conditions, including Rayleigh and Rician fading. Rician fading works in contexts with a significant line-of-sight (LOS) component, while Rayleigh fading usually represents non-line-of-sight (NLOS) scenarios [5].

In real-world wireless systems, mobility, the availability or lack of a line-of-sight (LOS) path between the transmitter and receiver, and the surrounding environment all affect how severe fading is. When buildings block the direct path and the received signal is made up entirely of dispersed multipath components, Rayleigh fading is frequently seen in crowded urban settings. Rician fading, on the other hand, happens in situations when there is a strong LOS component in addition to multipath signals, like in rural or suburban settings [6]. Both models are frequently used to assess modulation and coding strategies and are used as standard fading channel assumptions in simulations.

Because of its spectrum efficiency and noise resistance, quadrature phase shift keying (QPSK) is a favored modulation system in wireless communication and is appropriate for applications requiring low to moderate data rates. QPSK can further benefit from improved error performance when paired with diversity approaches, particularly in situations with multipath fading [7]. Knowing how QPSK behaves in combination with diversity reception is crucial as wireless systems develop to accommodate increased mobility and user density. Multiple antennas (spatial diversity), frequency diversity, or time diversity can all be used to implement diversity reception. The most extensively used and efficient of these in base stations and mobile devices is spatial diversity with several receive antennas. The combination of signals from several uncorrelated branches increases the probability of accurate signal identification, which is the specific emphasis of our study on receiver diversity. Although it is computationally demanding, MRC provides the best theoretical performance. Despite being less complicated, SC and EGC are not ideal, but they might be better in systems with limited resources [8].

This paper focuses on evaluating the performance of MRC, SC, and EGC diversity combining techniques for QPSK-modulated signals under uncorrelated Rayleigh and Rician fading channels. Through MATLAB-based simulation, the BER performance of each method is analyzed and compared across various SNR levels. The goal is to highlight the trade-offs between performance and computational complexity in practical wireless systems.

Research Background: The dynamic and unpredictable character of wireless channels has a significant impact on the dependability of wireless communication systems. Multipath fading, which causes phase distortion and variations in signal amplitude, is one of the most serious impairments. Across multiple wireless network generations, from 2G to 5G and beyond, diversity combining techniques have been thoroughly researched and used to counteract such degradations.

Combining several independently faded signal replicas greatly enhances detection performance, according to early diversity reception study. By weighting and summing signal branches according to their channel quality, Maximal Ratio Combining (MRC), which was first proposed as an ideal linear diversity strategy, guarantees the best Signal-to-Noise Ratio (SNR) [9]. However, at the expense of performance, Equal Gain Combining (EGC), which combines signals with equal amplitude and phase alignment, and Selection Combining (SC), which selects the signal path with the highest SNR, provide simpler solutions with less computing complexity [10].

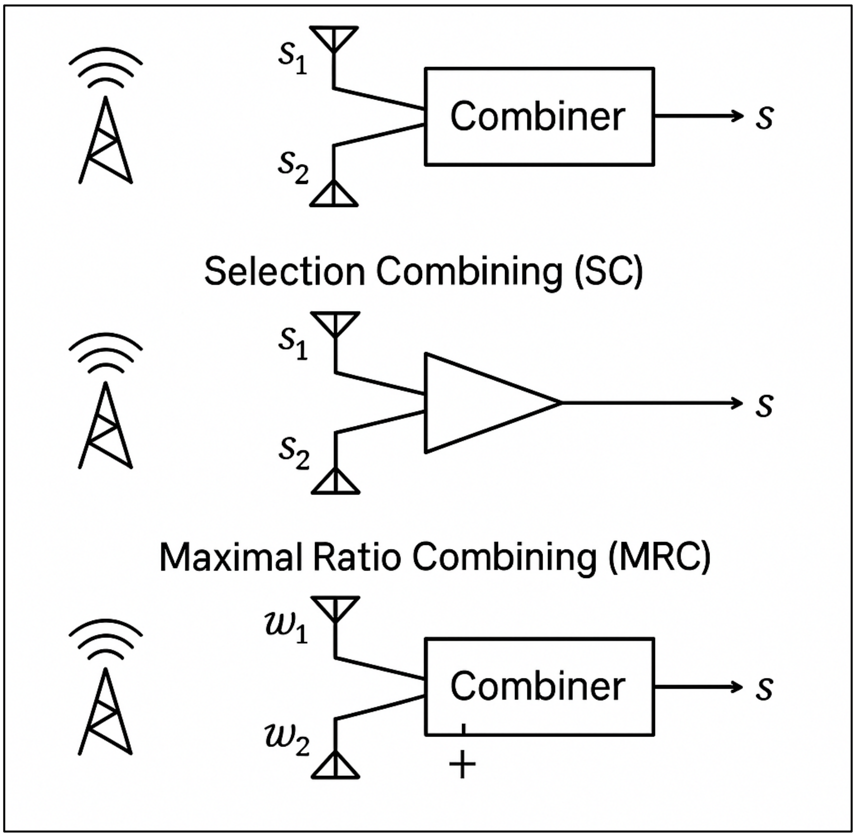

Figure 1: Diversity combining methods: EGC, SC and MRC

Well-known statistical models for simulating actual propagation situations are Rayleigh and Rician fading. Rayleigh fading models settings with high levels of scattering by assuming that there is no line-of-sight (LOS) component. Rician fading, on the other hand, includes a dominating LOS path, denoted by the K-factor, which measures the power ratio of the dispersed and direct components [11]. Stronger LOS presence is indicated by a greater K-factor, which enhances wireless link performance [12].

Because of its durability and bandwidth economy, QPSK modulation has also been investigated for use in fading settings. As a constant-envelope modulation method, QPSK is especially well-suited for non-linear power-limited devices like satellite transceivers and cell phones [13]. System designers are quite interested in how it behaves in multipath fading contexts under diversity combining techniques. The advantage of MRC in both Rayleigh and Rician scenarios was validated by simulation studies such as those conducted by E. Zvanovec and P. Pechac [14], which used MATLAB to assess the BER performance of QPSK over fading channels. However, more comparison analyses using EGC are yet largely unexplored, especially for moderate SNR regimes and uncorrelated branch situations.

SIMULATION SETUP

To evaluate the performance of diversity combining techniques—Maximal Ratio Combining (MRC), Selection Combining (SC), and Equal Gain Combining (EGC)—under uncorrelated Rayleigh and Rician fading channels, a simulation-based approach is employed using QPSK modulation. The setup involves generating a wireless communication system model, applying different channel models, implementing the diversity combining techniques, and computing the Bit Error Rate (BER) for performance comparison.

1. **The System Model:** To simulate the wireless communication system and accurately analyze the effects of diversity combining methods (MRC, SC, EGC) on QPSK signals in fading environments, the following system model is defined:

   1.1 Transmitter: Data generation: Generate a random binary sequence of size N. Modulation: Use Quadrature Phase Shift Keying (QPSK). Group input bits into pairs and map each pair to a QPSK symbol using gray coding. The QPSK symbols are normalized to have unit average power.

1.2 Wireless Channel: The wireless channel is modeled as flat fading and uncorrelated across multiple receive branches. Rayleigh Fading Channel: Applicable when there is no line-of-sight (NLOS). Channel coefficients hi are modeled as independent complex Gaussian variables. Each diversity branch experiences independent fading. Rician Fading Channel: Models scenarios with a dominant LOS path. Additive White Gaussian Noise (AWGN): Complex Gaussian noise n is added to the faded signal at each branch.

1.3 Receiver Diversity Model: Receive Antennas: L (e.g., 2 or 4) uncorrelated branches. Signal at receiver i at i-th branch. Combining methods (MRC, SC, EGC) will be applied to ri for demodulation.

This system model enables BER simulation over a wide SNR range, incorporating realistic channel fading and diversity effects. It supports robust performance comparison for diversity schemes across both Rayleigh and Rician fading environments.

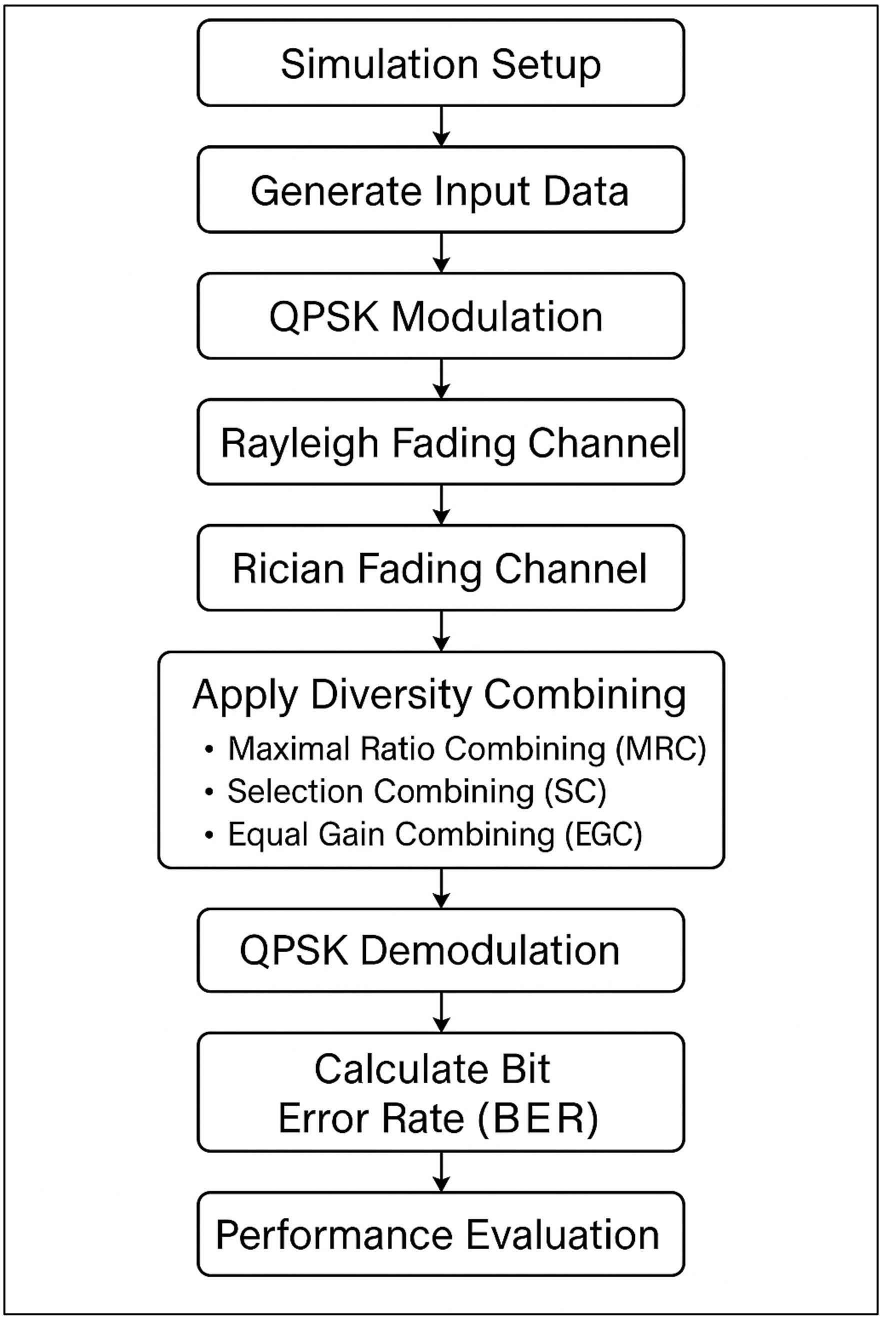

Figure 2: Proposed Method of Evaluation

2. **Channel Models: Fading Environments:** Fading is a crucial characteristic of wireless channels caused by multipath propagation and Doppler shifts. To evaluate the robustness of diversity combining techniques, we simulate two statistically distinct and widely accepted fading models: Rayleigh and Rician. These represent non-line-of-sight (NLOS) and line-of-sight (LOS) wireless environments respectively.

   2.1 Rayleigh Fading Channel: Occurs when there is no direct line-of-sight (NLOS) between transmitter and receiver. Multipath Scenario: The received signal is the sum of many scattered paths with randomly varying amplitudes and phases.

   2.2 Rician Fading Channel: Occurs when a strong LOS component is present along with multiple scattered components. Multipath Scenario: The received signal is a combination of a deterministic LOS path and several random scattered paths. Strong LOS component with scattered paths.

   2.3 Channel Properties in Simulation: Uncorrelated Fading: Each receive branch experiences independent fading realization. Slow Flat Fading Assumption: The fading is constant over a symbol period but may change between symbols. The channel is frequency non-selective (i.e., flat) since the bandwidth of the signal is much smaller than the channel coherence bandwidth.

Table1: Significant Differences

Parameter	Rayleigh Fading	Rician Fading
LOS Path	Absent	Present
K-Factor	0 (purely scattered)	K>0K > 0
Environment	Urban, indoor, dense areas	Rural, LOS, suburban
BER Performance	Worse	Better as K increases

This channel modeling allows us to realistically evaluate how diversity combining techniques perform in both harsh (Rayleigh) and moderate (Rician) propagation conditions.

3. **Diversity Combining Techniques Implementation:**

   MRC (Maximal Ratio Combining):

   - Each branch is multiplied by the conjugate of its channel coefficient
   - Weighted sum of all branches is used for detection

   SC (Selection Combining):

   - The branch with the highest instantaneous SNR is selected
   - Only one branch is used for detection per symbol

   EGC (Equal Gain Combining):

   - All branches are co-phased (same phase) and summed with equal weights
   - All combining techniques assume perfect channel state information (CSI) at the receiver.

4. **QPSK Modulation and Demodulation**

   Quadrature Phase Shift Keying (QPSK) is a widely used digital modulation scheme in wireless communication systems due to its balance between spectral efficiency and robustness to noise and fading. It transmits 2 bits per symbol, making it more bandwidth-efficient than BPSK while maintaining relatively simple implementation.

3.1 QPSK Modulation: Input: Binary data stream, Output: Complex QPSK symbols mapped to the I-Q (in-phase and quadrature) plane.

3.2 Received Signal Model: After combining (via MRC, SC, or EGC), a single complex symbol s is obtained for detection at receiver side.

3.3 QPSK Demodulation: Input: Combined complex symbol s. Output: Recovered bit pair.

3.4 BER Calculation: Compare transmitted and received bit streams.

$$\boldsymbol{BER} = \frac{\text{Number of incorrect bits}}{\boldsymbol{Total\ Transmitted\ bits}} \quad \textbf{(1)}$$

5. Output Analysis

Performance Metric: BER vs. SNR. In digital wireless communication systems, evaluating the reliability of transmission under noise and fading conditions is essential. The Bit Error Rate (BER) as a function of Signal-to-Noise Ratio (SNR) is a fundamental performance metric used to assess the effectiveness of modulation schemes, channel models, and diversity combining techniques. The BER quantifies how often a bit is incorrectly received due to noise, fading, or other impairments in the channel. A lower BER indicates better system performance. SNR measures the strength of the signal relative to background noise. A higher SNR typically leads to lower BER. In an AWGN channel, the BER of QPSK decreases rapidly as SNR increases. In fading channels (Rayleigh/Rician): BER is higher due to multipath effects. Performance degrades significantly compared to AWGN. Diversity combining techniques improve BER by mitigating fading effects: MRC achieves steep BER drop with increasing SNR. EGC performs close to MRC. SC improves over single-antenna but performs worse than MRC and EGC. The BER vs. SNR metric provides deep insights into how modulation and diversity strategies perform in real-world fading environments. It is especially valuable for comparing the efficiency of MRC, SC, and EGC techniques under Rayleigh and Rician fading when using QPSK modulation.

There exist L diversity branches of independent Rayleigh/Ricean fading signals (L = 1, 2, 3, 4). For every branch, the average symbol energy-to-noise power ratio (Es/N0) is 1, 3, 5, 7, and 9 db. The Figure 3 below shows the BER vs. SNR curves for SC, MRC, and EGC under Rayleigh fading with varying numbers of diversity branches (L = 1, 2, 3, 4). As expected, MRC achieves the best performance, especially as L increases. SC improves with diversity but lags behind MRC. EGC performance lies between SC and MRC.

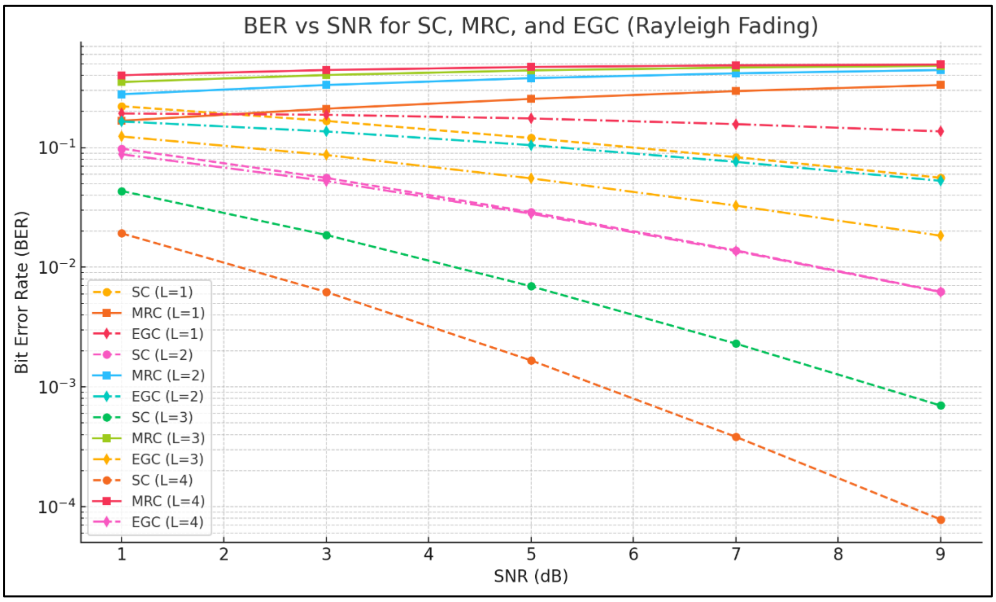

Figure 3: Rayleigh Fading

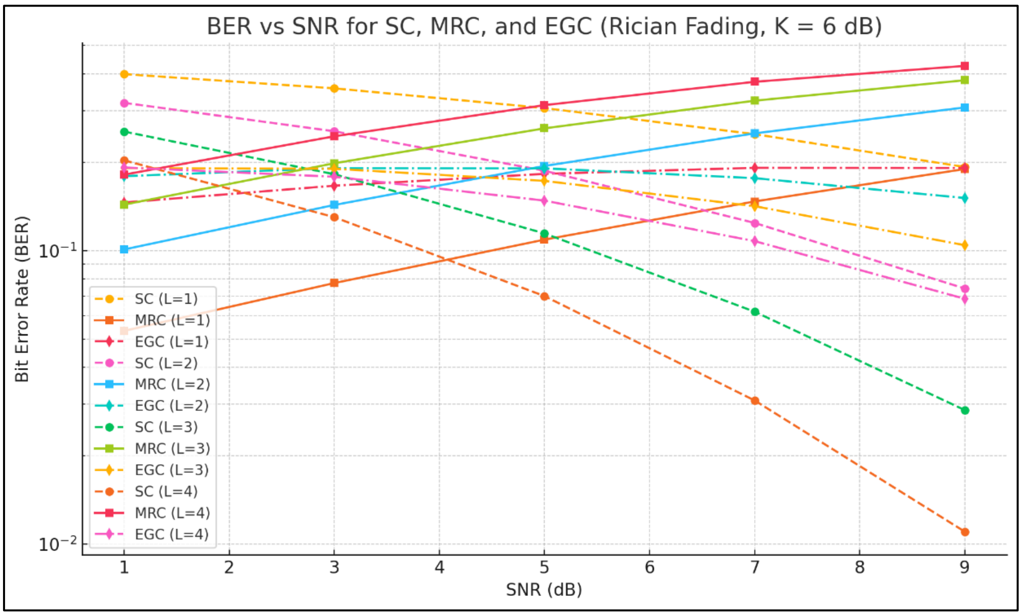

Figure 4: Rician Fading

Figure 4 shows BER vs. SNR under Rician fading (K = 6 dB) for SC, MRC, and EGC with diversity branches $\{L = 1,2,3,4\}$. MRC again outperforms other techniques, especially as L increases. SC shows performance gains with more branches but is consistently the least effective. EGC maintains a performance between SC and MRC. Compared to Rayleigh fading, Rician fading yields better BER due to the presence of a dominant LOS component, especially at higher SNR.

CONCLUSION

This study evaluated the performance of three diversity combining techniques Maximal Ratio Combining (MRC), Selection Combining (SC), and Equal Gain Combining (EGC) in the context of QPSK modulation over uncorrelated Rayleigh and Rician fading channels. MRC consistently outperforms SC and EGC in both Rayleigh and Rician fading environments. It provides the lowest BER due to its optimal weighting of received signal components based on channel conditions. EGC offers a favorable trade-off, delivering performance close to MRC while requiring less channel state information and computational complexity. SC, while the simplest to implement, exhibits the highest BER among the three, though it still benefits from increased diversity order. In Rician fading channels, the presence of a line-of-sight component improves the overall BER for all techniques compared to Rayleigh fading, especially as the Rician K-factor increases. In conclusion, MRC is the preferred technique for systems where complexity and channel estimation are manageable, while EGC serves as a viable alternative for moderate-complexity receivers. SC remains suitable for resource-constrained scenarios. These findings are critical for the design and optimization of reliable receivers in modern wireless systems such as LTE, 5G, and beyond.

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