Simulation and Evaluation of Adaptive Modulation under Varying Wireless Channel Conditions

IE2084 - Communication Technologies

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Abstract

Adaptive modulation dynamically selects the best digital modulation scheme according to real-time channel conditions, maximizing spectral efficiency and minimizing bit errors. In this report, we simulate an adaptive modulation system using BPSK, QPSK, and 16QAM schemes over AWGN, Rayleigh, and Rician channels. The system uses SNR and BER as adaptation criteria, switching modulation to maintain a target BER of 10^{-3}. Results reveal significant gains in spectral efficiency and reliability, particularly in highly variable wireless scenarios. All results are supported by Matlab simulations and constellation, BER, and spectral efficiency plots.

Contents

1. Introduction

Next-generation wireless systems demand high data rates and reliable communication, especially in environments subject to fading and interference. Fixed modulation schemes either waste spectral resources in good conditions or suffer high error rates in poor channels. Adaptive modulation offers a solution by enabling smart switching among available schemes, optimally balancing spectral efficiency and error robustness. This is foundational for modern SDRs and smart networks where channel conditions rapidly change due to mobility or interference.

2. Objectives

This project aims to evaluate adaptive modulation under wireless channel conditions. The main objectives are:

- Simulate adaptive modulation and fixed schemes.
- Model AWGN, Rayleigh, and Rician channels.
- Compare BER and spectral efficiency across all schemes.
- Analyze performance using MATLAB results.

3. Theoretical Background

3.1 Digital Modulation Schemes

- **BPSK (Binary Phase Shift Keying):** 1 bit/symbol, robust to noise but spectrally inefficient.
- **QPSK (Quadrature Phase Shift Keying):** 2 bits/symbol, a compromise of efficiency and robustness.
- **16QAM (16-level Quadrature Amplitude Modulation):** 4 bits/symbol, offers high spectral efficiency but is sensitive to channel impairments.

3.2 Channel Models

- **AWGN (Additive White Gaussian Noise):** Models random noise with normally distributed amplitude, basic for analysis.
- **Rayleigh Fading:** Characterizes environments with multipath and no dominant line-of-sight, leading to rapid amplitude variations.
- **Rician Fading:** Similar to Rayleigh but includes a dominant path, typical in urban environments.

3.3 Spectral Efficiency and BER

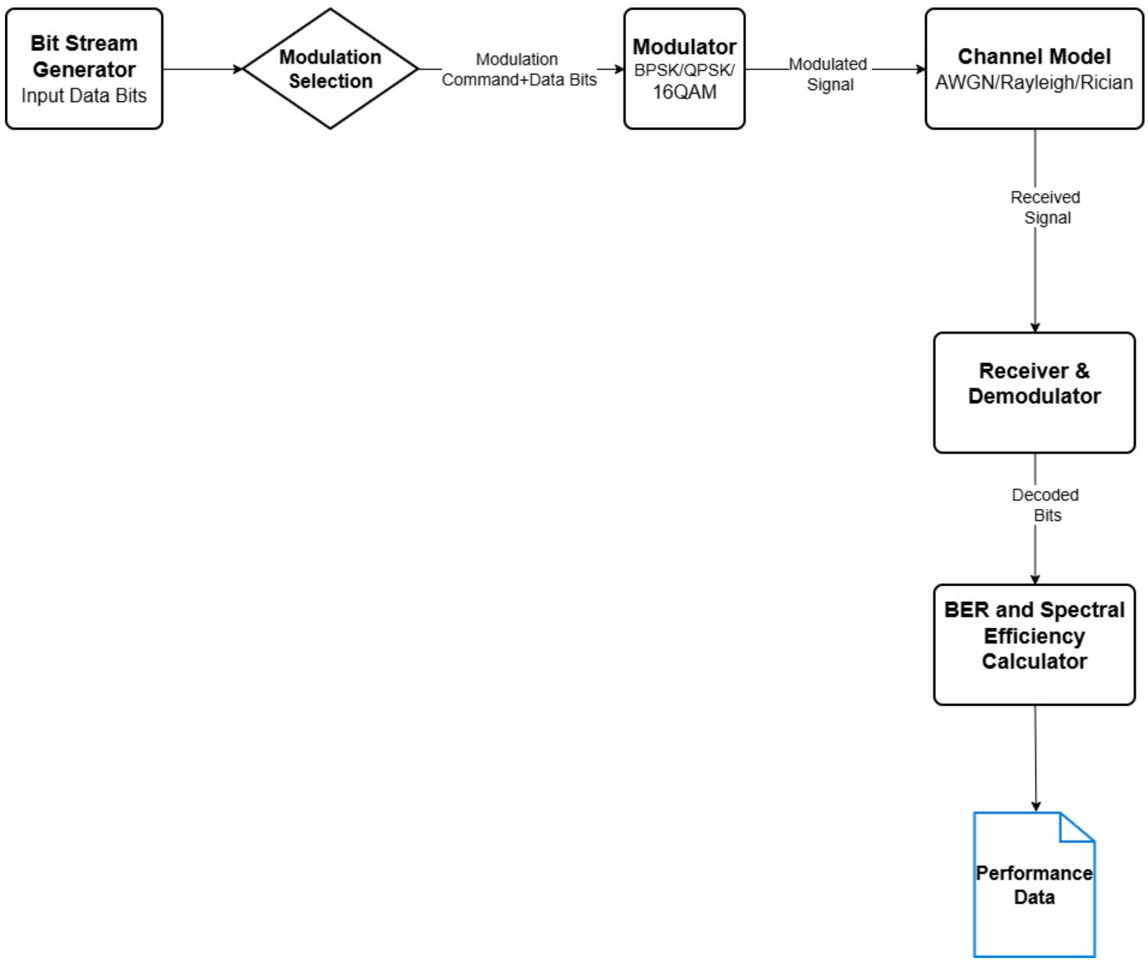
- **Spectral Efficiency:** $SE = (\text{bits per symbol}) \times (1 - BER)$; higher modulation increases SE under high SNR.
- **Bit Error Rate (BER):** Probability that a bit is incorrectly received; decreases with SNR and lower modulation order.

3.4 Adaptive Modulation

- The principle: Select the highest-order modulation that keeps BER $\leq$target. If SNR is low, stay with robust schemes (BPSK/QPSK); for high SNR, shift to 16QAM for maximum throughput.
- **Adaptation strategy:** At each SNR, estimate BER for each scheme and select the highest order that satisfies the constraint.

4. System Design

4.1 Block Diagram



The simulation framework is organized into three main functional components, each representing a key stage in evaluating and adapting the modulation performance under varying channel and noise conditions.

4.2 Fixed Modulation Evaluation under a Single Channel Type

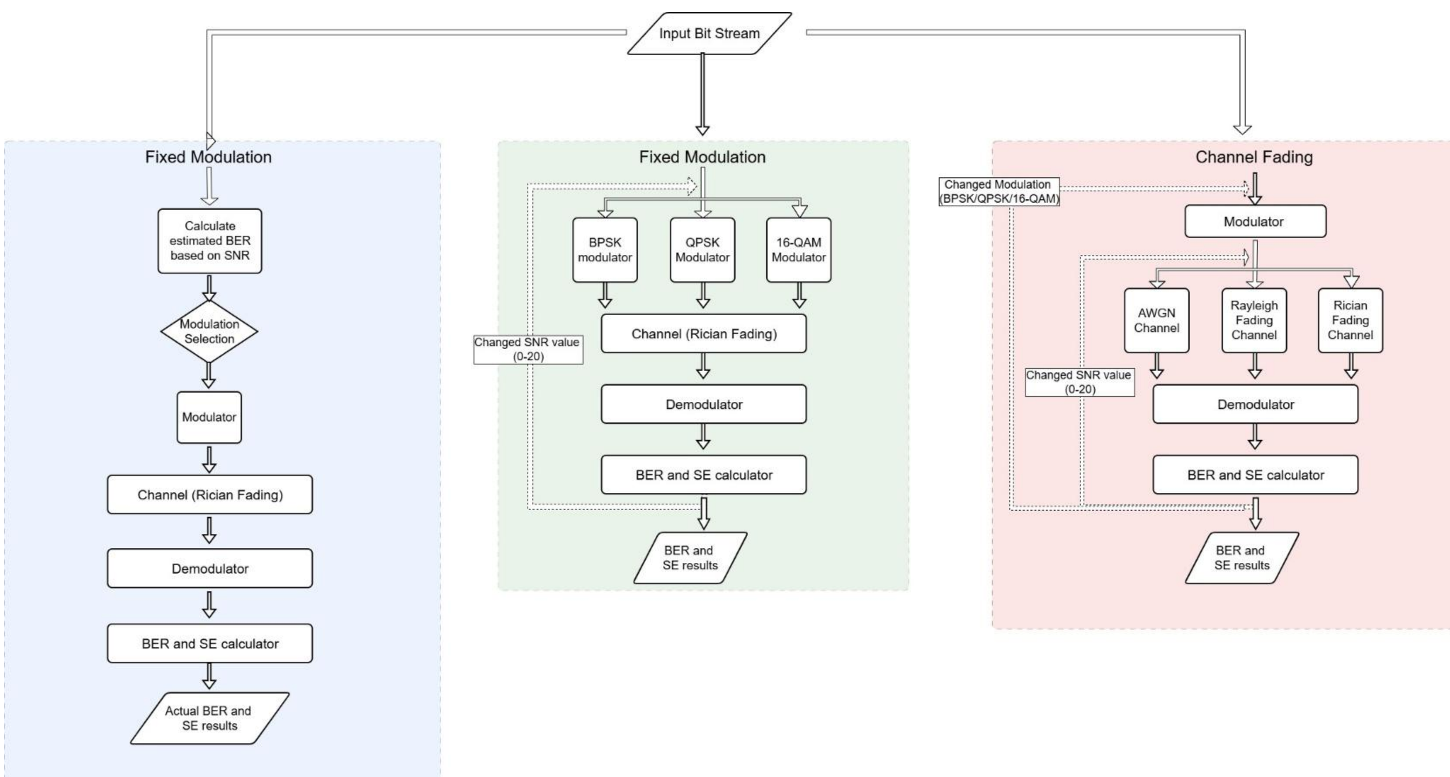
In the first stage, the input bit stream is transmitted using multiple modulation schemes—BPSK, QPSK, and 16QAM—across a range of SNR values while keeping the channel type fixed (e.g., Rician fading). For each SNR point, the system modulates, transmits, and demodulates the signal, calculating the corresponding bit error rate (BER). This allows direct comparison of the performance of different modulation schemes under identical channel conditions and varying noise levels.

4.3 Adaptive Modulation Based on Theoretical BER Estimation

The second stage implements an adaptive modulation mechanism that uses theoretical BER expressions to determine the most suitable modulation scheme for a given SNR value. For each SNR, the expected BER of BPSK, QPSK, and 16QAM is estimated analytically. The system then selects the highest-order modulation that satisfies a predefined target BER (e.g., 10^{-3}). Once selected, that modulation scheme is used to transmit data through the Rician fading channel. Although this adaptation is not performed dynamically during runtime, it effectively simulates how real-world systems adjust their modulation levels according to channel quality.

4.4 Comprehensive Evaluation across Multiple Channel Models

In the final stage, the system performs a full comparison by looping through all modulation schemes and all channel types (AWGN, Rayleigh, and Rician) over the same range of SNR values. This produces a complete set of BER curves, allowing analysis of how each modulation scheme behaves under different propagation environments. The results demonstrate how fading conditions influence communication reliability and the effectiveness of adaptive modulation strategies.



5. Simulation Setup

Parameters:

- Bits per frame: 10^6
- SNR Range: 0–20 dB (0:2:20)
- Channel Models: AWGN, Rayleigh ($K = 0$), Rician ($K = 5$)
- Frames per SNR: 50
- Modulation: BPSK (1), QPSK (2), 16QAM (4 bits/symbol)
- Target BER: 10^{-3}

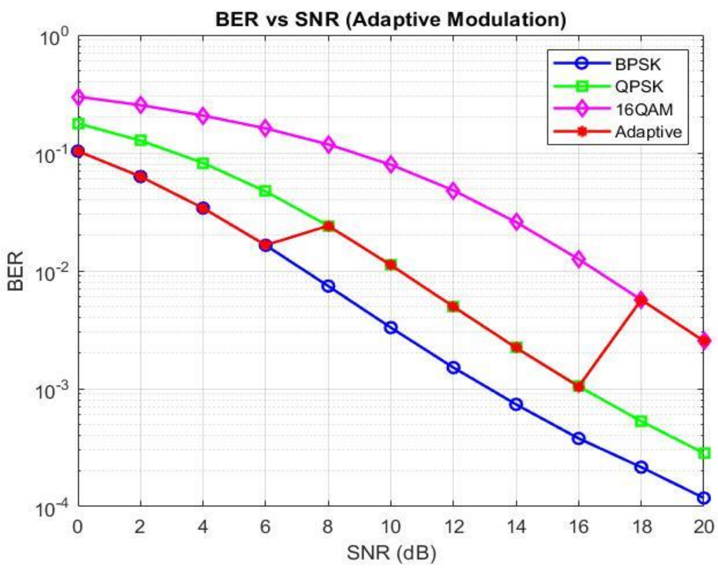
Key Functions:

Function / Process	Type	Purpose in Simulation
modulate_bits(bits, scheme)	User-defined	Converts input binary bits into complex symbols according to the selected modulation scheme (BPSK, QPSK, or 16QAM).
channel_model(symbols, SNRdB, channelType, ricianK)	User-defined	Applies channel effects such as AWGN, Rayleigh, or Rician fading to emulate realistic wireless transmission conditions.
demodulate_symbols(symbols, scheme)	User-defined	Recovers the transmitted bits from received noisy or faded symbols for BER computation.
Error counting and BER calculation (sum(bits ~= rxBits))	Built-in operation	Compares transmitted and received bits to determine the Bit Error Rate (BER).
Spectral Efficiency calculation (k * (1 - BER))	Built-in operation	Computes the effective spectral efficiency for each modulation scheme based on BER results.
Adaptive modulation logic	User-defined	Selects the optimal modulation scheme for each SNR value based on theoretical BER thresholds to maintain a target error rate.
randi()	Built-in	Generates random bit sequences for simulation input.
randn()	Built-in	Produces Gaussian random variables used for noise and fading signal components.
sqrt(), abs(), mean(), sum()	Built-in	Used in SNR conversion, normalization, signal power, and error accumulation calculations.

qfunc(), erfc()	Built-in	Computes theoretical BER values for different modulation schemes (BPSK, QPSK, and 16QAM).
10^(x/10)	Built-in	Converts SNR from decibel (dB) scale to linear scale for power-based calculations.
strcmpi(), lower()	Built-in	Ensures case-insensitive selection and handling of user-specified channel types.

6. Results and Analytics

6.1 BER vs SNR (Adaptive Modulation)

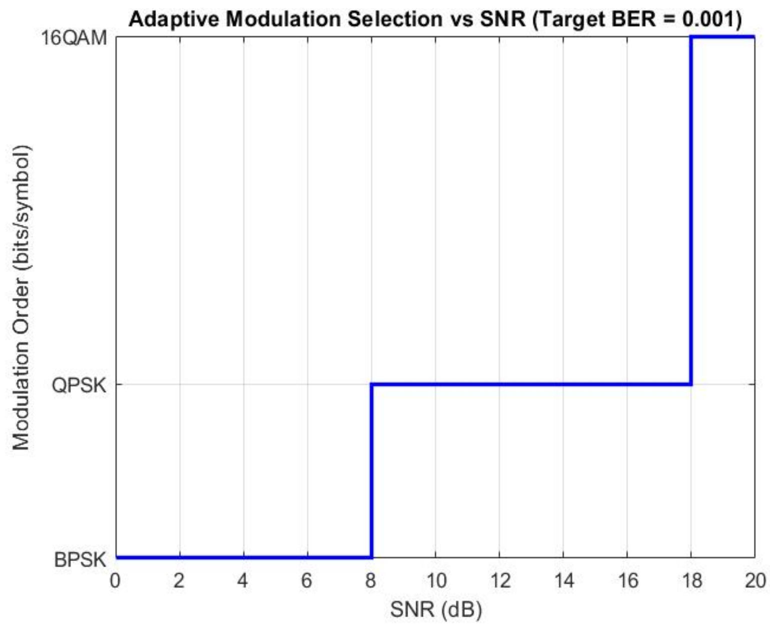


- **BPSK:** Consistently provides the lowest BER across the SNR range, demonstrating excellent error resilience, especially at low SNR values. However, this comes at the cost of lower spectral efficiency.
- **QPSK:** Outperforms 16QAM at low to medium SNR values by achieving lower BER, though it does not reach the extremely low error rates of BPSK as SNR increases.
- **16QAM:** Exhibits the highest BER at all SNR values, especially pronounced at low SNRs, reflecting its vulnerability to noise and interference due to the denser constellation.

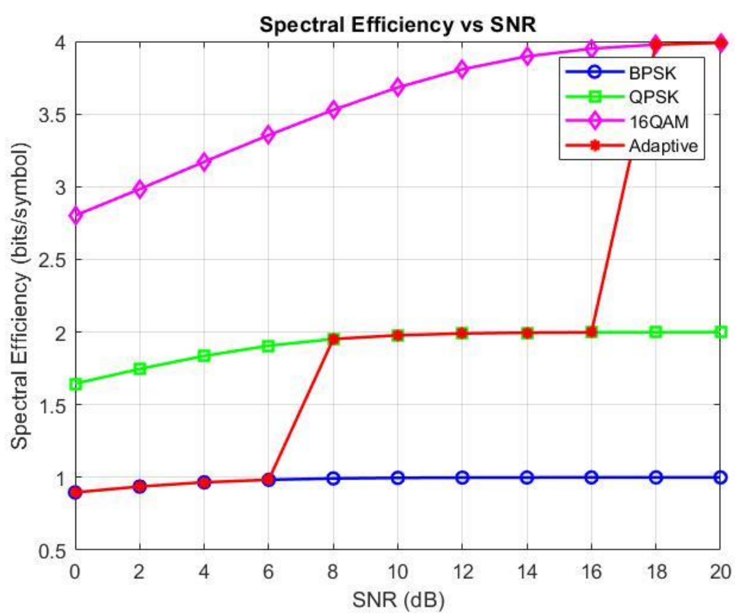
- **Adaptive Modulation:** Follows the lowest BER among the fixed schemes for each SNR region—initially overlapping with BPSK at low SNR, then QPSK at medium SNR, and switching towards 16QAM at higher SNR values where increased data rates are feasible. Notably, there is a noticeable increase in BER at very high SNR, likely due to a suboptimal switching threshold or sudden adaptivity to 16QAM.

6.2 Adaptive Modulation Selection vs SNR

- Modulation follows thresholds: starts with BPSK, switches to QPSK at ~8 dB, 16QAM at ~18 dB.
- Matches theory: use lowest order modulation that maintains target BER, maximizing spectral efficiency.



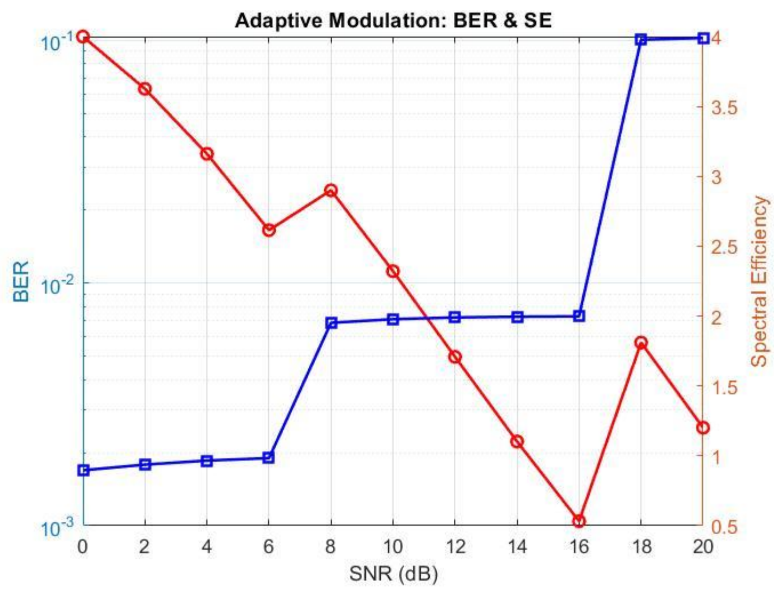
6.3 Spectral Efficiency vs SNR



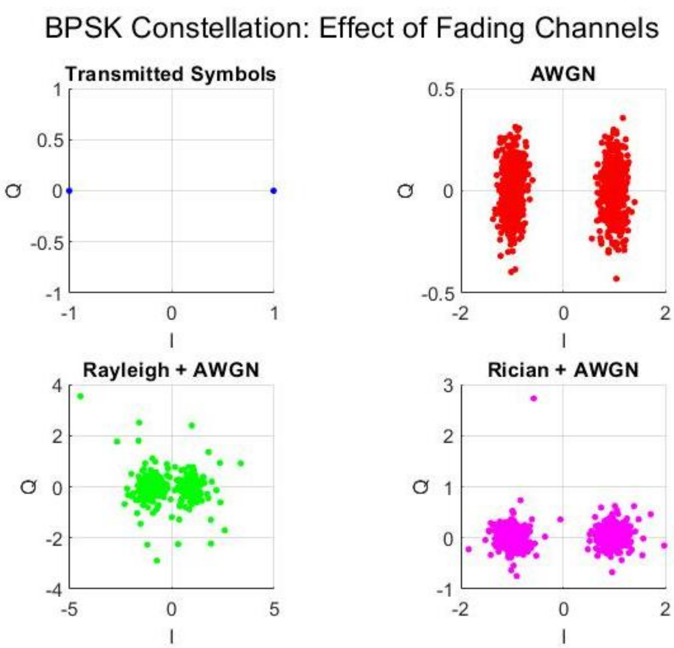
- BPSK and QPSK plateau at ~1 and ~2 bits/symbol, respectively.
- 16QAM increases with SNR, nearing 4 bits/symbol.
- Adaptive modulation matches BPSK/QPSK at low SNR; jumps to higher order at SNR thresholds, maximizing efficiency at every SNR while maintaining target BER.

6.4 Adaptive Modulation: BER & Spectral Efficiency

- BER decreases with increasing SNR.
- Spectral efficiency increases in steps as modulation switches.
- At SNR ≈ 8 dB, scheme changes from QPSK to 16QAM for maximum efficiency with low BER.
- At SNR ≈ 18 dB, 16QAM dominates.

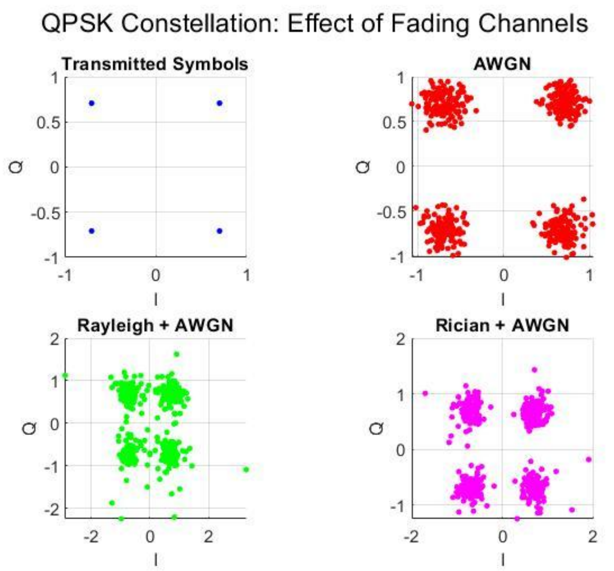


6.5 BPSK Constellation: Effect of Fading Channels



- Transmitted: Two points (highest robustness).
- AWGN: spread along real axis, but still distinguishable.
- Rayleigh and Rician: spreading increases, but bit separation remains clear.

6.6 QPSK Constellation: Effect of Fading Channels



•Transmitted symbols: 4 distinct points.

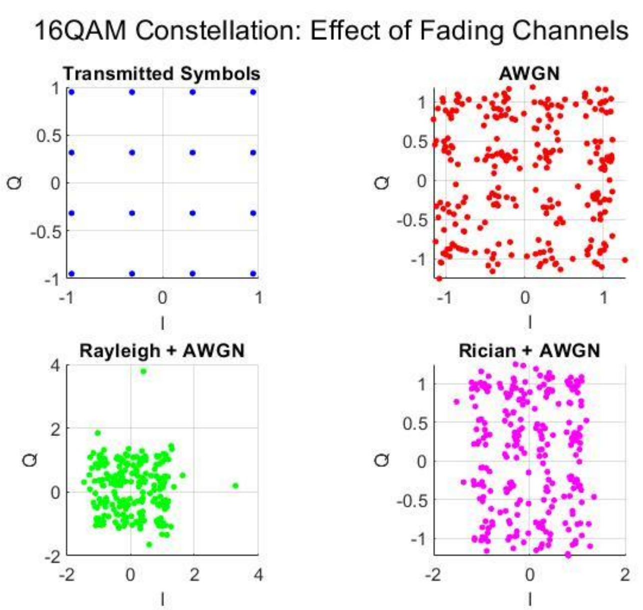
•AWGN only: tight clusters, small noise corruption.

•Rayleigh + AWGN: clusters spread, more symbol overlap, fading impacts.

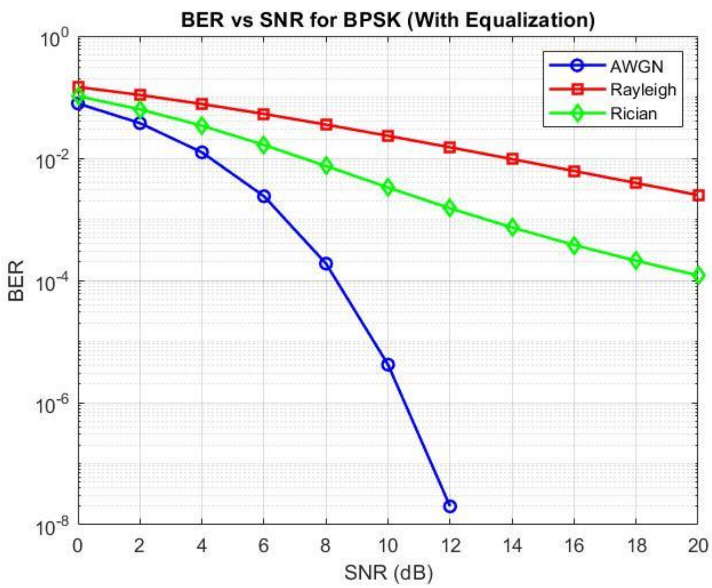
•Rician + AWGN: clusters somewhat more concentrated than Rayleigh.

6.7 16QAM Constellation: Effect of Fading Channels

- Transmitted: 16 distinct grid points.
- AWGN: visible clusters with noise spread.
- Rayleigh/Rician: severe spreading and overlap, lower reliability at low SNRs.



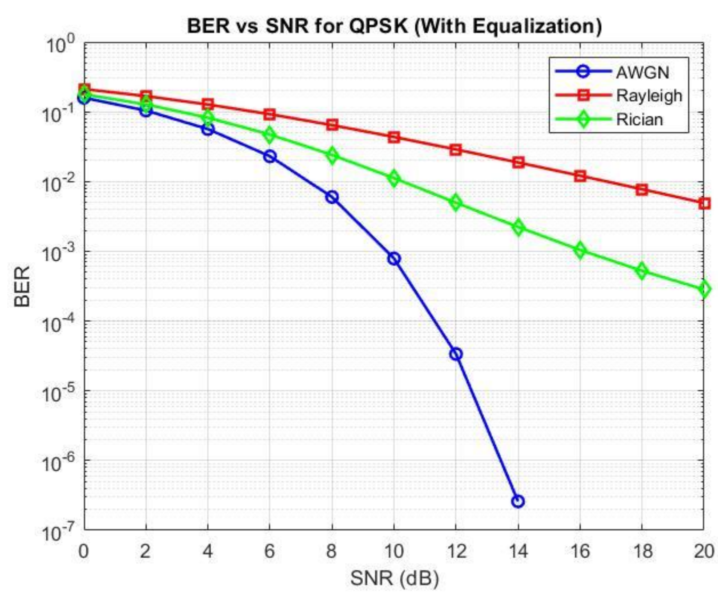
6.8 BER vs. SNR for BPSK



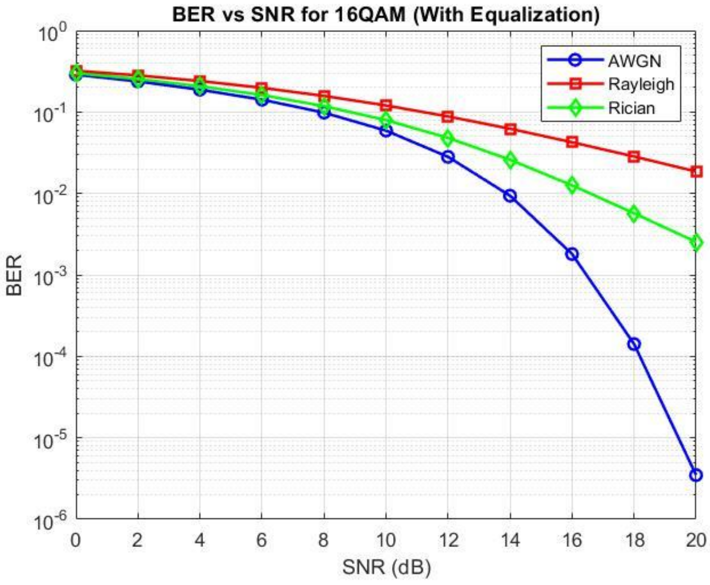
- **AWGN Channel:** The BER drops very sharply as SNR increases. At SNRs above 8 dB, the BER approaches negligible values (10^{-6} and below), showing excellent robustness against noise.
- **Rayleigh Channel:** Although BER reduces with increasing SNR, performance is much worse than AWGN. Error rates remain relatively high even at 20 dB SNR due to severe fading effects.
- **Rician Channel:** BER performance sits between AWGN and Rayleigh. The presence of a strong line-of-sight component (Rician $K > 0$) enhances reliability compared to Rayleigh, but BER is still noticeably higher than AWGN at practical SNRs.

6.9 BER vs. SNR for QPSK

- **AWGN Channel:** BER decreases exponentially with increasing SNR, reaching very low values (below 10^{-6}) from about 12 dB onwards.
- **Rayleigh Channel:** QPSK suffers significant performance loss in Rayleigh fading. BER remains above the target (10^{-3}), even at higher SNR values, due to multipath interference.
- **Rician Channel:** BER improves over Rayleigh but does not match AWGN performance. QPSK benefits from the stronger line-of-sight path in Rician fading, reducing errors versus Rayleigh.



6.10 BER vs. SNR for 16-QAM



- **AWGN Channel:** BER decreases steadily with SNR, but at a slower rate compared to BPSK/QPSK. At SNRs above 18 dB, BER drops below 10^{-5} but remains higher than BPSK/QPSK for the same SNR.
- **Rayleigh Channel:** BER improves as SNR increases but stays significantly above the target, highlighting 16QAM's vulnerability to fading. High error rates persist throughout the SNR range due to constellation overlap and amplitude variations.
- **Rician Channel:** 16QAM performance is better than Rayleigh owing to the dominant signal path, but BER still remains much higher than AWGN, requiring higher SNR to reach acceptable reliability.

7. Conclusion and Future Work

The simulation and evaluation of adaptive modulation under varying wireless channel conditions demonstrate its clear advantages over fixed modulation schemes. By dynamically adjusting the modulation order based on real-time SNR and BER criteria, adaptive modulation consistently maintains reliable communication and optimal spectral efficiency, even in challenging fading environments like Rayleigh and Rician channels. Results validate that adaptive modulation allows systems to exploit higher-order, bandwidth-efficient schemes when channel quality permits, and to fall back to more robust lower-order schemes as conditions deteriorate. This strategy maximizes throughput while ensuring error rates remain within acceptable limits, making it highly relevant for next-generation mobile and software-defined radio (SDR) systems.

Future Work:

Advancing this research further, future efforts could:

- Incorporate machine learning techniques for predictive adaptation to anticipate channel conditions.
- Evaluate the performance using even higher-order modulation schemes and wider SNR ranges.
- Integrate adaptive modulation into real-time feedback systems with dynamic pilot signaling for practical deployments.

Overall, adaptive modulation is foundational for modern wireless networks striving for high reliability and efficiency, especially in diverse and rapidly changing environments.