الجمـــهورية الجزائرية الديمــقراطية الشعــبية
REPUBLIQUE ALGERIENNE DEMOCRATIQUE ET POPULAIRE
وزارة التعـلـيـم الـعـالــي والـبـحـث الـعـلـمي
MINISTERE DE L'ENSEIGNEMENT SUPERIEUR ET DE LA RECHERCHE SCIENTIFIQUE
جـامـعـة عمّـــار ثـلـيـــجــي بالاغـــــــــــواط
UNIVERSITE AMAR TELIDJI LAGHOUAT
كـلـيــــة التكنولوجـــــــــــــــــا
FACULTE DE TECHNOLOGIE
قســم الالكترونيك
DEPARTEMENT D'ELECTRONIQUE

Mémoire de Master

Domaine : Technologie

Filière : Télécommunication

Option : Réseaux et télécommunications

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THEME

Error Performance Analysis of Trellis Coded Modulation (TCM) in Various Wireless Channel Conditions

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Année Universitaire 2024/2025

بسم الله الرحمن الرحيم

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إهداء

بسم الله الرحمن الرحيم
والصلاة والسلام على أشرف المرسلين سيدنا محمد الأمين، وعلى آله وصحبه أجمعين إلى يوم الدين.

إن أصبنا فمن الله، وإن أخطأنا فمن أنفسنا.

أهدي هذا العمل أولاً وقبل كل شيء إلى نفسي — لكل لحظة من الإصرار، ولكل ليلة بلا نوم، ولكل خطوة تقدّمت بها رغم التحديات. هذا الإنجاز هو دليل على قوتي وعزيمتي.

إلى والدي الغالي صف الدين — لقد كانت حكمتك، وصبرك، وإيمانك الثابت بي، أعمدة لقوتي. علّمتني قيمة العمل الجاد، والاستقامة، والصبر. تضحياتك الصامتة وحضورك الثابت شكّلا جزءًا كبيرًا من شخصيتي اليوم.

وإلى أمي الحبيبة فاطنة — محبتك غير المشروطة، ودعواتك المستمرة، وروحك الحنونة كانت أعظم نعمة في حياتي. أنتِ قلب عائلتنا، والنور الذي أضاء دربي في كل لحظة صعبة. شكرًا لأنكِ كنتِ دائمًا ملجئي، ومصدر راحتي، ودافعي الأول.

إلى أخواتي العزيزات: مروى، آمال، دنيا، إيمان، سعاد، أميرة — كل واحدة منكنّ تُضيء حياتي بطريقتها الخاصة. شكرًا على دعمكن، وضحكتكن، وعلى تذكيركن الدائم لي بأنني لست وحدي.

وإلى ابن أختي الغالي زكريا، لقد كانت ابتسامتك البريئة تبعث السكينة في قلبي في أكثر الأوقات توتراً.

وإلى صديقاتي العزيزات: رانية، آية، زينب،فادية، وهيبة، وخديجة — شكراً على وجودكن، دعمكن، وصداقتكن طوال هذه الرحلة.

من أعماق قلبي، أهدي هذا الإنجاز إليكم جميعاً.

"وراء كل إنجاز عظيم، رحلة من الشجاعة، والحب، والدعم الثابت".

ACKNOWLEDGMENT

I am profoundly grateful to Allah the Almighty, who granted me health, strength, patience, and willpower throughout the journey of completing this thesis. His blessings and guidance have been the cornerstone of my perseverance and success.

I would like to express my deepest gratitude to my supervisor, **Mr. Mourad Reggab**, for his invaluable guidance, support, and encouragement throughout the completion of this work.

I also extend my sincere thanks to **Mrs. Makhtaria Messeri**, president of the defense committee, for her valuable time, insightful remarks, and for honoring me by leading the evaluation of this thesis.

My sincere thanks also go to **Mr. Safouane Chelali**, examiner, for his constructive comments, availability, and his contribution to improving the quality of this work.

I would also like to sincerely thank all the professors who supported and accompanied me during my academic journey, especially the honorable **Mr. Ramdhani Saâdi,** whose dedication and kindness had a profound impact on me.

I am equally grateful to all my professors and the teachers who contributed to my education and training.

Finally, I would like to express my heartfelt gratitude to my family and friends, whose unwavering support and encouragement have accompanied me throughout my studies.

To anyone I may have unintentionally forgotten, and who participated in any way in the preparation of this work, please accept my sincere thanks and appreciation.

Abstract:

Reliable data transmission is a fundamental challenge in modern wireless communication systems, especially under adverse channel conditions such as noise and fading. Among various techniques developed to address this issue, Trellis Coded Modulation (TCM) stands out as an efficient approach that combines coding and modulation to enhance error performance without increasing bandwidth. This study explores the principle of TCM, its technical implementation, and its effectiveness across different wireless channel models.
Trellis Coded Modulation (TCM) is a technique that enhances the reliability of data transmission by combining convolutional coding with modulation, without increasing the required bandwidth. By introducing redundancy and exploiting the structured transitions of a trellis diagram, TCM improves error correction capability, making it particularly effective in challenging wireless environments.

Simulation studies reveal that TCM significantly reduces the Bit Error Rate (BER), especially in fading channels. The best performance is observed in AWGN channels, while in Rayleigh and Rician fading environments, TCM offers substantial robustness compared to uncoded systems.

The TCM system integrates **convolutional coding**, which introduces controlled redundancy to aid error correction, and a **Viterbi decoder**, which efficiently estimates the most probable transmitted sequence by navigating the trellis structure. Two modulation schemes are utilized:

- **8-PSK**, used for uncoded reference scenarios.
- **16-QAM**, a higher-order modulation offering higher spectral efficiency but increased noise sensitivity, mitigated by TCM.

Three wireless channel models are considered:

- **AWGN (Additive White Gaussian Noise)**: A baseline channel introducing random noise.
- **Rayleigh Fading**: Models severe multipath conditions with no line of sight.
- **Rician Fading**: Represents environments with a dominant direct path alongside multipath reflections.

TCM demonstrates clear performance gains across all channel types. Its ability to reduce BER is especially noticeable in fading environments, making it a valuable solution for improving reliability in modern wireless communication systems.

Key words: Trellis Coded Modulation (TCM), Bit Error Rate (BER), AWGN, Rayleigh Fading, Rician Fading, 8-PSK, 16-QAM, Viterbi Decoder.

Résumé :

La transmission fiable des données constitue un défi majeur dans les systèmes de communication sans fil modernes, notamment face aux conditions défavorables des canaux telles que le bruit et le fading. Parmi les techniques développées pour améliorer la performance dans ces environnements, la modulation codée en treillis (TCM) se distingue comme une approche efficace combinant codage et modulation, sans augmenter la bande passante. Cette étude présente le principe de la TCM, ses détails techniques ainsi que son efficacité sur différents modèles de canaux sans fil.

La modulation codée en treillis (TCM) est une technique qui améliore la fiabilité de la transmission de données en combinant le codage convolutif avec la modulation, sans nécessiter de bande passante supplémentaire. En introduisant de la redondance et en exploitant la structure organisée du treillis, la TCM renforce les capacités de correction d'erreurs, ce qui la rend particulièrement efficace dans les environnements sans fil difficiles.

Les simulations montrent que la TCM réduit significativement le taux d'erreur binaire (BER), notamment dans les canaux soumis au fading. Les meilleures performances sont observées dans le canal AWGN, tandis que dans les environnements Rayleigh et Rician, la TCM apporte une robustesse notable par rapport aux systèmes non codés.

Le système TCM intègre :

- **Le codage convolutif**, qui ajoute de la redondance contrôlée pour faciliter la correction d'erreurs.
- **Le décodeur de Viterbi**, qui estime efficacement la séquence transmise la plus probable en explorant la structure du treillis.

Deux schémas de modulation sont utilisés :

- **8-PSK**, utilisé pour modéliser les séquences non codées.
- **16-QAM**, une modulation d'ordre supérieur offrant une meilleure efficacité spectrale, mais plus sensible au bruit, un inconvénient atténué par la TCM.

Trois modèles de canaux sans fil sont étudiés :

- **AWGN (Bruit Blanc Gaussien Additif)** : canal de référence avec bruit aléatoire.
- **Fading de Rayleigh** : modélise des conditions sévères de multi-trajets sans ligne de vue directe.
- **Fading de Rician** : représente des environnements avec un trajet direct dominant en plus des réflexions.

La TCM démontre des gains de performance clairs dans tous les types de canaux. Sa capacité à réduire le BER est particulièrement remarquable dans les environnements soumis au fading, ce qui en fait une solution précieuse pour améliorer la fiabilité des systèmes de communication sans fil modernes.

Mots clés : Modulation codée en treillis (TCM), taux d'erreur binaire (BER), AWGN, Canal Rayleigh Fading, CanalRician Fading, 8-PSK, 16-QAM, décodeur Viterbi.

الملخص:

تُعد عملية نقل البيانات بشكل موثوق تحديًا كبيرًا في أنظمة الاتصالات اللاسلكية الحديثة، خصوصًا في ظل الظروف غير المواتية للقنوات مثل الضجيج والتلاشي .(fading) ومن بين التقنيات المطورة لتحسين الأداء في مثل هذه البيئات، تبرز تقنية **المُعدّلة المشفرة بالشبكة (TCM)** كنهج فعّال يجمع بين التشفير والتعديل دون زيادة في عرض النطاق الترددي. يعرض هذا البحث مبدأ عملTCM ، وتفاصيلها التقنية، وكذلك فعاليتها عبر نماذج مختلفة من القنوات اللاسلكية.

تُعد تقنية TCM أسلوبًا يُعزّز موثوقية نقل البيانات من خلال دمج التشفير الالتفافي مع التعديل، دون الحاجة إلى عرض نطاق إضافي. ومن خلال إدخال التكرار واستغلال البنية المنظمة للشبكة، تُعزّز TCM قدرات تصحيح الأخطاء، مما يجعلها فعالة بشكل خاص في البيئات اللاسلكية الصعبة.

تُظهر المحاكاة أن TCM تُقلّل بشكل ملحوظ من معدل الخطأ في البتات(BER) ، لا سيما في القنوات التي تتعرض للتلاشي. وقد لوحظت أفضل النتائج في قناةAWGN ، بينما أظهرت البيئات التي تتضمن تلاشي Rayleigh و Ricianأن TCM تضيف صلابة واضحة مقارنة بالأنظمة غير المشفّرة.

يتكوّن نظام TCM من:

- **التشفير الالتفافي** :الذي يُضيف تكرارًا مضبوطًا لتسهيل تصحيح الأخطاء.
- **مُفكك الترميز** :**Viterbi** الذي يُقدّر بكفاءة أكثر تسلسل مرجّح للإشارة المرسلة من خلال استكشاف بنية الشبكة.

وقد تم استخدام مخططين للتعديل:

- :**8-PSK**يُستخدم لنمذجة التسلسلات غير المشفّرة.
- :**16-QAM**تعديل عالي الرتبة يوفر كفاءة طيفية أفضل، إلا أنه أكثر حساسية للضجيج، وهي نقطة ضعف تُخفف بواسطة.TCM

كما تم دراسة ثلاثة نماذج للقنوات اللاسلكية:

- **AWGNالضجيج الأبيض الغاوسي الإضافي** :قناة مرجعية بضجيج عشوائي.
- **تلاشي** :**Rayleigh** يُمثّل ظروفًا صعبة لتعدد المسارات بدون خط رؤية مباشر.
- **تلاشي** :**Rician** يُجسّد بيئات تحتوي على مسار مباشر مهيمن إلى جانب الانعكاسات.

أثبتت TCM تحقيق مكاسب أداء واضحة في جميع أنواع القنوات، وقدرتها على تقليل BER تُعد ملحوظة خاصة في البيئات المعرضة للتلاشي، مما يجعلها حلاً قيّمًا لتعزيز موثوقية أنظمة الاتصالات اللاسلكية الحديثة.

الكلمات المفتاحية :التعديل المشفّر بالشبكة(TCM) ، معدل الخطأ في البتات(BER) ، AWGN، قناة تلاشي Rayleigh، قناة تلاشيRician ، 8-PSK، 16-QAM، مفكك ترميز .Viterbi

كلمات مفتاحية:التضمين المشفر بالتعريش (TCM)، معدل خطأ البت (BER)، AWGN، قناة تلاشيRayleigh،قناة تلاشيRician،تضمين8-PSK، تضمين16-QAM ،خوارزميةViterbeلفك التشفير

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LISTE OF ABBREVIATION:

- **AWGN : Additive White Gaussian Noise**

- **ASK : amplitude-shift keying**
- **BER : Bit Error Rate**
- **BPSK : Binary phase-shift keying**
- **BFSK : Binary frequency-shift keying**
- **CLT : Central Limit Theorem**
- **DSL : digital subscriber lines**
- **DCT : Discrete Cosine Transform**
- **DPCM : Differential Pulse-Code Modulation**
- **FSK : frequency-shift keying**
- **FEC : forward error correction**

- **FDM : Frequency-Division Multiplexing**
- **ISI : Inter Symbol Interference**
- **LDPC : low-density parity-check**
- **LZW : Lempel-Ziv-Welch**
- **LOS : line-of-sight**
- **NLOS : No Dominant Line-of-Sight**
- **OFDM : Orthogonal Frequency-Division Multiplexing**
- **PDF : Probability Density Function**
- **PSK : Phase Shift Keying**
- **QAM : Qaudrature Amplitude Mudulation**
- **QPSK : Quadrature Phase-Shift Keying**
- **SQNR : Signal-to-Quantization-Noise Ratio**
- **SNR : Signal-to-Noise Ratio**
- **TCM : TrellisCoded Modulation**
- **TDM : Time-Division Multiplexing**
- **WLANs : wireless local area networks**

INTRDUCTION

General Introduction:

The evolution of communication systems, from simple human interactions to complex wireless transmissions, highlights the increasing need for reliable and efficient data transfer. In modern digital communication, particularly wireless systems, the integrity of the transmission channel is constantly threatened by various impairments such as noise, interference, fading, and multipath propagation. These challenges can severely affect the quality and reliability of transmitted data. To overcome these limitations, advanced coding and modulation techniques have been developed. Among these, Trellis Coded Modulation (TCM), introduced by Gottfried Ungerboeck in the 1980s, represents a major breakthrough. By combining convolutional coding with signal constellation mapping, TCM provides significant coding gain without increasing the bandwidth, making it a widely adopted solution in systems such as DSL, satellite communications, and WLANs.[7]
However, while TCM has demonstrated excellent performance under ideal conditions like additive white Gaussian noise (AWGN) channels, its behavior under more realistic wireless environments — characterized by fading, Doppler effects, and intersymbol interference — remains an active area of research.[8]

Wireless channels, such as Rayleigh and Rician fading models, introduce complex distortions including amplitude fluctuations and time-variant impairments that degrade system performance. In this context, a key research question arises:

How does TCM improve error performance in varied channel environments, particularly under fading and multipath conditions compared to ideal AWGN channels? Addressing this problem is essential for the development of robust, adaptive communication systems, especially for next-generation wireless networks like 5G and beyond.[2]

This dissertation aims to:

- Analyze the error performance of TCM across different wireless channel models, including AWGN, Rayleigh, and Rician channels.

- Compare the performance of TCM systems with uncoded systems in terms of Bit Error Rate (BER).
- Provide insights into the potential of TCM to enhance reliability in realistic, dynamic wireless environments.

Ultimately, the goal is to contribute to the optimization of TCM schemes for practical applications in modern and future wireless communication systems.

To achieve these objectives, the following approach is adopted:

- Theoretical Modeling: Review of TCM principles and channel characteristics.

- Numerical Simulations: Implementation of TCM systems using MATLAB, Python, or equivalent simulation tools.

- Performance Evaluation: Comparative analysis of Bit Error Rate (BER) across different channel models and system configurations.[1]

- Empirical Validation: Simulation of realistic channel impairments to assess TCM's robustness. The dissertation is organized into three main chapters:

1. Introduction to Digital Communication Systems: Overview of fundamental principles and challenges.
2. Principles of TCM and Channel Models: In-depth exploration of TCM, its technical implementation, and interaction with AWGN, Rayleigh, and Rician channels.

3. Simulation Results and Performance Analysis: Presentation and interpretation of simulation results to evaluate TCM's effectiveness under various conditions.

Finally, this projectattempts to bridge the gap between idealized studies and real-world applications, offering valuable insights into the optimization of TCM for modern wireless communication systems. By advancing the understanding of TCM's capabilities and limitations, this work aims to pave the way for more resilient and adaptive communication technologies[4]

CHAPTER 1:INTRODUCTION

TO DIGITAL

COMMUNICATION SYSTEMS

1.1 Introduction

Digital communication systems form the backbone of modern information exchange, enabling reliable and efficient transmission of data across various media. Unlike analog communication, which relies on continuous signals prone to distortion and noise, digital communication represents information in discrete form, significantly improving robustness and flexibility. This chapter provides a systematic overview of the fundamental components of digital communication systems, their functionalities, and the underlying theories that govern their operation. [8]

The chapter begins with a broad perspective on digital communication, highlighting its advantages over analog systems, such as enhanced noise immunity, error correction capabilities, and ease of encryption. Following this, the discussion delves into the core building blocks of a digital communication system, explaining each element in detail. Key topics include the conversion of analog signals to digital form through sampling and quantization, the principles of source and channel coding, modulation techniques, and synchronization methods. The chapter also explores advanced coding schemes that optimize performance in noisy environments.

1.2 Overview of Digital Communication Systems

A digital communication system is designed to transmit information from a source to a destination using discrete signals. The primary advantage of digital over analog communication lies in its ability to mitigate noise and distortion. Since digital signals are represented by binary digits (bits), they can be regenerated at intermediate points, reducing the cumulative effects of channel impairments. Additionally, digital systems support sophisticated error detection and correction mechanisms, ensuring data integrity even in adverse transmission conditions. [8]

The basic structure of a digital communication system consists of several key stages. The process begins at the source, which could be a human voice, a video feed, or a text file. If the source is analog, it undergoes digitization before transmission. The transmitter then processes the digital data, applying source coding to remove redundancy, channel coding to introduce error control redundancy, and modulation to adapt the signal for transmission over the physical medium. The channel, which may be wired (e.g., optical fiber) or wireless (e.g., radio waves), introduces noise and other impairments. At the receiver, the signal is demodulated, decoded, and reconstructed before being delivered to the destination. [8]

1.3 Key Elements of a Digital Communication System

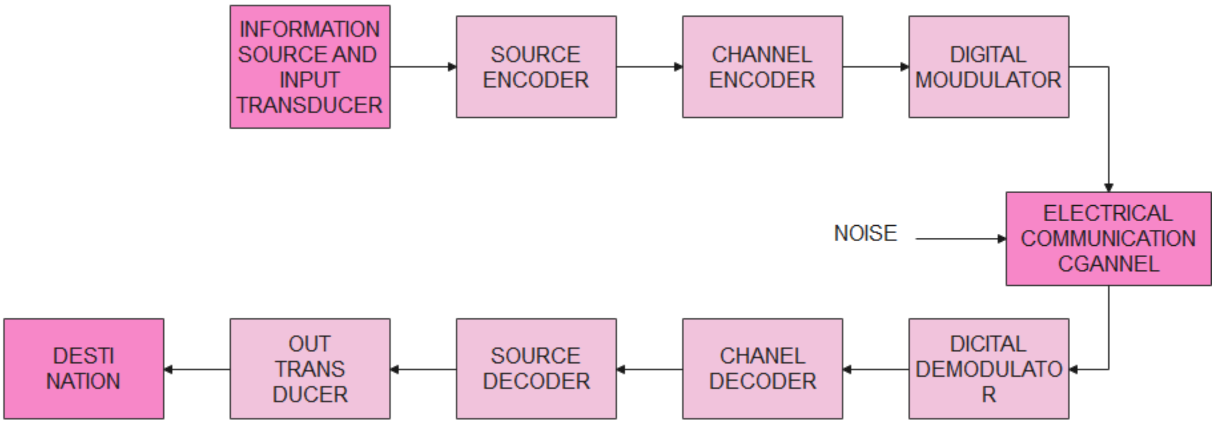

Figure 1:Basic Elements of a Digital communication system

1.3.1 Source and Input Transducer

The source generates the information to be transmitted, which can be in analog or digital form. Analog sources, such as speech or video signals, require conversion into digital format before processing. The input transducer, such as a microphone or camera, captures the analog signal and converts it into an electrical form. Digital sources, such as text files or computer data, are already in a discrete format and can be directly processed by the system. [5]

1.3.2 Source Encoder

The source encoder plays a crucial role in reducing the redundancy present in the original data, thereby improving transmission efficiency. By employing compression techniques, the source encoder minimizes the number of bits required to represent the information without significant loss of quality. Lossless compression methods, such as Huffman coding and arithmetic coding, ensure perfect reconstruction of the original data, making them suitable for text and medical imaging. Lossy compression techniques, such as those used in JPEG and MPEG standards, achieve higher compression ratios by discarding perceptually insignificant information, making them ideal for multimedia applications. [8]

1.3.3 Channel Encoder

The channel encoder introduces controlled redundancy into the data stream to facilitate error detection and correction at the receiver. This redundancy allows the system to recover the original data even if some bits are corrupted during transmission. Common channel coding techniques include block codes, such as Hamming codes and Reed-Solomon codes, which operate on fixed-length data blocks, and convolutional codes, which process data in a continuous stream. Advanced coding schemes, such as turbo codes and low-density parity-check (LDPC) codes, approach the theoretical limits of channel capacity, providing near-optimal performance in noisy environments.[8]

1.3.4 Digital Modulator

The digital modulator converts the encoded binary data into analog waveforms suitable for transmission over the communication channel. Modulation techniques vary in complexity and performance, with simpler schemes like amplitude-shift keying (ASK) and frequency-shift keying (FSK) being suitable for low-data-rate applications. More sophisticated methods, such as phase-shift keying (PSK) and quadrature amplitude modulation (QAM), offer higher spectral efficiency, enabling faster data rates within limited bandwidth. The choice of modulation scheme depends on factors such as channel characteristics, power constraints, and required data throughput. [5]

1.3.5 Communication Channel

The communication channel serves as the medium through which the modulated signal travels from the transmitter to the receiver. Channels can be classified as wired (e.g., coaxial cables, optical fibers) or wireless (e.g., radio, satellite links). Each type of channel introduces specific impairments, including additive noise, attenuation, and multipath fading. The additive white Gaussian noise (AWGN) channel model is commonly used to analyze the effects of random noise, while fading channel models, such as Rayleigh and Rician, describe the variations in signal strength experienced in wireless environments. [6]

1.3.6 Digital Demodulator

At the receiver, the digital demodulator extracts the transmitted symbols from the noisy received signal. The demodulation process involves filtering, sampling, and decision-making to recover the original binary data. Optimal demodulation techniques, such as matched filtering and maximum likelihood detection, minimize the probability of symbol errors by exploiting knowledge of the transmitted signal structure. The performance of the demodulator is often evaluated in terms of the bit error rate (BER), which quantifies the likelihood of incorrect bit decisions. [5]

1.3.7 Channel Decoder

The channel decoder utilizes the redundancy introduced by the channel encoder to detect and correct errors that occurred during transmission. For block codes, the decoder identifies errors by computing syndromes and applying correction algorithms. Convolutional codes, on the other hand, employ the Viterbi algorithm to determine the most likely transmitted sequence based on the received data. The effectiveness of the channel decoder is critical in maintaining the integrity of the transmitted information, especially in high-noise environments. [5]

1.3.8 Source Decoder

The source decoder reconstructs the original information from the compressed data received from the channel decoder. In lossless compression systems, the decoder perfectly reverses the encoding process, while in lossy systems, it approximates the original signal based on the received data. The quality of reconstruction in lossy systems depends on the compression ratio and the encoding techniques employed. [6]

1.3.9 Destination and Output Transducer

The destination is the final recipient of the transmitted information, which could be a human user or a storage device. If the output is in analog form, such as speech or video, an output transducer, such as a speaker or display, converts the electrical signal back into its original form. The overall performance of the digital communication system is judged by the fidelity and timeliness of the information delivered to the destination. [|6]

1.4 Sampling and Quantization

The transition from analog to digital communication begins with the conversion of continuous-time signals into discrete-time signals through sampling, followed by quantization, which maps continuous amplitudes into discrete levels. [8]

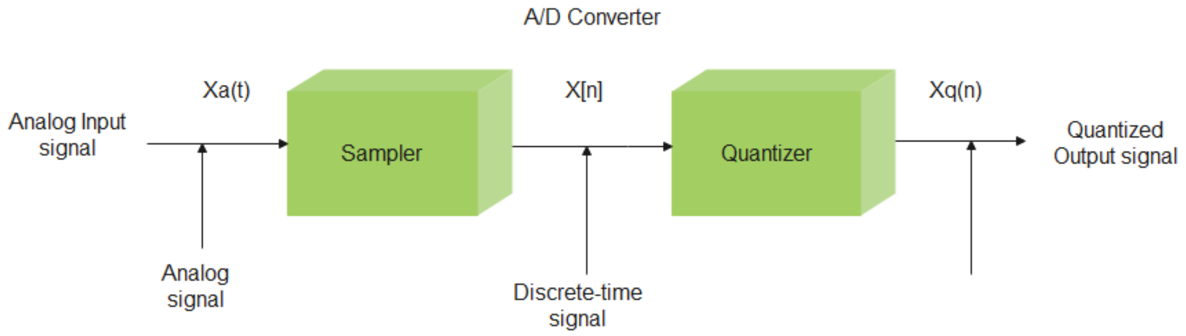

Figure 2: Sampling and Quantization Process

1.4.1 Sampling Theorem

The Nyquist-Shannon sampling theorem states that a bandlimited signal with a maximum frequency of B Hz can be perfectly reconstructed if sampled at a rate of at least 2B samples per second. Sampling below this rate results in aliasing, where higher-frequency components distort the reconstructed signal. Practical systems often use anti-aliasing filters to bandlimit the signal before sampling, ensuring compliance with the Nyquist criterion.

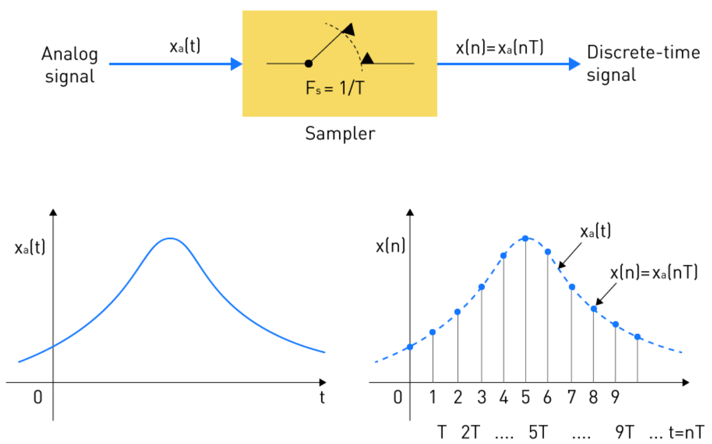

Figure 3:Sampling process

1.4.2 Quantization Process

Quantization converts the continuous amplitudes of the sampled signal into a finite set of discrete values. Uniform quantization divides the amplitude range into equal intervals, each represented by a fixed number of bits. Non-uniform quantization, used in applications like speech coding, employs companding (compression-expansion) to allocate more levels to smaller amplitudes, improving the signal-to-quantization-noise ratio (SQNR) for dynamic signals. The choice of quantization parameters involves a trade-off between resolution and bit rate, with higher bit depths providing better fidelity at the cost of increased data rates. [21]

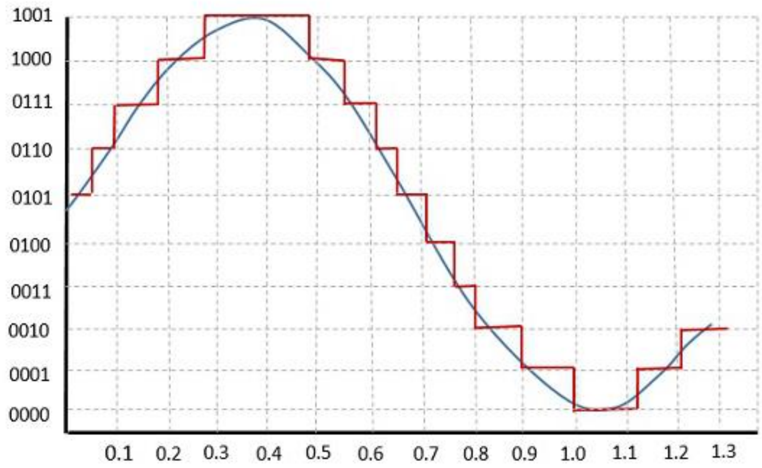

Figure 4: Quantization of an analog signal

1.5 Source Coding and Data Compression

Source coding aims to reduce the number of bits required to represent information by eliminating redundancy, thereby improving transmission efficiency. [21]

1.5.1 Entropy and Information Theory

Claude Shannon's information theory establishes the fundamental limits of data compression through the concept of entropy, which measures the average information content of a source. The source coding theorem asserts that a source can be compressed to a rate close to its entropy without significant loss, providing a theoretical basis for lossless compression algorithms. [21]

1.5.2 Lossless Compression Techniques

Lossless compression algorithms, such as Huffman coding, exploit statistical redundancies in the data to achieve compression without any loss of information. Huffman coding assigns variable-length codes to symbols based on their probabilities, with more frequent symbols receiving shorter codes. LZW(Lempel-Ziv-Welch) coding builds a dictionary of recurring patterns, replacing them with shorter references during encoding. [8]

1.5.3 Lossy Compression Techniques

Lossy compression techniques achieve higher compression ratios by discarding perceptually irrelevant information. Transform coding methods, such as the discrete cosine transform (DCT) used in JPEG, decompose the signal into frequency components, quantizing the coefficients to reduce data size. Predictive coding techniques, like differential pulse-code modulation (DPCM), encode the difference between consecutive samples, leveraging temporal redundancy in signals like speech and video. [8]

1.6 Channel Coding and Error Control

Channel coding enhances the reliability of digital communication by introducing redundancy that enables error detection and correction.

1.6.1 Purpose of Channel Coding

Error control mechanisms are essential in mitigating the effects of channel noise and interference. Automatic repeat request (ARQ) protocols detect errors and request retransmissions, while forward error correction (FEC) codes allow the receiver to correct errors without additional transmissions. The choice between ARQ and FEC depends on factors such as latency requirements and channel conditions. [5]

1.6.2 Linear Block Codes

Linear block codes, such as Hamming codes and Reed-Solomon codes, operate on fixed-length blocks of data, adding parity bits to facilitate error detection and correction. Hamming codes can correct single-bit errors and detect double-bit errors, making them suitable for memory systems. Reed-Solomon codes, with their strong error-correcting capabilities, are widely used in optical communications and storage media like CDs and DVDs. [8]

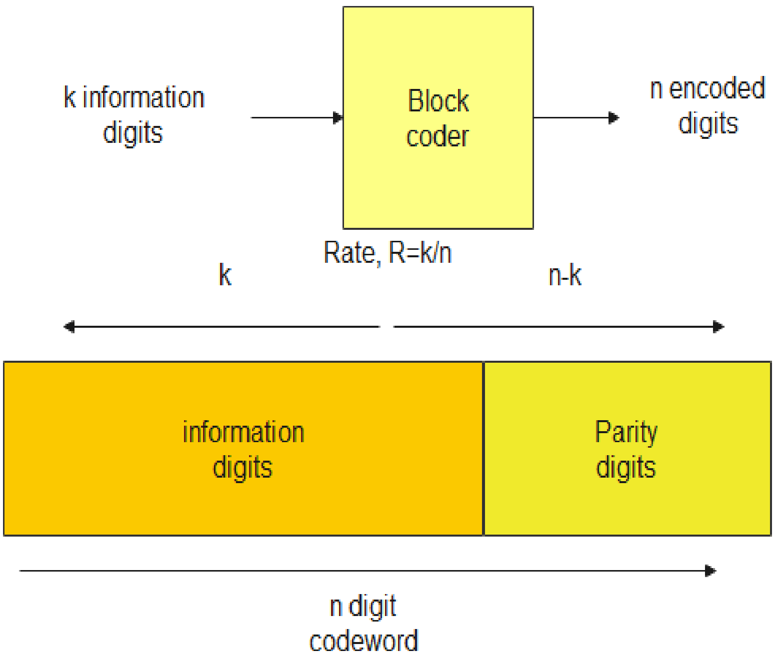

Figure 5:Linear Block Codes

1.6.3 Convolutional Codes

Convolutional codes process data in a continuous stream, using shift registers and modulo-2 adders to generate encoded outputs. The Viterbi algorithm, a maximum likelihood decoding technique, efficiently decodes convolutional codes by tracing the most probable path through a trellis diagram. These codes are particularly effective in satellite and deep-space communications. [8]

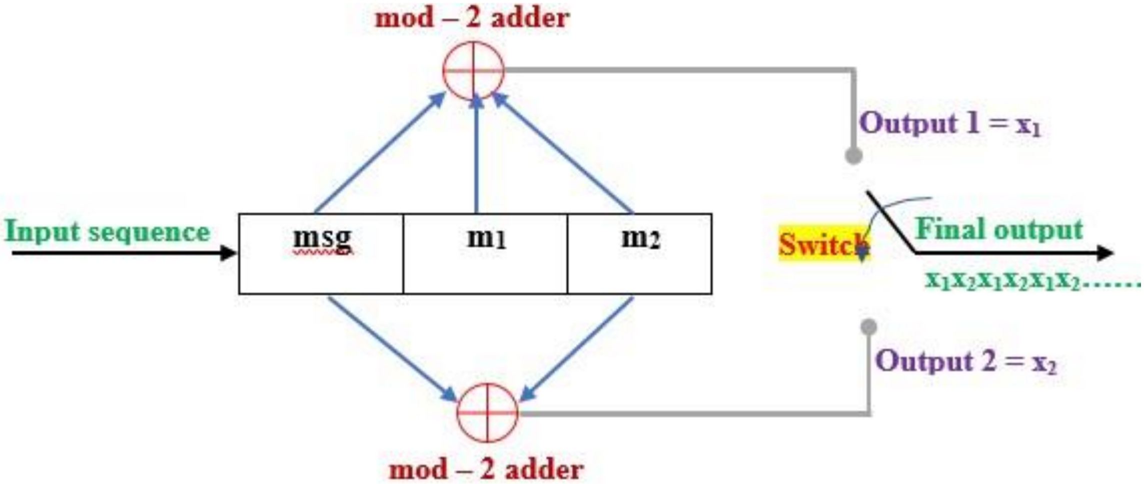

Figure 6: Convolutional Codes

1.6.4 Advanced Coding Schemes

Modern coding schemes, such as turbo codes and LDPC codes, achieve performance close to the Shannon limit. Turbo codes use parallel concatenated convolutional codes with iterative decoding, while LDPC codes rely on sparse parity-check matrices and belief propagation algorithms. These advanced codes are employed in 4G/5G cellular networks and deep-space communication systems.[6]

1.7 Modulation Techniques

Modulation translates digital data into analog signals suitable for transmission over physical channels.

1.7.1 Binary Modulation Schemes

Binary phase-shift keying (BPSK) modulates the phase of the carrier wave to represent binary data, offering robust performance in noisy environments. BFSK varies the carrier frequency between two values, providing simplicity and ease of implementation.

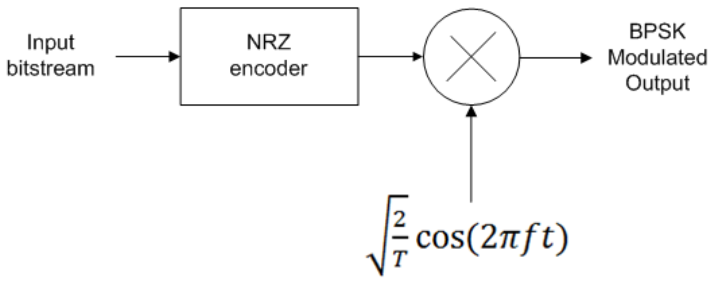

Figure 7:BPSK Modulator

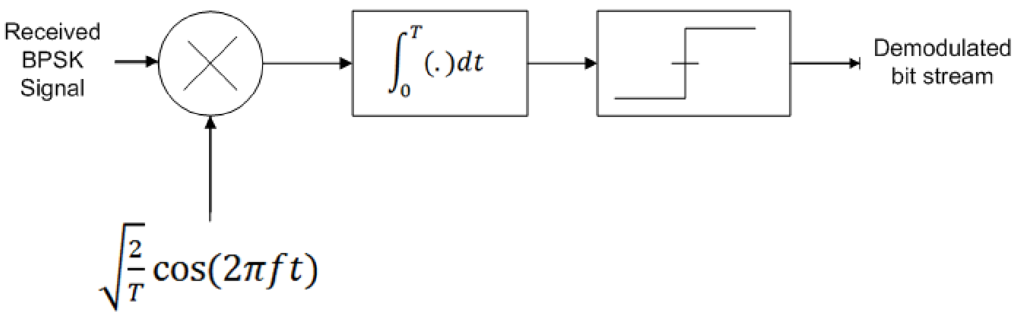

Figure 8: BPSK Demodulator

1.7.2 M-ary Modulation

Higher-order modulation schemes, such as quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM), transmit multiple bits per symbol, enhancing spectral efficiency. QPSK uses four phase shifts to represent two bits per symbol, while 16-QAM and 64-QAM combine amplitude and phase modulation to achieve even higher data rates.

a) Amplitude Shift Keying (ASK) : In an M-ary ASK scheme, the transmitted signals are defined by:

$$S_i(t) = \sqrt{\frac{2E_0}{T}} a_i \cos(\omega_c t) \qquad i = 1, 2, \cdots, M$$

Where the symbols a_i take their values in the alphabet $\pm 1, \pm 3, \cdots, \pm(M-1)$.

E_0 : the signal energy, which has the smallest amplitude and *T*, is the delay of each symbol m_i

$\omega_c = \frac{2\pi n_c}{T} \qquad n_c \in$ is the carrier frequency.

We take as basis function :

$$\Phi_1(t) = \sqrt{\frac{2}{T}} \cos(\omega_c t) \qquad 0 \le t \le T$$

Then:

$$S_i(t) = \sqrt{E_0} a_i \Phi_1(t) \qquad i = 1, 2, \cdots, M$$

The ASK modulation is therefore linear unidimensional. Figure below shows a geometric representation of M-ary ASK signals with the decision regions.

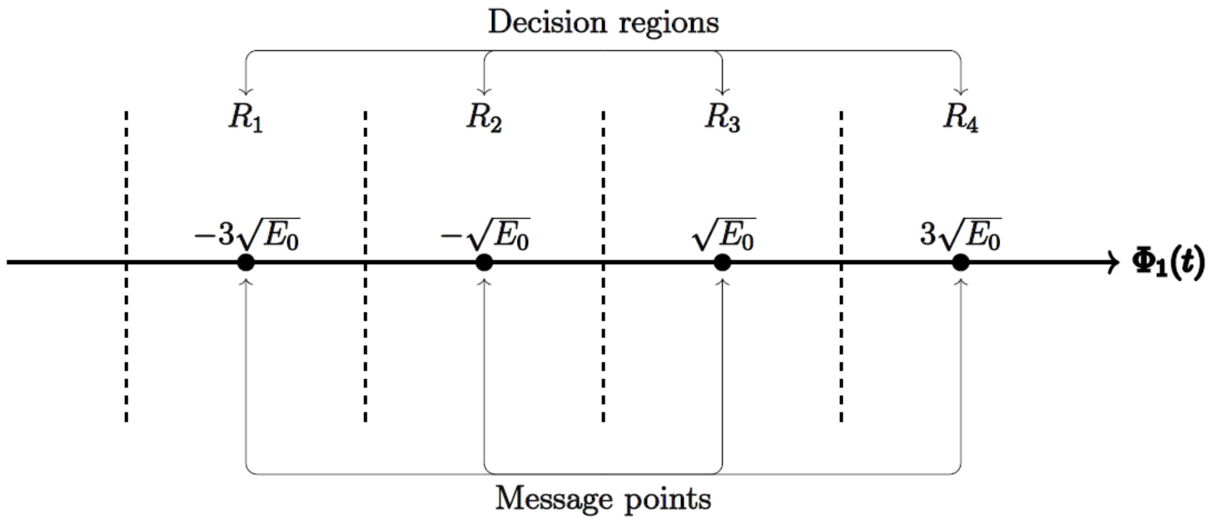

Figure 9: M-ary ASK signals with the decision regions

Figure below shows an ASK modulator and demodulator, the signal $Z(t) = S(t) + W(t)$ is multiplied by $\Phi_1(t)$, during each signaling interval of duration *T*. That gives:[8]

$$Z_1 = \sqrt{E_0}a_i + W, \qquad i = 1, \cdots, M$$

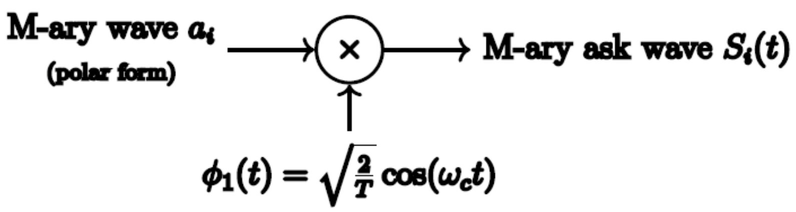

Figure 10: M-ary ASK Modulator

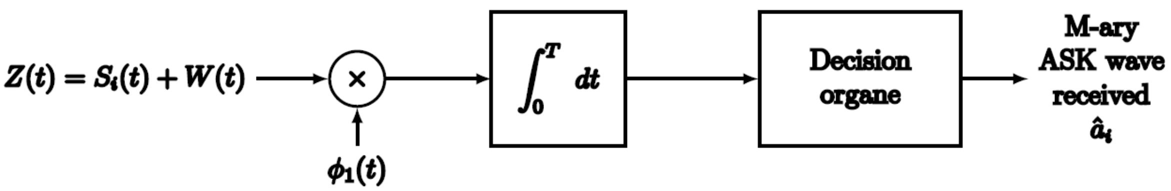

Figure 11: M-ary ASK Demodulator

Where $W(t)$ is a Gaussian random variable of zero mean and variance $\sigma^2 = \frac{N_0}{2}$ representing $W(t)$ in the space spanned by $\Phi_1(t)$.

b) Phase Shift Keying (PSK) :

In M-ary PSK, the phase of the carrier takes on one of M possible values, namely, $\theta_i = \frac{2i\pi}{M}$, where $i = 0,1,\cdots,M-1$. So the PSK signals are given by the formula:

$$S_i(t) = \sqrt{\frac{2E}{T}}\cos(\omega_c t + \theta_i), \qquad \theta_i = \frac{2\pi i}{M}, \quad i = 0,1,\cdots,M$$

Where E is the signal energy per symbol. The carrier frequency $\omega_c = \frac{2\pi n_c}{N} \quad (n_c \in □)$

We develop $S_i(t)$ to obtain:

$$S_i(t) = \sqrt{\frac{2E}{T}}\cos(\omega_c t)\cos(\theta_i) - \sqrt{\frac{2E}{T}}\sin(\omega_c t)\sin(\theta_i)$$

thus each S(t) can be represented in terms of two basis functions, $\Phi_1(t)$ and $\Phi_2(t)$, defined as:

$$\begin{cases} \Phi_1(t) &= \sqrt{\frac{2}{T}}\cos(\omega_c t), \quad 0 \le t \le T \\ \Phi_2(t) &= \sqrt{\frac{2}{T}}\sin(\omega_c t), \quad 0 \le t \le T \end{cases}$$

Both $\Phi_1(t)$ and $\Phi_2(t)$ have unit energy, the signal constellation of M-ary PSK is therefore two-dimensional. The M message points are equally spaced on a circle of radius $\sqrt{E}$ and centered at the origin, as illustrated in figure below for M=8.

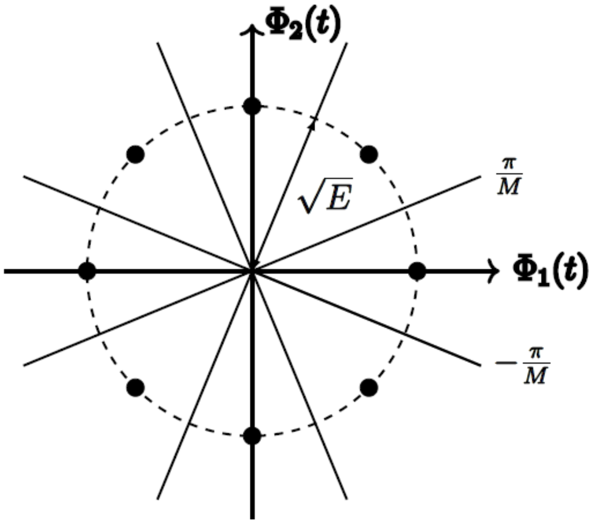

Figure 12: Signal constellation of 8-PSK

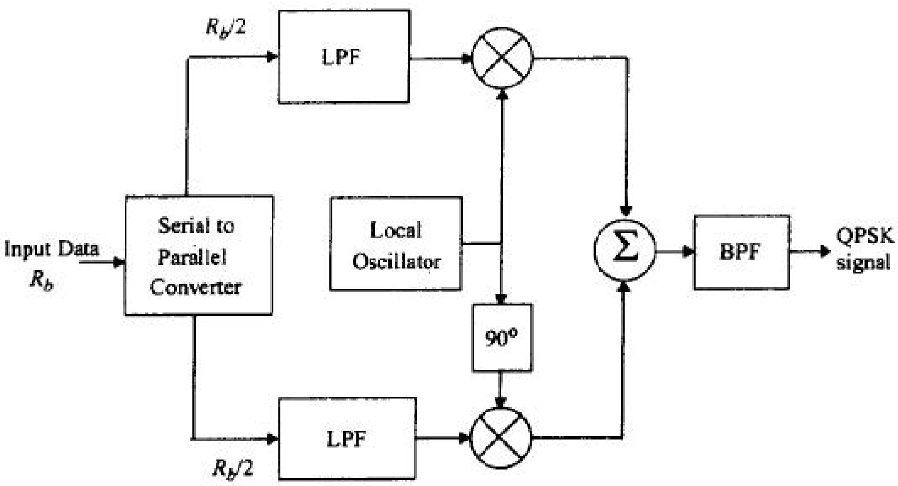

Figure 13: M-ary PSK Modulator

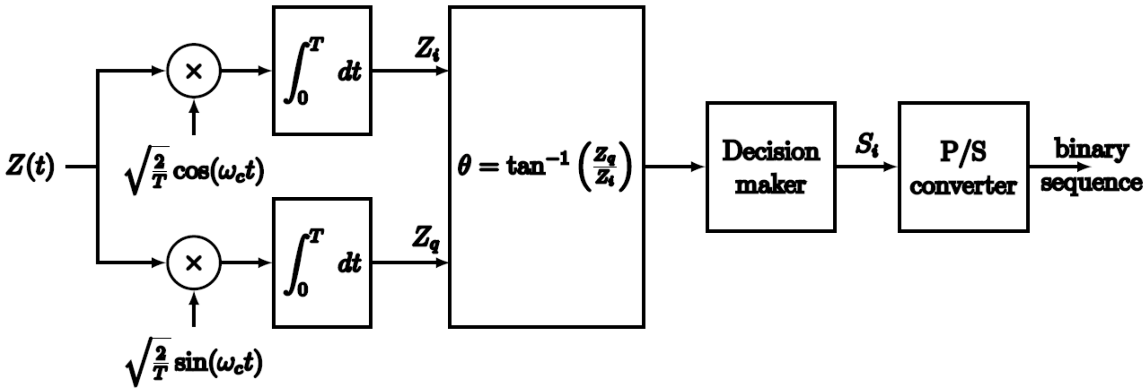

Figure 14: M-ary PSK Demodulator

c) Quadrature Amplitude Modulation QAM:

For a high number of points M, neither ASK nor PSK constitute a satisfying solution to effectively use the transmitted energy. The error probability is a function of the minimum Euclidian distance between the constellation's points. The best modulation (for a gaussian channel) is that in which the distance for a given average power is maximum. so a better choice than ASK where the constellation points are on straight line and the PSK where the points are on a circle, is to use amplitude modulation with two carriers in Quadrature, let the signals

$$S_i(t) = \sqrt{\frac{2E_0}{T}} a_i \cos(\omega_c t) - \sqrt{\frac{2E_0}{T}} b_i \sin(\omega_c t), \qquad 0 \le t \le T$$

Where E_0 is the energy of the signal with the lowest amplitude, $a_i$and b_i is a pair of independent integers.

The signals $S_i(t)$ can be expressed in terms of a pair of basis functions:

$$\begin{cases} \Phi_1(t) = \sqrt{\frac{2}{T}} \cos(\omega_c t) \\ \Phi_2(t) = \sqrt{\frac{2}{T}} \sin(\omega_c t) \qquad 0 \le t \le T \end{cases}$$

The coordinates of the ith message point are $(a_i\sqrt{E_0}, b_i\sqrt{E_0})$ where (a_i, b_i) is an element of the $L \times L$ matrix

$$(a_i, b_i) = \begin{pmatrix} (-L+1, L-1) & (-L+3, L-1) & \cdots & (L-1, L-1) \\ \vdots & \vdots & \vdots & \vdots \\ (-L+1, -L+1) & (-L+3, -L+1) & \cdots & (-L-1, -L+1) \end{pmatrix}$$

where L is the amplitude levels of the basis axis in the signal space. For example for L=4, M=16 whose signal constellation is depicted in figure below where L=4, we have the matrix

$$(a_i, b_i) = \begin{pmatrix} (-3,+3) & (-1,+3) & (+1,+3) & (+3,+3) \\ (-3,+1) & (-1,+1) & (+1,+1) & (+3,+1) \\ (-3,-1) & (-1,-1) & (+1,-1) & (+3,-1) \\ (-3,-3) & (-1,-3) & (+1,-3) & (+3,-3) \end{pmatrix}$$

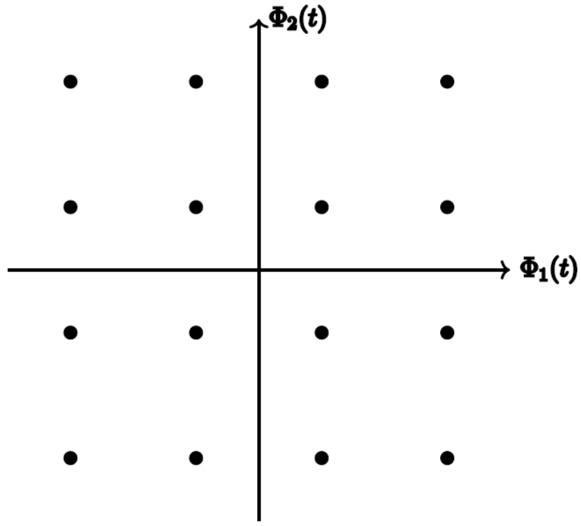

Figure 15: Signal constellation of 16-QAM

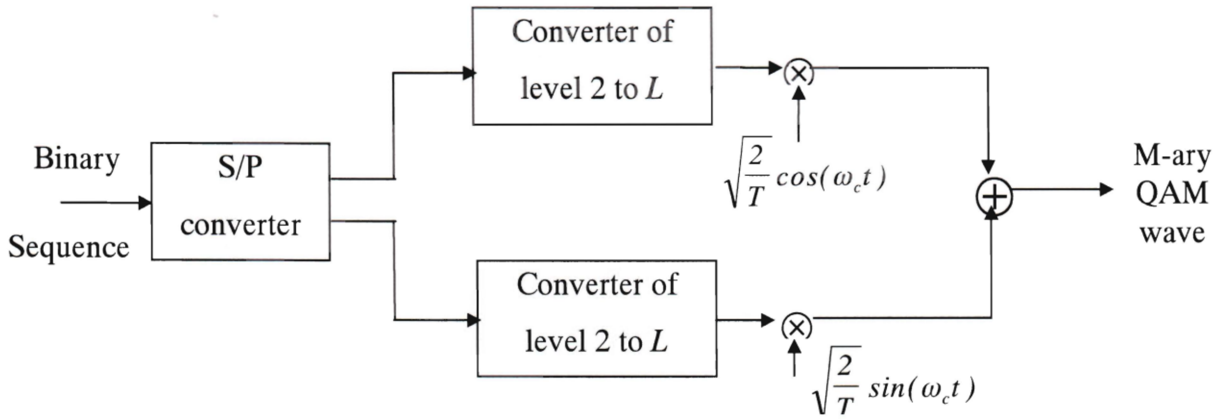

Figure 16:M-ary QAM Modulator

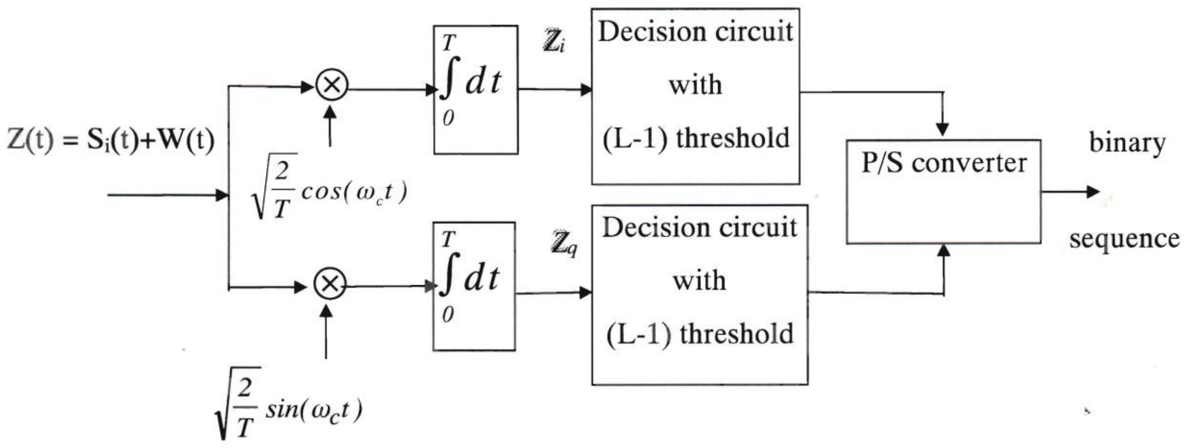

Figure 17:M-ary QAM Demodulator

1.7.3 Performance Metrics

The performance of digital modulation schemes is evaluated using metrics such as bit error rate (BER) and bandwidth efficiency. BER measures the probability of incorrect bit detection, while bandwidth efficiency quantifies the data rate per unit bandwidth. These metrics guide the selection of modulation schemes based on channel conditions and system requirements.

1.8 Synchronization and Multiplexing

1.8.1 Synchronization

Synchronization ensures that the receiver accurately interprets the transmitted signal by aligning its clock and carrier phase with the transmitter. Carrier recovery techniques, such as the Costas loop for PSK signals, extract the carrier phase, while symbol timing recovery methods, like the early-late gate, synchronize the sampling instants. [6]

1.8.2 Multiplexing Techniques

Multiplexing enables multiple signals to share a common communication channel. Time-division multiplexing (TDM) allocates distinct time slots to different signals, while frequency-division multiplexing (FDM) assigns separate frequency bands. Orthogonal frequency-division multiplexing (OFDM), used in Wi-Fi and LTE, divides the channel into orthogonal subcarriers, enhancing resistance to multipath fading.[6]

1.9 Conclusion

This chapter has presented a comprehensive introduction to digital communication systems, covering their fundamental components, signal processing techniques, and coding schemes. The discussion highlighted the advantages of digital over analog communication, emphasizing noise immunity, error correction, and efficient data handling. Subsequent chapters will explore advanced topics, including wireless channel modeling, multiple-access techniques, and emerging technologies in digital communications.

CHAPTER 2: PRINCIPLES OF TRELLIS-CODED MODULATION (TCM) AND CHANNEL MODELS

2. Introduction to Trellis-Coded Modulation (TCM)

Trellis-Coded Modulation (TCM) is a powerful technique that combines error correction coding and modulation to improve the performance of digital communication systems over noisy channels. Unlike traditional systems where coding and modulation are treated as separate entities, TCM integrates these two processes, allowing for more efficient use of bandwidth and improved error performance. TCM was first introduced by Gottfried Ungerboeck in the early 1980s.The fundamental principle of TCM is to use a convolutional code to increase the Euclidean distance between signal points in the modulated signal space, thereby enhancing the system's ability to resist noise and interference. This is achieved by integrating convolutional coding with modulation schemes, such as Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM).

The fundamental components of TCM are:

1. Convolutional Encoder:This is a finite-state machine that takes in a stream of input bits and produces a stream of output bits. The encoder is characterized by its constraint length and generator polynomials, which determine the structure of the trellis diagram.

2. Signal Constellation: This is the set of possible signal points that can be transmitted over the channel. In TCM, the constellation is typically larger than what would be used in an uncoded system, allowing for the introduction of redundancy without increasing bandwidth.

3. Mapping Function: This function maps the output bits from the convolutional encoder to the signal points in the constellation. The mapping is designed to maximize the Euclidean distance between signal sequences, which improves the error performance of the system.

4. Viterbi Decoder: At the receiver, the Viterbi algorithm is used to decode the received signal. The Viterbi decoder searches through the trellis diagram to find the most likely sequence of transmitted symbols, taking into account the redundancy introduced by the convolutional code[7].

2.1 Convolutional Codes in TCM

Convolutional codes are a class of error-correcting codes that generate parity symbols via a sliding application of a Boolean polynomial function to a data stream. In TCM, convolutional codes are used to map input bits to a set of modulated symbols. The encoder operates on a continuous stream of data, producing a sequence of coded bits that depend not only on the current input bits but also on previous inputs, creating a memory effect [8].

The key idea in TCM is to use a convolutional encoder to select a subset of the available signal points in the modulation scheme. This subset is chosen to maximize the minimum Euclidean distance between any two valid signal sequences. By doing so, the system can achieve a coding gain without increasing the bandwidth or power requirements [9].

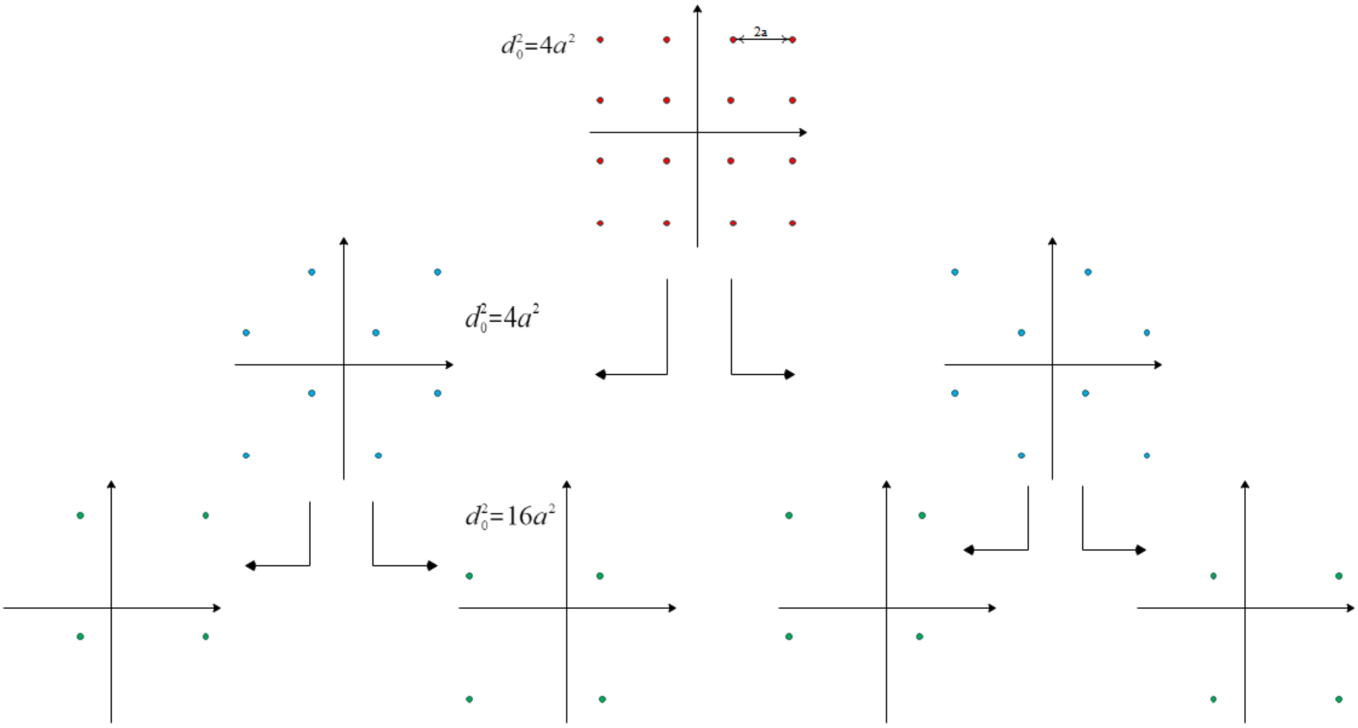

Figure 18: Signal Constellation Partitioning

2.1.1 Combining Convolutional Codes with Modulation Schemes

In TCM, the convolutional encoder and the modulator are designed jointly. The encoder's output determines the sequence of symbols to be transmitted, and these symbols are mapped to points in the signal constellation. The mapping is done in such a way that the Euclidean distance between sequences of symbols is maximized, which directly translates to improved error performance [10].

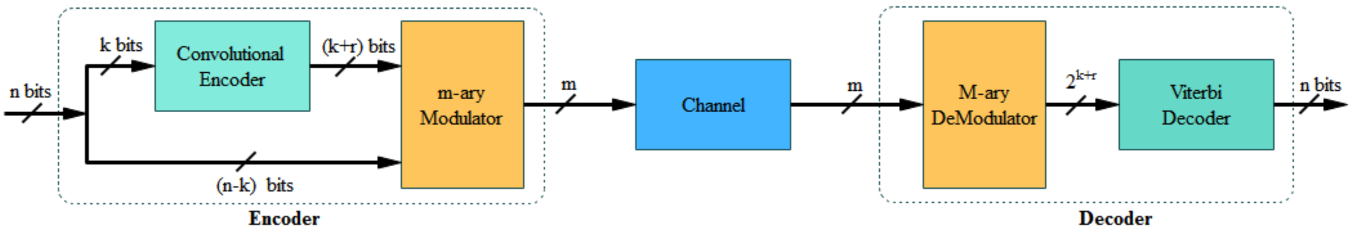

Figure 19: Block Diagram of a TCM System

For example, consider a system using 8-PSK modulation. Without coding, each symbol represents 3 bits of information. In a TCM system, a convolutional encoder might be used to map 2 input bits to a 3-bit output, which is then mapped to one of the 8-PSK symbols. The extra redundancy introduced by the encoder allows the receiver to correct errors caused by channel noise [11].

The Euclidean distance $\mathrm{d_E}$ between two signal pointss_i and s_j in the constellation is given by:

$$\mathrm{d_E} = \sqrt{\sum_{\mathrm{k}=1}^{N} \left|\mathrm{s}_{i,k} - \mathrm{s_{j,k}}\right|^2}$$

where N is the number of dimensions in the signal space. The minimum Euclidean distance $\mathrm{d_{min}}$ is the smallest distance between any two valid signal sequences, and it determines the error performance of the TCM system [12].

2.1.2 The Trellis Diagram

The trellis diagram is a graphical representation of the convolutional encoder's state transitions over time. Each node in the trellis represents a possible state of the encoder, and each branch represents a possible transition between states, labeled with the corresponding input and output bits. The trellis diagram is essential for decoding TCM signals using the Viterbi algorithm, which finds the most likely sequence of transmitted symbols by searching for the path through the trellis with the minimum cumulative metric [13].

The cumulative metric M for a path in the trellis is given by:

$$M = \sum_{k=1}^{L} |r_k - s_k|^2$$

where $r_k$is the received symbol at time$k$, $s_k$is the transmitted symbol corresponding to the path, and L is the length of the sequence. The Viterbi algorithm selects the path with the smallest cumulative metric as the most likely transmitted sequence [14].

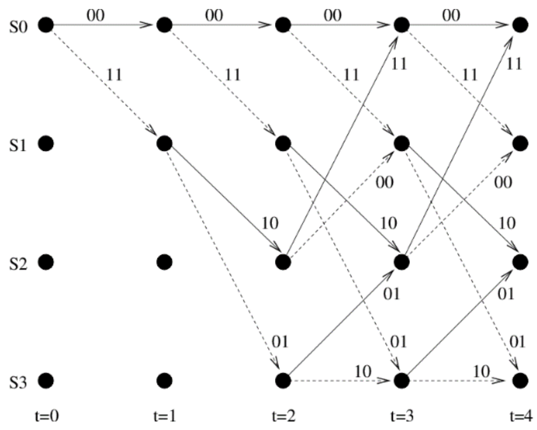

Figure 20:Trellis Diagram for a Convolutional Code

2.2 Channel Models

The performance of TCM systems depends heavily on the characteristics of the communication channel. Different channel models are used to represent various real-world scenarios, each with its own set of challenges. In this section, we review three common channel models: Additive White Gaussian Noise (AWGN), Rayleigh fading, and Rician fading.

2.2.1 Additive White Gaussian Noise (AWGN)

The AWGN channel model is the simplest and most widely used model for analyzing communication systems. It assumes that the only impairment to the transmitted signal is the addition of white Gaussian noise, which is characterized by a constant power spectral density and a Gaussian distribution of amplitudes [15].

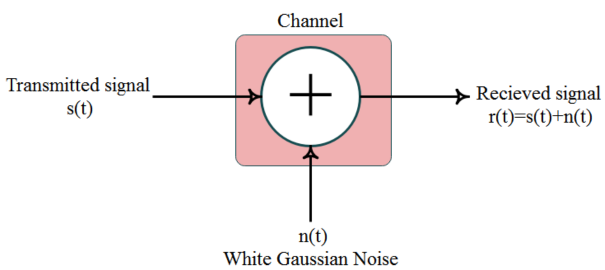

Figure 21: AWGN Channel Model

2.2.2 Characteristics of AWGN

The AWGN channel is often used for initial analysis and simulation of communication systems because of its simplicity. However, it does not capture the effects of multipath propagation or fading, which are common in wireless communication systems. The main characteristics of AWGN are:

- ***Additive:*** The noise is added to the signal, and the received signal is the sum of the transmitted signal and the noise.
- ***White:*** The noise has a constant power spectral density across all frequencies, meaning that it is uncorrelated in time and frequency.
- ***Gaussian:*** The noise is Gaussian distributed, which means that the probability density function (PDF) of the noise is a bell-shaped curve.
- ***Thermal Noise:*** AWGN models the thermal noise generated by the receiver's electronic components. This noise is present in all communication systems and is typically the dominant noise source in well-designed systems.
- ***Flat Frequency Response:*** The AWGN channel has a flat frequency response, meaning that all frequency components of the signal are affected equally by the noise.
- ***Usefulness:*** The AWGN model is useful for initial analysis and design of communication systems because it provides a baseline performance metric. It is also used to compare the performance of different modulation and coding schemes [16].

2.2.3 Performance of TCM in AWGN

In an AWGN channel, the performance of a TCM system is primarily determined by the minimum Euclidean distance between signal sequences. The coding gain achieved by TCM over uncoded modulation can be quantified by comparing the bit error rate (BER) of the two systems at the same signal-to-noise ratio (SNR).

The probability of bit error P_b for a TCM system in AWGN can be approximated by:

$$P_b \approx Q\left(\sqrt{\frac{d_{\min}^2}{2N_0}}\right)$$

where $Q(x)$is the Q-function, $d_{\min}$is the minimum Euclidean distance, and N_0 is the noise power spectral density [17].

2.3.1 Rayleigh Fading

Rayleigh fading is a statistical model for the effect of a propagation environment on a radio signal, such as that used by wireless communication systems. It is particularly applicable to urban environments where there is no direct line-of-sight (LOS) path between the transmitter and receiver, and the signal is reflected off buildings, vehicles, and other obstacles [18].

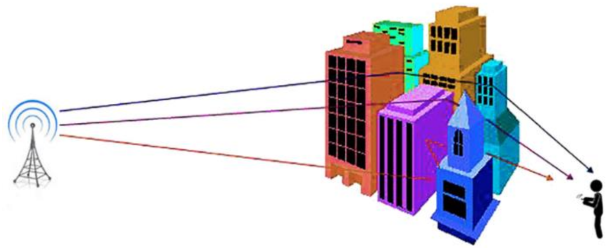

Figure 22: Rayleigh Fading Channel Model

2.3.2. Characteristics of Rayleigh Fading

- **Multipath Propagation:** In a Rayleigh fading channel, the transmitted signal arrives at the receiver via multiple paths, each with a different delay and phase shift. The combined effect of these paths results in a signal that fluctuates randomly in amplitude and phase.
- **No Line-of-Sight:** Rayleigh fading assumes that there is no dominant LOS component. The received signal is the sum of many scattered components, leading to a Rayleigh distribution of the signal amplitude.
- **Frequency Selectivity:** In a frequency-selective fading channel, different frequency components of the signal experience different levels of fading. This can lead to intersymbol interference (ISI) in wideband systems
- **Rayleigh Distribution:** The amplitude of the received signal follows a Rayleigh distribution, which is astatistical distribution that describes the magnitude of a complex random variable with zero-mean Gaussian components.The Rayleigh fading channel is a good model for urban wireless environments, where the signal is likely to experience significant multipath propagation. However, it does not account for the presence of a strong line-of-sight component, which is common in other environments[19].

2.3.3 Performance of TCM in Rayleigh Fading

In a Rayleigh fading channel, the performance of TCM is affected by the random fluctuations in the signal amplitude. The diversity gain provided by TCM can help mitigate the effects of fading by ensuring that errors are spread out over time rather than occurring in bursts. The use of interleaving in conjunction with TCM can further improve performance by breaking up error bursts.

The probability of bit error P_b for a TCM system in Rayleigh fading can be approximated by:

$$P_b \approx \frac{1}{2}\left(1 - \sqrt{\frac{\bar{\gamma}}{1+\bar{\gamma}}}\right)$$

where $\bar{\gamma}$is the average SNR per bit [20].

2.3.4 Concepts of Rayleigh Fading Channels

(A) Multipath Propagation

- In wireless channels, signals travel from the transmitter to the receiver via multiple paths due to reflections, diffractions, and scattering.

- Each path has:

  - A different *time delay* (causing time dispersion).
  - A different *attenuation* (amplitude variation).
  - A different *phase shift* (due to varying path lengths).

(B) No Dominant Line-of-Sight (NLOS) Component

- Rayleigh fading occurs when there is ***no strong direct path*** (LOS) between the transmitter and receiver.

- The received signal is ***the sum of many scattered signals*** with random phases and amplitudes.

(C) Central Limit Theorem (CLT) Justification

- The sum of many independent random phasors (due to multipath) leads to a complex Gaussian distribution for the received signal. [10]

- The ***envelope*** (magnitude) of this signal follows a *Rayleigh distribution*.

- The ***phase*** is uniformly distributed in $[0, 2\pi[$

2.3.5 Mathematical Model of Rayleigh Fading

The received signal $r(t)$ can be represented as[3]:

$$r(t) = \mathrm{Re}\left\{h(t) \cdot e^{j2\pi f_c t}\right\}$$

where:

- $h(t) = h_I(t) + j\, h_Q(t)$ is *the complex baseband channel impulse response*.
- $h_I(t)$ and $h_Q(t)$ are *independent, zero-mean Gaussian random processes* (due to CLT).

Envelope Distribution (Rayleigh)

The magnitude $|h(t)|=\sqrt{h_I^2+h_Q^2}$ follows a *Rayleigh PDF*:

$$f_R(r)=\frac{r}{\sigma^2}e^{-r^2/2\sigma^2}, \quad r\geq 0$$

where:

- σ^2 = average power of the multipath components.

Phase Distribution (Uniform)

The phase $\theta=\tan^{-1}(h_Q/h_I)$ is uniformly distributed:

$$f_\Theta(\theta)=\frac{1}{2\pi}, \quad 0\leq\theta<2\pi$$

2.3.6 Causes of Rayleigh Fading:

Rayleigh fading arises primarily in environments with ***rich multipath scattering***, where signals reflect off numerous obstacles (e.g., buildings, trees) without a dominant line-of-sight (LOS) component. The absence of a strong direct path means the received signal is the sum of many scattered waves with random phases and amplitudes, leading to destructive/constructive interference.

This phenomenon is classified as ***small-scale fading*** because signal strength varies rapidly over short distances (on the order of the radio wavelength). For instance, a mobile receiver moving at vehicular speeds may experience significant signal fluctuations within a few centimeters.

Additionally, ***Doppler spread*** exacerbates fading when the transmitter, receiver, or surrounding scatterers are in motion. The relative movement shifts the frequency of multipath components, creating time-varying channel conditions. In urban or indoor NLOS scenarios, these factors combine to produce the characteristic Rayleigh fading statistics.

2.3.7 Parameters of Rayleigh Fading Channels

1. Coherence Bandwidth B_c: The frequency range over which the channel is approximately flat.

   It is Related to *delay spread* $\tau_{\max}$ by:

$$B_c\approx\frac{1}{\tau_{\max}}$$

2. Coherence Time T_c: The time duration over which the channel remains roughly constant.

   It is Related to *Doppler spread* f_d by:

$$T_c \approx \frac{1}{f_d}$$

3. Fading Rate: How quickly the channel changes due to mobility.

2.3.8 Techniques for decreasing Rayleigh Fading

Rayleigh fading causes significant signal degradation due to deep fades, which can severely impact wireless communication reliability. To counteract these effects, several advanced techniques are employed:

1. **Diversity Techniques**

Diversity Techniquesleverage multiple independent signal paths to improve reception. ***Space diversity*** uses multiple antennas (MIMO systems) to exploit spatial variations, while ***frequency diversity*** (e.g., spread spectrum and OFDM) spreads the signal across different frequencies to minimize simultaneous fading. ***Time diversity*** introduces redundancy through error correction and interleaving, allowing the receiver to reconstruct lost data.

2. **Equalization:** helps compensate for channel-induced distortions by using adaptive filters to reverse the effects of multipath propagation. This ensures the received signal closely matches the transmitted waveform.
3. **Channel Coding & Interleaving:** enhance robustness by incorporating error-correcting codes such as Turbo codes and Trellis Coded Modulation. These codes add structured redundancy, enabling the receiver to detect and correct bit errors caused by fading. Interleaving further disperses errors, preventing concentrated bursts of signal loss.

By combining these methods, wireless systems can significantly reduce the impact of Rayleigh fading, ensuring stable and efficient communication even in challenging environments.[24]

2.3.9 When is Rayleigh Fading Not Applicable?

Rayleigh fading is not a suitable model in scenarios where a ***strong line-of-sight (LOS) component*** exists between the transmitter and receiver. In such cases, the fading characteristics follow a *Rician distribution* rather than Rayleigh, as the dominant LOS signal significantly alters the statistical behavior of the channel.

Additionally, Rayleigh fading does not apply in ***free-space propagation environments***, where there is no multipath scattering. In free space, the signal experiences minimal fading since it travels unobstructed without reflections or diffractions, resulting in a near-constant channel response. Thus, Rayleigh fading is specifically relevant in *non-line-of-sight (NLOS)multipath-rich environments*, such as urban areas or indoor wireless systems, where no single dominant signal path exists.

2.4 Rician Fading

Rician fading is a more general model than Rayleigh fading and is applicable to environments where there is a dominant LOS component in addition to scattered components. This model is often used to represent semi-rural or mixed environments where the receiver has a partial view of the transmitter [21].

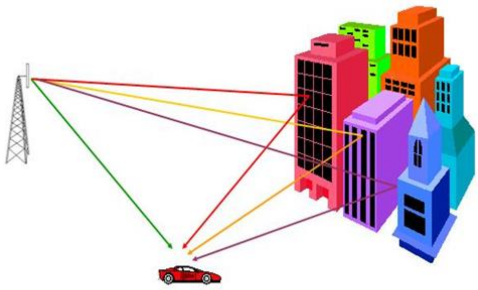

Figure 23:Rician Fading Channel Model

2.4.1 Characteristics of Rician Fading:

The Rician fading channel is a good model for semi-rural or mixed environments, where there is a clear line-of-sight path but also significant multipath effects. The Rician K-factor is an important parameter in this model, as it determines the relative strength of the LOS component compared to the multipath components.

- **Line-of-Sight Component*:*** In a Rician fading channel, the received signal consists of a dominant LOS component and multiple scattered components. The presence of the LOS component results in a Rician distribution of the signal amplitude.
- **K-Factor*:***The Rician K-factor is the ratio of the power in the LOS component to the power in the scattered components. A higher K-factor indicates a stronger LOS component and less severe fading.
- **Fading Severity:** Rician fading is less severe than Rayleigh fading because the presence of the LOS component reduces the likelihood of deep fades [22].
- **Rician Distribution*:*** The amplitude of the received signal follows a Rician distribution, which is a statistical distribution that describes the magnitude of a complex random variable with non-zero-mean Gaussian components. The Rician distribution is characterized by the Rician K-factor, which is the ratio of the power in the LOS component to the power in the multipath components.

2.4.2 Performance of TCM in Rician Fading

In a Rician fading channel, the performance of TCM is influenced by the strength of the LOS component. As the K-factor increases, the channel becomes more like an AWGN channel, and the performance of TCM improves. However, even in the presence of a strong LOS component, the scattered components can still cause some fading, and TCM can provide additional robustness against these effects.

The probability of bit error P_b for a TCM system in Rician fading can be approximated by:

$$P_b \approx Q\left(\sqrt{\frac{2K\bar{\gamma}}{1+K+\bar{\gamma}}}\right)$$

where K is the Rician K-factor and $\bar{\gamma}$ is the average SNR per bit [23].

2.4.3 Concepts of Rician Fading Channels

(A) Multipath Propagation with a Dominant LOS Component

Unlike Rayleigh fading, Rician fading includes:[8]

- A *strong direct (LOS) signal*(e.g., from a base station).
- Multiple *weaker scattered (NLOS) signals* (reflections, diffractions).
- The *total received signal*is the sum of the LOS and NLOS components.

(B) Rician *K*- Factor

The ***Rician K-factor*** defines the ratio of the ***LOS power*** to the ***scattered power***:

$$K = \frac{\text{Power in LOS component}}{\text{Power in scattered components}}$$

- When K = 0, the channel reduces to ***Rayleigh fading*** (no LOS).
- When $K \to \infty$, the channel becomes ***AWGN*** (only LOS, no fading).

(C) Mathematical Model of Rician Fading

The received signal $r(t)$ can be written as [9]:

$$r(t) = \mathrm{Re}\left\{h(t)\cdot e^{j2\pi f_c t}\right\}$$

where the complex channel gain $h(t)$ is:

$$h(t) = Ae^{j\phi} + \underbrace{h_I(t) + jh_Q(t)}_{\text{Random scattered components}}$$

- A = amplitude of the LOS component.
- ϕ = phase shift of the LOS component.
- $h_I(t)$, $h_Q(t)$ = independent Gaussian random variables (scattered components).

Envelope Distribution (Rician)

The magnitude $|h(t)|=\sqrt{(A+h_I)^2+h_Q^2}$ follows a *Rician PDF*:

$$f_R(r)=\frac{r}{\sigma^2}e^{-\frac{r^2+A^2}{2\sigma^2}}I_0\left(\frac{rA}{\sigma^2}\right),\quad r\geq 0$$

where:

- σ^2 = average power of the scattered components.
- $I_0(\cdot)$ = modified Bessel function of the first kind (order 0).

Phase Distribution (Non-Uniform)

Unlike Rayleigh fading, the phase is ***not uniform*** due to the dominant LOS component.

2.4.4Causes of Rician fading:

Rician fading occurs in wireless communication scenarios where the signal propagation includes both a dominant line-of-sight (LOS) component and weaker multipath signals. This phenomenon typically arises in environments with ***partial LOS conditions***, where a strong direct path between the transmitter and receiver coexists with scattered reflections. Common examples include ***satellite and microwave communication links***, where the dominant LOS signal is accompanied by minor reflections from atmospheric conditions or surrounding terrain. Similarly, in ***indoor wireless environments such as Wi-Finetworks***, Rician fading can occur when the access point is visible to the device but the signal still experiences reflections from walls, furniture, or other obstacles. These combined effects of a strong direct path and scattered multipath components characterize the Rician fading model, distinguishing it from Rayleigh fading where no dominant LOS path is present. [11]

2.4.5Parameters of Rician Fading Channels

The behavior of Rician fading channels is primarily characterized by three key parameters:[11]

1. **Rician K-Factor**

   The K-factor is a critical parameter that quantifies the ratio of the power in the **Line-of-Sight (LOS) component** to the power in the **scattered (multipath) components**. A higher K-factor indicates a stronger dominant LOS signal, leading to **less severe fading** and a more stable received signal. Conversely, when K=0, the channel reduces to **Rayleigh fading**, where no dominant path exists.

2. **Coherence Bandwidth & Coherence Time**

   Similar to Rayleigh fading, Rician channels experience **frequency-selective fading** (due to multipath delay spread) and **time-selective fading** (due to Doppler effects). However, the presence of a strong LOS component makes these effects **less severe** compared to Rayleigh fading. The coherence bandwidth (B_c) and coherence time (T_c) still depend on delay spread and Doppler spread, respectively, but the impact of fading is mitigated by the dominant path.

3. **Doppler Spread**

   In Rician fading, **mobility-induced Doppler effects** primarily influence the LOS component, leading to **slow fading** variations. Since the LOS signal dominates, Doppler spread causes gradual changes in the channel response rather than rapid fluctuations. This is in contrast to Rayleigh fading, where the absence of a strong LOS path results in faster, more unpredictable signal variations.

2.5 Comparison of Channel Models:

The choice of channel model depends on the specific environment in which the communication system is operating. The AWGN channel is the simplest model and is useful for initial analysis and simulation. However, it does not capture the effects of multipath propagation or fading, which are critical in wireless communication systems.

The Rayleigh fading channel is a good model for urban environments where there is no direct **line-**of-sight path and the signal is subject to significant multipath propagation. The Rician fading channel is more appropriate for environments where there is a strong line-of-sight component, but there are also significant multipath effects.

In practice, the performance of a TCM system will vary depending on the channel model. For example, in an AWGN channel, the performance of a TCM system is primarily determined by the Euclidean distance between signal sequences. In a Rayleigh fading channel, the performance is also affected by the diversity of the signal paths, which can help to mitigate the effects of fading. In a Rician fading channel, the presence of a strong LOS component can improve the performance of the system, but the multipath components can still cause significant fluctuations in the received signal.

2.6 Conclusion

Trellis-Coded Modulation (TCM) is a powerful technique that combines convolutional coding with modulation to improve the performance of digital communication systems. By carefully designing the encoder and modulator, TCM can achieve significant coding gains without increasing bandwidth or power requirements. The performance of TCM systems depends on the characteristics of the communication channel, and different channel models, such as AWGN, Rayleigh fading, and Rician fading, are used to represent various real-world scenarios.

In AWGN channels, TCM provides a clear advantage over uncoded modulation by increasing the minimum Euclidean distance between signal sequences. In fading channels, TCM can mitigate the effects of random signal fluctuations and provide diversity gain. The choice of channel model is crucial for accurately predicting the performance of TCM systems in different environments

CHAPTER 3: SIMULATION FRAMEWORK AND PERFORMANCE ANALYSIS OF TRELLIS-CODED MODULATION

3.1 Introduction:

The performance evaluation of Trellis-Coded Modulation (TCM) under various channel conditions is critical for understanding its practical implementation in digital communication systems. This chapter presents a comprehensive simulation study conducted in MATLAB to analyze the effectiveness of TCM in mitigating errors induced by additive white Gaussian noise (AWGN), Rayleigh fading, and Rician fading channels. The primary objectives are to model the complete TCM system, quantify its performance gains through key metrics such as bit error rate (BER) and coding gain, and compare its efficiency against uncoded modulation schemes. The analysis focuses on two modulation techniques—8-PSK and 16-QAM—integrated with TCM to evaluate the trade-offs between spectral efficiency and error robustness.

The chapter is structured as follows: Section 3.2 details the simulation methodology, including the system model and MATLAB implementation. Section 3.3 describes the parameter selection process for the simulations. Section 3.4 presents the performance metrics and their interpretations, supported by numerical results and graphical plots. Section 3.5 provides a comparative analysis of TCM across different channel conditions, followed by a discussion of the results in Section 3.6. Finally, Section 3.7 summarizes the key findings and suggests directions for future research.

3.2 Simulation Methodology

3.2.1 System Architecture

The TCM simulation framework consists of three primary components: the transmitter, the channel model, and the receiver. At the transmitter, input bits are first encoded using a convolutional encoder, which is then mapped to a modulated symbol constellation using either 8-PSK or 16-QAM. The encoded and modulated signal is passed through one of three channel models—AWGN, Rayleigh fading, or Rician fading—where noise and fading effects are introduced. At the receiver, the signal is demodulated and decoded using the Viterbi algorithm to recover the original bitstream.

The system's block diagram is illustrated in Figure 24, where each functional block is implemented in MATLAB to ensure modularity and reproducibility. The simulation leverages MATLAB's Communications Toolbox for accurate modeling of channel impairments and signal processing operations.

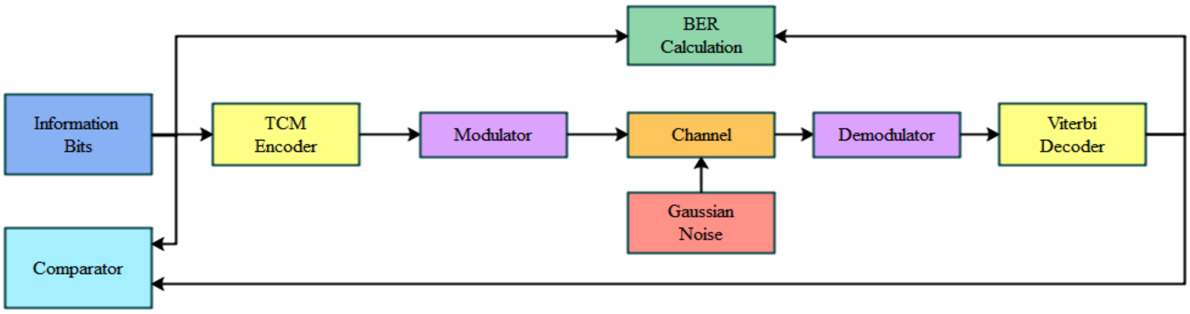

Figure 24: Block Diagram of the TCM Simulation Framework

3.2.2 MATLAB Implementation

The simulation was implemented using MATLAB R2013a, with scripts designed to automate the generation of BER curves and coding gain calculations. Below are the key implementation steps:

3.3 TCM Encoding and Modulation

The convolutional encoder is configured using a rate-1/2 trellis structure with a constraint length of *n=3,4,5,…etc*. The encoder output is mapped to a 16-QAM constellation using Gray coding to minimize bit errors in adjacent symbols. The following MATLAB snippet demonstrates the encoding and

modulation process:

```
seqlen=100000;
Psig=10; %normalised signal power
SNRdB=25; %signal to noise ratio in dB
noise_power=Psig/10^(SNRdB/10); %noise power
n=3; %The constraint length of the convolutional encoder
numstates=2^n; %Number of states
gen1=7;Genrating polynomial 1
gen2=5; Genrating polynomial 2
% 16-QAM constellation points
Mx=[3 3 -1 -1;1 1 -3 -3;1 1 -3 -3;3 3 -1 -1];
My=[-1 3 3 -1;-1 3 3 -1;-3 1 1 -3;-3 1 1 -3];
% 8-PSK constellation points
r=2/(sqrt(2-sqrt(2)));
rr=1/sqrt(2);
MPx=[r r*rr 0 -r*rr  -r -r*rr 0 r*rr];
MPy=[0 r*rr r r*rr  0 -r*rr -r -r*rr];
s1=randsrc(1,seqlen,[0,1]); %Bit stream 1 to be Encoded
s2=randsrc(1,seqlen,[0,1]); %Bit stream 2 (Uncoded)
s3=randsrc(1,seqlen,[0,1]); %Bit stream 3 (Uncoded)
```

3.4Channel Modeling

3.4.1 Additive White Gaussian Channel:

The channel introduces AWGN, Rayleigh fading, or Rician fading effects. For Rician fading, a K-factor of 3 is used to simulate a moderate line-of-sight (LOS) component. The MATLAB code below illustrates the channel modeling process:

```
nx=wgn(1,seqlen,noise_power,'linear','real');
ny=wgn(1,seqlen,noise_power,'linear','real');
```

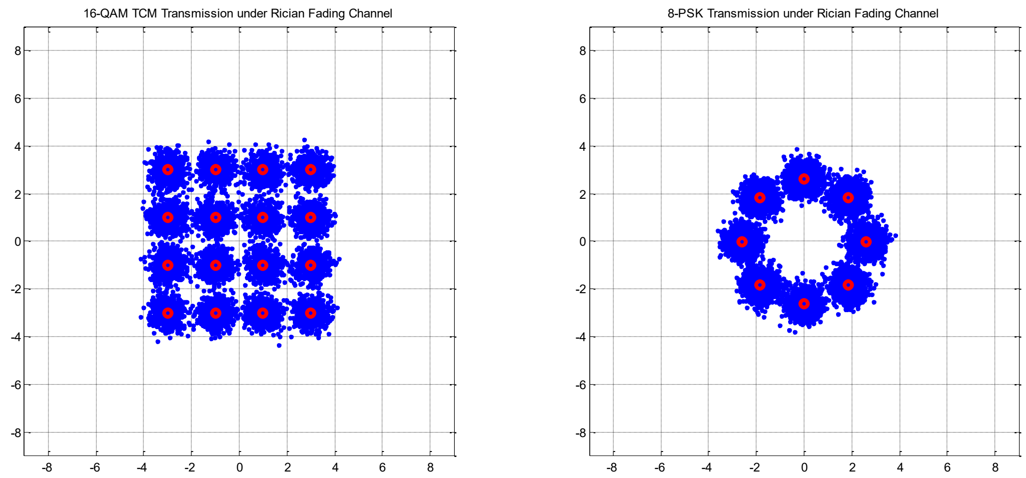

Figure 25: 16-QAM vs 8-PSK transmitted symbols under AWGN Channel

3.5Rayleigh Fading Channels:

Rayleigh fading is a statistical model used to describe the effect of a propagation environment on a radio signal, particularly in wireless communication systems where there is ***no dominant line-of-sight (LOS) component*** between the transmitter and receiver. It is commonly encountered in urban and indoor environments where multipath propagation dominates.[7]

```
functionsRx = rayleigh_chan2(sTx,N, N_taps,hMean)
hSigma = hMean/20;
    h = (randn(N_taps, N) + 1i * randn(N_taps, N)).*repmat(hSigma.' /
sqrt(2), 1, N) + repmat(hMean.', 1, N);
sRx = zeros(size(sTx));
for k = 1:N_taps
        delay = k - 1;
delayed_signal = [zeros(1, delay), sTx(1:end-delay)];
sRx = sRx + h(k,:).* delayed_signal;
end
end
```

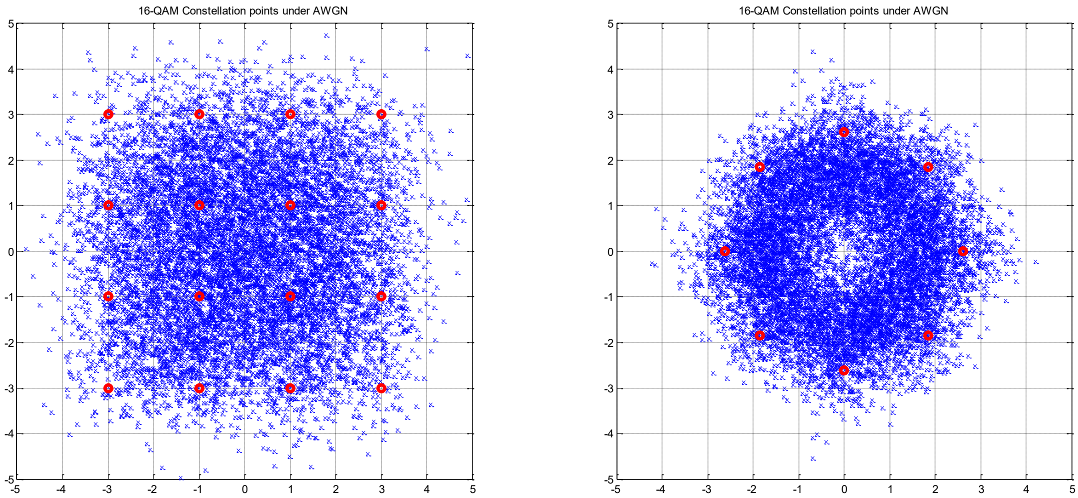

Figure 26: 16-QAM vs 8-PSK transmitted symbols under Rayleigh Channel

3.6 Rician Fading Channels:

Rician fading is a statistical model used to describe wireless channels where there is ***a dominant line-of-sight (LOS) component*** along with multiple scattered (NLOS) components. It is commonly observed in environments such as satellite communications, rural areas, and microcellular systems with a clear direct path.

```
functionsRx = rician_chan2(sTx,N, N_taps,hMean,K)
hSigma = hMean/20;
    h = (randn(N_taps, N) + 1i * randn(N_taps, N)).*repmat(hSigma.' / sqrt(2),
1, N) + repmat(hMean.', 1, N);
sRx = zeros(size(sTx));
    h(1,:)=h(1,:)*sqrt(K/(K+1));
    h(2:end,:)=h(2:end,:)*sqrt(1/(K+1));
fori = 1:N_taps
        delay = i - 1;
delayed_signal = [zeros(1, delay), sTx(1:end-delay)];
sRx = sRx + h(i,:).* delayed_signal;
end
end
```

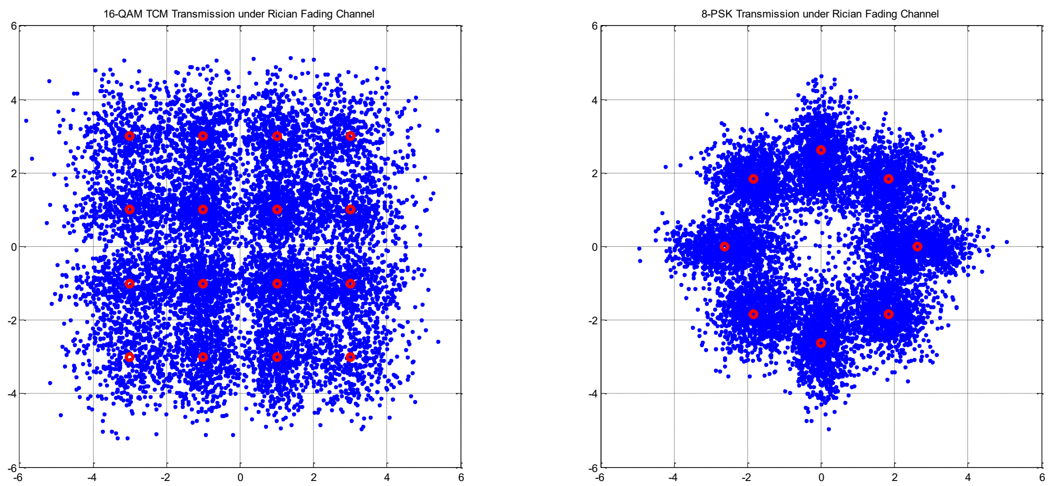

Figure 27: 16-QAM vs 8-PSK transmitted symbols under Rician Channel

3.7 Demodulation and Viterbi Decoding

The received signal is demodulated and decoded using a hard-decision Viterbi decoder. The BER is computed by comparing the decoded bits with the original transmitted bits:

```
perr=0;
surv=0;
cum1=zeros(numstates,1);
cum2=zeros(numstates,1);
states=starting_state;
for j=1:n
    k=1;
     for m=states
        p1=0;
        p2=0;
        mind1=0;
        mind2=0;
        [next1,next2]=nextstates(m,n);
        csnb1=coset(next1,gen1,gen2,n);
        [mind1,p1]=distances(csnb1,px(j),py(j),Mx,My);
sprevious(next1+1,j)=m+1;
sindex(next1+1,j)=p1-1;
        cum2(next1+1)=cum1(m+1)+mind1;
        csnb2=coset(next2,gen1,gen2,n);
        [mind2,p2]=distances(csnb2,px(j),py(j),Mx,My);
sprevious(next2+1,j)=m+1;
sindex(next2+1,j)=p2-1;
        cum2(next2+1)=cum1(m+1)+mind2;
        states(2*k-1)=next1;
        states(2*k)= next2;
        k=k+1;
      end
    cum1(:)=cum2(:);
end…………………………………………….
```

3.7.1 Parameter Selection:

The simulation parameters were carefully selected to ensure a comprehensive evaluation of TCM performance. The SNR range was varied from 3 dB to 19 dB in 1 dB increments to observe the system's behavior under low, moderate, and high noise conditions. Two modulation schemes: 8-PSK for uncoded bit streams and 16-QAM for convolutional coded bit stream were tested to assess the trade-off between spectral efficiency and error resilience.

Tableau 1: Simulation ParametersTableau 1

<table>
<tr><th>Parameter</th><th colspan="4">Value/Range</th><th>Description</th></tr>
<tr><td>SNR Range</td><td colspan="4">3–21 dB (1 dB steps)</td><td>Evaluated SNR levels</td></tr>
<tr><td>Modulation Schemes</td><td colspan="4">16-QAM, 8-PSK</td><td>With and without TCM</td></tr>
<tr><td>Channel Models</td><td colspan="4">AWGN, Rayleigh, Rician (K=10)</td><td>Fading scenarios</td></tr>
<tr><td>Constraint length n</td><td colspan="4">3,4,5</td><td>Different constraint lengths</td></tr>
<tr><td rowspan="5">Generating polynomials for n=3,4,5</td><td colspan="2">Good</td><td colspan="2">Bad</td><td rowspan="5">Good vs bad codes</td></tr>
<tr><td>Gen1</td><td>Gen2</td><td>Gen1</td><td>Gen2</td></tr>
<tr><td>5</td><td>7</td><td>1</td><td>3</td></tr>
<tr><td>13</td><td>14</td><td>3</td><td>7</td></tr>
<tr><td>26</td><td>29</td><td>3</td><td>17</td></tr>
</table>

3.8 Performance Evaluation

3.8.1Effect of codes on BER:

a) n=3

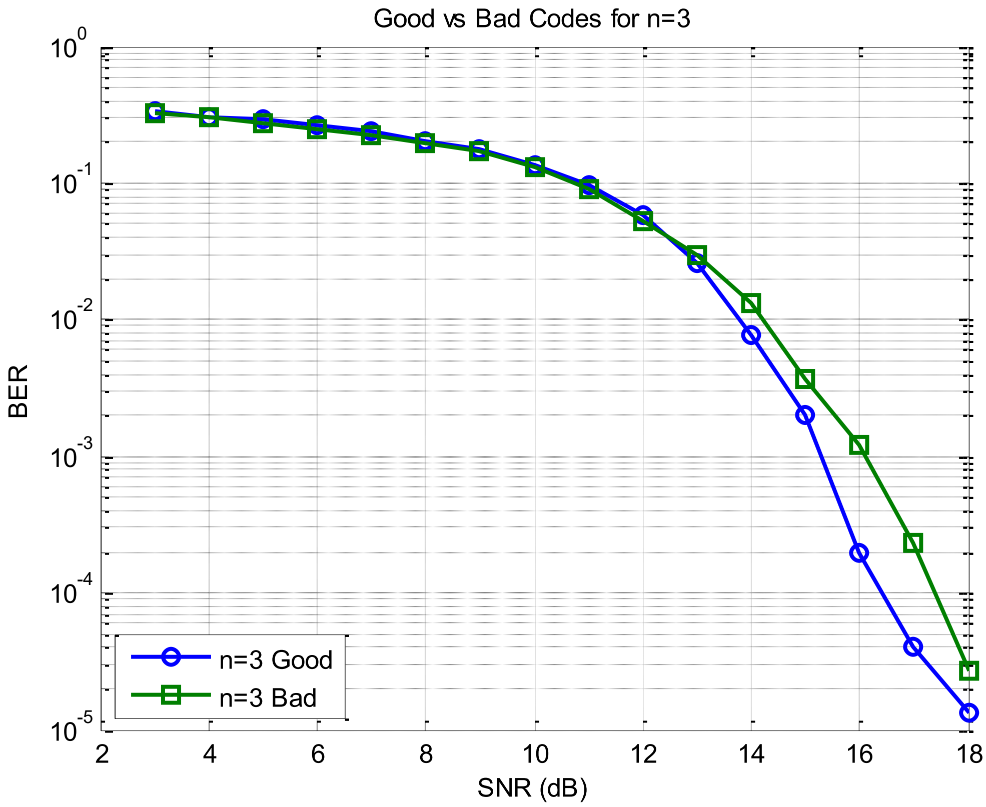

Figure 28: Good vs Bad Codes for n=3

b) n=4

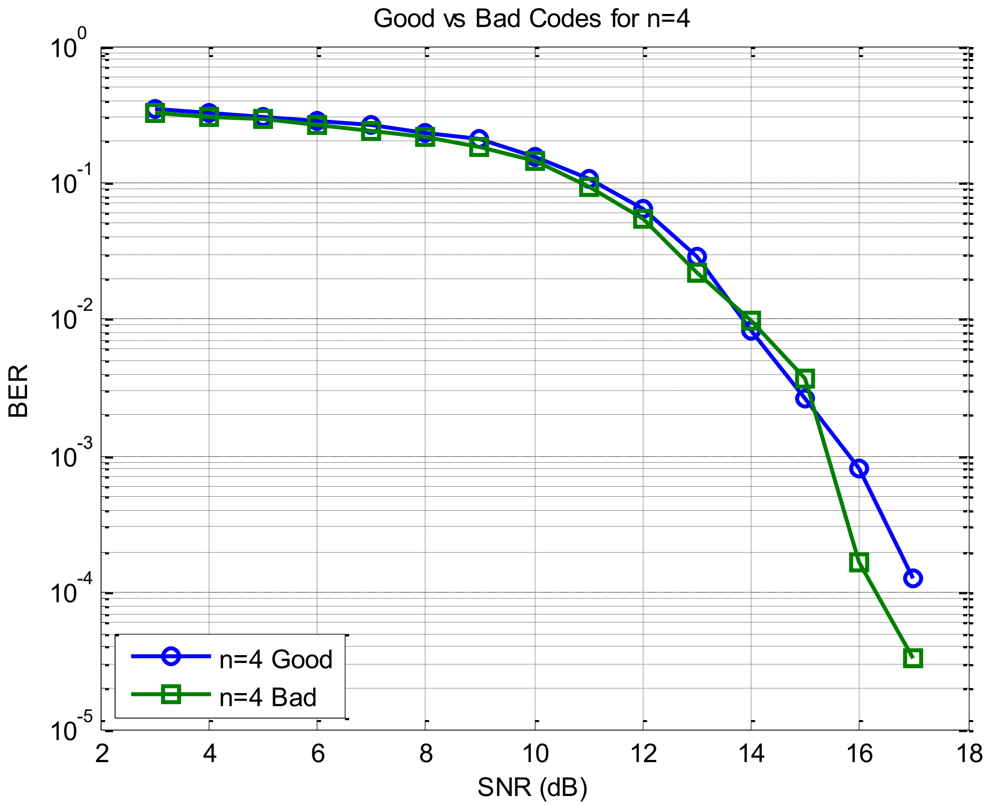

Figure 29: Good vs Bad Codes for n=4

c) n=5

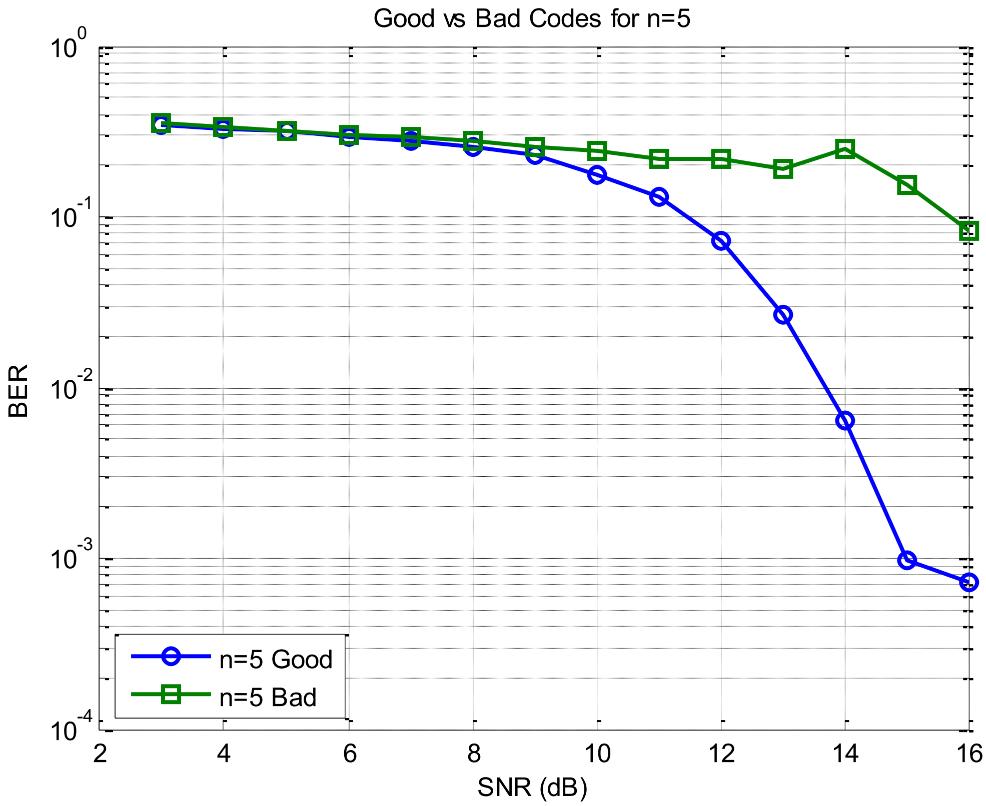

Figure 30: Good vs Bad Codes for n=5

3.8.2 Bit Error Rate (BER) Analysis

The BER performance of TCM was evaluated under AWGN, Rayleigh, and Rician fading channels. Figure 33 shows the BER vs. SNR curves for 16-QAMTCM in AWGN, highlighting the significant improvement over uncoded 8-PSK. At a BER of 10^{-4}, TCM provides a coding gain of approximately 4.4 dB in AWGN.

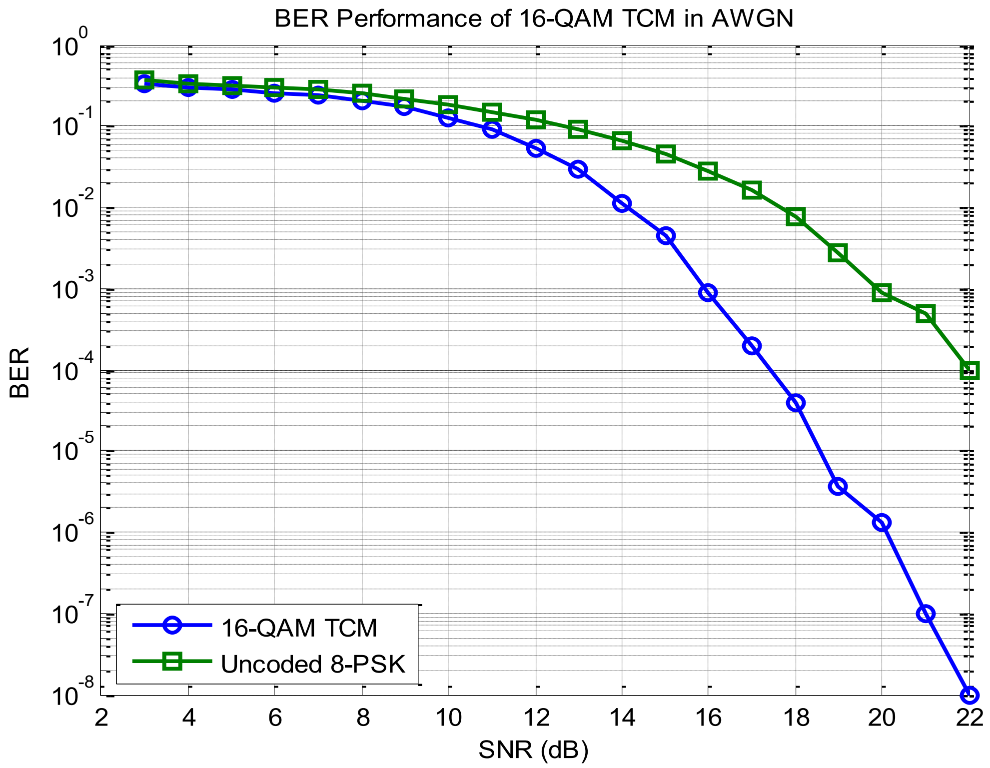

Figure 31: BER Performance of 16-QAM TCM in AWGN

Tableau 2: BER at 19 dB SNR for Different Channels

Scheme	AWGN	Rayleigh	Rician (K=10)
Uncoded 8-PSK	**2.9×10^{-3}**	**1.16×10^{-2}**	**5.9×10^{-3}**
TCM 16-QAM	**1.33×10^{-6}**	**5×10^{-4}**	**3.33×10^{-5}**

The results demonstrate that TCM significantly reduces BER, particularly in fading channels where the improvement can exceed two orders of magnitude.

3.8.3 Coding Gain Calculation

Coding gain, defined as the reduction in SNR required to achieve the same BER as an uncoded system, was calculated for each channel condition. Table 3.3 summarizes the coding gains for 16-QAMTCM.

Tableau 3:Coding Gain of 16-QAM TCM at a certain BER

Channel	Coding Gain (dB)
AWGN	**4.4 (BER=10^{-4})**
Rayleigh	**2.8 (BER=4×10^{-3})**
Rician (K=10)	**2.9 (BER=10^{-2})**

3.9 Comparative Analysis

3.9.1 BER Performance Across Channels

Figure 34 compares the BER performance of 16-QAM TCM in AWGN, Rayleigh, and Rician channels. The results indicate that Rician fading, due to its dominant LOS component, performs closer to AWGN than Rayleigh fading.

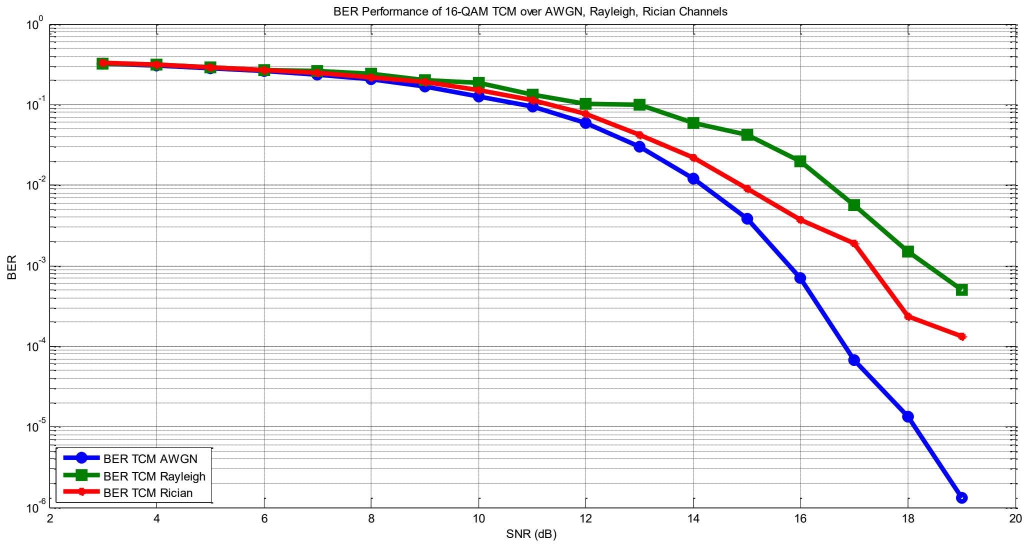

Figure 32: BER of 16-QAM TCM in AWGN, Rayleigh, and Rician Channels

4 Discussion of Results

The simulation results highlight several key insights:

1. TCM's Superior Error Resilience: TCM provides substantial coding gains across all channel conditions, with the most significant improvements in AWGN.

2. Fading Channel Behavior: Rician fading exhibits intermediate performance between AWGN and Rayleigh fading, underscoring the impact of LOS components.

3. The constraint length n and good vs bad codes are investigated in this project to conclude that codes must be chosen carefully to obtain high performance TCM systems

5 Conclusion

This chapter presented a detailed simulation study of TCM, demonstrating its effectiveness in improving BER performance without bandwidth expansion. The results validate TCM's robustness in fading channels and.

CONCLUSION GENERAL

general Conclusion:

This dissertation has examined the error performance of Trellis Coded Modulation (TCM) across a range of wireless channel conditions, including Additive White Gaussian Noise (AWGN), Rayleigh fading, and Rician fading environments. Through a combination of theoretical insights and simulation-based analysis, it has been demonstrated that while TCM performs reliably in AWGN channels, its robustness is challenged under fading conditions typical of real-world wireless systems.

The findings reveal that fading channels, particularly Rayleigh and Rician, introduce amplitude and phase distortions that significantly impact the Bit Error Rate (BER) of TCM systems. Nonetheless, TCM continues to provide notable coding gains over uncoded modulation schemes even under these adverse conditions, reaffirming its value as a bandwidth-efficient and error-resilient technique for modern wireless applications.

The study has also highlighted the importance of adopting adaptive modulation strategies and channel-aware design to fully exploit TCM's potential in time-varying environments. Integrating techniques such as channel estimation, diversity methods, or hybrid modulation schemes could further enhance system performance, especially in the context of next-generation wireless networks like 5G and beyond.

Ultimately, this research bridges the gap between theoretical performance and practical deployment by offering insights into TCM’s behavior under realistic channel conditions. It lays a foundation for future work aimed at optimizing TCM in conjunction with advanced technologies such as OFDM, MIMO, and cognitive radio systems. By deepening the understanding of TCM’s strengths and limitations, this study contributes to the development of more reliable, efficient, and adaptive digital communication systems.

Future work could explore adaptive TCM systems that dynamically switch between modulation orders based on real-time channel conditions, as well as the implementation of soft-decision decoding for further performance enhancements.

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Appendix: MATLAB Code for BER Curve Generation

```
SNR = 3:1:19;

BER_TCM_AWGN = [--,--,--,--,…….--];  % Fill in BER values for TCM

BER_Uncoded = [--,--,--,--,…….--];  % Fill in BER values for Uncoded 8-PSK

semilogy(SNR, BER_TCM_AWGN, '-o', SNR, BER_Uncoded, '-s');

xlabel('SNR (dB)');ylabel('BER');gridon;

legend('8-PSK TCM', 'Uncoded 8-PSK', 'Location', 'southwest');
```