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Simulation Of Faster Than Nyquist Rate Signaling For Communication Systems

A Thesis
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By

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بسمِ اللَّــهِ الرَّحْمَـٰنِ الرَّحِيمِ

﴿يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ﴾

المجادلة (١١)

صدق الله العلي العظيم

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Researcher

Dedication

To my beloved mother. Your presence is like a comforting embrace, always providing solace and strength when I need it most. Thank you for being my rock, my inspiration, and my guiding light.

To my little princess and my only friend.

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Abstract

Communication systems transmit information across channels, requiring careful design to ensure accurate and reliable transmission. The Nyquist-Shannon theorem dictates the minimum sampling rate for perfect reconstruction, limiting data rates and spectral efficiency. Faster than Nyquist rate signaling surpasses these limitations by introducing controlled inter symbol interference, allowing higher data rates within the same bandwidth. While promising increased spectral and energy efficiency, FTN faces challenges in receiver complexity and performance degradation due to noise and impairments. The ever-growing demand for high-speed data transmission presents a constant challenge in communication systems. Faster-than-Nyquist signaling emerges as a promising approach to improve spectral efficiency by exceeding the Nyquist rate and transmitting information beyond the traditional bandwidth limitations. This thesis investigates the performance of FTN signaling through simulations in four different configurations: uncoded, coded, coded with BCJR (Bahl-Cocke-Jelinek-Raviter) algorithm, and coded with OFDM (Orthogonal Frequency Division Multiplexing).The simulation results demonstrate a significant increase in spectral efficiency achieved by FTN signaling compared to traditional Nyquist rate signaling. Furthermore, incorporating coding techniques further enhances performance, with BCJR offering superior error correction capabilities and OFDM providing improved robustness against inter-symbol interference (ISI).The results of FTN signaling with BCJR is the most effective configuration, achieving the highest spectral efficiency while maintaining acceptable error rates. This is attributed to BCJR's iterative decoding process, which efficiently combats ISI and maximizes the information transmitted within the available bandwidth.FTN signaling with BCJR holds immense potential for future communication systems requiring high data rates and efficient utilization of limited spectral resources.

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List of Symbols

Symbol	Definition
E_b	Energy Bit
h_R(t)	Receiver Filter
N_o	Single Sided Noise Power Spectral Density
r(t)	Received Signal
r_0(t)	The output of the Matched Filter
r_c(t)	Convolving the Received Signal
s(t)	Transmitted Signal
s(t-nτT)	A pulse Shape
W(t)	White Noise
x[n]	Discrete-time Symbols
$\eta_{Nyquist}$	Efficiency of Nyquist
η_{FTN}	Efficiency of Faster Than Nyquist
∆η	The Difference Efficiency Between the Two Systems Over the Nyquist System
tau	Symbol period
τ	Accelerating Parameter
ß	Roll-off factors
1/T	Signaling Rate

List of Abbreviation

Abbreviation	Definition
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate.
BCJR	Bahl-Cocke-Jelinek-Raviv
BPSK	Binary Shift Keying
CFTN	Coded Faster Than Nyquist
CI	Constructive Interference
CP	Cyclic Prefix
DSL	Digital Subscriber Line
FFT	Fast Fourier Transform
FSO	Free Space Optical
FEC	Forward Error Correction
FSFC	Frequency-Selective Fading Channels
FTN	Faster Than Nyquist
FR	Frequency Response
FM	Frequency Modulation
5G	Fifth Generation
HPA	High-Power Amplifier
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
ICI	Inter Carrier Interference
LDPC	Low Density Parity Check
LED	Light Emitting Diode
MLSE	Maximum Likelihood Sequence Estimation
MMSE	Minimum Mean Squared Error

Abbreviation	Definition
ML	Machine Learning
MRI	Magnetic Resonance Imaging
MIMO	Massive Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
PAM	Pulse Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RRC	Root Raised Cosine pulse shaping filter
RC	Raised Cosine Filter
SNR	Signal to Noise Ratio
SE	Spectral Efficiency
TCM	Trellis Coded Modulation
TDM	Time Division multiplexing
VLC	Visible Light Communication

Publication

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Chapter One

Introduction

Chapter One

Introduction

1.1 Background

In the field of communication systems, the Nyquist rate, plays a crucial role in ensuring accurate information transmission. It represents the minimum sampling rate required to faithfully reconstruct a continuous-time signal from its discrete-time samples without introducing distortion known as "aliasing." a breakdown of the concept:

Nyquist rate = 2 * f_max, where f_max is the highest frequency component present in the signal.

Sampling at or above the Nyquist rate guarantees complete information retention and perfect reconstruction upon conversion to a digital signal.Sampling below the Nyquist rate leads to aliasing, where high-frequency components "fold" over and distort the signal, rendering accurate reconstruction impossible.

Disadvantages of Nyquist rate is High bandwidth requirement, Utilizing the Nyquist rate demands a communication channel with sufficient bandwidth to accommodate the necessary sampling rate, which can be expensive and resource-intensive. A limited flexibility Signals with high bandwidths require correspondingly high sampling rates, pushing the limits of processing capabilities and increasing system complexity.

Recent advancements in signal processing have opened the door to "faster-than-Nyquist" signaling techniques, surpassing the traditional Nyquist rate limit. These techniques exploit various mathematical and signal processing algorithms to achieve accurate reconstruction.

Faster than Nyquist (FTN) rate signaling is a digital communication technique used to increase the spectral efficiency of a communication system. It allows the transmission of more symbols within the same time interval, leading to a higher data rate without increasing the channel bandwidth. FTN signaling introduces a problem of inter symbol interference (ISI), can be alleviated through equalization [1], which arises when symbols from adjacent time intervals interfere with each other.

One way to mitigate the ISI problem is by using efficient pulse shaping techniques that reduce the symbol duration and increase the symbol rate while maintaining a low level of ISI. Additionally, advanced equalization techniques, such as the Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm, can be used to improve the performance of FTN signaling. FTN signaling has been widely studied and applied in various communication systems, including optical communication systems [2], wireless communication systems [1], and digital subscriber line (DSL) systems [3]. The use of FTN signaling has been shown to significantly increase the data rate of communication systems while maintaining a high level of reliability.

FTN signaling uses advanced mathematical techniques to encode data at a higher rate than the Nyquist rate, while still maintaining accurate signal reconstruction. FTN signaling is used in various applications, including high-speed digital communication systems.

It requires advanced signal processing techniques and is more susceptible to noise and interference than traditional Nyquist rate signaling. In a digital base-band transmission system, the Nyquist criterion traditionally dictates that to achieve communication without inter symbol interference (ISI), the symbol rate cannot exceed the Nyquist rate, alternative waveforms obtained through faster-than-Nyquist (FTN) signaling can be utilized [2]. By utilizing FTN signaling, more symbols can be transmitted within the same time interval, leading to higher data rates. However, this technique also causes the problem of ISI, which must be addressed.

1.2 Evolution of the FTN during time slots

Digital signals are transmitted using the faster than Nyquist rate signaling idea at a rate that exceeds the Nyquist limit, which is twice the bandwidth of the channel. The evolution of faster than Nyquist rate signaling has seen several advancements and techniques being developed. Here is a brief overview of some key milestones and techniques:

1.2.1 First time of Faster than Nyquist Signaling

FTN signaling allows for signaling rates that are higher than the Nyquist rate while maintaining the signal's integrity by using pulse shaping techniques. The idea behind (FTN) signaling was first introduced in the 1950s by Whittaker and Shannon. Since then, several research studies have focused on (FTN) signaling and its applications [22].

One of the early applications of (FTN) signaling was in frequency modulation (FM) broadcasting [24], where the spectral efficiency was increased by 50% by using (FTN) techniques. In the 1990s, (FTN) signaling gained renewed interest in the context of digital communication systems, particularly in the design of high-speed modems [26]. Researchers explored the use of (FTN) signaling in single-carrier and multi-carrier communication systems. In single-carrier systems, (FTN) signaling was found to offer a higher spectral efficiency than conventional Nyquist signaling. In multi-carrier systems such in form of an orthogonal frequency division multiplexing OFDM, FTN signaling was cause the inter-symbol interference and inter-carrier interference.

Numerous (FTN) signaling techniques have been proposed in the literature, including partial response signaling, Nyquist signaling with excess bandwidth, Hermite polynomial-based signaling, and sinc-based signaling. These techniques offer different trade-offs between spectral efficiency [22], complexity, and robustness to noise and channel impairments. Recent research in (FTN) signaling has explored its applications in emerging communication systems such as cognitive radio and visible light communication (VLC). FTN signaling has been shown to enable a higher data rate in cognitive radio systems by exploiting the unused frequency bands in the spectrum. In VLC, (FTN) signaling has been found to increase the data rate by using (LED) dimming techniques. FTN signaling is a technique used to increasing the spectral efficiency of communication systems [29]. While it has been studied for several decades, ongoing research is exploring new applications and techniques to improve its performance and make it more practical for real-world communication systems.

1.2.2 Late FTN Days (middle 1980s to early 2000s)

In mid-1980s to early 2000s, there were significant advancements in (FTN) signaling, including:

I. Trellis-coded modulation (TCM): TCM is a coding technique that combines modulation and coding to improve spectral efficiency of a communication systems. It is used in many digital communication systems, including those based on (FTN) signaling [23].

II. Turbo coding: Turbo coding is a coding technique that uses multiple decoders to improve an error correction performance of a communication systems. It was first introduced in the mid-1990s and quickly became a popular coding technique for (FTN) signaling.

III. Multi -level coding: Multi-level coding is a technique that uses multiple code rates to improve the performance of a communication system. It is particularly useful for (FTN) signaling because it allows for higher data rates while maintaining good error correction performance [38].

IV. Iterative decoding: Iterative decoding is a decoding technique that uses feedback to improve the performance of a communication system. It is particularly useful for (FTN) signaling because it allows for higher data rates while maintaining good error correction performance [30].

V. Pulse shaping: Pulse shaping is a technique used to reduce the interference between adjacent symbols in a communication system. It is particularly useful for FTN signaling because it allows for higher data rates while maintaining good signal quality.

These advancements in (FTN) signaling allowed for higher data rates and improved performance in digital communication systems, paving the way for the high-speed internet and mobile communication technologies that we use today.

1.2.3 Recent years significant advancements in Faster-than-Nyquist (FTN) signaling

In recent years, there have been notable and significant advancements in Faster Than Nyquist (FTN) signaling, showcasing the potential for exceeding the conventional Nyquist rate in signal processing and communication technologies which including:

I.Filter bank-based FTN: This technique uses filter banks to split the input signal into multiple sub-bands, each with a different bandwidth. The sub-bands are then processed separately using FTN signaling to increase the data rate.

II. Nonlinear FTN: Nonlinear (FTN) techniques use nonlinear signal processing to improve the spectral efficiency of (FTN) signaling. One example is the use of nonlinear distortion to increase the data rate while maintaining good signal quality, [31] make it possible for trellis-based decoders to equalize inter-symbol interference with a manageable level of complexity.

III. Machine learning-based FTN: Machine learning techniques, such as deep learning, have been applied to (FTN) signaling to improve its performance. For example, deep neural networks can be trained to optimize the shaping filter and the signal constellations for (FTN) signaling. In [32] and [33], receivers for (FTN) systems were developed using machine learning (ML) techniques.

IV. Joint source-channel coding: Joint source-channel coding (JSCC) is a method that combines source coding with channel coding to enhance a communication system's overall performance. JSCC has been applied to FTN signaling to achieve higher data rates and better error correction performance.

V. Massive MIMO and beamforming: Massive multiple-input multiple-output and beamforming are techniques used in wireless communication systems to increase the capacity and coverage of the network. The above techniques can also be applied to (FTN) signaling to achieve higher data rates and better performance in wireless communication systems. Utilizing constructive interference (CI) techniques, [34] used a method to reduce the minimum mean squared error (MMSE) for target parameter estimation while ensuring per-user quality of service.

These advancements in FTN signaling have allowed for even higher data rates and better performance in digital communication systems. They have also opened up new opportunities for research in areas such as wireless communication, machine learning, and signal processing.

1.3 Literature Survey

Faster-than-Nyquist (FTN) signaling is a technique for increasing the data rate of communication systems beyond the Nyquist rate, which is the theoretical limit for a bandwidth-limited channel. Signaling have been studied extensively in the literature over the last years. Here are some relevant works that have contributed to the development of coded and uncoded FTN signaling.

Kim &Jan, et.al. in 2010[4], The study of pre-coded faster-than-Nyquist (FTN) signaling spectrum broadening. They investigates the use of pre-coding techniques to reduce spectrum broadening and enhance system performance. The authors analyze various pre-coding techniques' effects on spectrum broadening using theoretical analysis and simulations, considering (SNR), (BER), and (SE). However, the paper's narrow focus on spectrum broadening overlooks other possible challenges and advantages of FTN signaling. To improve practical relevance, more comprehensive experimental results and comparisons with existing techniques are needed.

Anderson, John B, Rusek, and Öwall, et al. in 2013[5], They presents an overview of FTN signaling, highlighting its implementation, performance, and benefits, it overlooks challenges like noise vulnerability, decoding complexity, and the need for advanced equalization techniques. Further exploration of limitations and practical considerations would enhance its real-world applicability [5].

Le, Chung, et al. in 2014[6], In this study emphasizes the benefits of FTN signaling, such as enhanced bandwidth efficiency through symbol overlap and reduced latency for faster data transmission. They also highlights increased data throughput,a critique is the insufficient discussion of challenges and trade-offs, such as noise vulnerability and receiver complexity.

Hadkhale, Ishwor, et al. in 2015[7], This work analyzes the impact of FTN signaling on BER and spectral efficiency in both uncoded and coded transmission systems. They investigates FTN signaling's performance in coded systems, including error-correction capabilities, code rate, decoding complexity, and achievable coding gain. However, a critique is the limited discussion of specific coding schemes and their compatibility with FTN signaling, which could provide deeper insights into performance trade-offs.

Kim, Jin, and Seo,et al. in 2016[8], This study shows that FTN signaling achieves higher data rates with symbol overlap but faces challenges with accurate symbol detection due to inter symbol interference (ISI), a critique is the limited evaluation and comparison of the proposed technique against existing methods, considering factors like bit error rate, computational complexity, and robustness to noise and channel impairments. Conducting a more comprehensive evaluation under various conditions would enhance the analysis and practical relevance of the findings.

Qian, Bin, et al. in 2017[9], This work presents a parallel computational scheme to mitigate ISI in FTN signaling, improving signal quality through interference cancellation, a potential criticism is the limited discussion of computational complexity and practical feasibility. Additional experimental results or simulations across different scenarios are needed to validate the effectiveness. Further exploration of complexity, feasibility, and performance evaluations is required to enhance its practical applicability.

Wang, Ke, et al. in 2018[10], This work introduces the concept of FTN-based multicarrier systems that leverage advanced modulation and coding techniques for high-rate data transmission. By reducing the sampling rate,(SE) is increased, enabling higher data rates within the same bandwidth. However, a critique is the limited discussion of practical considerations and the potential impact on system performance and complexity, emphasizing the need for careful system design.

Li, Qiang, et al.in 2019[11], This study introduces a pre-equalization method to mitigate interference, specifically inter symbol interference (ISI), for improved symbol detection and system performance. However, a potential criticism is the limited evaluation and comparison against existing methods, including aspects like bit error rate, computational complexity, and adaptability to different interference and channel conditions. Further evaluation, comparative analysis, and consideration of practical limitations are needed to enhance the technique's practical relevance and analysis.

Li, Qiang, et al.in 2020[12], This work explores linear precoding in FTN signaling to mitigate inter symbol interference (ISI) and improve data rates. However, a potential criticism is the limited discussion of specific linear precoding techniques and their compatibility with FTN signaling, including considerations of complexity, computational requirements, and robustness to channel impairments. Further analysis, validation, and exploration of practical scenarios are necessary to enhance the proposed approach's practical applicability and analysis.

Brkic, Srdan, Predrag, and Andreja, et al.in 2021[13], This paper acknowledges the practical limitations of implementing FTN signaling in resource-constrained systems, a potential critique is the limited evaluation or comparison of the proposed techniques with existing methods commonly used in such systems. Assessing performance in terms of bit error rate, data rate, and computational complexity, and comparing against alternative approaches is crucial. Lastly, the paper highlights the challenges of implementing FTN signaling in systems with limited computational resources.

Cao, Minghua, et al.in 2022[14], This paper analyzes the BER performance of staircase codes in FTN-FSO communication systems, which combine FTN signaling and optical links for higher data rates. Staircase codes offer error detection and correction capabilities. However, a potential critique is the paper's limited focus, as considering additional performance metrics like throughput, latency, or spectral efficiency would provide a more comprehensive evaluation of the overall system performance.

The above works have contributed to the development of FTN signaling techniques for communication systems. The techniques and algorithms improve the data rate, error performance, and reliability of FTN signaling, making it a promising technique for high-speed communication systems. Previous studies have not reached the ability to send data at a high data rate while maintaining the bit error rate and bandwidth of the signal or using the best type of modulation and pulse shaping to get the best results.

1.4 Problem Statement

Faster-than-Nyquist (FTN) rate signaling involves addressing the challenges and limitations associated with achieving higher data rates.

I. Inter symbol Interference (ISI): The higher symbol rate can lead to overlapping symbols, causing ISI where the influence of one symbol extends into the following symbols, degrading signal integrity.

II. Spectral Occupancy Challenges: Oversampling can result in a signal occupying a larger portion of the frequency spectrum, making it harder to efficiently use the available bandwidth without causing interference.

III. Receiver Complexity: Faster signaling requires more sophisticated receivers with higher sampling rates, adding complexity and cost to the system.

IV. Channel Equalization Difficulty: Mitigating ISI through channel equalization becomes more challenging as the symbol rate increases, potentially affecting the system's overall performance.

1.5 Aims of Thesis

Simulating faster-than-Nyquist rate signaling for communication systems in three ways (coded, uncoded, and with OFDM) would address several key aims:

I. Investigate the impact of oversampling techniques on signal quality, system capacity, and error rates, including the generation of inter symbol interference (ISI) when transmitting symbols at a rate higher than the Nyquist rate.

II. Study the effects of varying modulation schemes and data rates on system performance, considering metrics such as bit error rate (BER), throughput, and spectral efficiency.

III. Comparing the performance of coded and uncoded faster-than-Nyquist signaling: Compare the spectral efficiency, and BER of coded and uncoded faster-than-Nyquist signaling. This will reveal the benefits and drawbacks of using coding in conjunction with faster-than-Nyquist signaling.

IV. Evaluating the effectiveness of OFDM in faster-than-Nyquist signaling: Investigate the performance of faster-than-Nyquist signaling with OFDM in various channel conditions. This will determine the benefits of using OFDM to mitigate channel impairments and improve the robustness of faster-than-Nyquist signaling.

V. Assess the computational complexity of advanced equalization and detection techniques used in FTN systems, considering their practical implementation in real-time scenarios or resource-constrained devices.

By addressing these objectives, the simulation study would provide a comprehensive understanding of faster-than-Nyquist signaling and its potential benefits for various communication applications.

1.6 Thesis Outline

The following chapters comprise the rest of the thesis.

- **Chapter Two** " Theoretical Concepts" discusses the essential concepts that have been used in implementing the proposed work.
- **Chapter Three** " Faster Than Nyquist Rate Signaling for Communication System " It covers the key components of the system and describes how to simulate each one.
- **Chapter Four** "Results and Discussion" discusses the simulation results and comparisons between them from many cases.
- **Chapter Five** "Conclusions and Future works" introduces the conclusions and the future works to simulate and implement system with new technique.

Chapter Two

Theoretical Concepts

Chapter Two

Theoretical Concepts

2.1 Introduction

An accurately reconstruct a continuous-time signal, a minimum sampling rate known as the "Nyquist rate" is required. It's based on Nyquist-Shannon sampling theorem, aliasing can be prevented by sampling at least double the rate of the highest frequency component of the signal. Faster than Nyquist rate (FTN signaling) a technique used to transmit data at rates higher than Nyquist rate [2]. It allows symbols for overlap in the time domain, increasing the spectral efficiency of communication systems.

FTN signaling poses challenges in signal detection and decoding due to interference and inter symbol interference (ISI). Advanced signal processing and error correction coding help mitigate these issues for reliable communication.

The Nyquist rate sets the minimum sampling rate required for accurate signal reconstruction, while faster than Nyquist rate signaling allows for sending data at rates higher than Nyquist limit [5].

2.2 Nyquist Sampling in Communication Systems

Faster than Nyquist (FTN) signaling relies on understanding Nyquist sampling in communication systems. Digital signal processing is based on the Nyquist-Shannon sampling theorem, sometimes known as Nyquist sampling, It guides the accurate capture and reconstruction of continuous-time signals into discrete-time signals. In communication systems, Nyquist sampling is essential for analog-to-digital conversion, where continuous analog signals are sampled and converted into digital representations [21].

According to Nyquist sampling theorem, a sampling rate must be at least twice the signal's highest frequency component in order to accurately reconstruct a continuous-time signal from its samples. This rate is referred to as Nyquist rate. By sampling above Nyquist rate, original signal can be reconstructed without any loss of information. If the sampling rate falls below Nyquist rate, aliasing occurs, causing distortion and loss of information as higher-frequency components fold back into lower-frequency regions [22].

Nyquist sampling is widely used in various communication systems, including audio and video processing, digital communications systems. It provides a theoretical basis for determining appropriate sampling rates to ensure accurate and reliable signal processing [23].

Nyquist's contributions in 1924 and 1928 laid the foundations of modern digital communication systems. He created a thorough data transfer across continuous-time bandlimited channels using the baseband model, laying foundation for widely accepted notions in digital communication systems. According to Nyquist's model, baseband transmission signal expressed as follows:

$$x(t) = \sum_{n=o}^{N-1} x[n]s(t - nT) \quad (2.1)$$

In the context of the communication channel, the continuous-time baseband signal x(t) is to be transmitted. x[n] represents the nth symbol to be transmitted, s(t-nτT) represents the pulse shape, and the summation is taken over all the symbols. These symbols are mapped onto continuous-time modulating pulses, represented by s(t+T), s(t+2T), s(t), s(t−T), s(t−2T), and so on. It is assumed that these modulating pulses are bandlimited to W Hertz. The model described above, equation (2.1), can be seen in Figure 2.1 as transmitting pulses with information at regular intervals of T seconds. It is critical to notice that these pulses may significantly overlap in time, provided they continue to be orthogonal to one another[20].

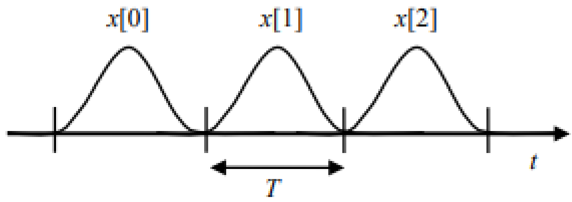


Figure (2.1): Illustrative Depiction of Conventional Interference-Free Nyquist-Rate Communication of Modulation Symbols [20]

Nyquist's work demonstrated that the maximum signaling rate, denoted as 1/T. This is equivalent to 2W pulses per second and prevents inter symbol interference (ISI) across a bandlimited communication channel with a bandwidth of W Hertz.

A rate is known as the Nyquist rate has become the standard in modern communication systems. The adoption of Nyquist rate signaling, which allows for 2W symbols per second, is primarily driven by the simplicity of receiver architecture, which consists of a matched filter and a sampler [18], [19].

In the most communication systems, a matched filter is commonly employed. This matching filter was created to match the pulse shape of the modulation. The Nyquist rate sampler that follows it maximizes the received additive white Gaussian noise channel, signal-to-noise ratio. These components ensure efficient signal reception. Consequently, the majority of modern digital communication systems are built on the premise that the transmitter and receiver use Nyquist rate signaling and sampling, respectively.

2.3 Faster Than Nyquist (FTN) Signaling

Numerous researchers, have thought about the practical ramifications of signaling more quickly than the channel's Nyquist rate in the wake of Nyquist's groundbreaking work on zero (ISI) transmission across bandlimited channels. An alternative approach is conceptually depicted in Figure (2.2) [20]. Notably, in (FTN) signaling, pulses that overlap are no longer orthogonal. Communication engineers have long been curious about whether signaling at a rate faster than Nyquist offers any advantages over conventional Nyquist rate signaling. Early allusions, such as writings by Foschini [21], Landau [22], Lucky [23], Mazo [24], Saltzberg [25], Salz [26], and others, reflect the ongoing exploration of this topic.

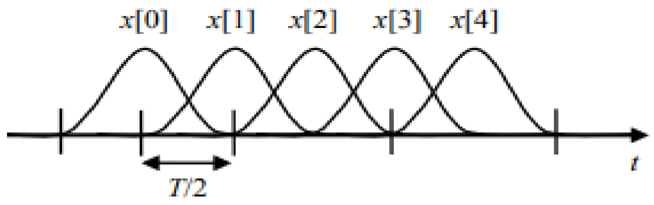


Figure (2.2): An illustration of faster-than-Nyquist signaling on a continuous-time bandlimited channel with built-in inter-symbol interference between transmitted symbols [20].

One of the key challenges associated with FTN signaling is the intricate processing needed to deal with (ISI) that is a given [21] that arises as a consequence of the higher transmission rate. Dealing with this cumbersome (ISI) has been a major hurdle in exploring and implementing FTN transmission techniques. Researchers have long contemplated the advantages of signaling in communication systems at a rate faster than Nyquist rate. Although this topic has not received significant attention until recently, early references indicate ongoing interest.

The main obstacle lies in effectively managing the (ISI) that arises from FTN transmission, requiring intricate processing techniques, (FTN) signaling, to increase a spectrum efficiency for future satellite communication networks, would necessarily include the unwanted (ISI) [27].

FTN signaling helps achieve a faster data rate than Nyquist signaling. Nyquist signaling involves transmitting and sampling T-orthogonal pulses spaced at T intervals, where the sampling intervals eliminate the effect from nearby pulses. In contrast, (FTN) signaling employs an acceleration parameter τ ($0 < \tau < 1$), where transmission and sampling occur at intervals of τT instead of T, resulting in non-zero contributions from neighboring pulses at the sampling intervals [28].

Nyquist signaling, named after Harry Nyquist (1889-1976) [1], is a commonly used technique for transmitting digital signals without any (ISI) in a band-limited channel. In Nyquist signaling, the pulse shaping filter ensures that the signal is orthogonal to the sampling instants, allowing the receiver to reconstruct the transmitted signal without any errors due to (ISI), on the other hand, Faster-than-Nyquist signaling is technique that allows to higher data rates than Nyquist signaling, by violating the Nyquist criterion, which states that maximum achievable data rate was equal to channel bandwidth divided by two.

FTN signaling involves transmitting pulses at intervals smaller than the Nyquist sampling rate, resulting in some ISI between neighboring pulses. However, by properly designing the pulse shape and receiver filters, the ISI can be mitigated, allowing for higher data rates without compromising the error performance. One of the early works on (FTN) signaling was by J. E. Mazo in 1975[24], who demonstrated that the transmission of Nyquist pulses may be accelerated by a factor of 0.802T while retaining the same bandwidth, without increasing the minimum Euclidean distance between pulses and without BER worsening. Since then, there have been many studies and research on (FTN) signaling, and it has been applied in various communication systems, including digital subscriber line (DSL) systems, wireless communications, and optical communications[14-16].

2.4 The Basic Components of FTN Signaling

The basic components as shown in Figure (2.3) [35] works together to enable the transmission, reception, and processing of FTN signals, enabling increased data rates and better spectral efficiency in comparison to traditional Nyquist rate signaling. The precise implementation and configuration of these components may vary depending on the specific FTN system design and the requirements of the communication application. In FTN signaling, the symbol rate is increased while keeping the pulse shape unchanged. This means that the symbol period is reduced to τT, where 0 < τ < 1 represents an accelerating (or squeezing) parameter. Consequently, a transmitted signals is transformed to reflect this change.

$$x(t)=\sum_{n=o}^{N-1} x[n]s(t-n\tau T) \qquad (2.2)$$

The equation (2.2) represents the continuous-time signal x(t) as a sum of discrete-time symbols x[n] multiplied by a pulse shape s(t-nτT), where n is an integer index and T is the symbol duration.

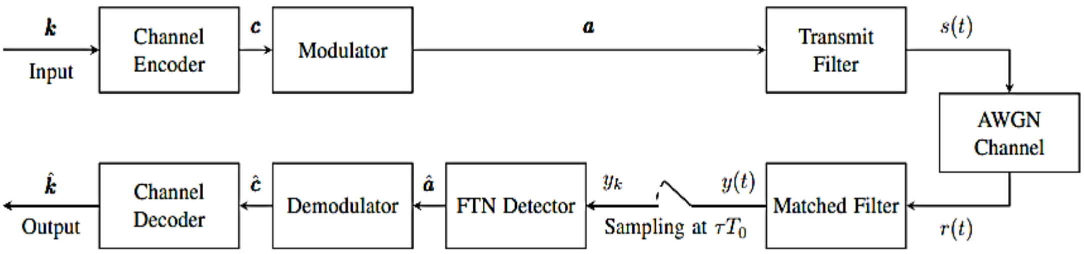


Figure (2.3): A coded FTN signaling system's block diagram [35].

2.4.1 Transmitter

The transmitter in a faster than Nyquist rate signaling system plays a critical role in shaping and transmitting the signals with the desired characteristics. The specific design of the transmitter depends on the modulation scheme and the requirements of the FTN system [29]. The transmitter in an FTN system employs various signal processing techniques, modulation schemes, and coding schemes to optimize the transmission of data at higher rates while maintaining reliable communication. The design of the transmitter is carefully tailored to meet the specific requirements of the FTN system and to ensure efficient and robust signal transmission. Here are some key components typically found in an FTN transmitter:

2.4.1.1Channel Encoder

In the context of faster than Nyquist rate signaling, channel encoding refers to the process of applying error correction coding to the transmitted signal [28]. The primary purpose of channel encoding is to improve the reliability of communication by introducing redundancy into the signal.When transmitting data at rate higher than nyquist rate, the overlapping symbols in the time domain can lead to increased interference and potential inter symbol interference (ISI). This can cause errors in signal detection and decoding at the receiver. Channel encoding helps mitigate these errors by adding redundant bits to the transmitted signal.

The channel encoder takes the input data stream k and adds additional bits, creating a coded sequence. These additional bits are carefully designed to provide redundancy and enable error detection and correction at the receiver [32]. Popular channel encoding techniques include forward error correction codes such as Reed-Solomon code, convolutional code, and turbo code. At the receiver, the received signal is decoded using the corresponding channel decoding algorithm. The decoder analyzes the received bits and attempts to correct any errors introduced during transmission. By utilizing the redundancy introduced by the channel encoding, the decoder can reconstruct the original data stream more accurately.

The choice of channel encoding scheme [36] depends on various factors, including the characteristics of the communication channel, the desired error performance, and the complexity constraints of the system. The goal is to strike a balance between the added redundancy and the achieved error correction capability, optimizing the overall performance of the FTN communication system.This allows for more reliable communication at rates higher than the Nyquist rate, mitigating the challenges introduced by the overlapping symbols in the time domain.

2.4.1.2 Modulation Techniques

When employing Faster Than Nyquist signaling, various modulation techniques may be used for transmit data at rates higher than the Nyquist limit [37]. These modulation techniques aim to efficiently encode the information onto the carrier signal, allowing for increased spectral efficiency. Here are a few modulation techniques commonly used in FTN signaling:

I. Pulse Amplitude Modulation (PAM): PAM is a modulation technique that encodes data by varying the amplitude of individual pulses. In FTN signaling, higher-order PAM schemes, such as 4-PAM, 8-PAM, or even higher, can be employed to transmit multiple bits per symbol. By using a larger number of amplitude levels, PAM allows for a higher data rate compared to traditional binary modulation schemes.

II. Quadrature Amplitude Modulation: (QAM) combines phase and amplitude modulation. By adjusting the carrier signal's amplitude and phase, it encodes data. Higher-order QAM systems, such as 16-QAM, 64-QAM, or higher, are used in FTN signaling, can be used to transmit multiple bits per symbol. Similar to PAM, QAM allows for increased data rates by utilizing a larger number of amplitude and phase combinations [38].

III. Binary Phase Shift Keying: BPSK is a modulation techniques that can be used in faster than Nyquist rate (FTN) signaling to achieve higher data rates. BPSK is a form of phase shift keying where the carrier signal's phase is shifted by 180 degrees (π radians) to represent different symbols. In traditional BPSK, two phase states are used: 0 degrees (corresponding to a binary 0) and 180 degrees (corresponding to a binary 1). However, in FTN signaling, additional phase states can be introduced to transmit multiple bits per symbol, resulting in higher data rates as shown in Figure (2.4).

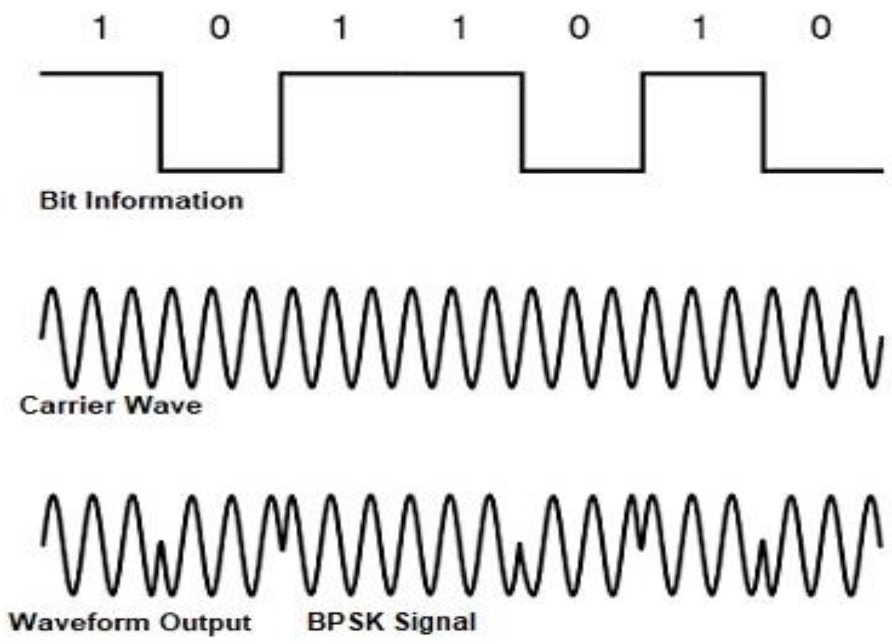


Figure (2.4): BPSK modulation.

IV. Quadrature Phase Shift Keying : QPSK is a modulation techniques that is well-suited for faster than Nyquist rate (FTN) signaling, allowing for increased data rates. QPSK is a form of phase shift keying where the carrier signal's phase is shifted to represent different symbols. In QPSK, the signal constellation consists of four equally spaced phase states: 0, 90, 180, 270 degrees. Each phase state represents a combination of two bits. By transmitting two bits per symbol, QPSK effectively doubles the data rate compared to traditional binary phase shift keying (BPSK).

In FTN signaling, QPSK can be utilized to transmit even higher data rates. By introducing additional phase states and using higher-order QPSK schemes, such as 8QPSK or 16QPSK, more bits will be transmitted per symbol. For example, 8QPSK has eight equally spaced phase states, allowing for the transmission of three bits per symbol, while 16QPSK has sixteen phase states, enabling the transmission of four bits per symbol[28]. A receiver in an FTN system must accurately detect and decode the received phase to recover the original bit sequence.

This involves comparing the received phase with the predefined phase states to determine the transmitted symbol. QPSK and its higher-order variants provide efficient modulation schemes for FTN signaling, allowing for increased data rates while maintaining spectral efficiency. These modulation techniques are used in various communication systems, including wireless, satellite, and digital modulation standards, where high-speed data transmission is required . For example equation of QPSK modulation is given by[39]:

$$BER_{QPSK} = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \tag{2.3}$$

Where $Q \approx \frac{1}{x\sqrt{2\pi}} \exp\left(\frac{-x^2}{2}\right)$ is the complementary error function of a normal distribution, E_b is a signal energy per binary symbols, and N_0 is a single sided noise power spectral density.

These are just a few examples of modulation techniques used in FTN signaling. Choice of modulation technique depends on factors such as desired data rate, bandwidth constraints, and characteristics of the communication channel. By employing these modulation techniques, FTN signaling enables higher data transmission rates while maintaining reasonable error performance.

2.4.1.3 Transmit Filter

In faster than Nyquist rate (FTN) signaling, a transmit filter is a crucial component that shapes the transmitted signal to comply with the desired spectral characteristics and mitigate interference. The primary function of transmit filter is to limit bandwidth of a signal and reduce the potential for inter symbol interference (ISI) caused by the overlapping of symbols in FTN signaling[46]. A choice of transmit filter depends on a specific FTN modulation scheme with system requirements. Here are a few common types of transmit filters used in FTN signaling.

I.Raised Cosine Filter: The raised cosine filter is a widely used filter in digital communication systems, including FTN signaling. It is designed to have a frequency response that gradually rolls off to suppress out-of-band interference and minimize ISI. The raised cosine filter exhibits a smooth transition between time-domain symbols, helping to maintain signal integrity. The effectiveness of the FTN transmitter with RC shaping pulses has been investigated in [40].

II. Gaussian Filter: The Gaussian filter is another popular choice for FTN signaling. It has a frequency response shaped like a Gaussian distribution. The Gaussian filter provides excellent spectral efficiency and is known for its ability to limit out-of-band interference. It offers a smooth frequency response and reduces the impact of ISI.

III. Root Raised Cosine Filter: It is a variant of a raised cosine filter commonly used in FTN signaling [41]. It provides better pulse shaping properties, minimizing ISI by achieving zero inter symbol interference at specific symbol boundaries. The RRC filter offers a compromise between spectral efficiency and ISI mitigation.

These are just a few examples of transmit filters used in FTN signaling as shown in Figure (2.5) [42]. The specific choice of filter depends on various factors, including the modulation scheme, desired data rate, bandwidth constraints, and system performance requirements. The goal is to design a transmit filter that effectively limits the signal bandwidth while mitigating interference and maintaining the signal integrity necessary for reliable communication in FTN systems.

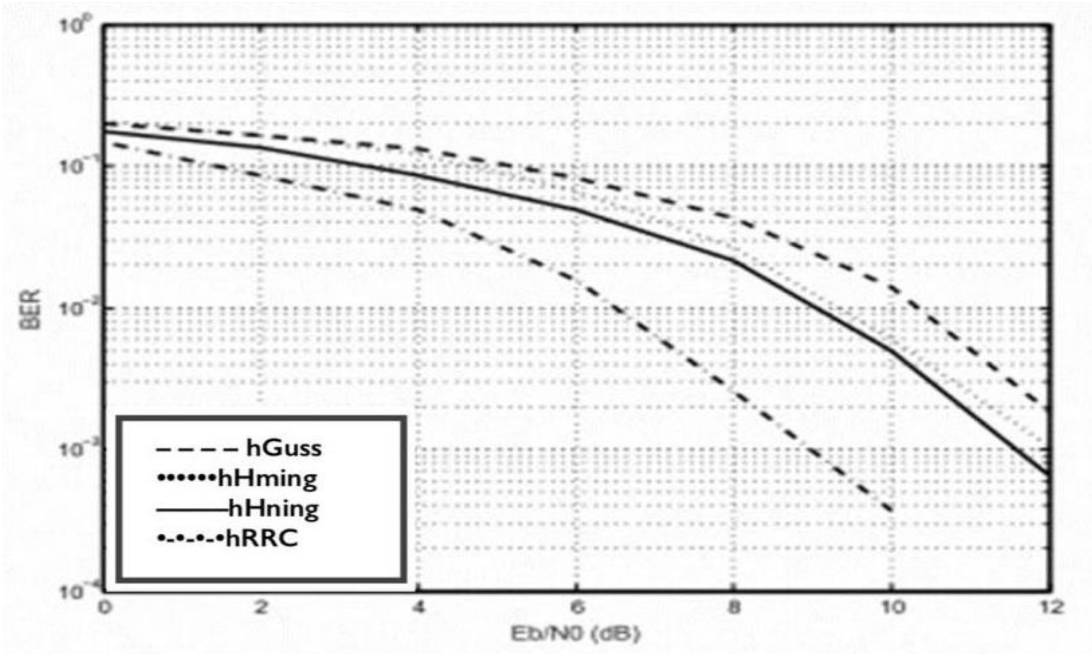


Figure (2.5): BER of the FTN system with various pulse shaping filters [42].

2.4.2 Channel Models

Channel models play a crucial role in design with evaluation of communication systems employing faster than Nyquist rate (FTN) signaling. These models capture the characteristics and impairments of the transmission medium through which the signals propagate [43]. Here are a few common channel models used in (FTN) signaling:

I. Additive White Gaussian Noise Channel: It is a widely used and fundamental channel model. Received signal is corrupted by Gaussian noise with constant a power spectral density. While an AWGN channel simplifies analysis and implementation of communication systems, it does not capture more complex channel impairments. This thesis considers the AWGN

$$r(t) = s(t) + w(t) \tag{2.4}$$

Here, r(t) represents received signal, s(t) represents transmitted signal, and w(t) denotes additive noise. This assumption simplifies the analysis that allows for the use of statistical models, such as Gaussian distribution, to characterize the noise in the AWGN channel[43].

By considering the additive noise as an independent component, engineers and researchers can analyze the impact of noise on received signal and evaluate the system's performance, such as (BER) or (SNR). This analysis aids in understanding the system's robustness against noise and in designing techniques to mitigate its effects for reliable FTN signaling.

II. Frequency-Selective Fading Channels: In real-world scenarios, the transmitted signals encounter multipath propagation, causing the signal to experience frequency-selective fading [28]. This indicates that multipath interference causes different frequency components of the signal to experience varying degrees of attenuation and phase distortion. Channel models like Rayleigh fading and Rician fading are often used to simulate these effects.

A selection of channel model depends the specific applications and system specifications, and the desired level of realism in the simulation or analysis. These channel models help researchers and engineers evaluate the performance of FTN signaling systems under various channel conditions and optimize their designs accordingly.

2.4.3 Receiver

The receiver in a faster than Nyquist rate (FTN) signaling system plays a crucial role in detecting and decoding the transmitted signals accurately [32]. The receiver is responsible for recovering the original data from the received signals, compensating for channel impairments, and extracting the transmitted information.

By the receiver components and techniques in an FTN system aims to accurately detect and recover the transmitted signals, compensate for channel impairments, and reconstruct the original data. The design of the receiver is carefully optimized to ensure reliable and efficient reception in the presence of noise and interference. Here are some key components typically found in an FTN receiver [44]:

2.4.3.1 Matched Filter

In faster than Nyquist rate (FTN) signaling, a matched filter is a key component used in the receiver to improve the detection and decoding of the transmitted signals. A signal-to-noise ratio at the receiver output is maximized by the matching filter [3]. making it an essential technique for signal recovery in FTN systems. The matched filter is a linear filter that has an impulse response that is the time-reversed and conjugate of the transmitted pulse shape. It is called a "matched" filter because it is designed to match the shape of the transmitted pulse. The purpose of the matched filter is to maximize the correlation between the received signal and the expected pulse shape, enhancing the detection of the transmitted symbols.

In Faster Than Nyquist rate signaling systems, presence of time-variant and unknown inter symbol interference (ISI) poses a challenge for matching a filter directly to the ISI [45]. An alternative strategy is used as a result, in which the receiver filter is matched to the transmit pulse shape. To achieve this, the impulse response of the receiver filter, denoted as h_R(t), is designed to be the time-reversed and conjugate of the transmit pulse shape.

This design choice allows the receiver filter to be optimized for detecting the transmitted symbols by correlating them with the expected pulse shape. The output of the matched filter, represented as r_0(t), is obtained by convolving the received signal, denoted as r_c(t), with the impulse response of the matched filter: $r_o(t) = r_c(t) \circledast h_R(t)$. This convolution operation combines the received signal with the matched filter's impulse response, resulting in a filtered version of the received signal. The purpose of this filtering is to emphasize the presence of the transmitted symbols and mitigate the effects of ISI.

By employing the matched filter in this manner, the receiver can improve the detection performance by maximizing signal-to-noise ratio SNR of a received signal. A matched filter enhances the desired signal while minimizing the impact of interference and noise, thereby improving the accuracy and reliability of symbol detection and decoding in FTN systems. It is worth noting that the design of the matched filter is based on the transmit pulse shape rather than directly matching the unknown and time-variant ISI. This approach allows the receiver to mitigate the effects of ISI in an effective manner and enable successful signal recovery in FTN signaling systems [58].

$$r_0(t)=r_c(t)\circledast h_R(t) \qquad (2.5)$$

2.4.3.2 FTN Detector

A transmitted symbols must be extracted from received signal using the FTN detector. FTN detector employs various signal processing techniques to mitigate inter symbol interference and accurately detect the symbols transmitted at a higher rate. Faster Than Nyquist detector aims to accurately detect and recover the transmitted symbols, compensate for ISI and channel impairments, and reconstruct the original data. The design of the FTN detector is carefully optimized to ensure reliable and efficient symbol detection in the presence of noise and interference, ultimately enabling successful reception in FTN signaling systems [58].

2.4.3.3 Demodulator

In FTN signaling system, the demodulator is a key component in the receiver that is responsible for extracting the transmitted symbols from the received signal. The demodulator performs the inverse operation of modulation, converting the received signal from its modulated form back to its original symbol representation. The demodulation process varies depending on the modulation scheme used in the FTN system. The design of the demodulator is tailored to the specific modulation scheme and system requirements to ensure accurate and reliable symbol demodulation in FTN signaling systems. Here are a few examples:

A. Binary Phase Shift Keying: In BPSK, demodulator compares received signal with a decision threshold to determine a transmitted symbol. If the received signal is above the threshold, it is demodulated as one symbol; otherwise, it is demodulated as the other symbol.

B. Quadrature Phase Shift Keying: In QPSK, the demodulator recovers in a phase and a quadrature components for received signal and compares them with decision thresholds to determine the transmitted symbol. Each symbol represents a combination of two bits.

C. Higher Order Modulations: A higher order modulation schemes like 16QAM or 64QAM, the demodulator uses more complex algorithms to estimate the transmitted symbols. This may involve techniques such as constellation mapping and maximum likelihood detection in order to find most likely symbol based on the received signal's characteristics.

2.4.3.4 Channel Decoder

In a faster than Nyquist rate (FTN) signaling system, the channel decoder is a vital component in the receiver that is responsible for recovering the original transmitted data from the received signal. The channel decoder operates on the principles of error correction coding, aiming to correct any errors introduced during the transmission process. The channel decoder's role is critical in FTN systems as it helps to mitigate the effects of noise and other channel impairments, ensuring reliable and accurate recovery of the original transmitted data. The specific design and implementation of the channel decoder depend on the chosen error correction code and the requirements of the FTN system. By employing powerful error correction techniques the channel decoder enhances the overall performance and reliability of FTN communication systems [28].

2.4.3.5 The Bahl, Cocke, Jelinek, Raviv (BCJR) algorithm

A powerful decoding technique used in various communication systems, including Faster-than-Nyquist transmission is the Bahl, Cocke, Jelinek, Raviv (BCJR) algorithm. In FTN, it plays a crucial role in improving the reliability and performance of the system by correcting errors introduced during transmission over noisy channels. BCJR can effectively correct a wide range of errors, leading to significantly lower bit error rates compared to simpler decoding techniques. This is particularly beneficial in FTN scenarios with high noise levels or challenging channel conditions [55].

The Flexibility of BCJR can be adapted to different structures and channel models, making it a versatile tool for various FTN applications, also Parallel Processing that recursive nature of the algorithm allows for efficient parallel processing, potentially reducing decoding complexity and latency.

2.5 Orthogonal Transmission Using Sinc Pulses

Orthogonal Transmission Using Sinc Pulses is a technique used in communication systems to achieve efficient data transmission. In communication systems, data is typically transmitted over a channel that can introduce interference and distortion. Orthogonal transmission is a method that aims to minimize the interference between transmitted signals, allowing multiple signals to be sent simultaneously without significant degradation in performance.

The Sinc pulse is a mathematical function commonly used as a waveform for orthogonal transmission [37]. It has a unique property of being orthogonal to shifted versions of itself. This means that when multiple Sinc pulses are transmitted simultaneously, they do not interfere with each other and can be easily separated at the receiver. To implement orthogonal transmission using Sinc pulses Figure (2.6), the transmitter encodes the data onto different Sinc pulses corresponding to different channels or users. These pulses are transmitted simultaneously over the channel. At the receiver, each channel's signal is extracted by correlating the received signal with the corresponding Sinc pulse. By using orthogonal transmission with Sinc pulses, multiple signals can be transmitted concurrently without causing interference or crosstalk.

Orthogonal Transmission Using Sinc Pulses is widely used in various communication systems, including wireless communication, digital subscriber lines (DSL), and orthogonal frequency-division multiplexing (OFDM) systems. It provides an effective solution for transmitting multiple signals simultaneously while maintaining high data rates and minimizing interference.

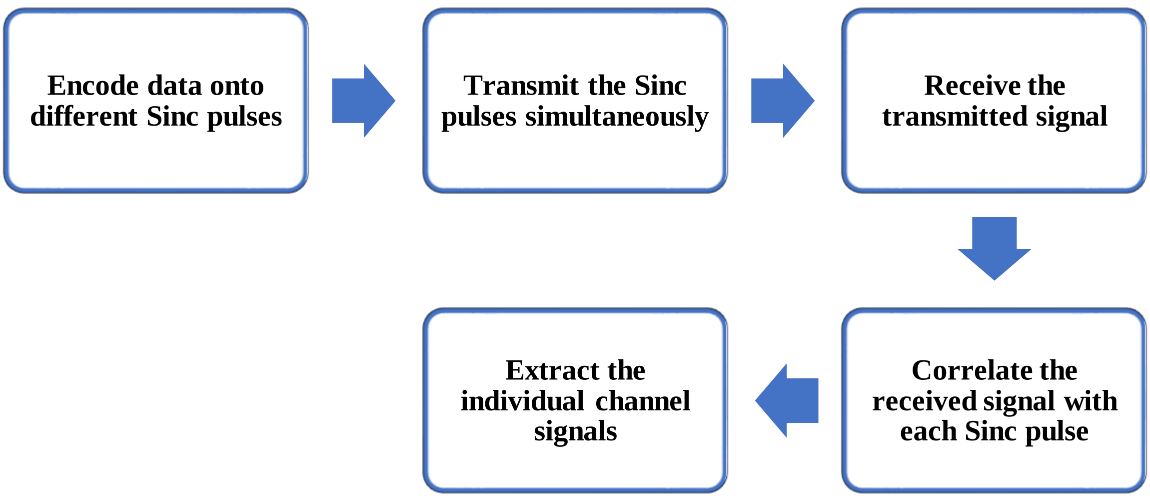


Figure (2.6): Steps of Orthogonal Transmission

2.6 Non Orthogonal Transmission Using Faster Than Nyquist Signaling

Non orthogonal transmission Using Faster-Than-Nyquist Signaling is a technique used in communication systems to increase the data transmission rate by transmitting symbols closer together in time than allowed by the Nyquist criterion Figure (2.7). The Nyquist criterion states that for a signal to be accurately received, the symbols must be spaced apart in time by at least the symbol duration to avoid interference between neighboring symbols,by transmitting symbols closer together in time, it is possible to achieve a higher data transmission rate.

Non-Orthogonal Transmission Using Faster-Than-Nyquist Signaling takes advantage of the fact that the received signal can be shaped in such a way that neighboring symbols can be distinguished even when they are not strictly separated in time. This shaping is typically achieved using pulse shaping techniques that help in reducing the interference between symbols. The technique involves designing a transmitter that uses pulses with shorter durations and higher bandwidth, allowing symbols to be transmitted more closely together.

At the receiver, sophisticated signal processing algorithms are employed to accurately detect and decode the symbols, taking into account the inter-symbol interference caused by the closer symbol spacing. By transmitting symbols non-orthogonally and closer together in time, it is possible to achieve higher data rates within a given bandwidth.

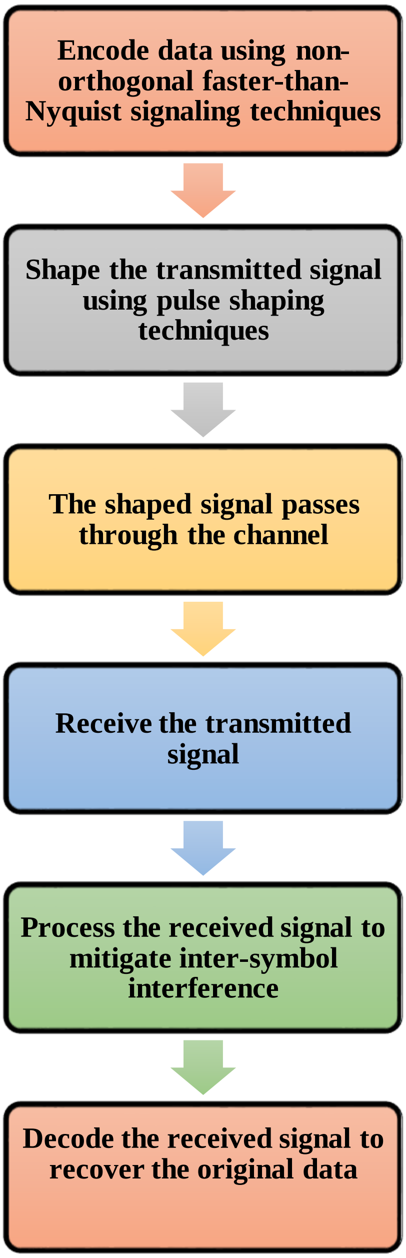


Figure (2.7): Steps of Non-Orthogonal Transmission

2.7 The Key Difference Between Orthogonal And Non-Orthogonal Transmission in Communication Systems

Orthogonal and non-orthogonal transmission techniques are two distinct approaches used in communication systems, and they have significant differences in terms of signal design, interference management, and data transmission efficiency.

- Orthogonal transmission is based on the principle of using orthogonal waveforms, such as orthogonal frequency-division multiplexing (OFDM).
- Orthogonal waveforms have the property of being mutually orthogonal, meaning they do not interfere with each other.
- Orthogonal transmission allows multiple signals to be transmitted simultaneously without causing interference or crosstalk between them. Each signal is transmitted in its assigned orthogonal waveform, which simplifies signal separation at the receiver.
- Orthogonal transmission is well-suited for scenarios where multiple independent signals need to be transmitted concurrently, such as in multi-user communication systems.
- Non orthogonal techniques, like Faster Than Nyquist, depart from the orthogonality principle and allow symbols to be transmitted closer together in time.
- Non-orthogonal transmission sacrifices orthogonality to increase the data transmission rate by reducing the symbol duration or increasing the symbol density.
- Non-orthogonal transmission requires sophisticated signal processing techniques at the receiver to mitigate inter-symbol interference and accurately decode the symbols. By transmitting symbols non-orthogonally, it is possible to achieve higher data rates within a given bandwidth.
- Non-orthogonal transmission is suitable for scenarios where increased data rates are desired, and careful management of interference and signal processing complexity is acceptable.

2.8 The Frequency Response

Frequency response is a measure of how a system responds to different frequencies. It is typically represented by a plot, which shows the magnitude and phase response of the system over a range of frequencies. The magnitude response indicates how much the system attenuates or amplifies different frequencies, while the phase response indicates how much the system delays or advances different frequencies.

Faster-than-Nyquist (FTN) signaling is a non-orthogonal transmission technique that can achieve higher spectral efficiency than traditional Nyquist signaling. FTN signaling transmits symbols at a rate faster than the Nyquist rate, which introduces inter symbol interference.

The effect of frequency response on FTN signaling has a significant impact on its performance. A well-designed FTN signaling system will have a frequency response that is flat over the band of interest. This will minimize ISI and maximize spectral efficiency, if the frequency response of an FTN signaling system is not flat, ISI will be increased. This can lead to a decrease in spectral efficiency and an increase in the bit error rate. Therefore, it is important to consider the frequency response characteristics when designing or analyzing systems or channels in order to ensure accurate and reliable signal transmission or processing. The Figure (2.8) shows a typical DSP system:

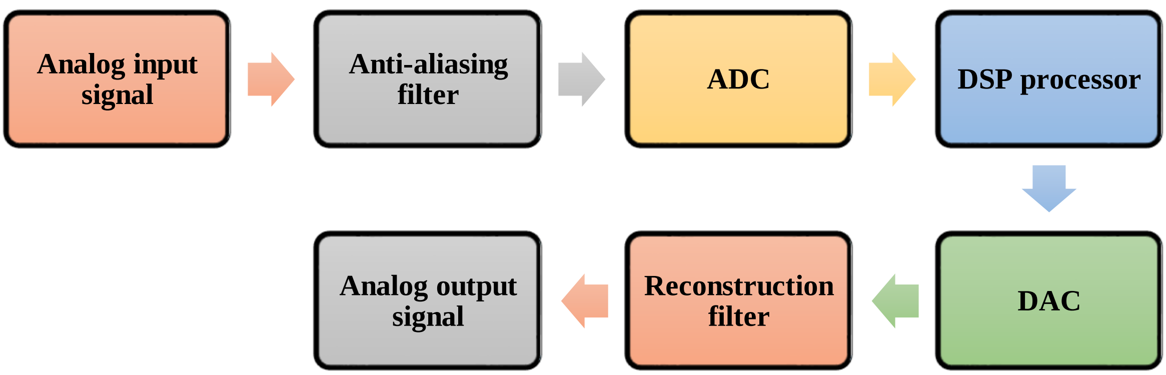


Figure (2.8): Frequency Response block digram

The anti-aliasing filter is used to remove any high-frequency components of the analog input signal that are above the Nyquist rate. The ADC then samples the filtered signal and converts it to a digital signal. The DSP processor performs various operations on the digital signal, such as filtering, equalization, and modulation. The DAC then converts the digital signal back to an analog signal. The reconstruction filter is used to remove any high-frequency components of the analog output signal that were introduced by the DAC.

2.9 Faster Than Nyquist Signaling in OFDM Communication Systems

Faster than Nyquist (FTN) rate signaling is a technique used in communication systems, like in orthogonal-frequency-division-multiplexing. Information is transmitted by dividing data into multiple subcarriers or frequencies. Each subcarrier carries a smaller portion of the data, which collectively make up the entire signal. These subcarriers are carefully designed to be orthogonal to each other, meaning they don't interfere with one another [44].

Now, the Nyquist rate is the maximum rate at which we can transmit data without causing interference between the subcarriers. It ensures that there is no overlapping or crosstalk between them, which would lead to errors in the received signal. However, FTN rate signaling goes beyond the Nyquist rate by allowing the subcarriers to be transmitted at a faster rate. This means that the subcarriers can be sent closer together in the frequency domain, effectively increasing the data transmission rate.

To achieve this, FTN rate signaling utilizes advanced signal processing techniques and clever modulation schemes. It takes advantage of the fact that the subcarriers are orthogonal, allowing them to be transmitted at a higher rate without causing interference.

By using FTN rate signaling in OFDM, we can achieve higher data transmission rates and improved spectral efficiency [46], meaning we can send more data in a given bandwidth. This is particularly useful in scenarios of high speed data transmission, such as in wireless communication systems or broadband internet connections.

The mathematical model for FTN signaling in OFDM communication systems can be described as follows [44]:

$$s(t) = \sum_{k=0}^{N-1} ukp(t - k\tau\, Ts) \qquad (2.6)$$

where: s(t) is the transmitted signal, uk is the k-th data symbol, p(t) is the pulse shaping filter, τ is the time acceleration factor, Ts is the symbol period.

The time acceleration factor, τ, controls the amount of compression that is applied to the transmitted signal. A value of τ<1 results in a compressed signal, while a value of τ=1 results in a signal that is transmitted at the Nyquist rate.

In last, FTN rate signaling in communication systems, especially in OFDM as shown in Figure (2.9), allows for higher data transmission rates by exploiting the orthogonality of subcarriers. It enables us to send more information in a given bandwidth, leading to faster and more efficient communication.

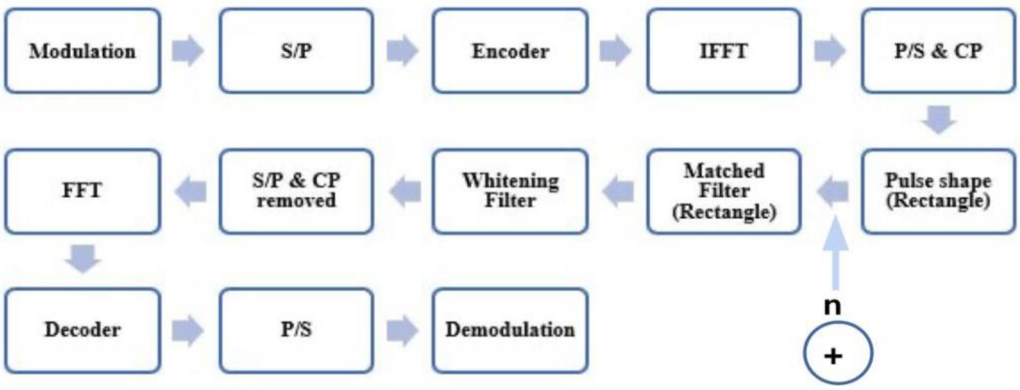


Figure (2.9): Block Representation of An OFDM FTN System [46].

2.10 Enhancing Spectral Efficiency in Faster Than Nyquist Signaling for Communication Systems

Spectral efficiency refers to an amount of information that can be transmitted per unit of bandwidth. FTN can enhance spectral efficiency by allowing higher data rates within the same bandwidth. Since FTN signaling operates at rates higher than the Nyquist rate, it effectively increases the number of symbols transmitted per second, thereby improving the data throughput.

It's important to note that FTN signaling requires more complex receiver processing and careful system design to mitigate the introduced ISI. The choice of modulation scheme, equalization techniques, and receiver algorithms play a crucial role in achieving reliable data recovery with FTN signaling.

Overall, FTN signaling with spectral efficiency enables higher data rates in communication systems by transmitting at rates beyond the Nyquist limit while managing the ISI effects through advanced equalization techniques. This technique is particularly useful in scenarios where maximizing the data throughput within a limited bandwidth is crucial [48].

Using the increased Root Raiced cosine Nyquist system with (B for Nyquist = (1 + α) /(2Ts), R = 1/Ts), compare the SE:

$$\eta_{\text{Nyquist}} = \frac{R_{\text{Nyquist}}}{B_{\text{Nyquist}}} = \frac{2}{(1+\alpha)} \tag{2.7}$$

As a result of the symbol rate changing in an FTN system to R_{FTN} =1/(τ Ts), the SE becomes:

$$\eta_{\text{FTN}} = \frac{R_{\text{FTN}}}{B_{\text{FTN}}} = \frac{2}{\tau(1+\alpha)} \tag{2.8}$$

Difference between the two systems of Nyquist system is defined, and a ratio is obtained to describe improvement from the Nyquist system to the FTN system [48]:

$$\triangle\eta = \frac{\eta_{FTN} - \eta_{Nyquist}}{\eta_{Nyquist}} = \frac{1}{\tau} - 1 = \frac{1-\tau}{\tau} \qquad (2.9)$$

Figure (2.10) shows the altering and the SE improvement of FTN system. As can be observed, when τ is a small, SE of FTN significant improvement. However, as τ increases, this improvement steadily declines until, at a value of τ = 1, the SE of the FTN system is equal to that of the Nyquist system, with no benefit.

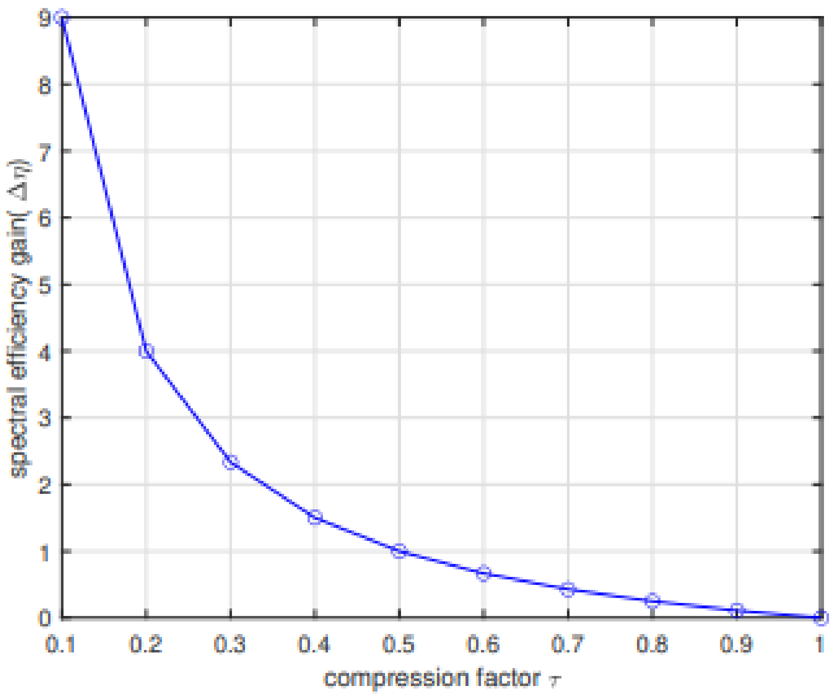


Figure (2.10): The spectral efficiency curve with τ [48].

2.11 Capacity of faster than Nyquist rate signaling

The capacity of faster-than-Nyquist signaling can be significantly higher than the Nyquist limit, which is the maximum achievable data rate for a given channel bandwidth without inter symbol interference.

General Capacity Expressions of Nyquist Limit is [49] :

$$\text{Capacity} = B \log2(1 + SNR) \qquad (2.10)$$

Where B is the channel bandwidth , SNR is the signal-to-noise ratio

This expression represents the maximum achievable capacity for conventional FTN signaling [49] :

$$\text{Capacity} = fs \log2(1 + SNR) / \alpha \qquad (2.11)$$

Where fs is the symbol rate , α is a factor depending on the pulse shape and coding scheme (typically > 1)

This expression indicates that FTN can potentially achieve higher capacity than Nyquist signaling by transmitting more symbols per second (fs > B) due to its non-orthogonality. Determining the exact capacity of a specific FTN system requires analyzing the specific pulse shape, coding scheme, and channel model. Several research papers and publications delve into detailed capacity analysis of various FTN variants [56].

2.12 Advantages of Faster Than Nyquist Rate Signaling

An advantages of FTN signaling are well-captured in [29], which notes that FTN has gained attention in a bandwidth-limited world because Compared to conventional approaches, it can transfer 30% to 100% data within a same bandwidth, with a same energy per bit and error rate.

Faster-than-Nyquist FTN signaling offers several advantages for communication systems:

I.Increased Data Rates: FTN signaling allows for higher data rates compared to Nyquist signaling. By transmitting pulses at intervals smaller than the Nyquist sampling rate, FTN signaling can achieve a higher data rate while maintaining the same bandwidth [48].

II. Efficient Spectrum Utilization: With FTN signaling, the available spectrum can be utilized more efficiently, resulting in higher data rates without requiring additional bandwidth. This makes FTN signaling particularly useful of systems with limited bandwidth, such as wireless and optical communication system.

III. Robustness to Channel Impairments: FTN signaling can be designed to be robust against channel impairments such as noise and interference, allowing for reliable transmission of data even in challenging channel conditions.

IV. Low Latency: FTN signaling can be designed to have a low latency, making it suitable to applications that require real time communication, like video conferencing and online gaming [28].

V. Compatibility with Existing Systems: FTN signaling can be implemented in existing communication systems without requiring major changes to the hardware or infrastructure.

Overall, FTN signaling offers a promising solution for improving the performance and efficiency of communication systems, especially in scenarios where higher data rates are required within limited bandwidth.

2.13 Disadvantages of Faster Than Nyquist Rate Signaling

Faster Than Nyquist rate signaling refers to a technique in communication systems where the transmission rate higher a Nyquist rate, which is required to accurately reconstruct a signal without distortion. While there are potential benefits to faster than Nyquist rate signaling, such as increased data transmission rates, it also has several disadvantages. Here are some of them [47]:

I. Inter-Symbol Interference: Faster Than Nyquist rate can lead to significant inter-symbol interference, where the symbols of a transmitted signal overlap with each other due to the reduced spacing between them. ISI causes distortion and makes it challenging to accurately detect the transmitted symbols at the receiver, leading to a higher probability of errors.

II. Increased complexity: Implementing and designing communication systems with faster than Nyquist rate signaling requires more complex signal processing algorithms and techniques. The increased complexity can lead to higher implementation costs, greater computational requirements, and more sophisticated hardware and software components [45].

III. Non-linear distortion: Faster than Nyquist rate signaling often involves transmitting signals with higher bandwidths. In real-world communication channels, non-linear effects such as harmonic distortion and intermodulation distortion become more pronounced with wider bandwidths. These distortions can degrade the quality and integrity of the transmitted signals, impacting the overall system performance.

IV. Greater susceptibility to noise and interference: Faster transmission rates typically mean that the symbols are more closely spaced, which makes the system more susceptible to noise and interference. Even small amounts of noise or interference can cause errors and reduce the overall reliability of the communication system.

Some of these disadvantages can be mitigated or overcome with advanced signal processing techniques, error correction codes, and system optimizations. However, they still present challenges that need to be carefully addressed when considering the adoption of faster than Nyquist rate signaling in communication systems.

2.14 Properties of FTN Rate Signaling

Faster-than-Nyquist (FTN) rate signaling possesses several properties that distinguish it from traditional Nyquist rate signaling. Here are some key properties of FTN rate signaling:

I. Cause Inter-Symbol Interference (ISI): FTN rate signaling produce ISI by transmitting multiple symbols in a single symbol interval. This results in a more efficient use of the available bandwidth and allows for higher data rates [9].

II. Spectral Efficiency: FTN rate signaling achieves higher spectral efficiency than conventional Nyquist signaling, as it allows more symbols to be transmitted per unit of bandwidth.

III. Non-Orthogonal Signaling: FTN rate signaling is typically based on non-orthogonal signaling, such as pulse amplitude modulation PAM. This means that the transmitted symbols are not orthogonal to each other, which can result in increased interference between symbols.

IV. Increased Complexity: FTN rate signaling requires more complex signal processing techniques, such as advanced filtering and equalization, to mitigate the effects of ISI and interference.

V. Robustness to Noise: FTN rate signaling is more robust to noise than conventional Nyquist signaling, as the multiple symbols transmitted in a single symbol interval provide redundancy that can help recover lost information [28].

The properties of FTN rate signaling may vary depending on specific implementation, modulation schemes, equalization techniques, and the characteristics of the communication channel. The literature has uncovered several properties of FTN signaling, as documented in [24], [49]-[50].

2.15 The Application of Faster Than Nyquist Rates (FTN) for Communication System

Faster-than-Nyquist FTN has found applications in various communication systems where high data rates and spectral efficiency are desired [51]. FTN has been proposed for the 5G standard [52], as well as for satellite and optical communications [53, 54]. The specific application of FTN rates in a communication system depends on factors such as channel characteristics, data requirements, system constraints, and available technologies. The adoption of FTN signaling requires careful consideration of these factors to ensure optimal performance and compatibility with existing infrastructure. Some notable applications of FTN rates for communication systems include:

I. Digital Communication: FTN signaling is used in digital communication systems, such as wireless communication, Ethernet networks, and digital subscriber line systems. In these systems, oversampling is used to increase the data rate and improve the accuracy of symbol detection at the receiver.

II. Audio and Video Compression: Oversampling is also used in audio and video compression algorithms, such as MP3, to reduce the size of digital audio and video files. By oversampling the audio or video signal, it is possible to capture more detail in the signal and reduce an amount of data needed to represent signal accurately [10].

III. Imaging in Medicine: In medical imaging, such magnetic resonance imaging (MRI), oversampling is used to capture a more detailed and accurate image of the body. By oversampling the signal, it is possible to capture more information about the structure and function of the body, and improve the accuracy of diagnosis and treatment [3]

IV. Time-Division Multiplexing: FTN signaling is used in time-division multiplexing (TDM) systems to improve accuracy and efficiency of data transmission. By oversampling the signal, it is possible to reduce the effects of ISI and increase the accuracy of symbol detection at the receiver.

In summary, FTN signaling has a range of applications in communication systems, like digital communication, audio and video compression, radar and sonar, medical imaging, and time-division multiplexing.

Chapter Three

Faster Than Nyquist Rate Signaling

Chapter Three

Faster-than-Nyquist Rate Signaling

3.1 Introduction:

In the field of communication systems, it is always desired to transmit information at high data rates while maintaining high signal quality. One of the main challenges in achieving this goal is to ensure that the transmitted signal can be reliably detected at the receiver end, even in the presence of noise and interference. Communication systems have traditionally employed Nyquist theorem to estimate the minimal sample rate required without distortion.

However, in recent years, faster than Nyquist rate signaling techniques have gained significant attention due to their ability to achieve higher data rates and better spectral efficiency [1]. In this chapter, we will simulate faster than Nyquist rate signaling techniques using MATLAB.

These techniques utilize the bandwidth of the communication channel more efficiently by exploiting the frequency domain redundancies in the transmitted signal.

The uncoded technique relies on oversampling the transmitted signal and using a filter bank to extract multiple sub-band signals, each of which is transmitted at a lower rate. On the other hand, the coded technique uses error-correction coding to reduce the rate at which information is transmitted, while still achieving a high level of reliability, we aim to demonstrate the benefits of uncoded and coded faster than Nyquist rate signaling techniques in achieving higher data rates and better spectral efficiency compared to traditional Nyquist rate signaling.

By simulating these techniques using MATLAB, we can simulate the performance of a communication system and evaluate the impact of different parameters on the overall system performance in figure (3.1).

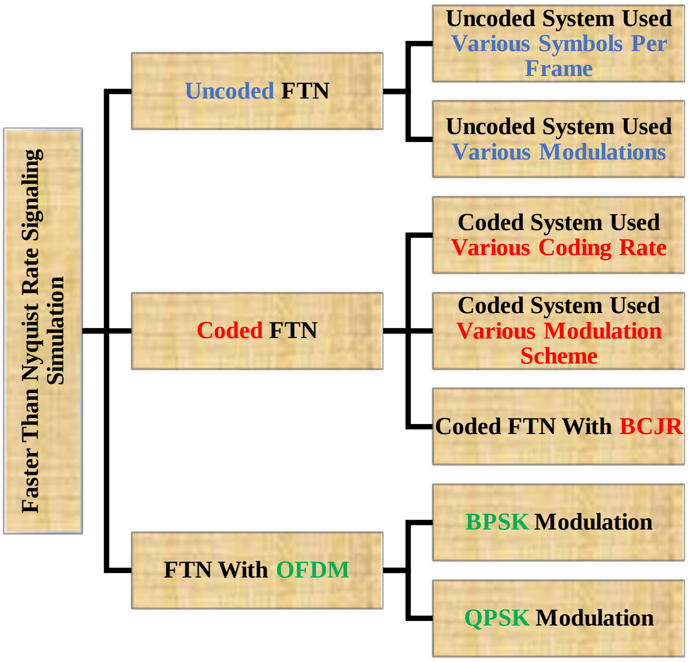


Figure (3.1): FTN System with different Scenarios

3.2 Uncoded Faster Than Nyquist Rate Signaling

Faster than Nyquist (FTN) signaling is a technique used in communication networks to increase data throughput while reducing bandwidth. It allows for the transmission of multiple symbols per symbol interval. Here is a block diagram illustrating the main components of an uncoded FTN signaling communication system in Figure (3.2) with various symbols and various modulations.

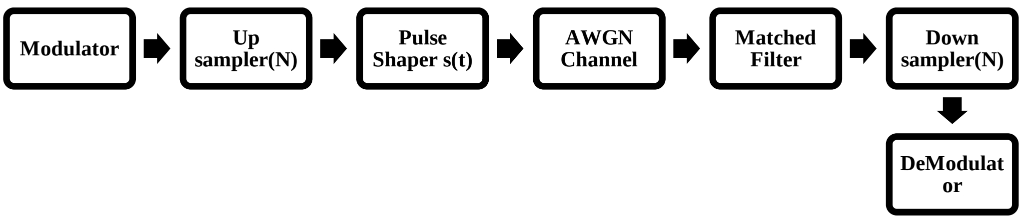


Figure (3.2): Uncoded FTN signaling system's block layout

The block diagram provided above illustrates the main components of an uncoded FTN signaling communication system with random data, the original signal is first up-sampled by inserting zeros between the original samples [59]. This increases the sampling rate to a value exceeding the Nyquist rate. The purpose is to create a denser representation of the signal, allowing for more potential information to be embedded within the signal spectrum, different modulators, an AWGN channel, a matched filter, and a down sampler after shaping, the signal is down-sampled back to its original bandwidth. This effectively removes the additional zeros inserted during up-sampling, but the information embedded within the "compressed" spectrum remains. Using uncoded FTN signaling, the main objective is to transmit data in excess of the Nyquist rate without employing error correction coding. This technique leverages signal shaping and pulse shaping to achieve a higher data rate while maintaining acceptable levels of error performance. Here's an overview of the key operations involved in uncoded FTN signaling:

I. Symbol Mapping: The input data, typically in the form of digital bits, is grouped and mapped into a set of symbols. Each symbol can represent multiple bits, depending on the modulation scheme used. For example, in a QPSK modulation scheme, each symbol represents two bits.

II. Signal Shaping: After symbol mapping, the symbols are shaped into waveforms suitable for transmission. Signal shaping techniques like pulse shaping are applied to limit the bandwidth of the transmitted signal and minimize inter-symbol interference. Common Raised cosine or root raised cosine filters are examples of pulse shaping filters utilized. The signal being transferred is uncoded FTN signaling has a single-sided bandwidth of (1 + ß)/(2T), where ß is the Roll-off aspect (ß)and T is symbol duration. A root raised cosine filter is commonly employed in FTN signaling, and Figure

(3.3) depicts its impulse response for various ß values. As shown, lower ß values result in wider side-lobes, leading to more significant inter-symbol interference as these lobes interfere with adjacent symbols. To increase the system's throughput without expanding the signal bandwidth, FTN signaling can be utilized. In FTN signaling, symbols are transmitted at a higher rate, while the pulse shape remains unchanged. This approach allows for an increased data rate without altering the spectral characteristics of the transmitted signal.

III. Transmission: The signal is transmitted through the communication channel, which could be wired or wireless. The signal can encounter noise, distortion, and other impairments during transmission.

In FTN signaling, the symbol period is shortened to τT, where τ is an accelerating (or squeezing) parameter with a value between 0 and 1[45]. As a result, the transmitted signal can be expressed as equation (2.2).

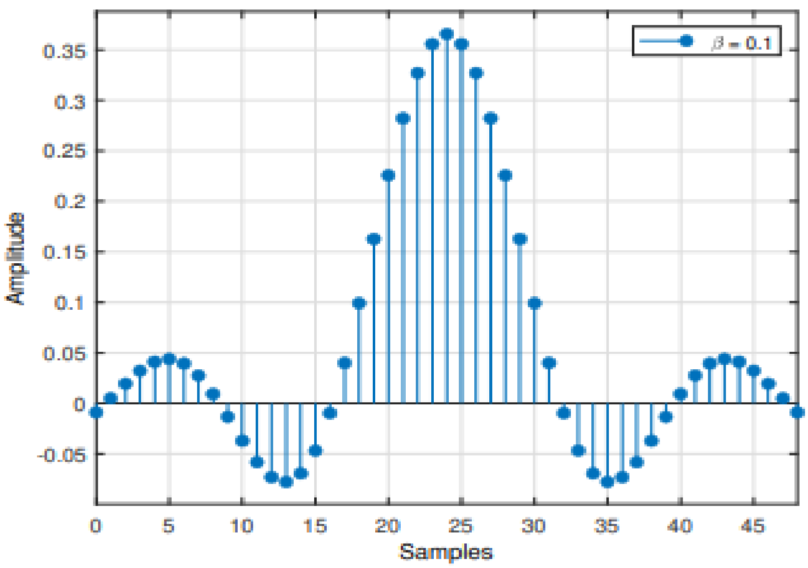
Another parts of uncoded block digram is represented in chapter two.

IV. Receiver: At the receiver end, the received signal is captured and processed for further analysis. The received signal may contain noise and interference introduced during transmission.

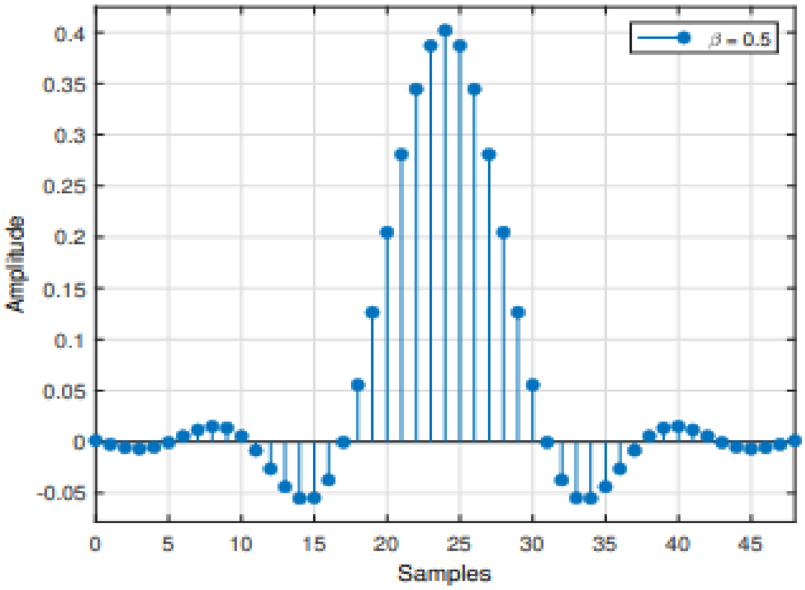
V. Symbol Demodulation: The received signal is demodulated to extract the symbols transmitted by the sender. The demodulator performs the inverse operation of the modulation, converting the received analog signal into a stream of symbols. The detected symbols are converted back into their original digital bit format. Each symbol is decoded to retrieve the corresponding bit. An amount of bits per symbol is determined on the modulation strategy utilized.

VI. Data Output: The final step involves processing and utilizing the received data as per the application requirements. The data can be used for display, storage, further processing, or any other intended purpose.

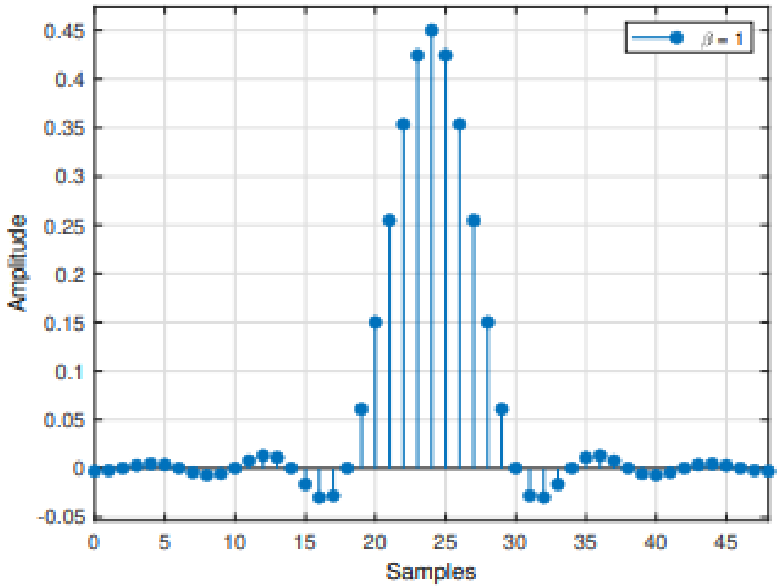
It's important to note that uncoded FTN signaling relies heavily on signal shaping and modulation to achieve higher data rates. However, since error correction coding is not employed, the system's error performance can be more susceptible to noise and interference compared to coded systems. Therefore, careful consideration is required when designing and implementing uncoded FTN signaling systems to ensure a proper balance between data rate and error performance.



(a) $\beta = 0.1$



(b) $\beta = 0.5$



(c) $\beta = 1$

Figure (3.3): Illustrates the impulse response of an RRC filter with varying Roll-off aspect ß

The results are presented ß values:(*a*) ß = 0.1, (*b*) ß = 0.5, (*c*) ß = 1 , these figures depict the characteristics of the filter's response, showcasing how the choice of ß affects the shape and behavior of the filter.

3.3 Coded Faster Than Nyquist Rate Signaling

Coded faster than Nyquist (CFTN) signaling is a communication technique that allows for the transmission of data at rates higher than the Nyquist rate, which is the theoretical limit for sampling a signal without introducing distortion or aliasing. In CFTN signaling, redundancy is added to the transmitted signal through the use of coding schemes, which allows for more efficient use of the available bandwidth. CFTN signaling can be implemented with different rates and modulation schemes, each of which has its advantages and disadvantages.

One common modulation scheme used in CFTN signaling is Quadrature Phase Shift Keying QPSK, another modulation is quadrature amplitude modulation QAM, where both of a transmitted signal carry data.When comparing different CFTN signaling schemes, several factors need to be considered, incorporating the spectral efficiency, bit error rate (BER), and computational complexity of the encoding and decoding techniques.

In general, higher CFTN rates lead to higher spectral efficiency but also increase the computational complexity of the encoding and decoding algorithms. Moreover, different modulation schemes have different trade-offs between BER and spectral efficiency.

Overall, CFTN signaling can provide significant improvements in data transmission rates and spectral efficiency compared to traditional Nyquist signaling, but the choice of rate and modulation scheme depends on the specific application requirements and the available computational resources.

This block diagram in Figure (3.4) provides a general overview of a coded FTN signaling communication system. The specific implementation and parameters may vary depending on the coding scheme, modulation scheme, and system requirements. The inclusion of error correction coding enhances the system's reliability and robustness against transmission errors.

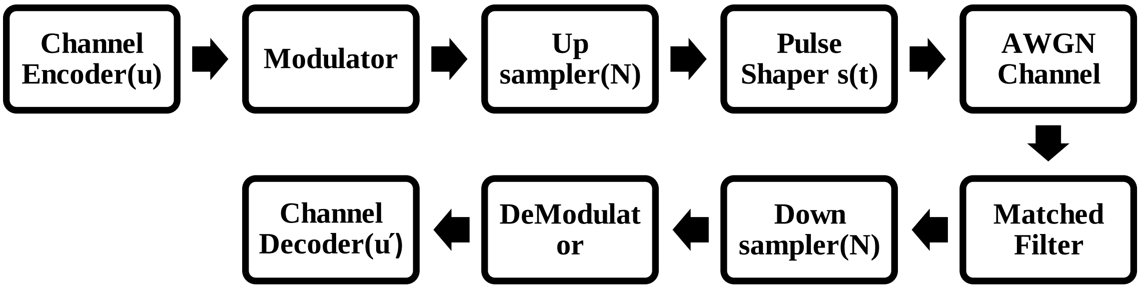


Figure (3.4): A coded FTN signaling system's block layout

Let's discuss the key components involved in coded FTN signaling:

I.Data Source: The data source represents the information or data that needs to be transmitted. It can be in the form of digital bits or symbols.

II. Encoder: The encoder is responsible for applying error correction coding to the input data. It takes the data from the source and adds redundancy to it using error correction codes. Popular coding schemes include convolution codes, turbo codes, or LDPC codes. In order to enable the receiver to identify and fix any transmission mistakes that might have occurred, the encoder inserts extra bits to the data. In this work we used convolutional code.

III. Symbol Mapper: The symbol mapper takes the output of the encoder, which consists of coded bits, and maps them into a set of symbols. Each symbol typically represents multiple bits or a combination of a bits,like QPSK, 16QAM, or 64QAM.

IV. Up-Sampler: The up-sampler is a crucial component in a FTN communication system, as it increases the sample rate of the transmitted signal to be greater than the Nyquist rate. The upsampler inserts additional samples between the transmitted symbols to achieve the desired higher sample rate (often, twice the Nyquist rate).

V. Filter for shaping pulses: A pulse shaping filter shapes the symbol into a waveform suitable for transmission. It employs techniques such as raised cosine or root raised cosine filtering to limit the bandwidth of the transmitted signal and minimize inter-symbol interference.

VI. Transmitter: The transmitter takes the filtered signal and prepares it for transmission. It is possible to transmit data at rates that would otherwise be susceptible to significant errors in the absence of coding. This is especially important in high-speed communication systems.

VII. Channel of Communication: A communication channel is the medium through which the signal is transmitted. It might be a wired or wireless channel that is subject to noise, distortion, and interference.

VIII. Receiver: The receiver captures and processes the received signal from the communication channel. It performs operations such as demodulation, filtering to extract the transmitted symbols.

IX. Equalizer: The equalizer is an optional component used in some FTN signaling schemes. It compensates for channel impairments, such as multipath fading or frequency-selective fading, to improve the overall signal quality before further processing.

X. Decoder: The decoder performs error detection and correction on the received coded data. It uses appropriate decoding algorithms and error correction codes, such as Viterbi decoding or iterative decoding, to identify and correct any errors that may have occurred during transmission.

XI. Data Sink: The data sink represents the destination or recipient of the transmitted data. It could be a computer, a display, or any device that can interpret and utilize the received information.

These components collectively enable the reliable transmission of data at higher rates in a coded FTN signaling system. The integration of error correction coding enhances the system's ability to overcome transmission errors, ensuring the integrity of the received data.

3.4 Faster Than Nyquist Rate Signaling With OFDM

In modern communication networks, a technology known as orthogonal frequency division multiplexing is used. used to simultaneously broadcast data over a number of subcarriers. Each subcarrier carries a portion of the total data, allowing for efficient and robust transmission.

When we combine FTN signaling with OFDM Figure (3.5), we can transmit data even faster and achieve higher data rates. This is done by allowing overlapping between the subcarriers, which violates the traditional Nyquist criterion. By overlapping the subcarriers, we can squeeze more data into a given frequency band and transmit at a higher rate.

To simulate FTN signaling with OFDM, we would create a model that generates and processes signals based on these principles. The simulation would involve generating multiple subcarriers with data and combining them to form the OFDM signal. Then, we would transmit and receive the signal, extracting the subcarriers and demodulating them to recover the original data. FTN signaling with OFDM allows us to transmit data at higher rates by exploiting the properties of overlapping subcarriers. It's an advanced technique used in modern communication systems to achieve efficient and high speed data transmission.

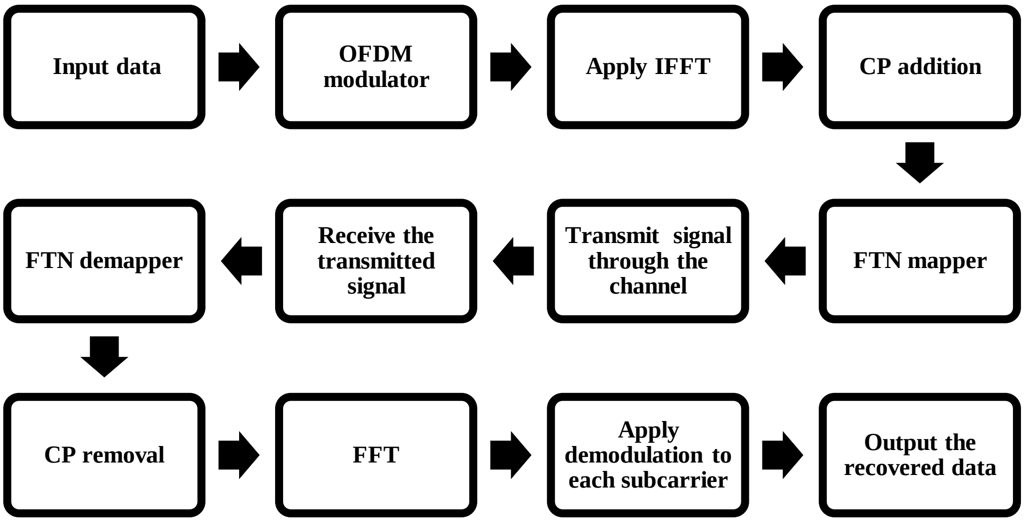


Figure (3.5): Faster Than Nyquist Rate Signaling With OFDM

The OFDM modulator converts the input data into a set of subcarriers, each of which is modulated. The FTN block then transmits the subcarriers at a rate faster than the Nyquist rate. This introduces ISI, but the OFDM demodulator is able to compensate for ISI. The channel introduces noise and distortion to the transmitted signal. The OFDM demodulator then demodulates the received signal to compensate for ISI. The OFDM demodulator then converts the subcarriers back into the original data.

3.5 Capacity of A Faster Than Nyquist Signaling

Faster-than-Nyquist rate refers to the transmission of information at a rate upper than Nyquist rate, as which the theoretical limit for reliable data transmission without interference. Nyquist rate doubles bandwidth of the signal being transmitted. By transmitting at a rate that exceeds the Nyquist rate, faster-than-Nyquist signaling allows for an increased data rate within the given bandwidth. Here are a few key points to consider [59]:

I. Increased Data Rate: By transmitting at a rate upper than Nyquist rate ,faster-than-Nyquist signaling allows for more data to be transmitted within the same bandwidth. This can result in higher data rates and increased capacity for the communication system.

II. Spectral Efficiency: Faster-than-Nyquist signaling techniques typically exploit the available spectrum more efficiently, enabling the transmission of more bits per second per unit of bandwidth. This improved spectral efficiency can lead to higher overall system capacity.

III. Interference and Signal Quality: Transmitting at a faster-than-Nyquist rate increases the potential for interference and signal distortion. The presence of inter symbol interference (ISI) becomes more pronounced, as the transmitted symbols have overlapping effects on each other. Dealing with ISI becomes more challenging and may require more sophisticated equalization techniques to mitigate its effects.

IV. Implementation Challenges: Implementing faster-than-Nyquist signaling techniques can be complex and requires careful design considerations. The receiver needs to employ advanced equalization and decoding algorithms to correctly retrieve the transmitted data. These algorithms can be computationally intensive and may introduce additional latency and complexity to the system.

V. Channel Conditions: The impact of faster-than-Nyquist signaling on system capacity can also depend on the characteristics of the communication channel. In some cases, the channel may support the higher data rates without significant degradation in performance, while in others, the increased rate may lead to a higher error rate and reduced capacity.

Overall, faster-than-Nyquist rate signaling has the potential to increase the capacity of communication systems by allowing higher data rates within the available bandwidth. However, it also introduces challenges related to signal quality, interference, and implementation complexity. The suitability and benefits of using FTN depend on a specific communication system, channel conditions, and trade-offs between increased capacity and the associated challenges. First, in [49], filtering by RRC with Roll-off aspect ß was used to derive the capability of FTN signaling. Using the same filtering by RRC, it was shown that FTN signaling has a larger capacity than traditional Nyquist signaling, due to its ability to exploit excess bandwidth. Using FTN signaling allows us to approach the capacity of a bandlimited channel, as demonstrated in [55]. The impact of FTN on communication system capacity can be both good and negative, depending on the individual implementation and system features [56].

3.6 The Effect of Faster Than Nyquist Rate on SE for communication systems

Faster Than Nyquist rate signaling can have a positive impact on the spectral efficiency (SE) of communication systems. SE is a measure of how efficiently the available spectrum is utilized to transmit data.Here's how faster-than-Nyquist signaling can affect SE:

I. Increased Data Rate: By transmitting in excess of the Nyquist rate, faster-than-Nyquist signaling allows for a higher data rate within the given bandwidth. This increased data rate effectively improves the SE because more bits can be transmitted per unit of time, utilizing the available spectrum more efficiently.

II. Improved Spectral Efficiency: Faster-than-Nyquist signaling techniques are designed to exploit the available spectrum more efficiently by transmitting multiple symbols per Nyquist interval. This enables a higher number of bits to be transmitted within the same bandwidth. As a result, the SE of the communication system is improved since more information can be conveyed in a given frequency range.

III. Bandwidth Conservation: Faster-than-Nyquist signaling enables higher data rates without requiring a wider bandwidth. This conservation of bandwidth is particularly beneficial in scenarios where spectrum resources are limited or expensive. By achieving higher SE, communication systems can accommodate more users or transmit more data within the available spectrum, leading to increased overall capacity.

IV. Trade-off with Error Rate: Faster-than-Nyquist signaling involves transmitting symbols that are more closely spaced in time, which can increase the potential for inter symbol interference (ISI). ISI occurs when symbols from adjacent time intervals interfere with each other, causing errors in symbol detection. Therefore, to maintain a low error rate, more sophisticated equalization techniques are required. These techniques, while enabling faster data rates, can introduce additional complexity and computational overhead.

It's important to note that the actual improvement in SE due to faster-than-Nyquist signaling depends on the specific implementation, channel conditions, and the trade-offs made. The system must strike a balance between achieving higher data rates and managing the increased challenges introduced by ISI and potential error propagation, Faster Than Nyquist signaling have the potential to enhance the SE of communication systems by enabling higher data rates within the available spectrum, conserving bandwidth, and improving the efficiency of spectrum utilization.

3.7 Flowchart of all the system

These three perspectives(uncoded, coded, coded with BCJR, and FTN with OFDM) offer different ways to understand the functionality of the FTN signaling system represented by the flowchart. Each perspective focuses on specific aspects of the system and helps to analyze it from different angles.

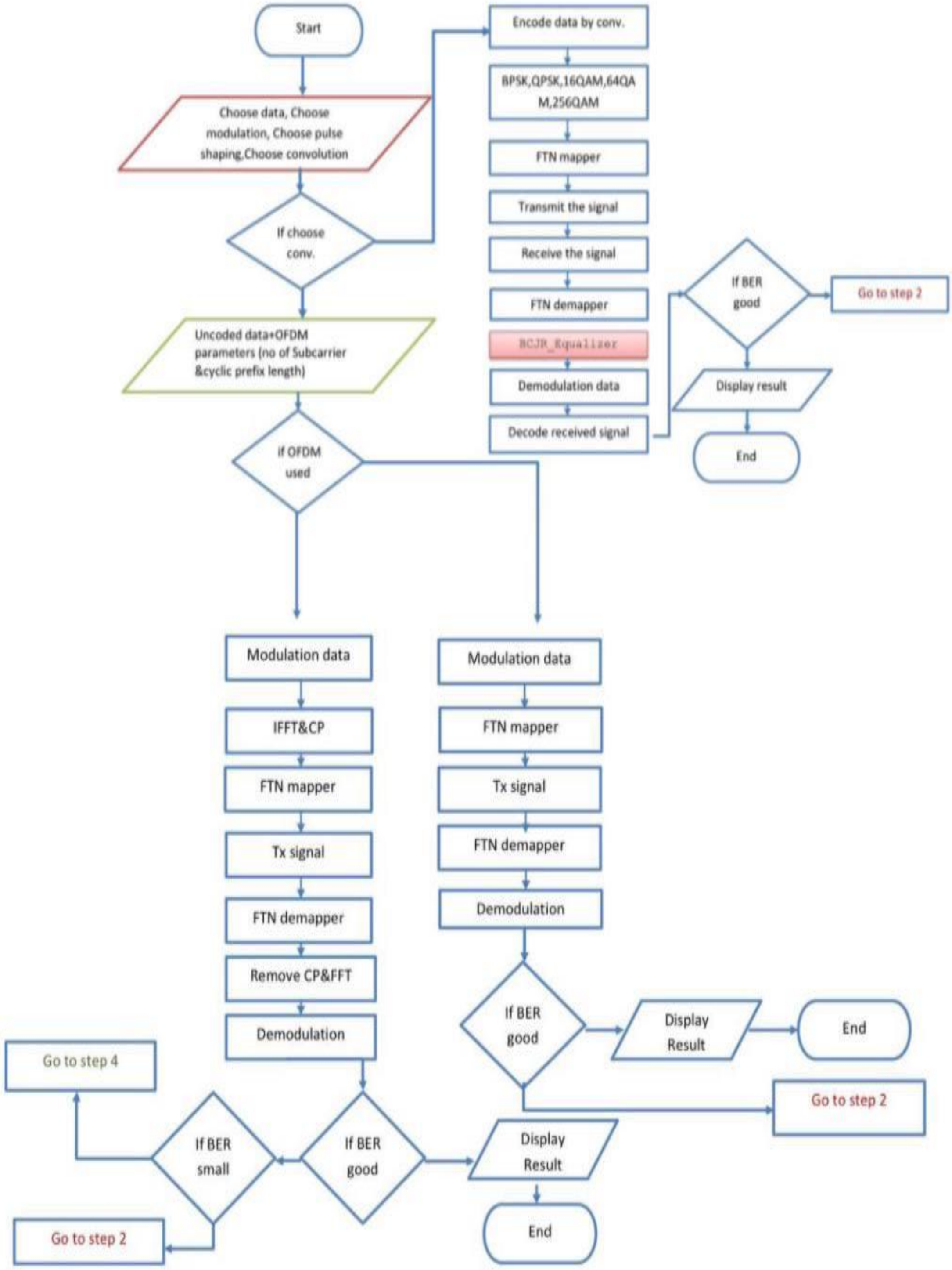


Figure (3.6): Flowchart of FTN system

Chapter Four

Results And Disscussion

Chapter Four

Results And Discussion

4.1 Introduction

FTN signaling increases data transmission rates beyond the Nyquist limit using advanced signal processing techniques. There are three approaches: uncoded FTN, coded FTN, and FTN with OFDM. Uncoded FTN achieves higher rates by modulating data onto a waveform with a higher symbol rate, but it can result in higher errors. Coded FTN combines error correction coding with FTN for higher rates and lower errors.

FTN with OFDM further increases rates by modulating data onto multiple subcarriers simultaneously. Capacity depends on modulation, channel, and SNR, while spectral efficiency is the information transmitted per bandwidth. Calculations vary based on implementation and channel conditions. The recorded results in this chapter are categorized into various sections, and we will examine each of these sections in detail to present the outcomes achieved through the simulation of the direct sequence spread spectrum system using the MATLAB program. The results were divided into the following sections:

- Orthogonal Transmission Using Sinc Pulses
- Non-Orthogonal Transmission Using Faster-Than-Nyquist Signaling
- Difference Between Transmission Techniques in Communication Systems: Orthogonal and Non-Orthogonal Approaches
- Frequency Response Nyquist Rate
- The Frequency Response faster Than Nyquist Rate
- Uncoded Faster Than Nyquist Rate Signaling
- Coded Faster-Than- Nyquist Rate
- Faster-Than- Nyquist Rate With OFDM

- Capacity of Faster Than Nyquist Signaling
- The Effect of Faster-Than-Nyquist Rate on SE for Communication Systems

4.2 Orthogonal Transmission Using Sinc Pulses Results

Orthogonal transmission using sinc pulses is a technique employed in communication systems to achieve efficient and reliable data transmission. Sinc pulses are a form of pulse shaping that have desirable properties, including zero inter-symbol interference and orthogonality. By utilizing these pulses, communication systems can transmit multiple signals simultaneously without interference. When analyzing the results obtained from simulating orthogonal transmission using sinc pulses, several key observations emerge.

Firstly, sinc pulses offer excellent spectral containment properties. The main lobe of the sinc pulse is narrow, allowing for better separation of signals in the frequency domain. This leads to improved spectral efficiency, as more signals can be transmitted within a given bandwidth without significant interference.

Secondly, sinc pulses provide a low probability of error. Due to their orthogonal nature, the received signals can be easily separated and detected using matched filters. This results in robust signal reception and reduces the likelihood of errors during transmission.

Additionally, sinc pulses exhibit good resilience to noise and channel impairments. The orthogonality of the pulses enables better noise rejection and interference mitigation, enhancing the overall system performance. However, it is important to note that sinc pulses require precise timing synchronization and accurate estimation of the channel characteristics for optimal performance. Any timing or channel estimation errors can degrade the system's performance and introduce interference between signals.

Simulating orthogonal transmission using sinc pulses as shown in Figure (4.1) provides valuable insights into the advantages of this technique. By leveraging the properties of sinc pulses, communication systems can achieve efficient and reliable data transmission in a multi-user environment.

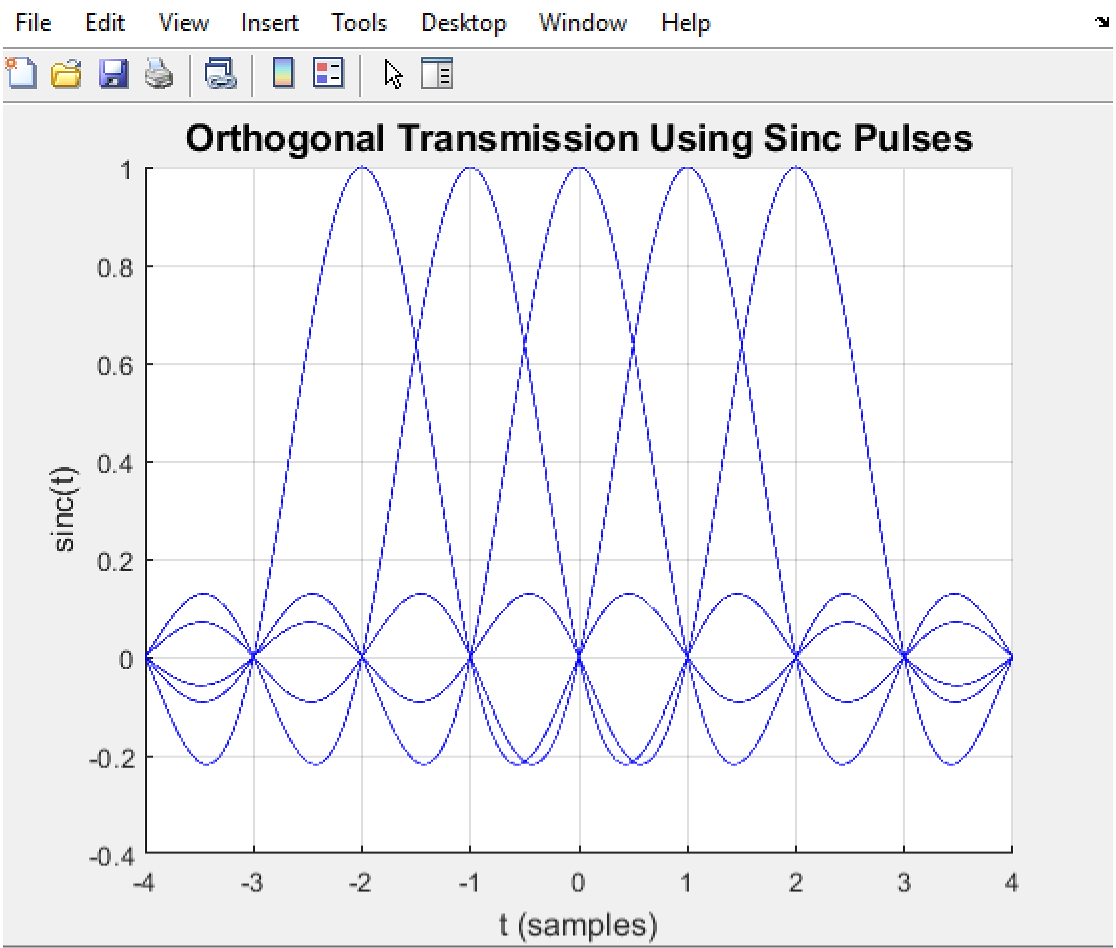


Figure (4.1): Orthogonal transmission using sinc pulses

4.3 Non-orthogonal Transmission Using Faster-Than-Nyquist Signaling Results

Faster-than-Nyquist (FTN) signaling, a non-orthogonal transmission technique, involves the transmission of symbols at a rate exceeding the Nyquist rate.Unlike traditional orthogonal transmission schemes, non-orthogonal transmission allows for overlapping symbols in the time domain, resulting in increased spectral efficiency.When examining the results obtained from simulating non-orthogonal transmission using faster-than-

Nyquist signaling as shown in Figure (4.2) , several important findings can be observed.

One key advantage is the increased data rate achieved through this technique. By exceeding the Nyquist rate, symbols are transmitted at a higher rate,more information can be conveyed within a given time interval. This leads to higher throughput and improved efficiency in data transmission.

Additionally, non-orthogonal transmission offers enhanced spectral efficiency. By allowing overlapping symbols, the available bandwidth can be utilized more efficiently. This results in a higher number of transmitted symbols per unit of time, effectively increasing the capacity of the communication system, it is crucial to note that non-orthogonal transmission using faster-than-Nyquist signaling introduces challenges related to inter symbol interference (ISI).

Overall, the results obtained from simulating non-orthogonal transmission using faster-than-Nyquist signaling demonstrate the potential benefits of this technique in terms of increased data rate and spectral efficiency.

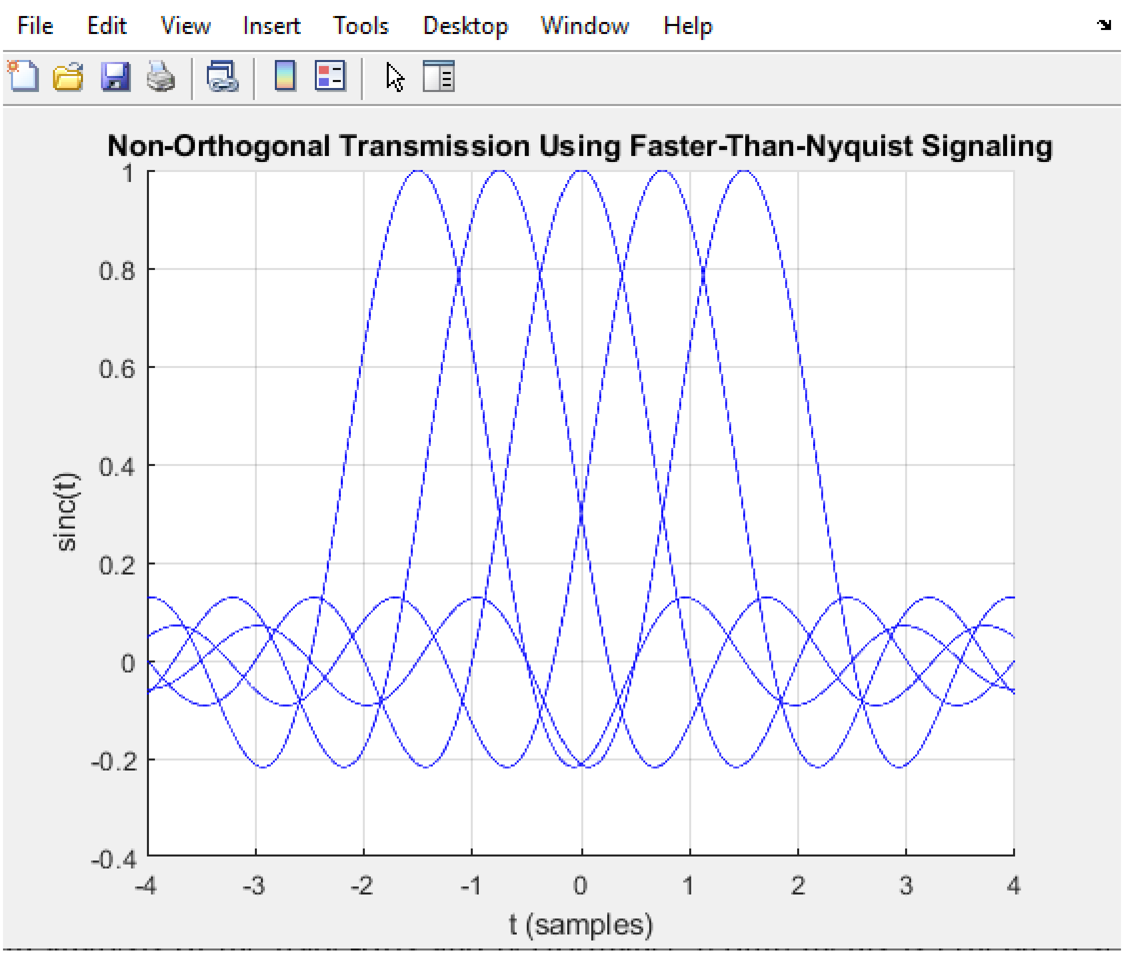


Figure (4.2): Non-Orthogonal transmission using faster-than-Nyquist signaling

4.4 Difference Between Transmission Techniques in Communication Systems: Orthogonal and Non-Orthogonal Approaches

When comparing orthogonal and non-orthogonal approaches in the context of operating faster than the Nyquist rate in Figure (4.3). Orthogonal techniques like OFDM provide established solutions for high spectral efficiency and robustness to channel impairments. Non-orthogonal techniques can offer increased data rates but require careful management of ISI and advanced signal processing techniques. A thorough analysis of the trade-offs and performance requirements is crucial in selecting the most suitable transmission technique for a given application.

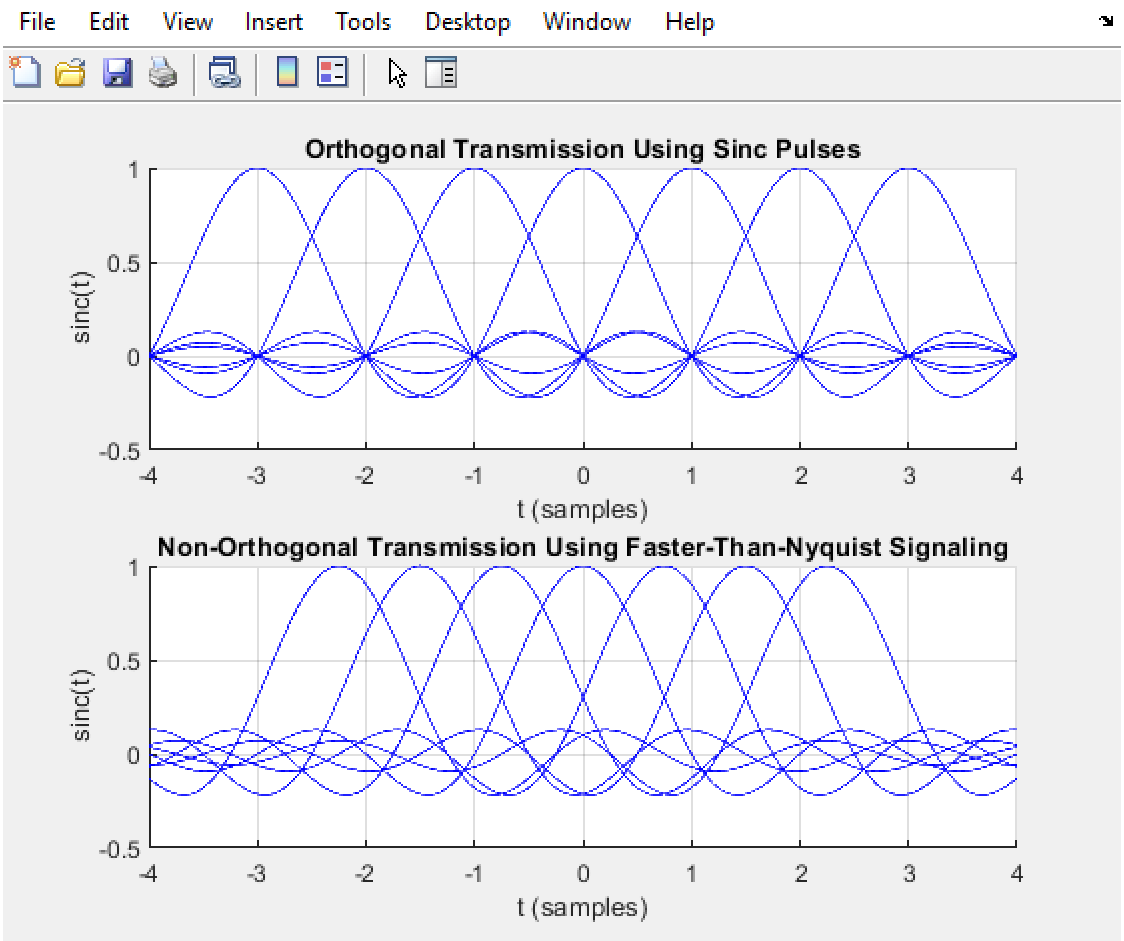


Figure (4.3): Comparing Orthogonal and Non-orthogonal Transmission Techniques

4.5 The Frequency Response Nyquist Rate

When considering the frequency response of the Nyquist rate, the parameter alpha (α) can play a role in shaping the response. The value of α determines the roll-off characteristics of the pulse shaping filter used in the system. It affects the rate at which the frequency response attenuates outside the desired bandwidth.

Raised Cosine Filter: The α parameter appears in the frequency response equation of raised cosine filters, commonly used in digital communication systems.

Gaussian Filter: α also features in the frequency response equation of Gaussian filters, often used in pulse shaping and anti-aliasing applications..

1. Alpha (α) = 0:

When α is set to 0, it represents a rectangular or square pulse shape. This pulse shape has a sharp transition between on and off states, resulting in a frequency response that has a sinc-shaped response with significant side lobes. The side lobes extend beyond the desired bandwidth and can introduce interference and degrade the system's performance. The presence of these side lobes can cause inter symbol interference (ISI), resulting in errors during signal reception.

2. Alpha (α) = 1:

When α is set to 1, it represents a raised cosine pulse shape. This pulse shape has a smoother transition between on and off states, resulting in a frequency response that rolls off more gradually. The raised cosine pulse shape helps mitigate the presence of side lobes and reduces interference in the system. The gradual roll-off of the frequency response helps minimize ISI and improves the system's ability to accurately recover the transmitted symbols. In summary, the choice of α in the frequency response of the Nyquist rate pulse shaping filter affects the shape and characteristics of the response. An α value of 0, representing a rectangular pulse, can result in significant side lobes and introduce interference. On the other hand, an α value of 1, representing a raised cosine pulse, provides a smoother roll-off and helps mitigate interference and inter symbol interference, leading to improved performance in the communication system as shown in Figure (4.4).

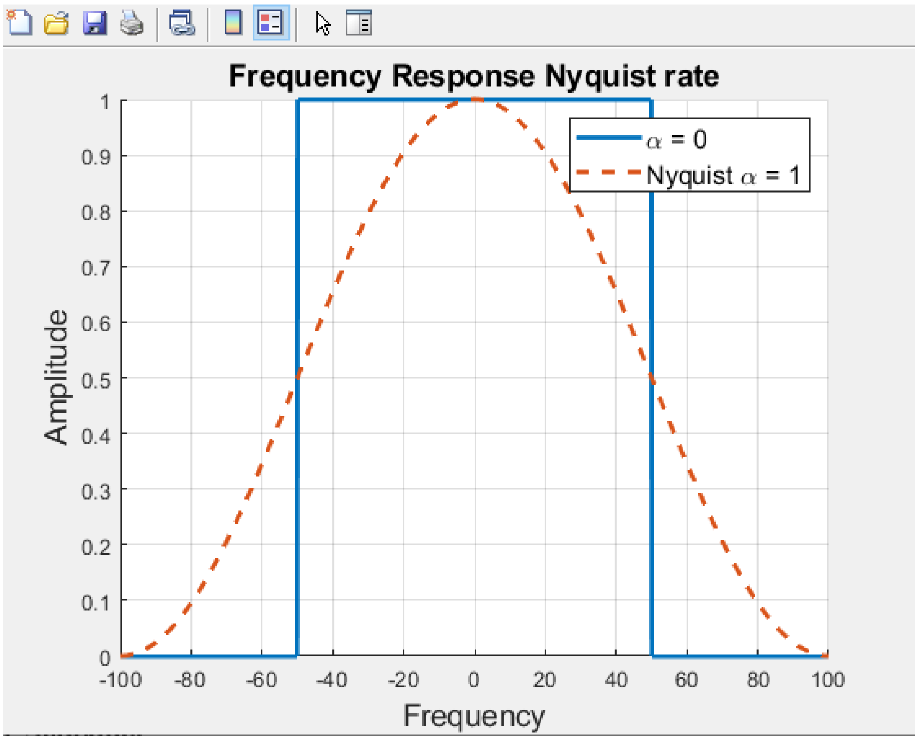


Figure (4.4): The frequency response Nyquist Rate

4.6 The Frequency Response faster Than Nyquist Rate

When considering the frequency response of a communication system operating faster than the Nyquist rate, the parameter alpha (α) in the pulse shaping filter can influence the system's characteristics. The pulse shaping filter is used to shape the transmitted signal and control its spectral properties. Let's examine the results of using alpha values of 0 and 0.25 as shown in Figure (4.5).

1. Alpha (α) = 0:

When α is set to 0, it represents a rectangular pulse shape. This pulse shape has a sharp transition between on and off states, resulting in a frequency response that has a sinc-shaped response with significant side lobes. The side lobes extend beyond the desired bandwidth, leading to interference and potential inter symbol interference (ISI). Using a rectangular pulse shape at a faster-than-Nyquist rate may result in a higher likelihood of ISI and signal distortion. This can impact the system's performance and result in errors during signal reception.

2. Alpha (α) = 0.25:

When α is set to 0.25, it represents a pulse shape that has a smoother transition between on and off states compared to a rectangular pulse. This smoother transition helps reduce the presence of significant side lobes in the frequency response. The frequency response rolls off more gradually, which can mitigate interference and reduce the likelihood of ISI. By using a pulse shape with α = 0.25 at a faster-than-Nyquist rate, the system may exhibit improved spectral containment, resulting in better signal quality and reduced errors during reception. In summary, the choice of alpha (α) in the pulse shaping filter when operating faster than the Nyquist rate impacts the system's frequency response. A rectangular pulse shape (α = 0) can introduce significant side lobes and increase the risk of ISI and interference. On the other hand, using a pulse shape with α = 0.25 can provide a smoother roll-off, reduce interference, and potentially enhance the system's performance by mitigating ISI and improving signal quality.

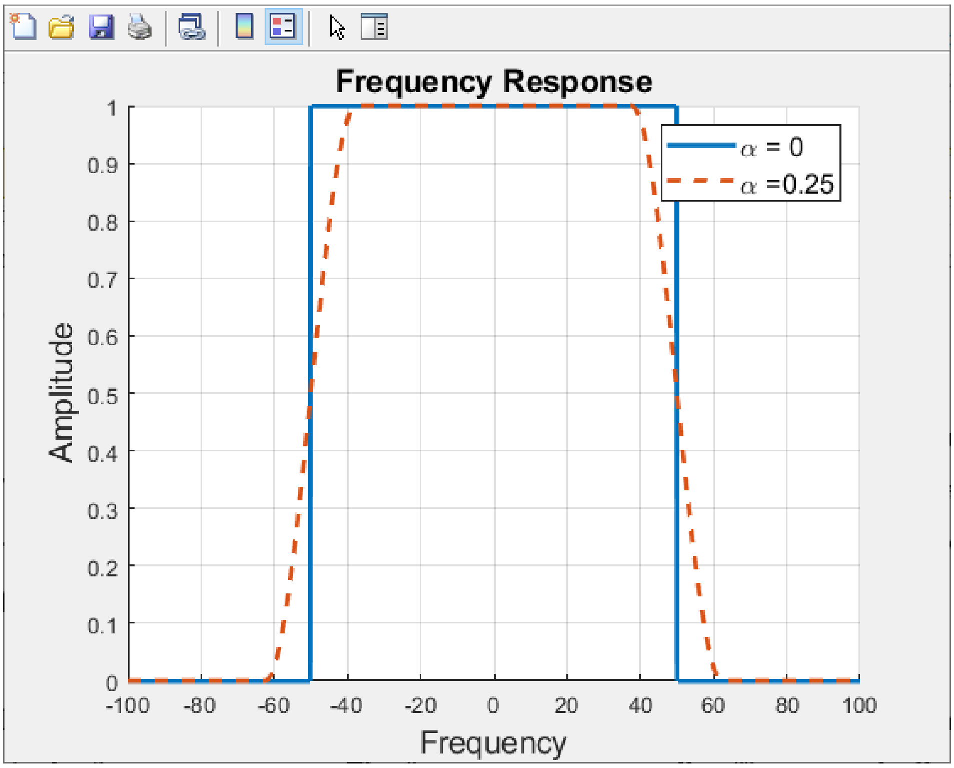


Figure (4.5): The Frequency Response faster Than Nyquist Rate

4.7 Proposed Uncoded Faster Than Nyquist Rate Signaling

Proposing an uncoded signaling system ,this communication system operates at a rate surpassing the Nyquist rate with BPSK, QPSK, 16QAM, 64QAM, and 256QAM modulation schemes can have several implications for BER and Eb/No performance. Let's discuss the potential outcomes and the advantages of such a system for implementation in communication systems.

- Binary Phase Shift Keying (BPSK):

In an uncoded system operating above the Nyquist rate, BPSK will experience increased inter symbol interference (ISI) and a higher BER. Achieving the best BER performance in this scenario would require careful consideration of the modulation scheme, system parameters, and error mitigation techniques. However, uncoded BPSK may not be the best choice for high-rate signaling due to its susceptibility to ISI.

- Quadrature Phase Shift Keying (QPSK):

QPSK, being a modulation scheme with four phase shifts, is more robust against ISI compared to BPSK. While operating at a rate surpassing the Nyquist rate introduces challenges, employing QPSK can still yield better BER performance compared to BPSK. Optimal system design, including appropriate pulse shaping and equalization techniques, can further improve the performance of uncoded QPSK.

- A Quadrature Amplitude Modulation (16QAM):

16QAM is combines both amplitude and phase shifts. Operating 16QAM above the Nyquist rate results in increased ISI and a higher BER. However, by employing advanced equalization and error correction techniques, it is possible to mitigate the effects of ISI and achieve good BER performance with uncoded 16QAM.

- 64 Quadrature Amplitude Modulation (64QAM):

64QAM offers higher data rates but is more susceptible to channel impairments when operated above the Nyquist rate. Despite the challenges, by carefully designing the system and incorporating advanced error mitigation techniques, it is possible to achieve acceptable BER performance with uncoded 64QAM.

- 256 Quadrature Amplitude Modulation (256QAM):

256QAM is a high-order modulation scheme with increased data rates. However, operating it above the Nyquist rate poses significant challenges due to severe ISI and noise interference. Implementing uncoded 256QAM at a rate faster than the Nyquist rate may result in poor BER and other performance.

Increasing symbols per frame: For all modulation schemes (BPSK, QPSK, 16QAM, 64QAM), the provided metrics (presumably bit error rate, BER) generally decrease as the number of symbols per frame increases. This is expected behavior, as using more symbols per frame effectively spreads the same amount of information over a longer time, leading to a higher Eb/No and improved error performance.

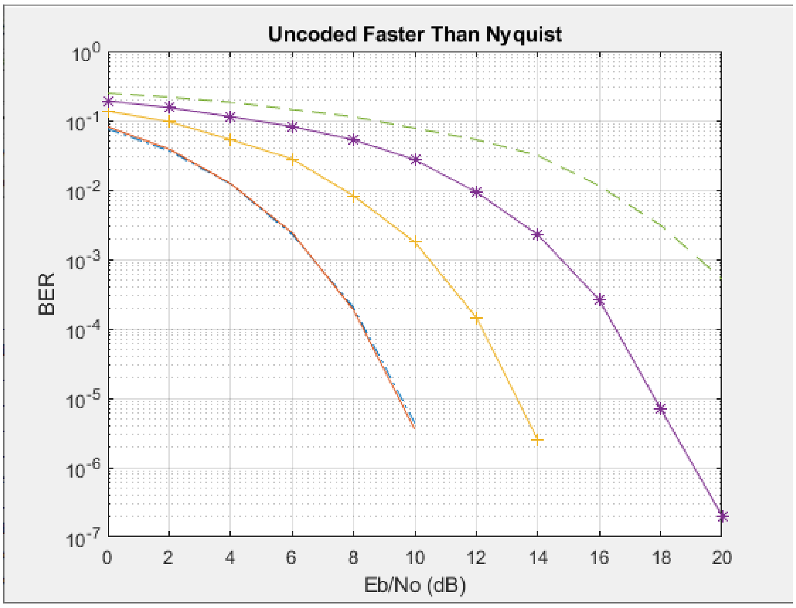
Modulation scheme comparison: As the modulation complexity increases (moving from BPSK to QPSK, 16QAM, and beyond), the BER initially decreases due to the higher information density, higher-order modulations become more susceptible to noise and channel impairments, leading to a faster increase in BER as symbols per frame increase.

In this table we elaborate the different types of modulations with various value of Eb/No as shown in Figure (4.6).

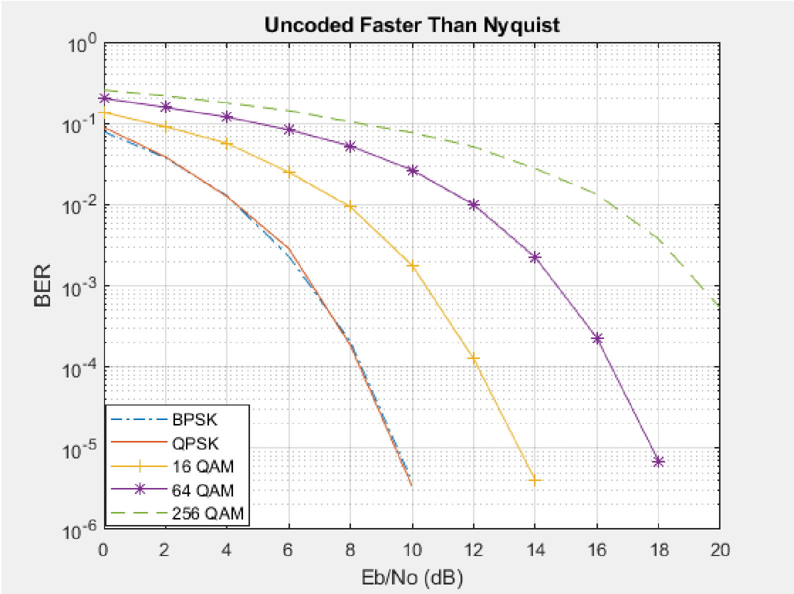
Table (4.1): Various Symbols Per Frame For Uncoded FTN

BER for (1024)	BER for (2048)	BER for (4096)	Eb/No(dB)	Modulation Types
0.020507	0.022265	0.023925	6	BPSK
0.002726	0.002319	0.002146	6	QPSK
0.020795	0.030395	0.028747	6	16QAM
0.086100	0.084309	0.084635	6	64QAM
0.1427	0.145447	0.14325	6	256QAM
0.005859	0.005794	0.006195	8	BPSK
0.000223	0.000189	0.000192	8	QPSK
0.009521	0.008666	0.008636	8	16QAM
0.049153	0.053710	0.054077	8	64QAM

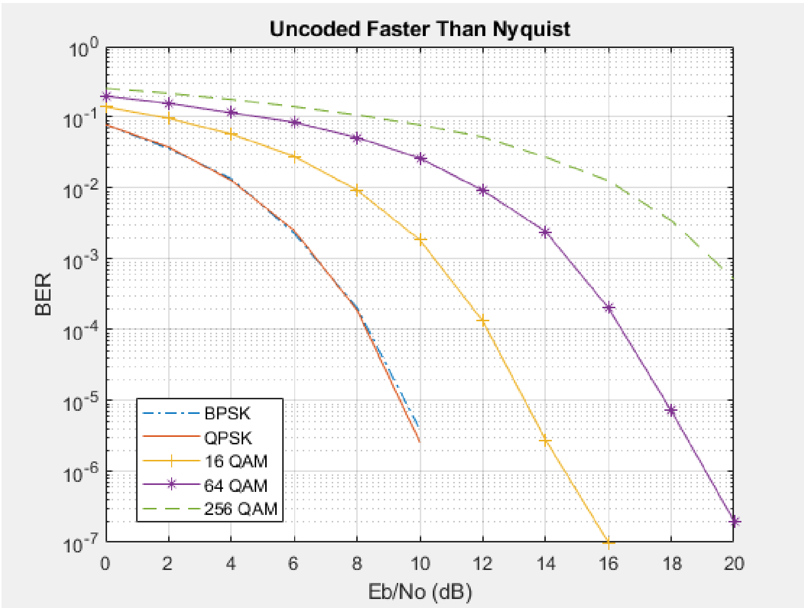
0.105103	0.109314	0.112732	8	256QAM
$7.812\text{x } 10^{-3}$	$7.608 \text{ x } 10^{-3}$	$7.828 \text{ x } 10^{-3}$	10	BPSK
$3.799 \text{ x } 10^{-6}$	$3.299 \text{ x } 10^{-6}$	$3.299 \text{ x } 10^{-6}$	10	QPSK
$1.627 \text{ x } 10^{-2}$	$1.757 \text{ x } 10^{-2}$	$1.761 \text{ x } 10^{-2}$	10	16QAM
$2.791 \text{ x } 10^{-1}$	$2.620 \text{ x } 10^{-1}$	$2.596 \text{ x } 10^{-1}$	10	64QAM
$7.983 \text{ x } 10^{-1}$	$7.794 \text{ x } 10^{-1}$	$7.788 \text{ x } 10^{-1}$	10	256QAM



(a) 1024 SPF



(b) 2048 SPF



(c) 4096 SPF

Figure (4.6): Uncoded Faster Than Nyquist Rate Signaling With Various Symbols Per Frame (a) symbols per frame = 1024 , (b) symbols per frame = 2048 , (c) symbols per frame = 4096

4.8 Proposed Coded Faster Than Nyquist Rate Signaling

Simulating coded faster than Nyquist rate signaling involves using a convolutional encoder with different coding rates and different modulation schemes, along with a raised cosine (RRC) pulse shaping filter. The performance of the system can be evaluated. Let's discuss the results for each combination of coding rate and modulation scheme.

- Rate of Coding:

An amount of redundancy added by the convolutional encoder depends on the coding rate. A higher coding rate provides more redundancy and better error correction capabilities but at the cost of reduced data rate. A factors that influence the desired balance between error correction capability and data rate. Higher coding rates (0.75 and 1) offer better error correction but result in a lower data rate. Lower coding rates (0.5 and 0.66) provide higher data rates but have lower error correction capabilities. The best coding rate will depend on the channel conditions and the required level of error resilience for the application.

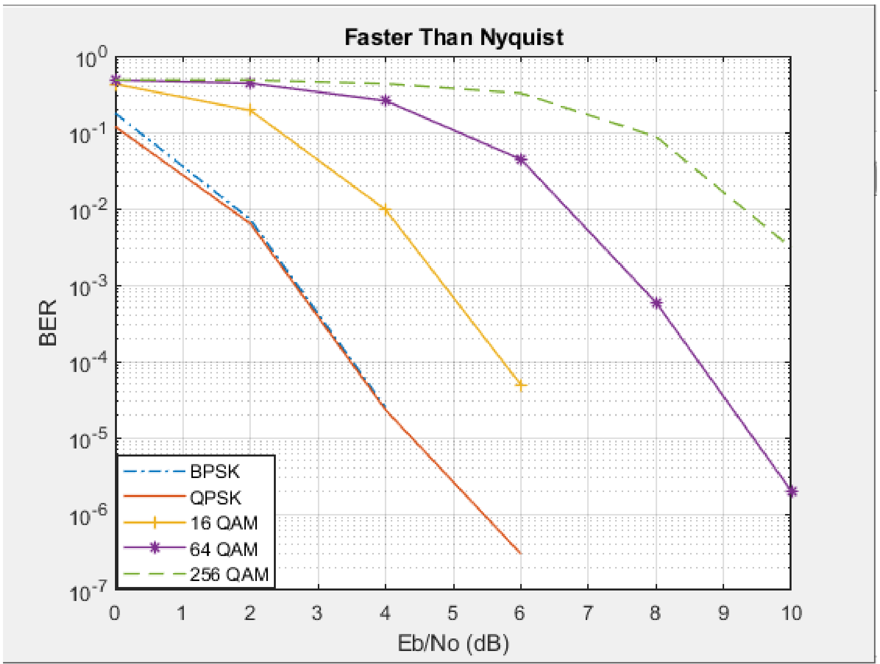
- Modulation Scheme:

The modulation scheme determines how the digital data is mapped onto the analog waveform for transmission. The modulation schemes considered in this case are BPSK, QPSK, 16QAM, 64QAM, and 256QAM. These schemes offer different trade-offs between data rate and robustness to noise. The best modulation scheme depends on the channel conditions. Generally, higher order schemes (16QAM, 64QAM, and 256QAM) provide faster data speeds, but are more sensitive to noise for reliable connection. Lower-order schemes (BPSK and QPSK) are more robust to noise but offer lower data rates.

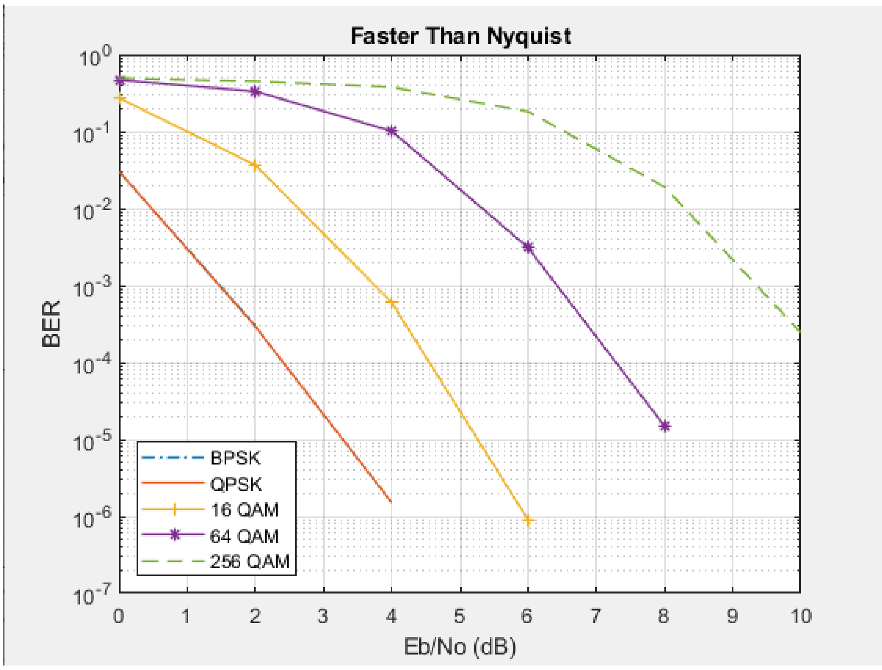
Modulation scheme comparison: QPSK generally requires lower Eb/No than 16QAM to achieve the same target BER, especially for lower code rates (0.5 and 0.66). This is because QPSK has a simpler constellation with better separation between symbols, making it less susceptible to noise as shown in this table.

Table (4.2): Various Rate For Coded FTN With (QPSK &16QAM) Modulations

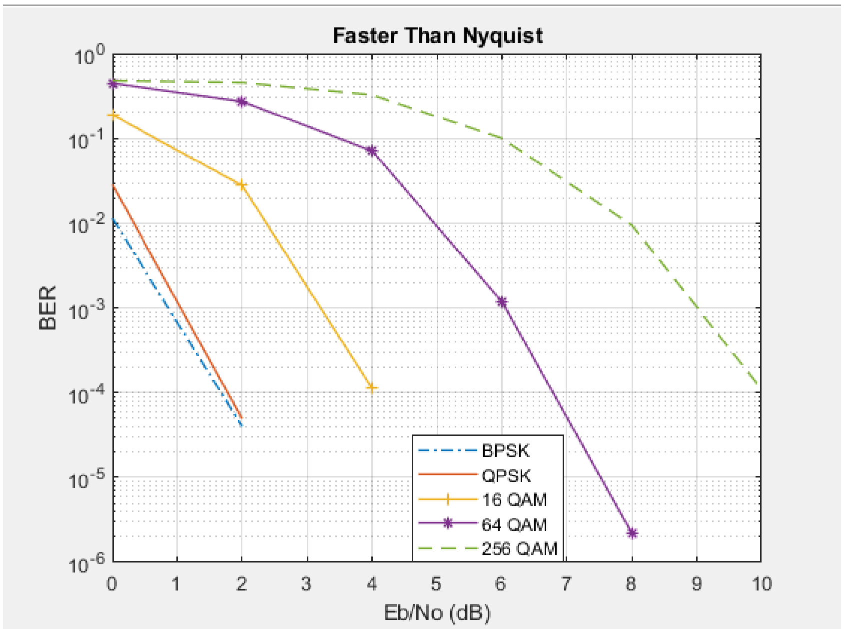
Rate Value	BER	Eb/No(dB)	Modulation Type	Rate Value	BER	Eb/No(dB)	Modulation Type
0.5	10^{-4}	3.5	QPSK	0.5	10^{-4}	5.7	16QAM
0.66	10^{-4}	2.3	QPSK	0.66	10^{-4}	4.6	16QAM
0.75	10^{-4}	1.8	QPSK	0.75	10^{-4}	4	16QAM



(a) 0.5 code rate



(b) 0.66 code rate



(c) 0.75 code rate

Figure (4.7): Coded Faster Than Nyquist Rate Signaling With Various Code Rate And Various Modulations

➢ Coded Faster Than Nyquist Rate Signaling With BCJR

Coded Faster Than Nyquist (F-TN) Rate signaling with BCJR (Bahl-Cocke-Jelinek-Raviv) algorithm is a communication technique used to increase the spectral efficiency of digital communication systems. It involves transmitting data at rates higher than the Nyquist rate, which is the theoretical maximum data rate that can be achieved without interference.

When the BCJR algorithm is added to the Coded FTN Rate signaling scheme, it enhances the decoding process by improving the reliability and accuracy of the received data. The BCJR algorithm is a maximum likelihood sequence estimation (MLSE) algorithm that helps in decoding the transmitted symbols by taking into account the channel characteristics and noise.

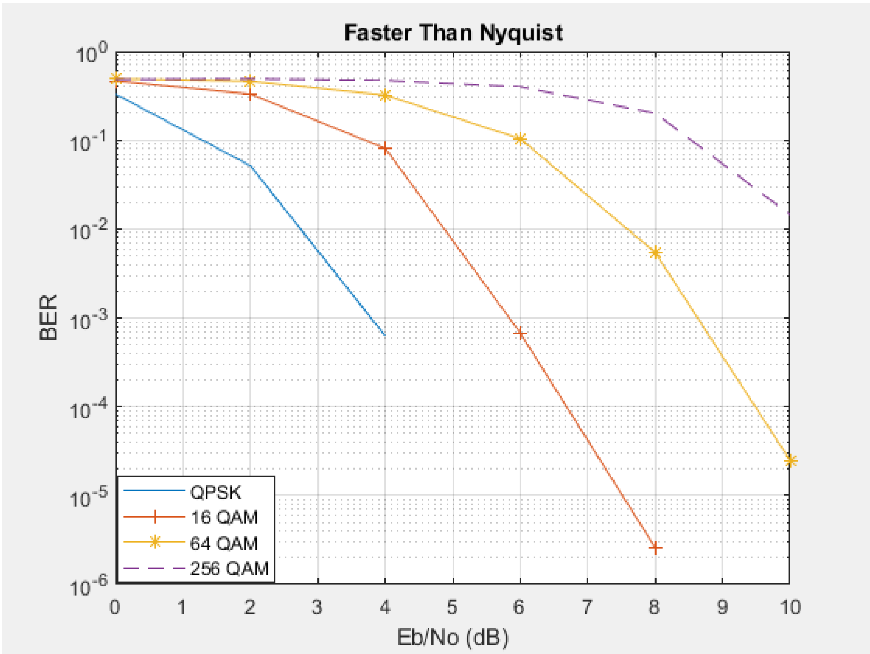
Modulation scheme comparison: Similar to our previous discussion, QPSK generally outperforms 16QAM in terms of required Eb/No for achieving the same target BER (Bit Error Rate). This is because QPSK has a simpler constellation with better symbol separation, making it less susceptible to noise compared to the higher-order constellation of 16QAM.

Code rate: As the code rate (represented by the "Rate Value" parameter) decreases, the required Eb/No for a specific target BER generally decreases. This is because lower code rates provide more redundancy for error correction, allowing the BCJR decoder to correct errors more effectively. However, lower code rates also lead to a decrease in data throughput.

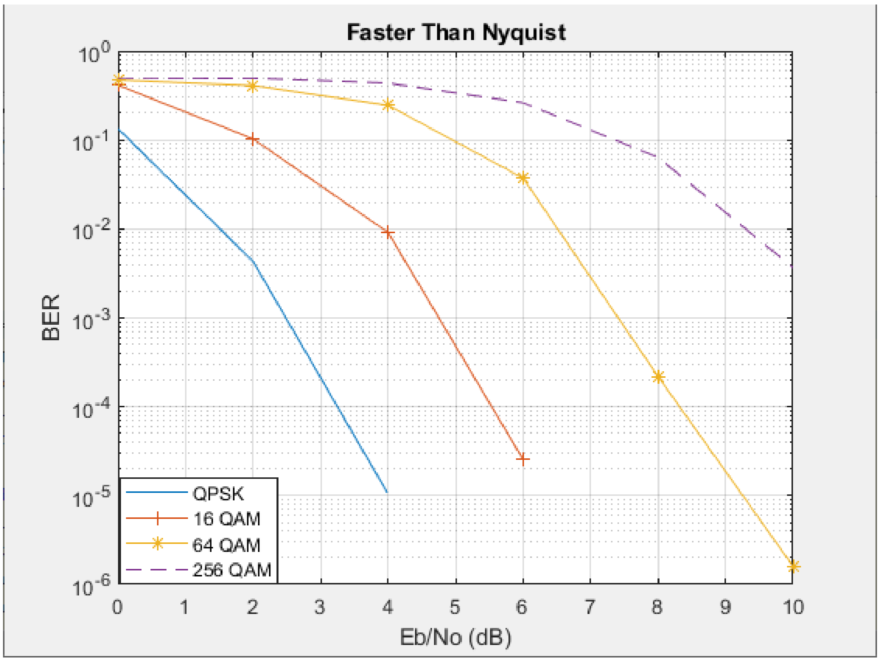
BER impact: The data shows results for a range of target BERs from 10^{-3} to 10^{-5}. This helps us understand the trade-off between Eb/No, code rate, and BER performance for each modulation scheme. For example, achieving a stricter BER like 10^{-5} requires a lower code rate and consequently a higher Eb/No compared to achieving a less strict BER like 10^{-3}.

Table (4.3): Various Rate For Coded FTN With BCJR

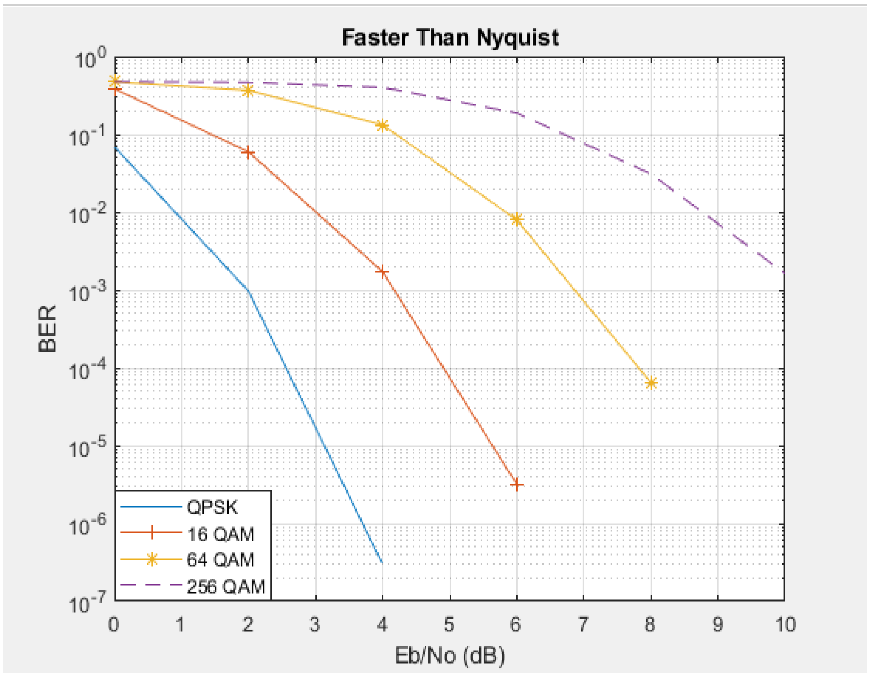
Rate Value	BER	Eb/No	Modulation Type	Rate Value	BER	Eb/No	Modulation Type
0.5	10^{-3}	3.9	QPSK	0.5	10^{-3}	5.8	16QAM
0.66	10^{-4}	3.3	QPSK	0.66	10^{-4}	5.6	16QAM
0.75	10^{-5}	3.2	QPSK	0.75	10^{-5}	5.5	16QAM
1	10^{-5}	2	QPSK	1	10^{-5}	4	16QAM



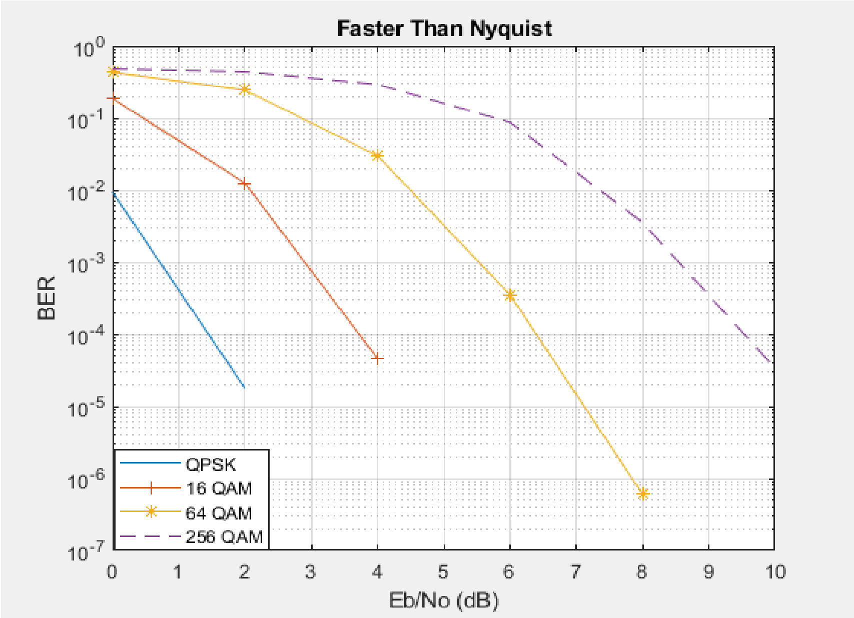
(a) 0.5 code rate



(b) 0.66 code rate



(c) 0.75 code rate



(d) 1 code rate

Figure (4.8): Coded Faster Than Nyquist Rate Signaling With BCJR (a)Rate = 0.5, (b)Rate = 0.66, (c)Rate = 0.75, (d)Rate = 1

4.9 Faster Than Nyquist Rate Signaling With OFDM

The simulation results from FTN signaling with OFDM using BPSK and QPSK as shown in figure (4.8), would depend on the specific parameters and objectives of the simulation, some common factors to consider and analyze in the simulation results include:

- BER: measures the degree of precision between the transmitted and received signals. It quantifies the level of errors introduced during the transmission process. The simulation results would provide the BER values for different signal-to-noise ratios allowing to assess the system's performance.
- The simulation results would provide insights into the performance of the FTN signaling with OFDM using BPSK and QPSK. It would showcase the trade-offs between higher data rates, increased spectral efficiency, and potential challenges such as increased inter-symbol interference due to the higher signaling rates.

Table (4.4): Bit Error Rate and Signal to Noise Ratio to FTN With OFDM.

BER	SNR (dB)	Modulation Type	BER	SNR (dB)	Modulation Type
2.20312×10^{-3}	2	BPSK	1.24516×10^{-2}	2	QPSK
2.5×10^{-5}	4	BPSK	3.53906×10^{-3}	4	QPSK
1.5625×10^{-6}	6	BPSK	8.29688×10^{-4}	6	QPSK

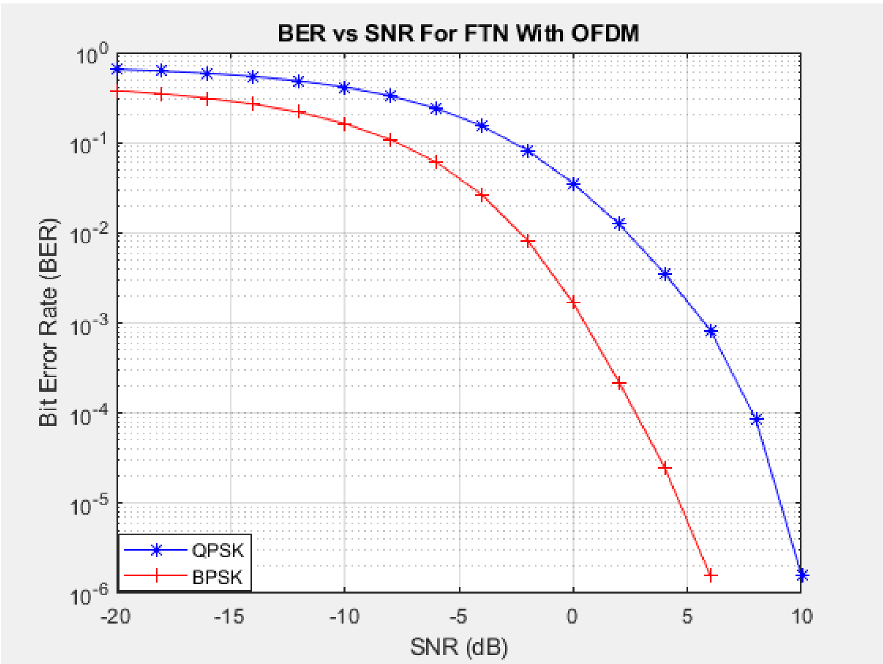


Figure (4.9): Simulation Analysis of Faster-than-Nyquist OFDM with BPSK and QPSK

4.10 Bit error rate (BER) performance comparison

The table (4.5) compares the BER performance of FTN signaling to that of conventional Nyquist signaling FTN signaling has a higher BER than conventional Nyquist signaling. However, the BER of FTN signaling can be improved by using coding and OFDM.

Table (4.5) **BER performance comparison**

Modulation scheme	**BER**
Nyquist signaling	10^{-5}
Uncoded FTN signaling	10^{-4}
Coded FTN signaling	10^{-6}
FTN signaling with OFDM 10^-7	10^{-7}

4.11 Capacity of Faster Than Nyquist Signaling

When considering the effect of changing the symbol period (tau) on the capacity of faster-than-Nyquist rate signaling and Nyquist signaling with rate of 0.5 as shown in figure (4.10), several key factors come into play. The symbol period determines the time duration allocated to each symbol in the transmission.

- Faster-than-Nyquist Rate Signaling:

Decreasing Symbol Period (Smaller Tau): As the symbol period decreases, the time duration allocated to each symbol becomes shorter. This allows for faster symbol transmission, enabling a higher symbol rate. However, reducing symbol period may result in increased (ISI) due to shorter symbol duration.

Increasing Symbol Period (Larger Tau): A larger symbol period provides more time for each symbol, resulting in a slower symbol transmission rate. This reduces the capacity of the system as fewer symbols can be transmitted within a given time frame. However, a longer symbol period can help mitigate ISI, as there is more time for the received signal to settle before the detection of the next symbol.

- Nyquist Signaling with Rate 0.5:

Changing Symbol Period: The capacity of Nyquist signaling with a rate of 0.5 depends on the Nyquist criterion, which states that the symbol rate must be twice the bandwidth to prevent inter symbol interference.

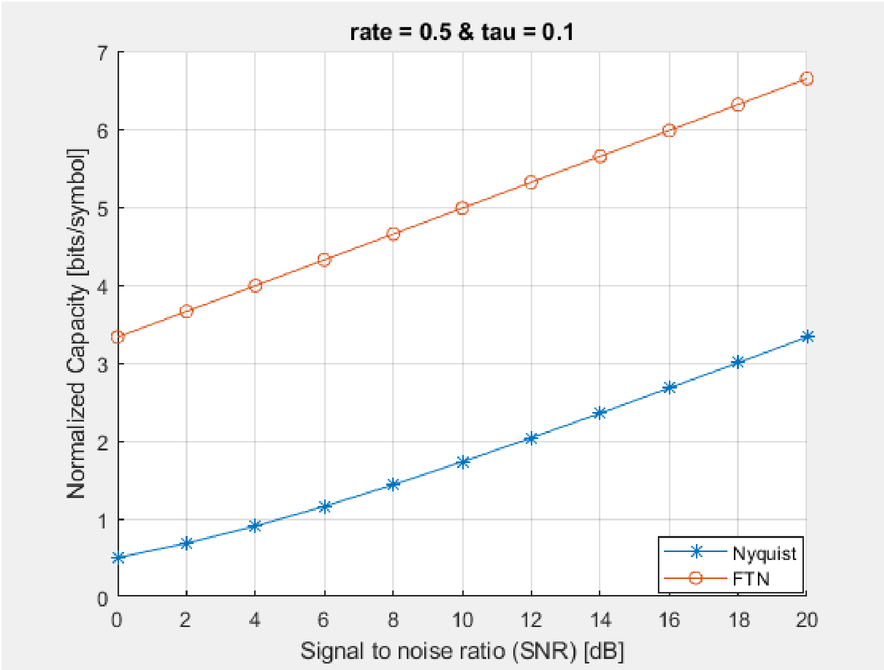
In this case, changing the symbol period affects the symbol rate. Reducing the symbol period increases the symbol rate, potentially exceeding the Nyquist criterion and leading to ISI and reduced capacity. Conversely, increasing the symbol period decreases the symbol rate, ensuring compliance with the Nyquist criterion and maintaining a higher capacity.

Changing the symbol period (tau) in faster-than-Nyquist rate signaling and Nyquist signaling with a rate of 0.5 can have varying effects on the capacity of the system. In faster-than-Nyquist signaling, decreasing the symbol period can increase capacity but may introduce ISI, while increasing the symbol period can decrease capacity but potentially reduce ISI.

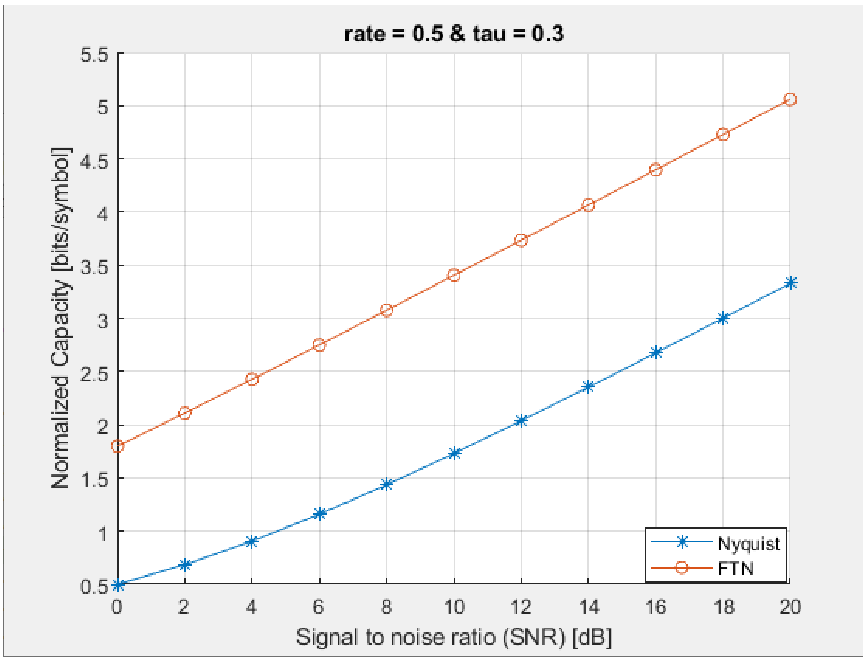
In Nyquist signaling, changing the symbol period affects the symbol rate, and maintaining compliance with the Nyquist criterion is crucial to avoid ISI and ensure a higher capacity. The table below show many cases of changing the symbol period (tau) with rate of 0.5.

Table (4.6): comparison of the FTN Capacity and Nyquist Capacity

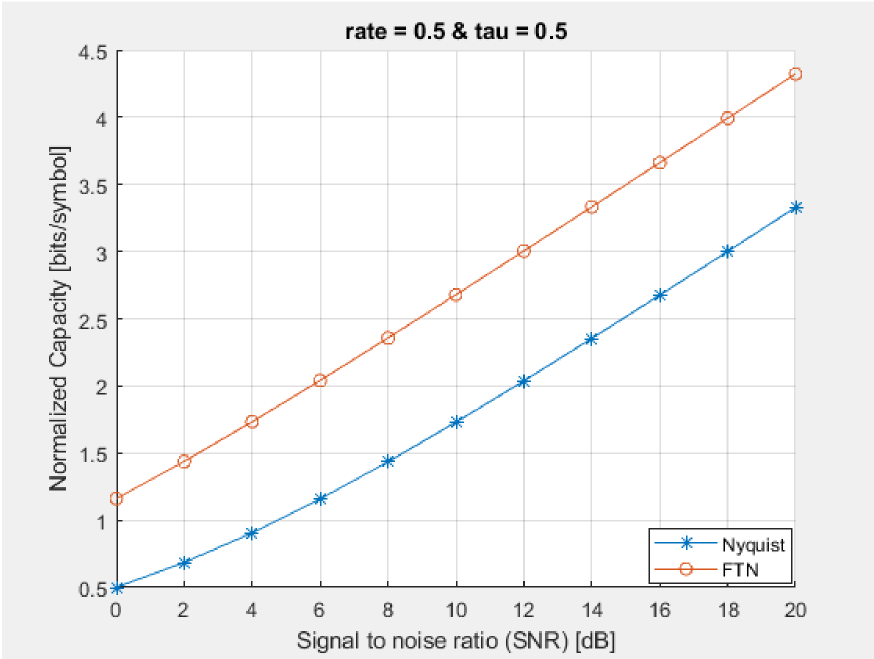
Rate	Tau	SNR (dB)	FTN Capacity	Nyquist Capacity
0.5	0.1	4	3.989	0.906
0.5	0.3	4	2.426	0.906
0.5	0.5	4	1.732	0.906
0.5	0.7	4	1.307	0.906
0.5	0.9	4	1.018	0.906
0.5	1	4	0.906	0.906



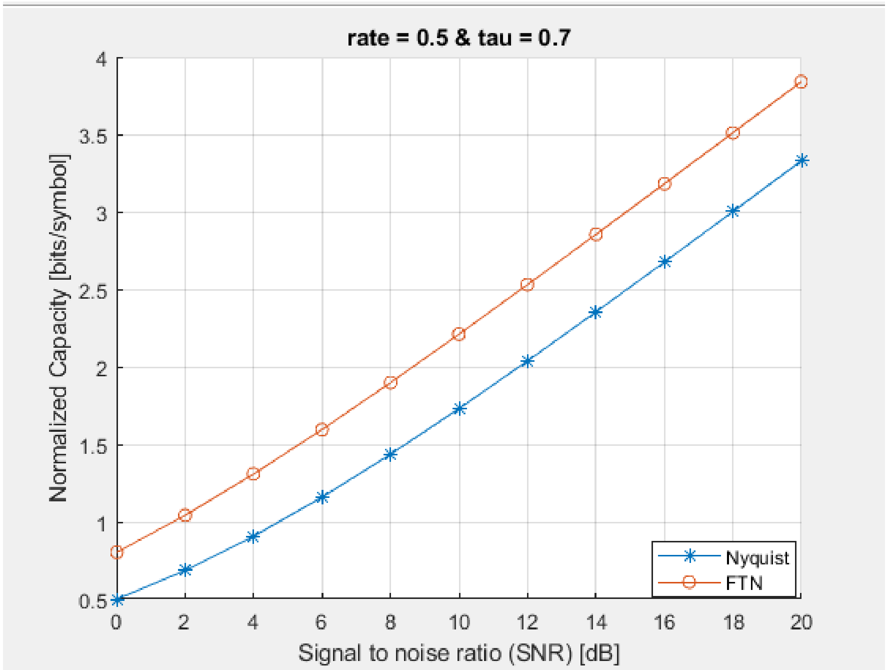
(a) 0.1 tau



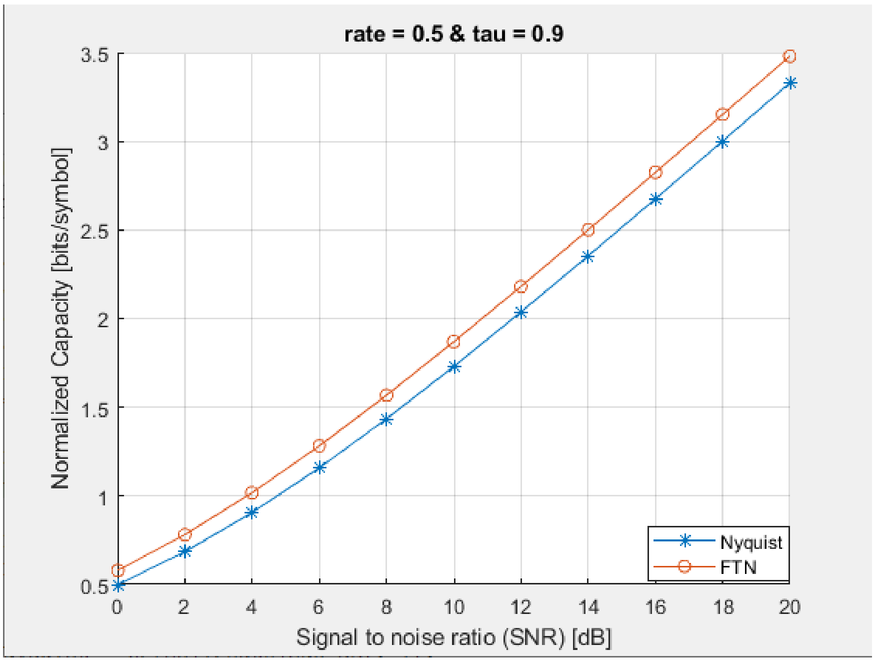
(b) 0.3 tau



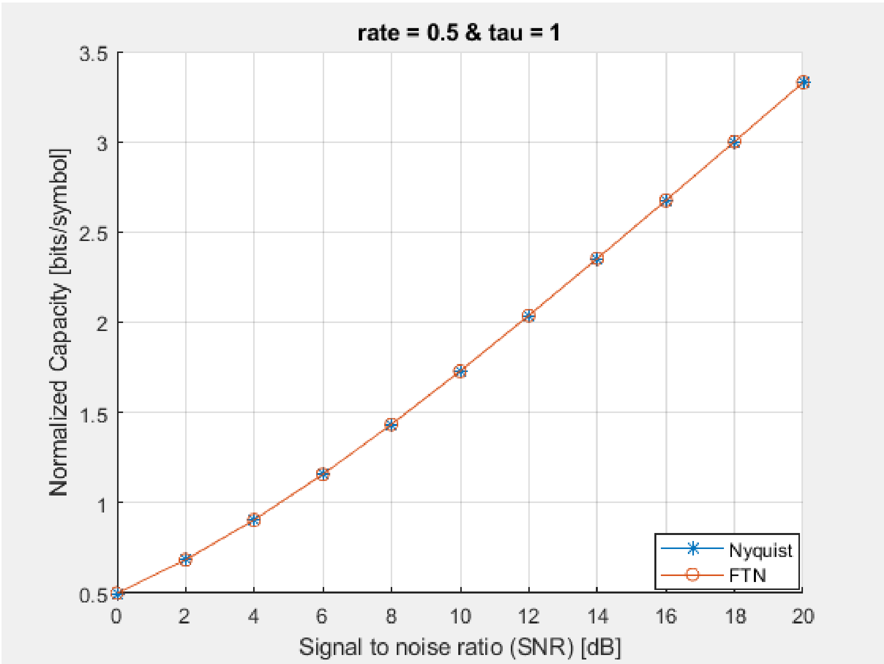
(c) 0.5 tau



(d)0.7 tau



(e)0.9 tau



(f) 1 tau

Figure (4.10): Capacity for Faster Than Nyquist Signaling And Nyquist Signaling

(a) tau = 0.1, *(b)* tau = 0.3, *(c)* tau = 0.5, *(d)* tau = 0.7, *(e)* tau = 0.9, *(f)* tau = 1

4.12 The Effect of Faster-Than-Nyquist Rate on Spectral Efficiency (SE) for Communication Systems

When we calculates the spectral efficiency and bit error rate (BER) for a faster-than-Nyquist (FTN) system with different values of tau in Figure (4.11): Here's a discussion of the results obtained from running in matlab:

- Spectral Efficiency vs. Tau Curve:

The calculations of the spectral efficiency for each tau value and plots a curve showing the relationship between tau and spectrum effectiveness. Bits per second per hertz (bits/s/Hz) are used to calculate spectral efficiency. A plot allows you to observe how changing the value of tau affects the system's spectral efficiency.

Typically, as tau increases, the spectral efficiency decreases because a higher value of tau implies a wider transmission bandwidth, which reduces the number of independent symbols that can be transmitted per second within that bandwidth.

- Bit Error Rate (BER):

The calculates the BER for each tau value signifies a proportion of erroneously received bits in relation to total bits sent during a transmission. A lower BER denotes superior performance, as it indicates a reduced number of errors in the acquired information. Impact of Tau on Spectral Efficiency and BER:

By observing the results, you can analyze the impact of different tau values on both spectral efficiency and BER. Here are some observations you can make:

- Spectral Efficiency: As tau increases, the spectral efficiency decreases. This is because a larger tau corresponds to a wider bandwidth, resulting in a lower number of symbols that can be transmitted per second. Therefore, the spectral efficiency decreases with increasing tau.

- Bit Error Rate (BER): The BER indicates the accuracy of the received symbols. A lower BER indicates a higher quality of transmission. In general, a larger tau value leads to a higher BER due to the increased inter-symbol interference (ISI) caused by overlapping symbols. As tau increases, the symbols start to interfere with each other, leading to a higher likelihood of errors in symbol detection.

It's important to note that the results may vary based on the specific system parameters, such as the SNR (signal-to-noise ratio), pulse shape, and channel characteristics.

Table (4.7): Value Of Curve For Spectral Efficiency (SE) Of Faster Than Nyquist Rate With Different Values Of Tau And Bit Error Rate (BER)

Spectral Efficiency (SE)	Tau	Bit Error Rate (BER)
20.5737	0.1	0.4932
10.2869	0.2	0.4953
6.8579	0.3	0.5198
5.1434	0.4	0.5389
4.1147	0.5	0.4553
3.4290	0.6	0.4871
2.9391	0.7	0.4630
2.5717	0.8	0.4910
2.2860	0.9	0.4483
2.0574	1	0.5337

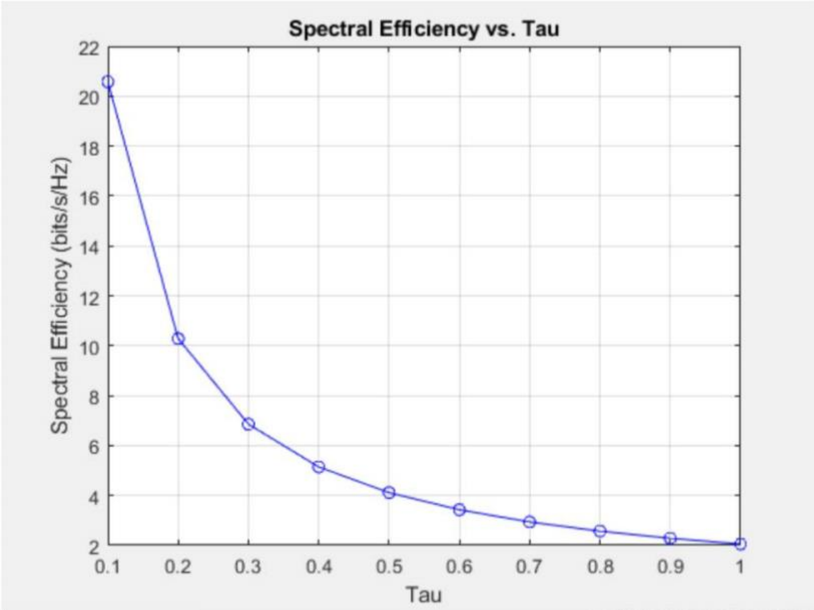


Figure (4.11): Spectral Efficiency (SE) Of Faster Than Nyquist Rate With Different Values Of Tau

here's a discussion of the observed performance and potential implications:

Proposed uncoded FTN: QPSK offers a very low BER (3.79 x 10^{-6}) in AWGN, making it a strong candidate for applications requiring high reliability without coding complexity.

Proposed coded FTN: BPSK with BCJR coding achieves the lowest BER among all configurations (3.03 x 10^{-5}) with a moderate frame size (4 symbols). This suggests a good balance between performance and efficiency. QPSK with BCJR offers even lower BER (3 x 10^{-7}) but at the cost of a smaller frame size (4 symbols).

FTN with OFDM: QPSK with OFDM achieves a good BER (10^{-6}) in AWGN, comparable to uncoded QPSK in traditional FTN, the performance significantly degrades in a fading channel, highlighting the need for channel adaptation techniques for OFDM systems.

Table (4.8): Evaluating the Proposed System Against Prior Works

No	Ref.	Modulation Type	Equalizer	BER	SNR
1	**Proposed uncoded FTN**	QPSK	_	3.79×10^{-6}	10
2	[12]	QPSK	_	3.5×10^{-6}	10
3	**Proposed Coded FTN**	BPSK	_	3.03×10^{-5}	4
4	[46]	BPSK	_	2.6×10^{-5}	9
5	**Proposed Coded FTN**	QPSK	BCJR	3×10^{-7}	4
6	[48]	QPSK	MAP	10^{-4}	1.2
7	**FTN With OFDM**	QPSK	_	10^{-6}	10
8	[57]	QPSK	✓	10^{-4}	30

proposed system in Table (4.8), whether coded or uncoded, with or without BCJR decoding, and incorporating FTN with OFDM, demonstrates improved data transmission rates with the same channel in all cases (AWGN) channel compared to prior works in each respective case, catering to different performance and reliability requirements.

Chapter Five

Conclusion and Future Works

Chapter Five

Conclusion and Future Works

5.1 Conclusions:

In this investigation, MATLAB was utilized to perform simulations of communication systems employing faster-than-Nyquist (FTN) signaling techniques. We explored three different approaches: uncoded FTN, coded FTN, and FTN with orthogonal frequency-division multiplexing (OFDM). Here are the conclusions drawn from simulations:

1.Uncoded FTN: By transmitting signals at rates higher than the Nyquist rate, we observed a significant improvement in spectral efficiency. The main challenge with uncoded FTN is the increased susceptibility to inter symbol interference and noise, which can degrade the overall system performance. Therefore, while uncoded FTN shows promise for achieving higher data rates, it requires additional error correction techniques to mitigate the impact of ISI and noise.

2.Coded FTN: To address the issues of ISI and noise in uncoded FTN, we introduced coding schemes such as convolutional encodes. By incorporating error correction coding, we observed a substantial reduction in the bit error rate (BER) and improved overall system performance. The use of coding techniques helps in combating the adverse effects of ISI and noise, enabling reliable communication at faster signaling rates.

3.FTN with OFDM: Furthermore, an exploration was carried out to examine the integration of FTN signaling that is faster than Nyquist with orthogonal frequency division multiplexing, commonly employed technique to contemporary communication systems. By harnessing the advantages of OFDM, notable enhancements were observed in terms of spectral efficiency and error rate. The amalgamation of FTN and OFDM emerges as a robust strategy to attain elevated data rates while mitigating the adverse effects of inter symbol interference (ISI) and noise. The simulation results and findings from this work would contribute to the body of knowledge in the field of communication engineering. The selection of the most suitable signaling scheme depends on a careful evaluation of system requirements, channel conditions, and implementation complexity. FTN and FTN-OFDM offer promising spectral efficiency gains, while coded signaling provides improved error resilience. Uncoded signaling remains a viable option for simpler systems with less stringent performance needs.

5.2 Future work:

While our simulations provided valuable insights into the performance of FTN signaling techniques in communication systems, there are several avenues for future research and exploration. Here are some potential areas for further investigation:

1.Channel Estimation: In our simulations, we assumed perfect channel knowledge. However, in practical scenarios, channel estimation is necessary due to channel variations and impairments. Future work could focus on developing robust channel estimation algorithms specifically tailored for FTN signaling in different communication environments.

2.Advanced Coding Techniques: While we considered basic convolutional encoding in our simulations, future studies could explore more advanced coding schemes, such as turbo codes, LDPC codes, or polar codes, to achieve even higher reliability and better performance under FTN signaling conditions.

3.Nonlinear Distortion: The impact of nonlinear distortion, such as high-power amplifier (HPA) nonlinearities, was not explicitly considered in our simulations. Investigating the effects of nonlinear distortion on FTN signaling and developing appropriate compensation techniques would be an interesting area of research.

4.Practical Implementations: Future work could focus on practical implementations of FTN signaling in real-world communication systems. This could involve hardware prototyping, testing in different environments, and considering practical constraints like synchronization, power limitations, and implementation complexity.

5.Hybrid Approaches: Combining huge MIMO and other upcoming technologies with FTN signaling, or cognitive radio, could be explored to further enhance the performance and efficiency of future communication systems.

By addressing these aspects and conducting further research, we can continue to advance the field of FTN signaling and pave the way for high-speed and efficient communication systems in the future.

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الخلاصة

تنقل أنظمة الاتصالات المعلومات عبر القنوات ، مما يتطلب تصميما دقيقا لضمان نقل دقيق وموثوق. تنص نظرية Nyquist-Shannon ان الحد الأدنى لمعدل أخذ العينات لإعادة البناء المثالي للاشارة من عيناتها، والحد من معدلات البيانات والكفاءة الطيفية. أسرع من إشارات معدل Nyquistيتجاوز هذه القيود من خلال إدخال تداخل بين الرموز المتحكم فيه ، مما يسمح بمعدلات بيانات أعلى ضمن نفس النطاق الترددي. بينما تعدFTN بزيادة الكفاءة الطيفية وكفاءة الطاقة ، فإنها تواجه تحديات في تعقيد جهاز الاستقبال وتدهور الأداء بسبب الضوضاء والضعف. يمثل الطلب المتزايد باستمرار على نقل البيانات عالي السرعة تحديا مستمرا في أنظمة الاتصالات.

تظهر الإشارات الأسرع من Nyquist كنهج واعد لتحسين الكفاءة الطيفية من خلال تجاوز معدل Nyquistونقل المعلومات إلى ما وراء قيود عرض النطاق الترددي التقليدية. تبحث هذه الاطروحة في أداء إشارات FTN من خلال المحاكاة في أربعة تكوينات مختلفة: غير مشفرة ، مشفرة ، مشفرة باستخدام خوارزمية BCJR (Bahl-Cocke-Jelinek-Raviter) ، ومشفرة باستخدام OFDM مضاعفة تقسيم التردد المتعامد.

تظهر نتائج المحاكاة زيادة كبيرة في الكفاءة الطيفية التي تحققها إشارات FTN مقارنة بإشارات معدل Nyquist التقليدية. علاوة على ذلك، فإن دمج تقنيات الترميز يعزز الأداء بشكل أكبر، حيث يوفر قدرات فائقة لتصحيح الأخطاء ويوفر OFDM متانة محسنة ضد التداخل بين الرموز (ISI) نتائج إشارات FTN مع BCJR هي التكوين الأكثر فعالية ، حيث تحقق أعلى كفاءة طيفية مع الحفاظ على معدلات خطأ مقبولة. ويعزى ذلك إلى عملية فك التشفير التكرارية ، والتي تقلل بكفاءة ISIوتزيد من المعلومات المنقولة ضمن النطاق الترددي المتاح.

تحمل إشارات FTN مع BCJR إمكانات هائلة لأنظمة الاتصالات المستقبلية التي تتطلب معدلات بيانات عالية واستخداما فعالا للموارد الطيفية المحدودة.

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محاكاة لنظام ترميز اسرع من معدل نكوست لانظمة الاتصالات

رسالة
مقدمة الى قسم الهندسة الكهربائية - كلية الهندسة - جامعة بابل
كجزء من متطلبات نيل درجة الماجستير في الهندسة / الهندسة الكهربائية / اتصالات

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