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5G NR OFDM Multi Numerologies Interference Mitigation

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Dedication

We thank God for granting us the ability to pursue knowledge. We would like to dedicate this work to our families. To my father, who taught me how to be human and inspired me to question life and its complexities, his guidance ultimately led me to the field of engineering. To my mother, for her unwavering support, and to my siblings and friends, to O. Nour, L. Nabila, L. Cylia, and the spirit of the gang, whose companionship and encouragement were invaluable.

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Special thanks to my partner, Aicha, whose presence made this journey enjoyable. It truly would have been different without her.

Zehor

Alḥamdulillah, whose mercy and strength sustained me throughout this journey.

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for their unwavering support

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to my friends,
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whose playful presence brought light even in the darkest moments.

Aicha

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Abstract

This work examines the importance of multi-numerologies in fifth-generation (5G) using orthogonal frequency-division multiplexing (OFDM). The impact of multi-numerologies on coexistence issues, latency, and spectrum efficiency is highlighted in this work. A discussion of potential future research directions following a comparative study of previous efforts is also presented. The proposed work presented is a hybrid mitigation approach that combines time domain mitigation by zero padding WOLA filtering and frequency domain mitigation using a fixed guard band. The work discusses each case separately, then combines them and studies the overall improvements and the possible trade-offs. The hybrid ZP-WOLA mitigation approach reached a 78% - 91% BER reduction percentage across the 0 - 30 dB SNR range in the ideal case (under AWGN), while under moderate flat Rayleigh fading it achieved BER reductions of 37% - 72% over the same range.

Keywords: **5G, Multi-Numerology, OFDM, Inter-Numerology Interference, Interference Mitigation, Wireless Communications**

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List of Acronyms

1G: First Generation. 2G: Second Generation. 3G: Third Generation.

3GPP: Third Generation Partnership Project. 4G: Fourth Generation.

5G: FifthGeneration.

5GC: 5G Core.

AWGN: Additive White Gaussian Noise.

EDGE: Enhanced Data Rates for Global Evolution. EIR: Equipment Identity Register.

eNB: Evolved Node Base Station. EPC: Evolved Packet Core.

EPS: Evolved Packet Serving.

eRAN: evolved Radio Access Network.

ETSI: European Telecommunications Standards Institute. E-RAB: EPS Radio Access Bearer .

E-UTRAN: Evolved Radio Access Network.

FDM: Frequency Division Multiplexing. FDMA: Frequency Division Multiple Access. FM: Frequency Modulation.

FR: Frequency Range

GGSN: Gateway GPRS Support Node. gNB: Next Generation Node Base Station. GPRS: General Packet Radio System.

GSM: Global System for Mobile communications. HLR: Home Location Register.

HO: Handover.

HSPA: High Speed Packet Access. HSS: Home Subscriber Server.

IMT: International Mobile Telecommunications. KPI: Key Performance Indicators.

INI: Inter Numerology Interference.

LTE: Long Term Evolution. ME: Mobile Equipment.

MIMO: Multiple Input Multiple Output. MISO: Multiple Input Single Output.

MME: Mobility Management Entity.

mMTC: Massive Machine-Type Communication. MS : Mobile Station.

MSC: Mobile Services Switching Center. NEF: Network Exposure Function.

ng-eNB: Next Generation Evolved Node Base Station. Node B: Node Base Station.

NR: New Radio.

NRF: NR Repository Function.

NSS: Network Switching Subsystem.

OFDM: Orthogonal Frequency Division Multiplexing. OFDMA: Orthogonal Frequency Division Multiple Access. OMC: operations and maintenance center.

OSS: Operation Support Subsystem. PCF: Policy Control Function.

PCRF: Policy Control and Charging Rules Function. PDN: Packet Data Network Gateway.

RA: Random Access.

RAN: Radio Access Network. RNC: Radio Network Controller. RRC: Radio Resource Control.

SC-FDMA: Single Carrier - Frequency Division Multiple Access. SGSN: Serving GPRS Support Node.

S-GW: Serving Gateway.

SIM: Subscriber Identity Module. SIMO: Single Input Multiple Output. SISO: Single Input Single Output.

SMF: Session Management Function. TDMA: Time Division Multiple Access. TNL: Transport Layer.

UDM: Unified Data Management. UL: Uplink.

UMTS: Universal Mobile Telecommunications System. UE: User Equipment.

UPF: User Plane Function.

uRLLC: Ultra-reliable low-latency Communication. VLR: Visitor Location Register.

W-CDMA: Wideband CDMA. xMBB: Extreme Mobile BroadBand.

ZP-WOLA: zero- padded Weighted Overlap and Add.

QPSK: Quadrature Phase Shift Keying

QAM: Quadrature Amplitude Modulation

ZP Hybrid: Hybrid of ZP-WOLA and Gard Band

BER: Bit Error Rate

WOLA: Weighted Overlap‑and‑Add

NLOS: Non‑Line‑Of‑Sight

INI: Inter-Numerology Interference

SNR: Signal-to-Noise Ratio

AR: Augmented Reality

VR: Virtual Reality

V2X: Vehicle-to-Everything

FFT: Fast Fourier Transform

IFFT: Inverse Fast Fourier Transform

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Introduction

As wireless networks evolve, the demand for higher data rates, lower latency, and enhanced connectivity has driven the adoption of multi-numerology OFDM systems. This approach facilitates service differentiation, where applications with distinct quality of service (QoS) requirements can be efficiently accommodated [1]. Despite these advantages, the introduction of multi numerologies results in the emergence of inter-numerology interference (INI), a fundamental challenge that affects signal integrity. INI arises due to spectral leakage and imperfect orthogonality between adjacent numerologies, leading to mutual interference that distorts received signals. This interference is intensified in scenarios where power levels vary significantly across numerologies [2].

The aim of this project is to enhance the hybrid INI mitigation scheme by testing and comparing different interference mitigation methods in both the time domain and the frequency domain—and evaluating their combined effect through BER performance. By synthesizing findings from multiple studies, we identify key insights that can inform future research directions, ultimately contributing to the development of more robust interference management strategies for next-generation wireless networks [3].

This project is structured as follows: The first chapter describes the OFDM and 5G principles. Then, the second chapter introduces and analyzes the different mitigation techniques. Finally, the third chapter deals with simulating the filtering and guard band approaches as a first step. Next, a proposed method, ZP- WOLA Hybrid, under AWGN channel and flat Rayleigh fading channel for both QPSK and 16-QAM schemes, is presented. This method is followed by a comparative analysis of the BER performance.

CHAPTER Ⅰ

Review on OFDM and 5G

I.1 Introduction

The coming of 5G is a revolutionary wireless communication technology that offers ultra-low latency, enhanced mobile broadband, and large-scale machine-type communications. As opposed to 4G LTE, with only one numerology, 5G can accommodate multiple numerologies existing alongside one another, enhancing service flexibility but causing the challenge of inter-numerology interference (INI). Even though OFDM, a very established technique in 4G and Wi-Fi, remains at the very center of 5G, its effectiveness is hampered in multi-numerology scenarios since subcarrier orthogonality is destroyed. This thesis seeks to understand these challenges, investigate 5G waveform design, and examine how INI can be restricted without sacrificing the flexibility nature of 5G.

I.2 Motivation

The research into multi-numerology in 5G has shown the significant impact it has in enabling a wide range of service requirements by means of flexible configurations of subcarrier spacing and symbol durations. This feature certainly empowers the network to be more flexible, but at the same time it also creates problems such as inter-numerology interference (INI). Next-generation wireless systems are both promising and complicated. They provide plenty of guidance in waveform design, resource allocation, and spectral efficiency. It marks the beginning of the journey that looks into ways to decrease INI and improve 5G performance relying on filtering and optimized numerology allocation strategies.

I.3 Evolution of Wireless Systems

The evolution from 1G to 5G in wireless communication testifies to a continuous revolution that is driven by innovation and the need for additional services. Starting with pure analog voice in 1G to digital communication and SMS in 2G, it opened the path to mobile data. 3G progressed to mobile internet, video calls, and multimedia services, a leap towards broadband mobility. 4G LTE brought major speed and efficiency improvements with OFDM and MIMO but was less accommodating of new requirements like URLLC and mMTC due to its fixed nature. This indicated the need for a more flexible system.

5G breaks these limitations with greater flexibility, enabling use cases across industries such as autonomous vehicles, smart cities, and industrial automation. Lessons from a recent internship in telecom operations in Algeria confirm this progression, illustrating how 4G drove data adoption and how 5G is now driving a broader digital transformation.

The need for 5G therefore arises out of an intersection of limitations intrinsic in previous generations as well as emerging requirements of today's digital economies. This involves the need to support consistent service quality across ultra dense networks, deliver on demand gigabit speed, and enable end-to-end network slicing to support differentiated service provisioning. And here comes multi-numerology OFDM as a significant 5G innovation that allows for adjustable subcarrier spacing to accommodate a range of services [1]. As 5G develops, reliable and efficient INI mitigation will be necessary to maintain performance [4].

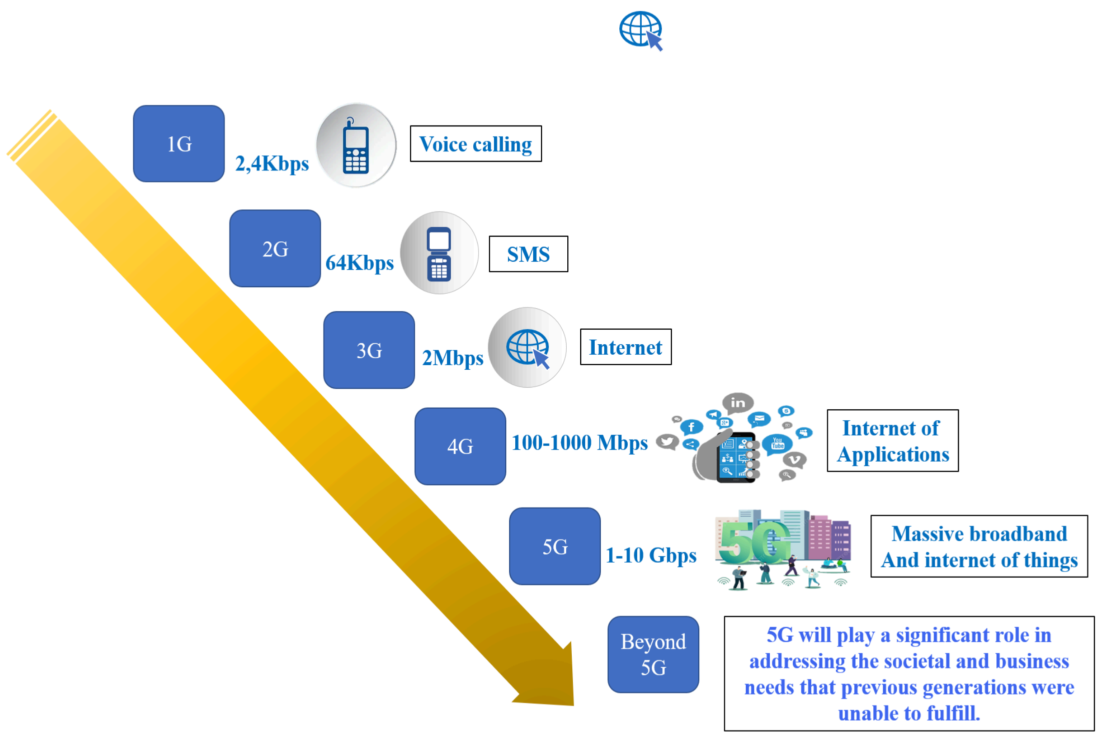


Figure 1.1. Overview of the principal stages of evolution in mobile communications [5]

I.4 System concept of 5G

The 5th-generation (5G) system architecture is revolutionary to the previous generations of wireless networks, as it focuses on increasing flexibility of services, scaling and performance. Unlike the centralized, rigid 4G LTE core network architecture that is based in the Evolved

Packet Core (EPC), 5G rests on a Service-Based Architecture (SBA) that is planned to take advantage of cloud-native techs like virtualization, containerization, and microservices. Such innovations provide greater control over network resources in lower granularity, accelerated service deployment, and enhancement of support of multi-scenario applications [6].

A key component of 5G is the introduction of 5G New Radio (5G NR), which supports scalable numerologies and bandwidth parts (BWPs) to meet the distinct needs of ultra-reliable low-latency communication (uRLLC), massive machine-type communication (mMTC), and enhanced mobile broadband (eMBB). To address the varying requirements of latency, reliability, and data throughput, 5G NR employs flexible transmission parameters, including multiple subcarrier spacing options of 15, 30, 60, 120, and 240 kHz, enabling it to operate efficiently across frequencies from sub-6 GHz to millimeter waves [7].

The 5G Core (5GC) is a revolutionary departure from its 4G counterpart in that it is completely software-defined and modular. It applies SBA concepts under which network functions (NFs) such as the Access and Mobility Function (AMF), Session Management Function (SMF), and User Plane Function (UPF) interact with one another based on standard-based APIs. This makes it very adaptive to shifting users' needs and supports interoperability with 3GPP (e.g., NR, LTE) and non-3GPP (e.g., Wi-Fi) access networks. NFV and SDN allow decoupling between hardware and software, making them scalable, more resilient, and more effective operationally [8].

Massive MIMO (Multiple Input Multiple Output) antennas and future beamforming technologies are also included in 5G radio access technology. These technologies enable the concentration of the power of a signal to individual users, thus increasing spectral efficiency while reducing interference [9]. Deployment of Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) in 5G NR also increases dynamic spectrum allocation, optimizing network capacity and flexibility.

One of the key features of 5G is dual-band operation at sub 6 GHz and millimeter wave frequencies. The lower band offers good coverage and penetration but with low bandwidth, and the upper band from 20 to 100 GHz offers huge bandwidths but with more propagation loss and poor coverage [10]. This band-sharing operation enables 5G to hit capacity and coverage utilizing hybrid deployment practices that supplement macro cells with dense small cell deployments.

Use cases of 5G, as ratified by the International Telecommunication Union (ITU) and 3rd Generation Partnership Project (3GPP), are [9]:

- eMBB (Enhanced Mobile Broadband): Enables applications requiring high data speeds such as UHD video streaming and augmented reality.
- mMTC (Massive Machine Type Communications): Supports high density of low-power IoT devices that connect intermittently.
- uRLLC (Ultra-Reliable Low Latency Communications): Targets mission-critical applications like industrial automation and autonomous driving, with sub-millisecond latency and ultra-high reliability.

Scalability of numerologies and dynamic bandwidth allocation in 5G NR, while required to support diverse services, also induces inter-numerology interference (INI) during sub-band multiplexing with different numerologies. Interference has a negative impact on throughput, latency, and reliability, and hence requires advanced physical and MAC layer techniques. In general, 5G's modular core, service-based architecture, and adaptive air interface are a major step towards an all-connected world, yet reducing mixed numerology interference is a building-block problem in multiservice scenarios.

I.5 Spectrum for 5G

The deployment of 5G technologies is largely dependent on the strategic allocation and efficient utilization of the radio frequency spectrum. Unlicensed spectrum access and dynamic spectrum sharing are the other approaches used to boost 5G coverage. As an example, spectra in the bands of 3.5 GHz and 26 GHz are being extensively utilized for rolling out the first commercial 5G. Besides, the regulatory framework has been evolving to facilitate spectrum aggregation, where operators can aggregate licensed and unlicensed bands for better performance. [10, 11]

To visualize the allocation of 5G spectrum bands, the following Figure 1.2 is a clear representation:

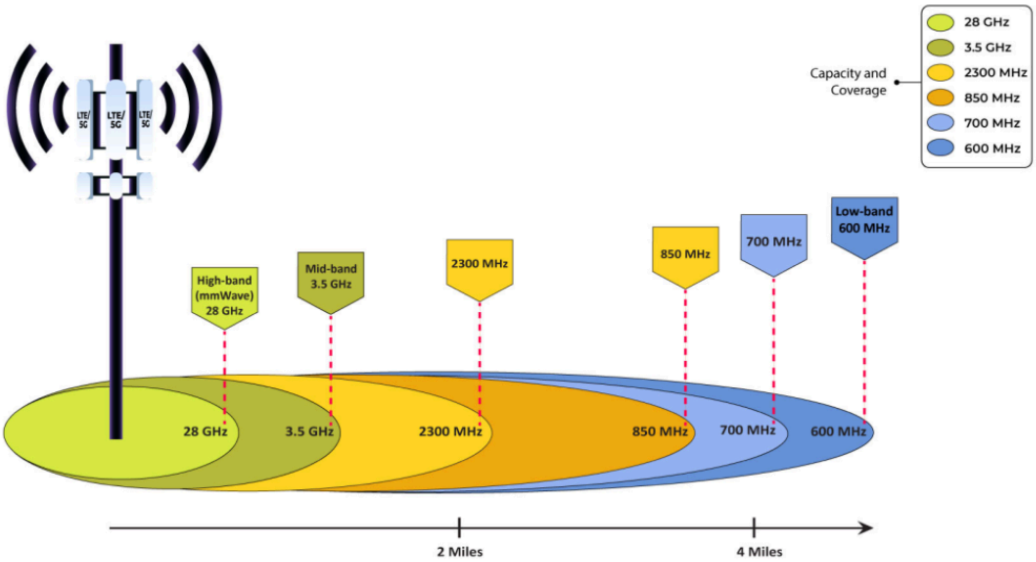


Figure 1.2. 5G Bands [11]

5G New Radio (NR) operates on two main frequency bands: FR1 and FR2. FR1 covers low-band (below 1 GHz) and mid-band (1–7 GHz) frequencies. Low-band has the capability of offering wide rural coverage and indoor penetration, while mid-band offers a good balance between capacity and coverage, which is ideal for urban conditions (Nybsys, 2024). FR2, 24.25 GHz to 52.6 GHz, offers ultra-high data rates and low latency for the advanced applications of AR, VR, and V2X. However, with high propagation loss and poor penetration, FR2 requires dense small cell deployment to provide good service [11], as shown in Figure 1.3.

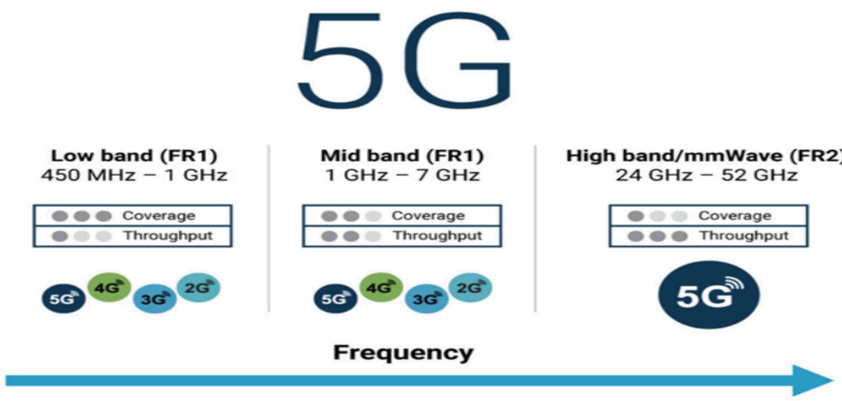


Figure 1.3. Low to High 5G Bands Explained [11]

In waveform compatibility, Orthogonal Frequency Division Multiplexing (OFDM) is the foundation of 5G New Radio (NR) due to its high multipath fading resistance, decent spectral efficiency, and flexibility in supporting various numerologies. Its merits are particularly evident in mid- and high-band frequencies (FR2), where wider bandwidths support subcarrier spacings of 15, 30, 60, 120, and 240 kHz. In FR2, the use of larger subcarrier spacings lowers Doppler effects and enables shorter symbol durations, which are necessary to provide ultra-low latency. Thanks to its flexible frame structure, OFDM is highly suitable for the multi-numerology design of 5G NR, allowing the network to meet diverse user requirements.

I.6 Overview of OFDM in 5G:

OFDM serves as the basis of 5G NR modulation methods for its efficiency, multipath fading tolerance, and compatibility with massive MIMO. It is flexible with its subcarrier spacing, thus allowing a wide range of 5G services that include eMBB, URLLC, and mMTC. This flexibility is essential for transition into various deployment contexts, particularly within low-to-high frequency bands.

However, using more than one numerology introduces Inter-Numerology Interference (INI), which degrades the system's performance. To manage INI, 5G uses guard bands, filtering, and scheduling. More work is put into advanced solutions like machine learning-based interference prediction and dynamic numerology adaptation to further enhance future network performance.

I.7 Basics of OFDM

I.7.1 Introduction to OFDM

The sophisticated modulation scheme that is Orthogonal Frequency Division Multiplexing allows data transmission through many narrowband subcarriers with orthogonal spacing for maximum spectral efficiency and avoiding inter-carrier interference (ICI). Subcarrier density reaches maximum levels because their orthogonal frequencies prevent mutual interference making high-speed wireless systems possible. OFDM signal management combines Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) methods that process parallel data transmissions across subcarriers for effective modulations and demodulations, as illustrated in figure 1.4 [12]. The implementation of Cyclic Prefix (CP) at the front of each OFDM symbol helps to minimize inter-symbol interference (ISI) that emerges from multipath propagation. The incorporated CP functions as a protective interval transforming channel linear convolution into circular convolution to simplify receiver equalization and improve overall performance.

The multichannel operation of OFDM eliminates communication issues caused by signal reflections which results in exceptional performance in broadband wireless environments. The use of OFDM as an integral component in Wi-Fi and LTE and the latest 5G New Radio (NR) demonstrates its diverse capabilities to provide stable high-speed connectivity. The strong advantages of OFDM exist yet the system faces certain implementation obstacles. The high Peak-to-Average Power Ratio (PAPR) affects the system performance negatively by requiring power-intensive linear amplifiers that boost both hardware complexity and energy consumption. The sensitivity of OFDM depends heavily on

Carrier Frequency Offset (CFO) because of Doppler shifts and oscillator mismatches which degrade orthogonality and boost ICI specifically at high mobility or high-frequency operations [13] [14].

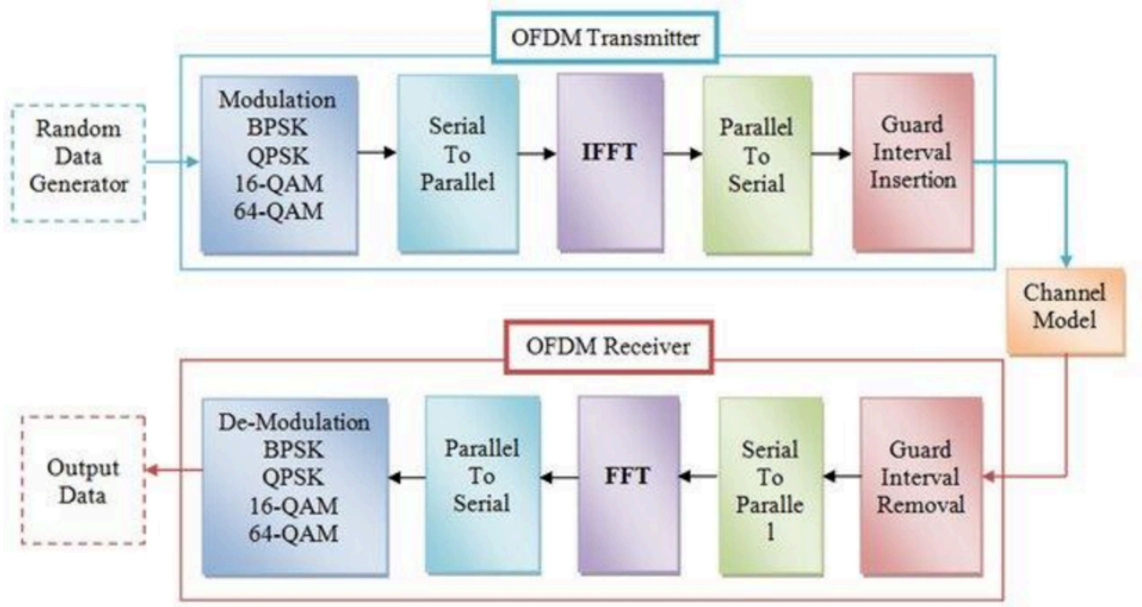


Figure 1.4. OFDM Block Diagram [12]

I.7.2 Orthogonality in OFDM

Classical Frequency Division Multiplexing (FDM) is plagued by signal interference caused by overlapping side lobes of sinc functions. However, Orthogonal Frequency Division Multiplexing (OFDM) employs specially selected orthogonal waveforms which coincide in the frequency domain, canceling interference. Multiple subcarriers are thus able to share the same channel without overlapping.

OFDM transmits digital data in sinusoidal signals and takes advantage of orthogonality by selecting frequencies as integer multiples of 1/T, enabling multiple independent parallel channels. OFDM employs digital processing using inverse and forward Discrete Fourier Transforms (DFT) instead of analog filtering, making OFDM efficient and immune to interference.

I.7.3 Cyclic Prefix in OFDM

In single-carrier Binary Phase Shift Keying (BPSK) systems, multipath propagation, a common characteristic of wireless channels, leads to the reception of delayed and attenuated versions of the transmitted signal. These multiple signal paths interfere with each other, causing inter-symbol interference (ISI). ISI is particularly problematic during symbol transitions in BPSK systems, as abrupt phase or amplitude changes are distorted by echoes from preceding symbols. This distortion results in discontinuities in the received waveforms, making detection difficult and increasing the bit error rate (BER) during coherent detection.

One proposed solution to mitigate waveform discontinuities in single-carrier systems involves extending each transmitted symbol to incorporate complete carrier cycle periods. This pulse transmission design allows delayed replicas of previous symbols to overlap with the beginning of new symbols. The objective is to seamlessly transfer energy from one symbol to the next throughout their entire duration, thereby minimizing the impact of ISI on the decision interval. However, implementing this method incurs monetary costs and reduces both spectral and energy efficiency due to the additional transmit power and time required for waveform extension. Furthermore, this approach is ineffective in dispersive channels where delay spreads exceed the accepted extension boundaries.

Orthogonal Frequency Division Multiplexing (OFDM) technology offers a robust solution to these challenges. OFDM divides a high-rate data stream into multiple lower-rate streams, each transmitted on a separate orthogonal subcarrier. These subcarriers are precisely arranged in frequency to allow spectral overlap without generating inter-carrier interference (ICI) at the sampling points. Before time-domain processing via the Inverse Fast Fourier Transform (IFFT) algorithm, data is mapped using various modulation schemes, such as QPSK or 16-QAM.

A key anti-multipath mechanism in OFDM systems is the Cyclic Prefix (CP). The CP is generated by duplicating the final length samples of the IFFT output and prepending them to the symbol sequence in the time domain, as shown in Figure 1.5. The length of the CP (number of length samples) must exceed the maximum time dispersion of the communication channel. This circular convolution operation preserves subcarrier orthogonality even in the presence of time dispersion [15].

At the receiver, the CP is removed before the Fast Fourier Transform (FFT) operation. If the channel's delay spread is shorter than the CP length, the OFDM symbol remains free from ISI and ICI, and each subcarrier experiences a flat-fading channel. This simplifies receiver design, as frequency-domain one-tap equalization can be achieved by inversely multiplying the channel frequency response with each subcarrier. While effective against multipath interference in high-data-rate networks, the CP consumes additional bandwidth and power, typically equivalent to 10–25% of the symbol duration [16].

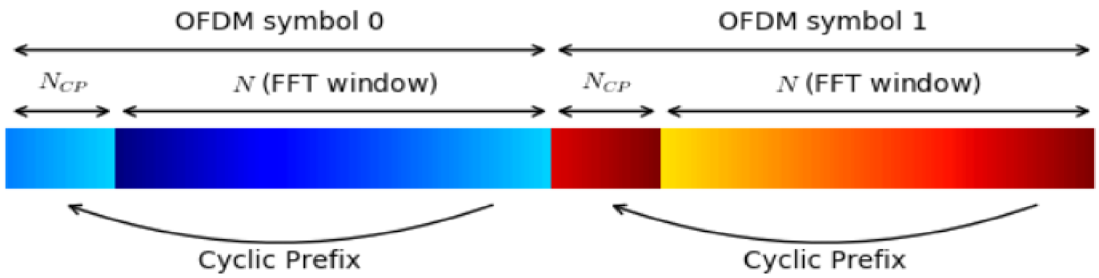


Figure 1.5. CP-OFDM placing [15]

I.8 Inter numerology interference

Inter-Numerology Interference (INI) is a problem introduced by the flexible numerology design in 5G New Radio (NR). Unlike the previous generations, particularly 4G LTE, where the subcarrier spacing was standardized to 15 kHz, 5G accommodates various numerologies. These numerologies differ in subcarrier spacing, cyclic prefix duration, and symbol duration and are chosen based on specific service requirements such as eMBB, mMTC, and URLLC [7]

However, the coexistence of all these different numerologies within the same spectrum band results in the loss of orthogonality between subcarriers. This results in mutual interference, known as inter-numerology interference (INI), particularly when the adjacent numerologies do not have sufficient guard bands between them [1]. Unlike typical inter-carrier interference in OFDM systems, which is usually caused by synchronization mismatches or channel distortion, INI is of an architectural nature. It arises due to the difference in subcarrier spacing and symbol alignment between users sharing the same bandwidth. In mixed-numerology OFDM systems, there is leakage of signals from one numerology into others, which distorts the reception and deteriorates signal quality [2].

In other words, INI to a numerology is the interference component provided by other numerologies. When a multiplexing signal is formed from several different numerologies, there is no longer orthogonality among subcarriers. Subcarriers of a numerology interfere with subcarriers of the others. Subcarriers of a numerology do not have to lie in zeros of the sinc response of subcarriers of another numerology, as illustrated in Figure 1.1, in which a numerology with subcarrier spacing Δf_2 interferes with another numerology with subcarrier spacing Δf_1. Note that even when subcarriers of Numerology 2 are at the zeros of the sinc response of subcarriers of Numerology 1, it does not necessarily mean that Numerology 1 will not interfere with Numerology 2 since the two numerologies have different symbol durations. A symbol of Numerology 1 will half fit in an FFT window of Numerology 2 when FFT processing is performed at a receiver of Numerology 2, and this will inevitably lead to spectrum shift, i.e., the zeros of the sinc response of subcarriers of Numerology 1 will be shifted from their original position, and this will generate interference to Numerology 2, as shown in Figure 1.6.

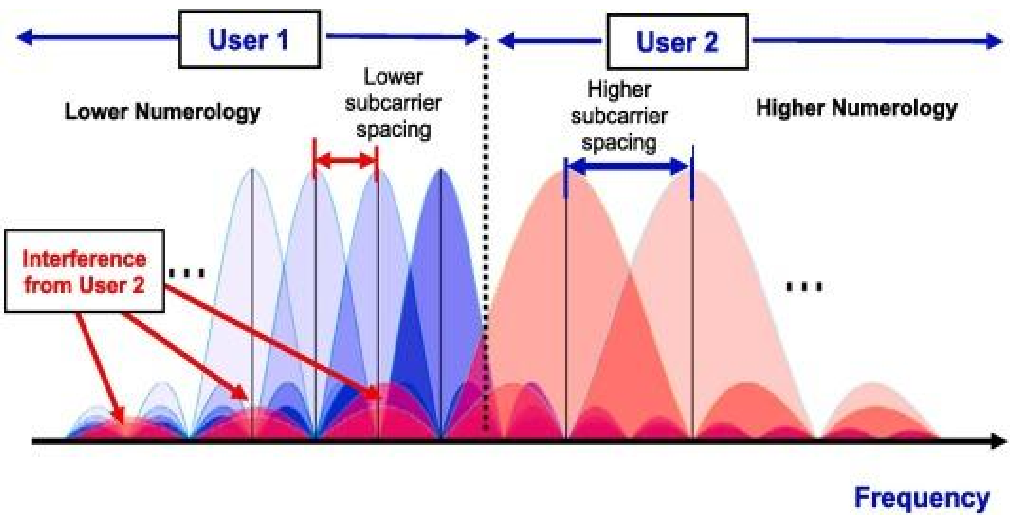


Figure 1.6. Coexistence of two numerologies in OFDM systems [18]

INI has maximum effect in the conditions of high density and low latency in which a plethora of services having different numerologies must coexist in a limited spectrum. Kihero, Solaija, and Arslan (2019) [19] continue that the interference is directly proportional to the disparity in subcarrier spacing of the numerologies and is a function of transmission alignment and spectral closeness. The features demand strict modeling and investigation, increasingly so as the 5G network is on an expansion roll.

I.9 INI Quantitative Model

Quantitative models of inter-numerology interference (INI) are essential for analyzing and mitigating its impact in 5G and beyond wireless systems. These models provide mathematical frameworks to estimate the interference power, evaluate system performance, and design effective mitigation strategies [20].

One such model, proposed by Cheng et al. [20], describes the INI power as a function of the subcarrier spacing ratio and the channel impulse response. The severity of INI depends on the subcarrier spacing ratio between the coexisting numerologies. The model is given by [20]:

$$P_{INI} = \sum_{k=1}^{N} \left|H_k\right|^2 . \left| Sinc\left(\frac{\pi(\Delta f_1 - \Delta f_2)}{\Delta f_1}\right)\right|^2 \qquad (1.1)$$

The channel frequency response at the k-th subcarrier is denoted as H_k, while Δf_1 and Δf_2 represent two distinct numerologies. The interference can substantially degrade the signal-to-interference-plus-noise ratio (SINR), especially in situations with high mobility or frequency-selective fading.

Another one of the usual tests to check INI is the Signal-to-Interference Ratio (SIR), which is the ratio of the strength of a desired signal to the interference from an adjacent numerology. Simulation models, including MATLAB-based models, are often employed to create numerical models of INI. Simulation takes into consideration system parameters like subcarrier spacing, symbol duration, and guard band assignment. A comparison of typical interference scenarios in a 5G NR system is summarized below:

Table 1.2 Interference scenarios in a 5G NR [3, 21]

Parameter	Numerology A (15 kHz)	Numerology B (60 kHz)	Impact
Subcarrier Spacing	15 kHz	60 kHz	High INI due to spectral leakage
Cyclic Prefix Duration	Long	Short	Temporal misalignment introduces additional interference
Guard Band	1 kHz	60 kHz	Insufficient guard band leads to INI
Symbol Duration	Longer	Shorter	Symbol misalignment disrupts orthogonality

I.10 Conclusion

This chapter provided an in-depth discussion of the theory and practice of Orthogonal Frequency Division Multiplexing (OFDM) and its basic implementation in 5G New Radio (NR) systems. The chapter introduced the motivation for considering OFDM, particularly for the record-breaking versatility and variety of services of 5G, and elaborated a little bit on the history of wireless communication systems, then discussed how with the arrival of future applications like autonomous vehicles, smart cities, and ultra-reliable low-latency communications (URLLC) demanding robust and resilient physical layer technologies, OFDM emerged as a cornerstone due to its spectral efficiency, multipath fading robustness, and ease of equalization in frequency-selective channels.

The math and underlying principles of OFDM were described, with emphasis placed on subcarrier orthogonality, the IFFT operation, and the application of the cyclic prefix to avoid inter symbol interference (ISI), then we talked about multi-numerology, the presence of co-simultaneous distinct subcarrier spacings and symbol periods, which was brought in as a new 5G feature as a means of catering to the heterogeneous requirements of eMBB, URLLC, and mMTC.

Nevertheless, this flexibility presents challenges, with the most significant being inter-numerology interference (INI), which occurs when neighboring numerologies interfere due to non-ideal isolation. The chapter proposed an INI quantitative model to gain better insight into the phenomenon, establishing the foundation for future mitigation methods.

The discussion then shifted to the 5G spectrum plan, describing its split into FR1 (sub-6 GHz) and FR2 (24–52.6 GHz) bands. These bands align with OFDM's flexibility to subcarrier spacing, wherein larger subcarrier spacings (e.g., 120 or 240 kHz) are suited for mmWave (FR2) to mitigate Doppler effects and short symbol durations. OFDM's versatility to these frequency partitions further solidifies its place at the center of delivering 5G's multi-service environment.

Finally, the chapter highlighted the cutting-edge 5G Core Network (5GC) architecture based on services and consisting of modular, cloud-native functions. The 5GC is not just a passive data processor but an active service provisioning manager, network slicing controller, and dynamic resource allocator in real time. Specifically, it allows for dynamic mapping of radio configurations like OFDM numerologies and TDD patterns onto logical service definitions with precise QoS guarantees, making it the ultimate cross-layer intelligence and full-stack programmability enabler.

CHAPTER Ⅱ

INI Mitigation Techniques

II.1 Introduction:

As multi-numerology configurations enter the scene to address the diverse 5G service requirements, the Inter-Numerology Interference (INI) challenge has become one of the most critical problems for contemporary wireless communication systems. That kind of flexibility, allowing for different subcarrier spacings and symbol lengths to coexist in the same system, inevitably leads to spectral leakage and interference between such numerologies, especially when densely packed without sufficient isolation. With the interference directly impacting the reliability and performance of 5G networks, researchers in the field and industry have been working on developing and evaluating a number of mitigation techniques. Ranging from traditional filtering [22] and windowing methods [23] to newer guard band optimization methods [24]. A wide range of solutions has been proposed, each with their respective strengths, weaknesses, and implementation complexity. In this chapter, we review the evolution of these mitigation solutions in detail, categorize them based on their application domain (i.e., time-domain, frequency-domain, or cross-layer solutions), and compare their performance under different system conditions. We set out to provide a critical snapshot of the state of the art while outlining the most promising avenues for maximizing INI mitigation, and especially so in the scenario of multiple services having to coexist transparently on the same spectrum. This chapter also paves the way for creating improved solutions based on our own findings and simulations, extending the current body of work toward 5G system performance enhancement and establishing the foundations for future generations of wireless technologies.

II.2 Frequency Domain Filtering Approaches

Frequency-domain filtering operates as an essential signal processing method that removes out-of-band emissions responsible for creating inter-numerology interference (INI) within multi-numerology systems, especially 5G NR. Various emissions from the signals will overlap with neighboring numerologies leading to degradative signal quality and systemic performance issues. Digital filter design for the filtering process creates bandwidth limitations to eliminate spectral components which extends the spectrum localization performance and reduces adjacent channel interference. Ouazziz et al. established through their study that specially designed low-pass filters for numerologies minimize INI and extend the Signal-to-Interference-plus-Noise Ratio (SINR) by 5 dB in unchanging channel environments [25].

Methodology:

- **Design of Specific Filter Parameters**:

The first step in filter design requires specifying all parameters including cutoff frequency together with roll-off factor and transition bandwidth alongside filter length. The selection process of parameters depends on subcarrier spacing ratios (such as 15 kHz and 30 kHz numerologies) to establish proper spectral component isolation and minimization. Filter symmetry between linear and circular methods and windowing approaches including Hamming and Kaiser functions together with implementation choices between FIR and IIR methods determine performance efficiency balance.

- **Optimization Based on Simulation Results**:

The filtering approach reaches its optimal version through detailed simulations of entire communication systems. Simulations analyze performance metrics that include SINR together with BER and PSD. The system uses a feedback mechanism to adjust parameters that reduce INI values when testing different channel models (EPA, EVA, ETU). Guaranteed optimization is achieved through gradient descent and genetic algorithms which lead the process to discover optimal filter configurations.

- **Evaluation of Latency Overhead:**

The research provides a complete assessment of the delays caused by filters during processing operations. The evaluation must include measurements of group delay together with filter tap length and processing complexity through multiply-accumulate operations. A thorough evaluation determines the effect of system latency on applications needing ultra-reliable low-latency communications (URLLC). The testing of the filtering technique for real-time deployment examines how it functions under various time-sensitive conditions.

The implementation of frequency-domain filtering provides superior spectral containment together with reduced INI but requires a high level of trade-off consideration. The increased length of filters alongside additional computation requirements results in higher processing delays and energy demands. A dynamic environment with many changes to the delivery channels makes these effects more noticeable.

II.3 Adaptive Guard Allocation Method

Adaptive Guard Allocation operates as an advanced interference reduction solution which manages spectrum performance within multi-numerology networks that will be used by 5G NR and next-generation 6G systems. The system differs from static fixed guard band procedures because it modifies guard band thickness automatically based on current network conditions. The system

optimizes its performance through adaptable guard bands between numerologies to minimize INI effects and enhance spectral efficiency in bandwidth-restricted wireless networks. The research of Demir and Arslan developed a complete adaptive guard allocation system which integrates physical and MAC-layer components through integrated scheduling policies and measurements [26]. Alongside meeting acceptable interference limits the proposed method succeeded in raising spectral efficiency levels according to their research findings applicable for modern network structures.

Methodology:

• **Real-Time Monitoring of Interference:**

The core principle of adaptive guard allocation requires permanent observation of interference conditions which exist among subcarrier spacings that use different numerologies. Through real-time feedback processes at the receiver endpoint the system detects interference intensity levels. The monitoring of signal-to-interference-plus-noise ratio (SINR) and bit error rate (BER) and power spectral density (PSD) provides the means for achieving this goal. Performance metrics showing detailed information of the channel's and interference pattern's immediate status become available to analysts. Machine learning technologies enable prediction of interference patterns to conduct proactive optimization of guard bands in sophisticated implementations.

• **Dynamic Adjustment of Guard Bands:**

The collected interference data enables automatic adjustments of guard bands to suit the current radio environment status. The guard bands expand during high interference times where different numerologies overlap to provide better spectral isolation which reduces INI by blocking numerical leakage. A system controls guard band sizes towards lower or higher values based on the observed interference conditions which may arise due to changes in traffic loads or changes in propagation conditions. The available bandwidth that becomes vacant after guard bands adjustment allows user data transmission to occur through improved spectral efficiency. Such algorithms exist inside the baseband unit which utilizes heuristic-based or optimization-based approaches to define appropriate guard band dimensions.

• **Integration with MAC Layer Scheduling:**

The main innovation of Demir and Arslan's methodology includes a cross-layer system structure. The system joins adaptive guard management to Medium Access Control to create coordinated choices between resource scheduling decisions and physical layer interference control. The integration of scheduling methods with MAC layer operations creates an all-encompassing allocation system that accounts for throughput interests and interference conditions simultaneously.

The MAC scheduler enables user-based service priority decisions through latency reliability criteria which guides guard band adjustability to keep numerology performance acceptable. A cooperative approach between guard band usage and scheduling yields essential results for scenarios with multiple service requirements.

Under realistic simulation conditions their framework demonstrated a 20% increase in spectral efficiency with a maximum 4 dB decrease in INI according to Demir and Arslan [26]. The performance-enhancing benefits are most beneficial when used in highly congested urban zones and high-density numerology coexistence environments. The achieved benefits of the system implementation imply additional expenses for the system. Real-time adaptive guard allocation requires complex system implementation because of necessary accurate channel estimation methods and additional layer signaling and sophisticated scheduling algorithms. The system requires proper management of real-time operational limitations to handle continuous interference monitoring and guard band recalibration tasks alongside the computational demands which affect the suitability for real-time operation in low-latency applications.

The implementation of adaptive guard allocation points toward an effective technique for future dynamic spectrum management systems in wireless communications. This technology demonstrates intelligent channel and traffic condition adaptation which fits perfectly into the service demands of 5G and beyond systems. Technological research aims to implement machine learning approaches alongside distributed control structures and hardware acceleration devices for enhancing the scalability and promptness of this approach in massive network operations.

II.4 Conclusion

In this chapter, we have observed two effective interference mitigation techniques for 5G systems: filtering and guard bands. Filtering is well known for its exceptional accuracy in canceling out-of-band emissions, thereby being extremely useful in high-density frequency environments. Its strongest point is its selectivity to suppress target frequency components with negligible impact on desired signals. But it comes at the cost of increased computational complexity and delay, which is not desirable for real-time use. An alternative is guard bands, which give a neater and more responsive solution by reserving unused bandwidth between sub-bands for non-overlap. While they are easier to apply and require less processing, their greatest weakness lies in the wastefulness of limited spectral resources, which in bandwidth-constrained environments is a significant flaw.

Given these trade-offs, a compelling area of future research is to explore hybrid approaches that combine filtering and guard bands. By combining the precision of filtering with the simplicity and flexibility of guard bands, these approaches have the potential to counteract the limitation of each technique. This hybrid approach can potentially offer a more balanced and affordable interference mitigation solution by maximizing spectral efficiency and signal quality for future 5G networks.

CHAPTER Ⅲ

Simulation and Results

III.1 Introduction

This chapter begins with checking the effectiveness of the OFDM against several channel models (e.g., AWGN, Rayleigh fading) and modulation formats (e.g., QPSK, 16-QAM, 64-QAM) to find out how much distorted data there is and what its signal-to-interference ratio is when INI is not applied. Then, we will simulate the performance of weighted overlap-and-add (WOLA) filtering and fixed guard-band allocation by running each method with the same channel and modulation setup, and checking the changes in BER curves for each method. Doing this, we come up with a hybrid scheme that uses both WOLA filtering and dynamic guard-band adaptation; after this, we compare its performance to that of WOLA filtering and guard-band schemes running in the same scenarios.

Section 2 presents the simulation environment such as the software needed, system variables and channel profiles. Section 3 sets out the test methods for OFDM together with instructions to apply WOLA, guard band and the suggested combined scheme. In Section 4, the scenarios and exact settings for each system when running the tests are defined. Section 5 explains the simulation outcomes and conflicts. Section 6 examines the significance of our findings and Section 7 ends with a conclusion and recommendations for more research.

III.2 Tools and Variables Overview

III.2.1 Simulation Environment

Any methodology for performance evaluation starts with the simulation environment. We carried out thorough MATLAB simulations to assess the effectiveness of INI mitigation strategies in 5G OFDM systems.

This environment's broad capabilities in signal processing, communications tools, and visualization allow it to integrate both time-domain and frequency-domain hybrid mitigation techniques. MATLAB is a powerful tool for quick prototyping and iterative testing of physical-layer algorithms since it has built-in support for OFDM waveform creation, filtering methods, channel modeling, and bit error rate (BER) computations.

III.2.2 Variables and Parameters

Based on the requirements of 5G NR numerology, key system characteristics were chosen to accurately simulate dual-numerology coexistence. Two numerologies: μ = 0 (15 kHz subcarrier spacing) and μ = 1 (60 kHz subcarrier spacing) are evaluated in the simulation in terms of their interaction. The most crucial parameters utilized in each test scenario are compiled in Table 3.1.

Table 3.1 Crucial parameters for numerology 1 and numerology 2

Parameter	**Numerology μ = 0**	**Numerology μ = 2**	**Notes**
Subcarrier Spacing (Δf)	15 kHz	60 kHz	Defined by Δf = 15×2^μ kHz
FFT Size	1024	256	Depends on bandwidth
OFDM Symbol Duration	66.7 μs	16.7 μs	Inversely proportional to Δf
CP Length	72 samples	18 samples	Maintains guard against ISI
Modulation Scheme	QPSK, 16-QAM	QPSK, 16-QAM	Used for BER comparison
SNR Range	0–30 dB	0–30 dB	Step size = 5 dB

Through iterative simulations, these parameter selections were adjusted to strike a compromise between accuracy and computational load.

III.2.3 Performance Metrics

To measure the effectiveness of each of the mitigation strategies, two main metrics were employed

- **Bit Error Rate (BER)**

The BER is specified as the ratio of the number of bits decoded in error to the number of bits transmitted. It is the simplest measure of signal reliability in digital communication systems. For each SNR value, the BER was averaged over a number of OFDM symbols and random realizations to ensure statistical reliability. Table 2 lists each BER range.

Table 3.2 Interpretation for each BER range

BER Value	Interpretation
High BER (closer to 0.5)	**Poor performance** (random guessing)
BER decreases as SNR increases	**Good system**: adding power improves accuracy
Flat BER	System **does not improve with SNR**, i.e., flawed or ineffective technique

- **Signal-to-Noise Ratio (SNR)**

SNR was varied methodically over a wide dynamic range (0–30 dB) to track the interference noise trade-off. For each of the mitigation methods under test (Filtering-only, Guard-only, and Hybrid), performance over this range of SNR was measured. The selection of SNR and BER as the chosen indicators is made from the widespread usage within the literature as accurate measures of physical layer performance.

III.3 Modulation types

Our objective is to investigate the impact of digital modulation schemes on INI. This was done based on the inherent difference in error resilience and spectral efficiency between the schemes. Lower-order modulations like QPSK tend to be more robust to interference and noise, while higher-order schemes like 256-QAM offer superior data rates but increased susceptibility to distortion and INI. During simulations, we observed that QPSK performed the best BER in all of the channels, especially in the worst fading conditions. On the other hand, 256-QAM, while being spectrally efficient, required highly superior channel conditions and mitigation to deliver good BERs. We selected QPSK and 16-QAM. QPSK's strength at low SNR, which is usually used in control channels, and 16-QAM's greater spectral efficiency, which more accurately represents INI effect because of a more compact constellation point.

III.4 Channel Profiles

Channel modeling is essential to validate the robustness of INI mitigation under practical radio conditions. For this project, two different channel models were utilized, introduced step by step to test the scalability and robustness of each mitigation strategy:

- **Additive White Gaussian Noise (AWGN) Channel**

  This fundamental reference model integrates additive Gaussian thermal noise, in which inter-numerology interference (INI) effects may be examined in isolation: without the complications that multipath fading introduces.

  The noise has a specific variance which is exactly dictated by the chosen SNR level. Such a model fits well within conventional Shannon-theoretic assumptions and allows for results to be compared with existing literature.

- **Rayleigh Fading Channel**

A more realistic fading channel, assuming no line-of-sight (NLOS), is to simulate urban NLOS environments. The profile contains frequency-selective fading over multiple taps and is modeled using MATLAB's rayleighchan object. It supports the testing of INI suppression in multipath interference scenarios.

To summarize, in the AWGN channel, interference and noise were relatively simpler to model and resist. Rayleigh fading introduced even more randomness, modeling multipath propagation with NLOS, making it a more challenging testbed for INI. Both channels affected the system in different manners, and understanding these performances allowed us to design more targeted mitigation schemes. As an example, filtering performance in Rayleigh conditions was far more affected by window function parameter values, requiring tuning based on the Doppler spread of the channel.

III.5 ZP Hybrid

III.5.1 INI mitigation over AWGN

III.5.1.1 Initial Filtering Approach: A Baseline

As a first approach to minimizing INI for our needs, the hybrid structure was created by combining time-domain filtering and frequency-domain guard band insertion. We began by incorporating a simple FIR filter as a starting point for filtering. The filter was configured to smooth the transition of the signal in the time domain while suppressing neighboring numerology spectral leakage. Concurrently, we employed guard bands regions of null subcarriers between two numerologies to provide spectral separation and eliminate frequency-domain overlap. This hybrid solution, by virtue of its rationale of addressing the temporal discontinuity and spectral interference caused by coexistence of multiple subcarrier spacings in 5G New Radio (NR) systems, was tackled. Although both techniques are mutually known to offer partial suppression of interference individually, our goal was to see whether a combination of the two could offer additive or even synergistic improvement of overall system performance. But our preliminary results indicated otherwise. As the corresponding BER vs. SNR plots illustrate in figure 3.1, the combined solution (filtering + guard band) performed nearly identically with guard band insertion alone. The "Filtering Only" blue curve was horizontal with a BER of about 0.47 for every SNR value, indicating that the FIR filter alone had very little effect in mitigating interference. As such, the hybrid approach's black curve overlapped extensively with the green "Guard Band Only" curve, suggesting that the filtering stage offered almost no additional benefit. This outcome highly validated that the standard FIR filter was not well matched to the multi-numerology signal structure of the 5G in terms of spectral and temporal specifications. Thus, the filter design had to be replaced with a more advanced method, one specifically designed to take care of abrupt signal changes and reduce Out-of-Band Emissions (OOBE). This understanding led us to incorporate the WOLA filtering method in the subsequent phase of our hybrid mitigation approach.

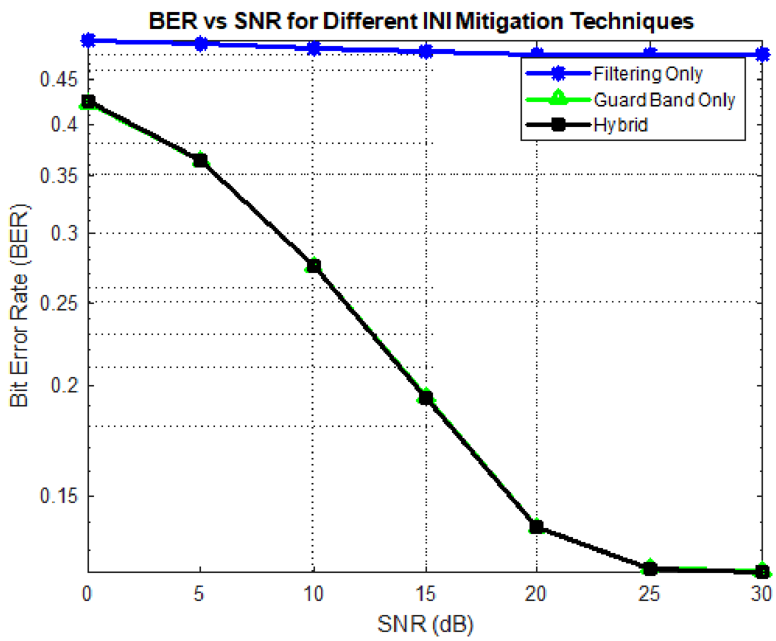


Figure 3.1. BER of Filtering (FIR), Gard band and Hybrid mitigation methods

III.5.1.2 Weighted Overlap and Add (WOLA) filtering

WOLA is a time-domain windowing algorithm specifically selected to reduce spectral leakage and soften signal transitions at the subband edges. It employs a raised cosine window on overlapping segments of OFDM signals, therefore reducing Out-of-Band Emissions (OOBE) and lowering the abrupt discontinuities that cause Inter-Numerology Interference (INI). After incorporating WOLA into our simulation cycle, we observed remarkable improvements in the BER traces compared to the FIR-based filtering approach. The improvements verified that WOLA was better aligned with the structural and spectral demands of multi-numerology systems. However, despite the result appearing more logical and promising on-screen, as shown in figure 3.2, some drawbacks still persisted.

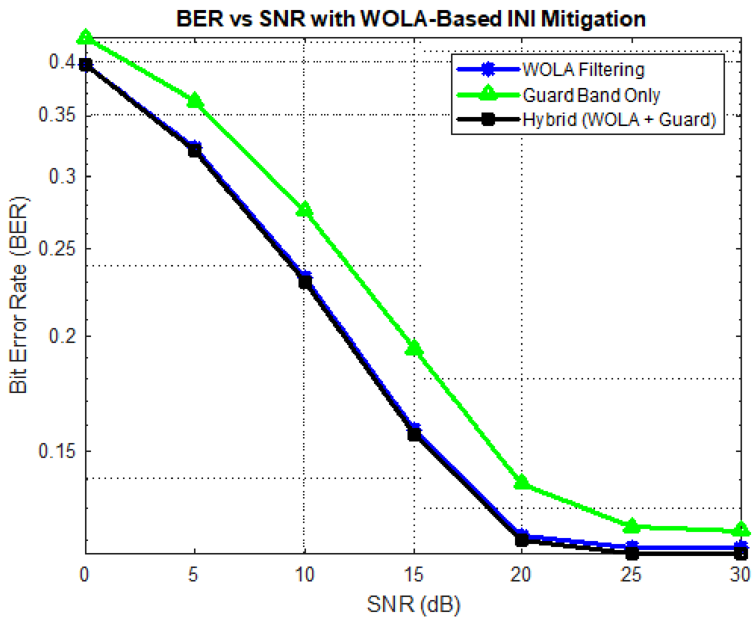


Figure 3.2. BER of WOLA filtering, Gard band and Hybrid mitigation methods

Notably, the BER remained excessively high at moderate and high SNR values. This meant that, despite increased smoothing, WOLA by itself was not able to completely prevent interference between adjacent numerologies. A big contributor to this was our subcarrier spacing and allocation, which offered too little guard bands between numerologies. This made it possible, even with WOLA, for overlapping FFT windows to pick up partially unwanted energy from nearby numerologies, especially in aggressive spectral packing scenarios.

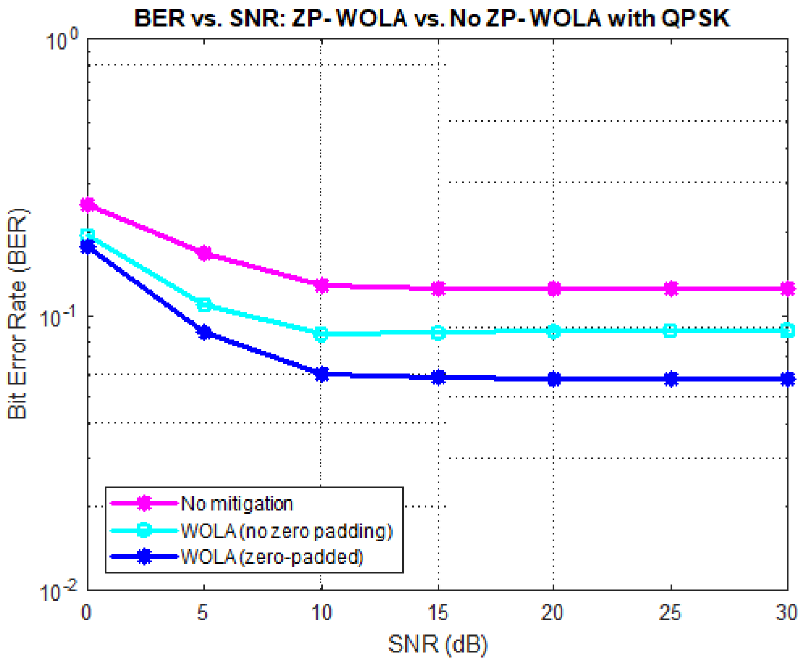
To correct this, we turned to a more sophisticated hybrid solution: hybridizing WOLA filtering with fixed guard band insertion and time-domain padding. Although guard bands provided spectral isolation, padding ensured that the WOLA-filtered signal avoided spilling over into the FFT window of the adjacent numerology, specifically Numerology-1 that uses a longer symbol duration. The motivation for padding was not simply temporal aliasing, but to relocate the energy of WOLA's roll-off tails outside the sensitive FFT processing window of the co-communicating numerology. This was important since even with a best-case shaped filter, if overlap bleeds into the FFT window, interference is still unavoidable. Padding and delaying the WOLA-filtered signal before combination allowed us to limit its interference footprint more effectively.

III.5.1.3 Padded WOLA filtering

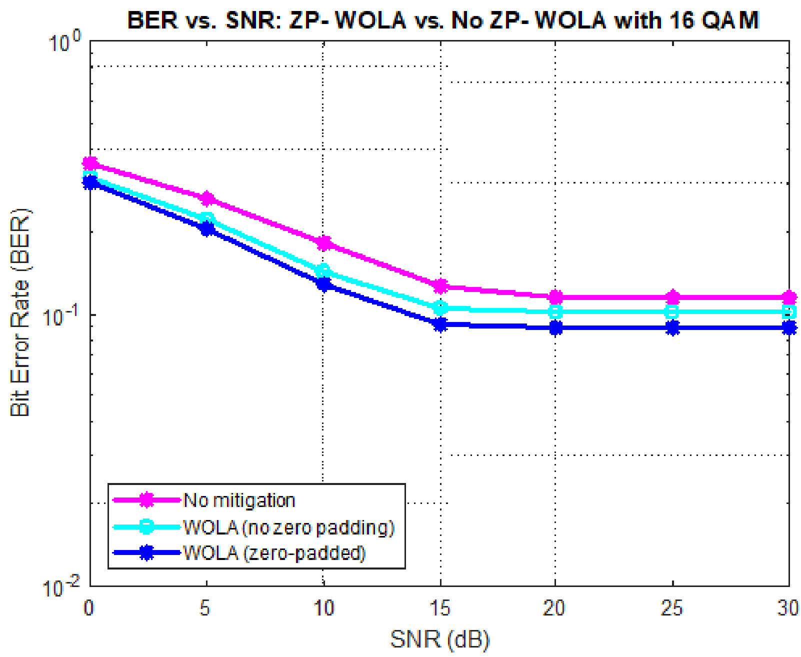
As we observed from WOLA performance that it was not optimal under all conditions, we devised a modification: zero-padded WOLA, in which the zero-valued samples are filled in between each OFDM symbol before applying the WOLA window. This padding achieves better isolation between adjacent numerologies by stretching the overlapping ends of the windowed waveform beyond the adjacent numerologies' FFT window.

Figure 3.3 plots BER vs. SNR performance in three scenarios: no mitigation, WOLA without zero-padding, and WOLA with zero-padding for (a) QPSK and (b) 16 QAM. The outcomes clearly show that the zero-padded WOLA (blue curve) gives superior performance compared to the non-padded WOLA (cyan) and the baseline without any mitigation (magenta). Though the original WOLA method itself improves the BER compared to no mitigation, especially in the low to mid-SNR regime, it once more saturates with large SNR values to expose residual interference. The zero-padded WOLA technique, however, continues to deliver lower BER at high SNR, exhibiting stronger suppression of INI.

This improvement is due to the additional delay introduced by the zero-padded guard band that prevents leakage of the end of one of the numerology's filtered symbols into another's FFT window. These outcomes thus confirm that while WOLA is a highly efficient filtering algorithm, it can be attained only if implemented in combination with appropriate time-domain shaping methods such as zero-padding.



(a)



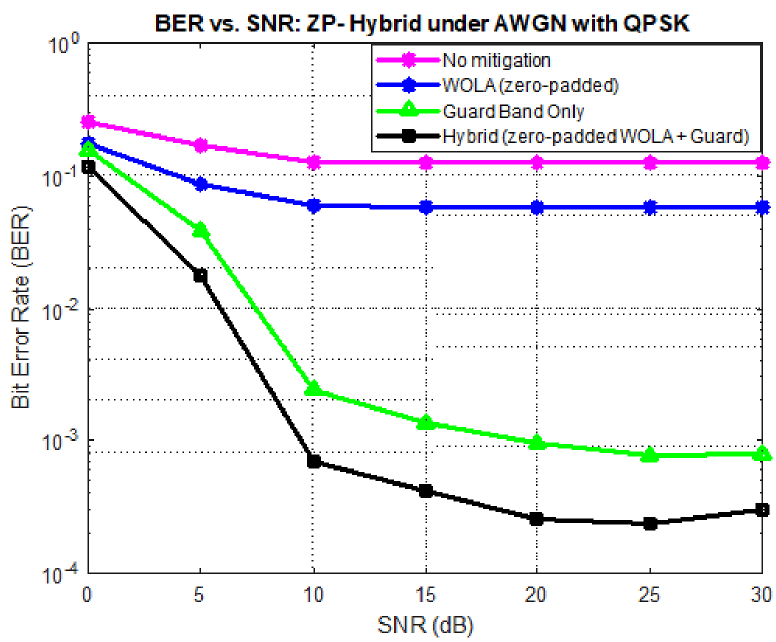
(b)

Figure 3.3. BER of ZP-WOLA filtering compared to no zero padding WOLA mitigation method. (a) for QPSK and, (b) for 16 QAM

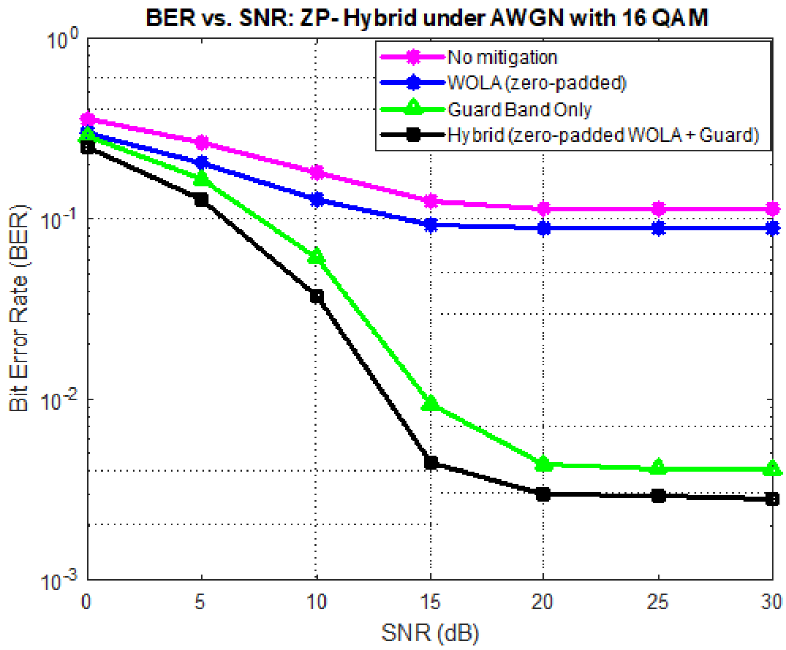
III.5.1.3 ZP-Hybrid (ZP- WOLA and Guard Band)

To reduce the persistent inter-numerology interference (INI) observed in the earlier techniques, our final proposed method integrates zero-padded WOLA filtering and adaptive guard band insertion in a hybrid mitigation system. This technique leverages the time-domain smoothing provided by WOLA and frequency-domain isolation achieved using guard bands.

As seen from the previous results, the simple filtering using generic FIR or WOLA without padding could not eliminate INI entirely, especially at larger values of SNR. Similarly, guard band insertion alone, although useful, was of limited effectiveness due to residual spectral leakage. Knowing that WOLA's effectiveness can be compromised both by spectral misalignment and the absence of transition shaping, we augmented it with zero padding to allow the raised cosine windows to gracefully decay without either truncating useful data or bridging significant subcarrier boundaries.

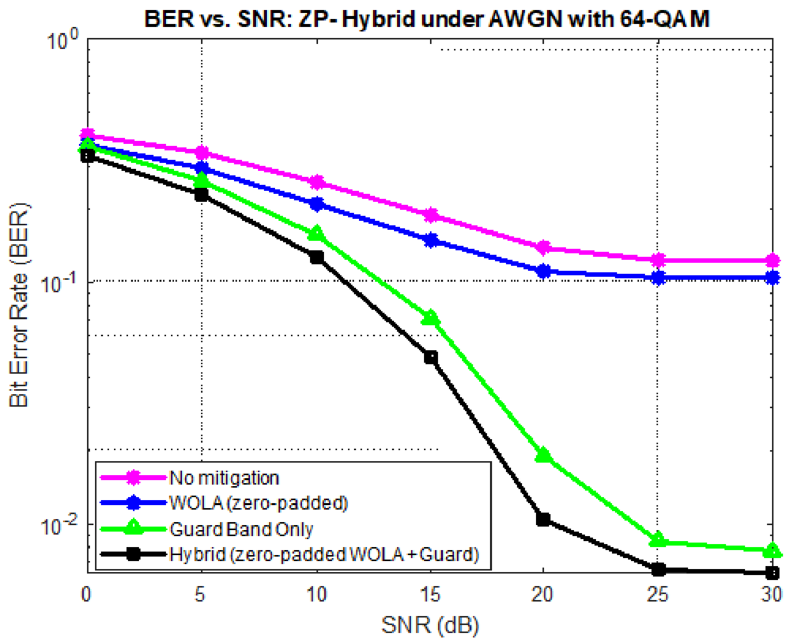


(a)



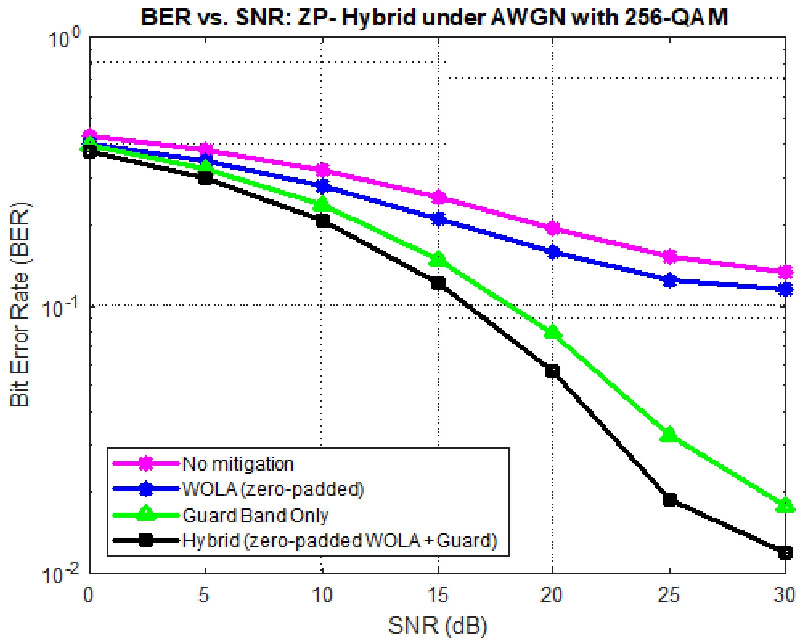
BER vs. SNR: ZP- Hybrid under AWGN with 16 QAM
No mitigation
WOLA (zero-padded)
Guard Band Only
Hybrid (zero-padded WOLA + Guard)
Bit Error Rate (BER)
SNR (dB)

(b)



BER vs. SNR: ZP- Hybrid under AWGN with 64-QAM
No mitigation
WOLA (zero-padded)
Guard Band Only
Hybrid (zero-padded WOLA + Guard)
Bit Error Rate (BER)
SNR (dB)

(c)



(d)

Figure 3.4. BER of ZP-WOLA, Gard band and ZP- Hybrid mitigation. (a) for QPSK, (b) for 16 QAM, (c) for 64 QAM and, (d) for 256 QAM

The comparative performance of these techniques is shown in Figure 3.4, plotting the BER against SNR for four configurations: (i) no mitigation, (ii) WOLA with zero padding, (iii) Gard Band, and (iv) the hybrid padded WOLA + guard band method and for four modulation schemes: (a) QPSK, (b) 16 QAM, (c) 64 QAM, (d) 256 QAM.

Figure 3.4 clearly shows that WOLA with zero padding outperforms non-padded WOLA, with lower BER at all levels of SNR. Furthermore, in conjunction with guard band insertion, the hybrid padded WOLA solution also performs best, having the lowest BER and steeper downward slope for increasing SNR. This validates the hypothesis that neither single-domain mitigation by itself is sufficient. Instead, cross-domain hybridization-simultaneous optimization of both time and frequency behavior is necessary for effective INI suppression in 5G systems with heterogeneous numerologies.

These findings underscore the practical significance of padding in WOLA and the necessity of joint optimization for robust interference suppression. Through time-aligning window functions, extending symbol durations, and allocating guard resources adaptively, the hybrid solution provides a scalable solution that is sufficiently flexible to be accommodated in real-world 5G scenarios, particularly those involving dynamic and asynchronous service multiplexing.

III.5.2 INI mitigation over Rayleigh fading channel

In this part, the transmission through the wireless channel is defined as frequency flat Rayleigh fading, each sample transmitted is multiplied by an independent complex Gaussian random which creates Rayleigh distributed amplitudes as in multipath, NLOS cases and then AWGN is added to represent thermal noise and other interfering signals that have a flat spectral density. The receiver employs single tap equalization, making use of the 'flat fading' assumption to fix the distortion in each sample. As a result, the Rayleigh-AWGN channel is useful for testing bit error rates in 5G OFDM, so that different interference management approaches—WOLA windowing, using guard subcarriers, and hybrid solutions—can be directly compared in practical fading and noise conditions.

III.5.2.1 ZP Hybrid over Rayleigh fading with QPSK

As discussed earlier, the ZP Hybrid approach uses zero-padding in time and a WOLA window along with guard subcarriers in frequency domain to reduce transient artifacts and out-of-band noise at the same time. Over a flat Rayleigh fading Rayleigh fading channel where every QPSK-modulated symbol has complex Gaussian amplitude, the padded-hybrid scheme gives good protection against INI and maintains the original spectral efficiency.

The results in the following figure 3.5 illustrate that the interference-limited error floor is drastically reduced by this scheme as opposed to methods that use only windows or guards for interference reduction:

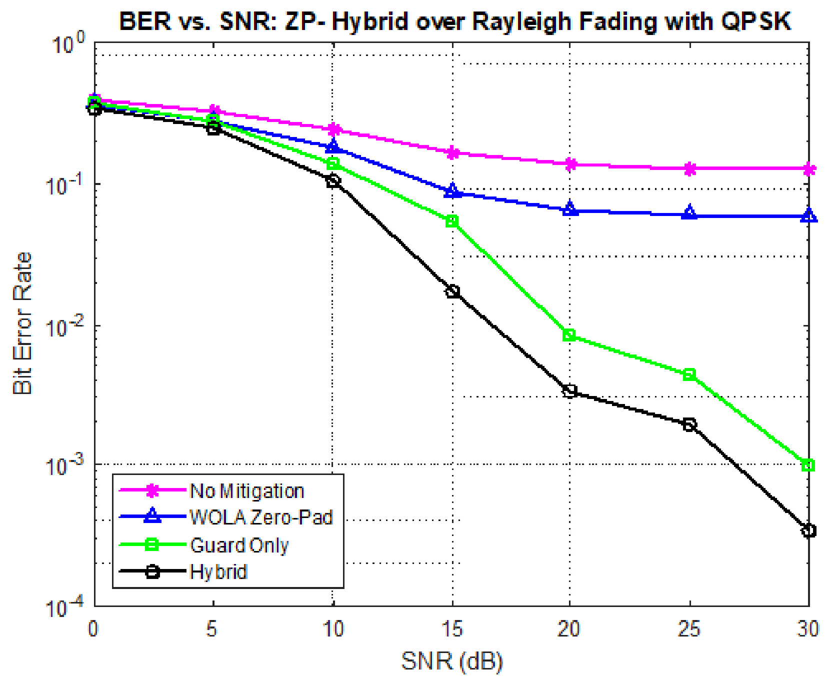


Figure 3.5. BER of ZP-WOLA, Gard band and ZP- Hybrid mitigation over Rayleigh fading for QPSK

III.5.2.2 Padded Hybrid INI mitigation over Rayleigh fading with 16 QAM:

Over a frequency-flat Rayleigh at 16 QAM, the constellation points are very close and thus become more sensitive to fades, as well as next-level constellation effects, so, around 12–15 dB SNR is usually needed to attain BERs of 10^{-3} when powered only by fading, as illustrated in figure 3.6. When this protection is used (which adds padded guard subcarriers to the WOLA zero-padding), simulations indicate raised SNR values by around 5–10 dB compared to the basic configuration and a 30 % reduction in the level of error floor.

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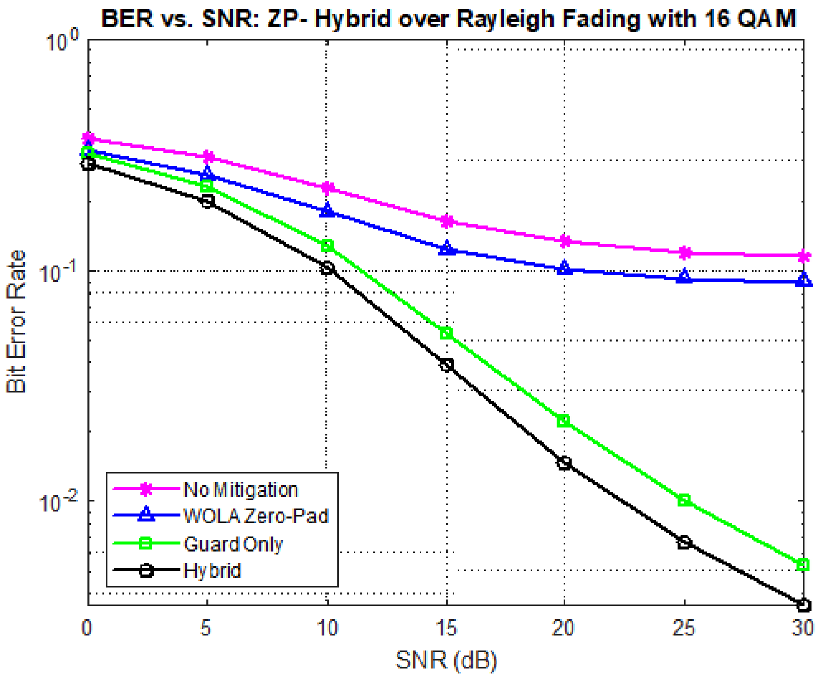


Figure 3.6. BER for ZP-WOLA, Gard band and ZP-Hybrid mitigation over Rayleigh fading for 16 QAM

III.5.3 Performance comparison between Rayleigh fading and AWGN channel

In assessing inter-numerology interference (INI) mitigation for mixed-numerology OFDM systems, it is instructive to compare performance under two canonical channel models—additive white Gaussian noise (AWGN) and frequency-flat Rayleigh fading in both QPSK and 16-QAM. In AWGN, the channel has only non-correlated white noise, so thermal noise and any influencing INI are the main reasons for the high BER. Alternatively, Rayleigh fading makes the signal's amplitude change in a random way, so random fades can often overshadow the benefits of spectral-leakage suppression.

III.5.3.1 QPSK under AWGN versus Rayleigh Fading

In an AWGN environment, QPSK's inherent noise resilience combines effectively with spectral‑leakage controls. Zero‑padded WOLA reduces the average BER by approximately 50% relative to an unmitigated baseline (over a representative 0–30 dB SNR range), while a dedicated guard band achieves roughly a 87 % BER reduction. The hybrid approach—integrating both WOLA windowing and guard‑band allocation—yields the greatest improvement, up to 91 %. When the same scheme is evaluated in flat Rayleigh fading, however, fading‑induced symbol erasures significantly curtail these gains: zero‑padded WOLA delivers only a 39 % average BER reduction, guard-band insertion about 65 %, and the hybrid method approximately 72 %. The drop in mitigation efficacy highlights that, under fading, residual INI benefits are only partially observable among the dominant fading errors.

III.5.3.2 16-QAM under AWGN versus Rayleigh Fading

With 16-QAM in an AWGN channel, the densest of these constellations exhibits higher absolute BERs, yet the relative effectiveness of INI mitigation mirrors that of QPSK:
ZP WOLA alone reduces BER by about 30 %, a dedicated guard-band by roughly 65 %, and the combined (hybrid) approach by nearly 72% on average across 0–30 dB SNR. When the same 16-QAM system operates over a flat Rayleigh-fading channel, however, deep fades intermittently drive symbol errors and obscure much of the leakage-control benefit. In this environment, the average BER reductions fall to approximately 13 % with ZP-WOLA, 29% with guard-bands, and approximately 37% with the hybrid method—roughly 20 - 50% less improvement than seen under AWGN, even though the ranking of mitigation schemes (hybrid > guard-band > WOLA) remains unchanged.

To quantify a mitigation scheme's impact on bit‑error‑rate (BER), one first computes the point wise percent reduction at each SNR point SNRi, via:

$$R_i = \frac{BER_{no\ mitigation}(SNR_i) - BER_{mitigation}(SNR_i)}{max\ (BER_{no\ mitigation}(SNR_i), \varepsilon)} \times 100\% \qquad (3.2)$$

where $BER_{no\ mitigation}$ and $BER_{mitigation}$ denote the baseline and post-mitigation BER curves, respectively and ε is a small floor to avoid dividing by zero at very high SNR.

The overall percent reduction R is then obtained by averaging Ri across all N SNR samples (0-30 dB):

$$R = \frac{1}{N}\sum_{i=1}^{N} R_i \quad (3.3)$$

The following table 3.3 delineates the mean BER reduction percentages attained by each mitigation strategy across two distinct channel models (AWGN and flat Rayleigh fading) for both QPSK and 16-QAM schemes:

Table 3.3. Average BER reduction percentages for different mitigation methods

Mitigation Method	**ZP-WOLA**	**Fixed Guard Band**	**Hybrid (ZP-WOLA + Fixed Guard Band)**
BER Reduction % (over AWGN, QPSK)	49.55%	87.23%	91.68%
BER Reduction % (over AWGN, 16-QAM)	22.90%	72.05%	78.48%
BER Reduction % (over flat Rayleigh, QPSK)	39.38%	65.80%	72.28%
BER Reduction % (over flat Rayleigh, 16-QAM)	13.03%	29.31%	36.74%

III.6 Discussions

Following a lengthy series of experiments on overcoming INI in 5G OFDM systems, the natural question to ask was: can a simple time-domain filter, such as a Finite Impulse Response (FIR) filter, successfully overcome the challenges of coexistence for multi-numerologies? The experimentally derived results quickly suggested otherwise.

While the smoothing action was what it aimed for, the FIR filter had little influence on interference levels, revealed by a nearly flat Bit Error Rate (BER) curve for every level of SNR. This called for a reevaluation of methods: would frequency-domain isolation through guard bands present an easier route? Surprisingly, guard bands alone demonstrated a considerable reduction in BER, far superior to the FIR filter.

However, this outcome led to an additional question: would a hybrid approach combining filtering with guard bands yield additive, even synergistic, performance improvement? Our initial hybrid approach, built around FIR filtering and fixed guard bands, failed to deliver significant improvements beyond those from guard bands in isolation. This outcome meant that the issue was not with the hybrid concept in itself, but with the inadequacy of the filtering mechanism to identify the temporal and spectral complexities of mixed numerology systems.

This led us to explore a more advanced method: Weighted Overlap and Add (WOLA) filtering. WOLA deviates from FIR by using time-domain windowing with raised cosine shape to reduce spectral leakage and smooth out symbol edges. Its switch over to WOLA yielded encouraging results, particularly in low and mid-SNR areas. A basic question came up: why is the BER still greater at high SNR values even when the smoothing ability of WOLA is exploited? More scrutiny revealed that WOLA's overlapping sections, though smoothed, still pumped energy into neighboring numerology FFT windows. Therefore, an added degree of finesse was needed.

The zero-padding technique emerged as the solution to this residual interference. By filling in the spaces between OFDM symbols with zero-valued samples, we effectively extended the WOLA window's decay past the surrounding numerologies' FFT capture duration. This ZP-WOLA configuration significantly reduced BER, particularly in the high SNR regime where INI is the dominant limiting factor. These findings led to a vital synthesis: would it happen that placing ZP-WOLA in combination with fixed guard band insertion would be an even more powerful and effective mitigation strategy?

Indeed, the hybrid approach blending ZP-WOLA with adaptive guard bands exhibited the most consistent and robust improvements in all modulation schemes (QPSK, 16-QAM, 64-QAM, and 256-QAM). The hybrid approach employed both time-domain shaping and frequency-domain isolation and achieved lowest BER levels and highest rate of decrease with increasing SNR. Its performance confirmed that INI mitigation is optimum when it is designed simultaneously in temporal and spectral domains.

To ascertain its true application in real environments, the hybrid scheme was next put to trial under a frequency-flat Rayleigh fading channel. This environment simulates a non-line-of-sight multipath system with amplitude variation and fading characteristic of real wireless systems. While the BER increased overall under Rayleigh conditions, as would be expected, the hybrid technique still held relative advantage over stand-alone WOLA or guard band approaches. Even while fading-induced symbol loss reduced absolute gains, the hybrid approach always produced the lowest error floors, showing it to be robust under more realistic propagation models

III.7 Conclusion:

The work proposed represents a hybrid mixing technique to be employed as a measure of mitigation to create a more effective solution. The use of WOLA and guard band mixing has been proven to increase efficiency in specific instances. These processes still have some errors, however. WOLA, although effective in processing the spectrum, can lead to excessive computational overheads and latency in processing, making it less suitable for real-time systems. Guard band mitigation, on the other hand, can lead to bandwidth wastage as sections of the spectrum are intentionally left unused to avoid interference.

To avoid such limitations, ZP-WOLA is used in order to improve performance. This approach enhances the quality of the transmitted signal and results in improved performance metrics, particularly Bit Error Rate (BER).

Conclusion and Recommendations for Future Work

Conclusion

The hybrid INI-mitigation framework that integrates time-domain windowing (zero-padded WOLA) with a specialized spectral guard-band exhibits consistently superior performance across both AWGN and flat Rayleigh-fading channels, applicable to both QPSK and 16 QAM modulations.

By implementing a square root Hann window at the edges of each OFDM symbol, the methodology accomplishes a smooth roll-off in the time domain, which in turn suppresses out-of-band radiation and reduces INI without introducing intersymbol interference, whilst the guard-band effectively isolates residual inter-numerology leakage within the frequency domain. This dual-domain methodology produces the most pronounced slopes in BER versus SNR and the highest average percentages of BER reduction.

Since the parameters used is a full symbol length ZP-WOLA window (1096 samples) and the guard band size is half of the second numerology, the BER reduction percentage reached up to 91 % under AWGN channel for QPSK and 78% for 16 QAM.

Under Rayleigh conditions and for a moderate realistic fading, the BER reduction percentage decreased to 72% for QPSK and approximately 34% for 16 QAM. The primary trade-off is manifested in the marginal elongation of symbol duration (attributable to zero-padding) which results small amount of time‑domain redundancy and the diminution of spectral efficiency (due to the presence of the large guard-band), balanced against the substantial enhancements in error resilience. Therefore, the hybrid ZP-WOLA combined with fixed guard-band technique presents a well-balanced dual suppression, high-performance solution for INI in multi-numerology OFDM based systems functioning under both ideal and fading channel conditions

Recommendations for Future Work

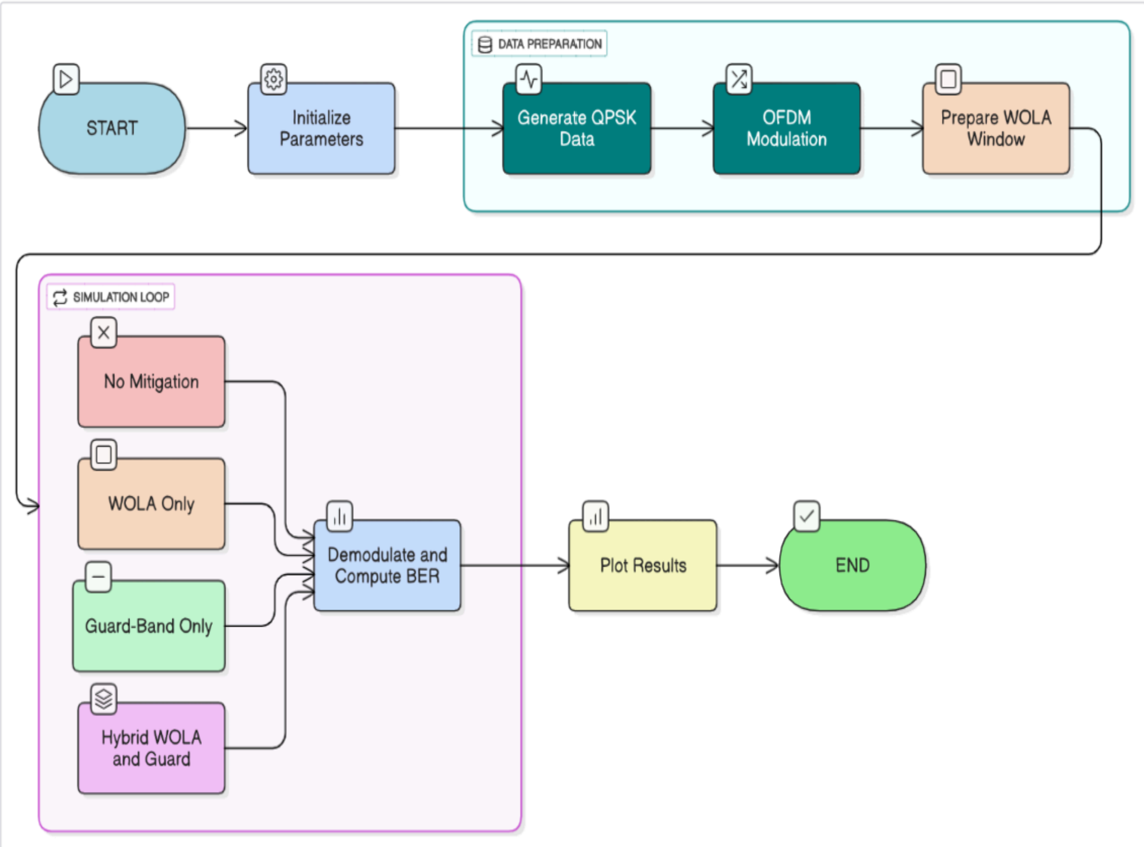
Building on the promising results of our hybrid INI mitigation approach, there are several directions for further improvement. We aim to:

- Design an RL agent for training guard band sizes and optimal filtering methods based on actual time interference.
- Use quantization-aware processing to improve hardware efficiency without affecting BER performance.
- Conduct further parameter adjustment to expand deployment cases.
- Experiment with different numerology combinations, FFT sizes, and symbol periods.

Ultimately, the project as it stands today is focused on realizing optimal interference cancellation without sacrificing the system on unnecessary engineering investments, horizoning on an optimized, adaptive, and hardware-conscious solution to meet the ever-extreme demands of current wireless networks.

Appendix A

A.1 General code flowchart



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