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5G New Radio OFDM Multi-Numerology Interference Mitigation

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Abstract

This work examines the importance of inter-numerology interference mitigation in fifth-generation (5G) NR orthogonal frequency-division multiplexing (OFDM) based systems. The impact of multi-numerology on coexistence issues, latency, and performance is highlighted in this work. The proposed work 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-off. The hybrid ZP WOLA mitigation approach reached 78% - 91% BER reduction percentage in the ideal case (under AWGN) and 37% - 72% BER reduction percentage under moderate fading (flat Rayleigh fading).

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

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1. Introduction

As the demand for higher data rates continues to increase, the shift to more advanced technologies that support more services is essential. The fifth generation (5G) wireless networks, which is based on the adoption of multi-numerology OFDM systems, addresses this need, offering different services and maintaining excellent quality of service (QoS) [1]. However, 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. Several techniques have been implemented to reduce the effect of this issue, such as filtering, equalization, and machine learning, each has its own advantages and disadvantages. In this paper, a hybrid INI mitigation model is proposed based on guard band and filtering technique, specifically, ZP-WOLA under AWGN channel and flat Rayleigh fading channel for both QPSK and 16-QAM schemes. This method is followed by a comparative analysis of the BER performance.

2. OFDM in 5G Networks

OFDM, short for Orthogonal Frequency Division Multiplexing, is a digital modulation and multiplexing technique used in wireless communication systems like 5G networks. It is widely recognized for its ability to minimize inter-symbol interference (ISI) and maximize spectral efficiency. By dividing bandwidth into orthogonal subcarriers, OFDM enables parallel data transmission, reducing multi-path fading and enhancing robustness in frequency- selective environments [2]. In 5G, OFDM has evolved into multi numerology OFDM, allowing flexible subcarrier spacing to support diverse use cases like eMBB, URLLC and mMTC [3]. In 5G, OFDM's flexibility is further enhanced through the introduction of multiple numerologies. Each numerology is characterized by a unique set of parameters, including subcarrier spacing, cyclic prefix (CP) duration, and symbol length. The relationship between these parameters is given by [2]:

$$T_s = \frac{1}{\Delta f} + \mathrm{T_{cp}} \qquad \textbf{(1)}$$

Where Ts represents the total symbol duration, Δf denotes the subcarrier spacing, and Tcp is the cyclic prefix duration. Different numerologies can be designed to meet specific service requirements, optimizing the balance between latency, reliability, and spectral efficiency [1].

2.1 Mathematical Foundations of OFDM

OFDM relies on the Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT). At the transmitter, the IFFT converts parallel data symbols into a time-domain OFDM signal, while at the receiver, the FFT transforms the signal back to the frequency domain for demodulation.[3]. The orthogonality of subcarriers is maintained by ensuring that the subcarrier spacing is equal to the inverse of the symbol duration. As a result, OFDM can be implemented effectively in both hardware and software since subcarrier bands overlap without interfering. Mathematically, the OFDM signal in the time domain can be expressed as [3]:

$$s(t)=\sum_{k=0}^{N-1} X_k \,.\, e^{j2\pi k\Delta f t},\ \ 0\leq t\leq T_s \qquad \textbf{(2)}$$

Where:

1. N is the total number of subcarriers.
2. X_k is the complex modulation symbol (e.g, QAM or PSK) assigned to the k-th subcarrier.
3. Δf is the subcarrier spacing.
4. T_s is the symbol duration.

The orthogonality condition is satisfied when the subcarrier spacing Δf is chosen such that [3]:

$$\Delta f=\frac{1}{T_S} \qquad \textbf{(3)}$$

This ensures that the integral of the product of any two subcarriers over the symbol duration *Ts* is zero, i.e.,

$$\int_0^{T_s} e^{j2\pi k\Delta f t}.\, e^{-j2\pi m\Delta f t}\, dt = T_s\ , If\ k=m \qquad \textbf{(4)}$$

$$\int_0^{T_s} e^{j2\pi k\Delta f t}.\, e^{-j2\pi m\Delta f t}\, dt=0\ \ , If\, k\neq m \qquad \textbf{(5)}$$

where *k* and *m* are indices of different subcarriers. This orthogonality allows for efficient spectrum utilization and simplifies the receiver design, as the subcarriers can be separated using a Fast Fourier Transform (FFT) without requiring complex filtering [3], [4].

2.2 Cyclic Prefix in OFDM

One of the key challenges in wireless communication is mitigating the effects of multipath propagation, which causes ISI and inter-carrier interference (ICI). To address this, OFDM employs a cyclic prefix (CP), which is a guard interval inserted at the beginning of each OFDM symbol. The CP is a copy of the last portion of the symbol appended to its start, ensuring that the linear convolution of the channel is transformed into a circular convolution. Mathematically, the CP length T_{cp} is chosen to be longer than the maximum delay spread τ_{max} of the channel [3]:

$$T_{cp} \geq \tau_{max} \quad \textbf{(6)}$$

The inclusion of the CP eliminates ISI and ICI, as long as the delay spread does not exceed the CP duration. However, the CP introduces an overhead that reduces the spectral efficiency, as the effective symbol duration becomes ($T_S + T_{cp}$). In 5G, the CP length is dynamically adjusted based on the channel conditions and the numerology configuration, balancing the trade-off between robustness and efficiency [1].

3. Inter numerology Interference

In 5G networks, INI happens when many numerologies with various subcarrier spacings (SCS) and symbol durations share a frequency band. The introduction of non-orthogonality between subcarriers of different numerologies causes energy leakage and performance deterioration, even if this flexibility facilitates a variety of applications. INI results from time-domain misalignment (various symbol lengths) and frequency-domain misalignment (different SCS values), which are exacerbated by Doppler effects in high-mobility situations [4]. This interference lowers dependability, spectral efficiency, and signal quality, especially for applications that are latency-sensitive [5].

A developing technology called orthogonal frequency division multiplexing with index modulation (OFDM-IM) improves spectral efficiency by modifying information in subcarriers' activation patterns in addition to their amplitude and phase. However, there are particular difficulties with INI when several numerologies coexist in OFDM-IM systems. Dogan-Tusha et al. [6] showed that because mixed numerologies are non-orthogonal, the subcarrier activation patterns in OFDM-IM systems worsen INI. Their research emphasizes the necessity of sophisticated interference mitigation strategies designed for OFDM-IM systems, especially in situations with high mobility and fluctuating channel conditions.

Optimizing resource allocation, maintaining accurate synchronization, minimizing interference through sophisticated signal processing, and addressing scalability as numerologies grow are some of the main obstacles. It's crucial to strike a balance between flexibility and performance trade-offs and to instantly adjust to changing network conditions [7],[8],[9].

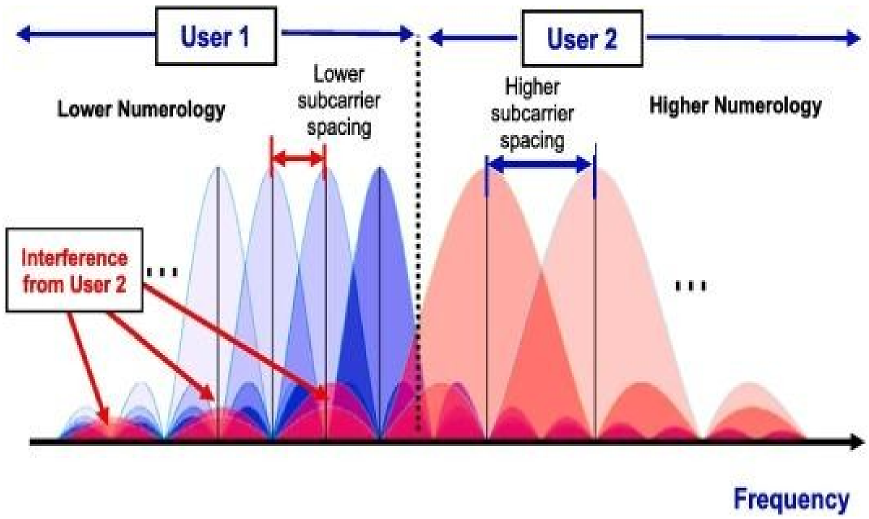


Figure 1. Coexistence of two numerologies in OFDM systems [4]

4. Related work

This section reviews the primary methodologies used to mitigate INI in multi-numerology OFDM systems. Each approach is examined in terms of its underlying principles, simulation results, and practical limitations.

Table 1 highlights the advantages, limitations, and performance gains of each method, offering a comprehensive overview of their applicability in different scenarios.

Table 1. Comparison of INI Mitigation Techniques

Technique	Advantages	Limitations	Performance Gain
Frequency- Domain Filtering [10]	Simple implementation; effective in static channels	Increased latency; less adaptive	3-5 dB SINR
Pre- Equalization [11]	Compensates interference pre-transmission	Requires accurate channel estimation; sensitive to	Notable gains in controlled scenarios

		mobility	
Adaptive Guard Allocation [12],[13]	Dynamic; preserves spectral efficiency	Complex integration with scheduling	Balances throughput and interference
Machine Learning-Based [14], [15]	Adaptive and predictive	High computational overhead; training data requirements	Early-stage promising results

5. Proposed work

Frequency-domain filtering aims to suppress out-of-band emissions that cause interference. This is achieved by designing digital filters that attenuate the energy of subcarriers outside the desired bandwidth. A key study by Ouazziz et al. [10] demonstrated that designing low-pass filters for individual numerologies can reduce INI by up to 5 dB in Signal-to-Interference-plus-Noise (SINR) under static conditions. However, it 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.
To reduce this effect, an initial hybrid experiment with a gard band and a Finite Impulse Response filter (FIR) was simulated, indicating minimal interference mitigation resulting in a high BER=0.47. Consequently, a more advanced filtering technique was required to reduce out-of-band emission (OOBE). The Weighted Overlap and Add (WOLA) filtering was adopted.

5.1 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 , some drawbacks still persisted.

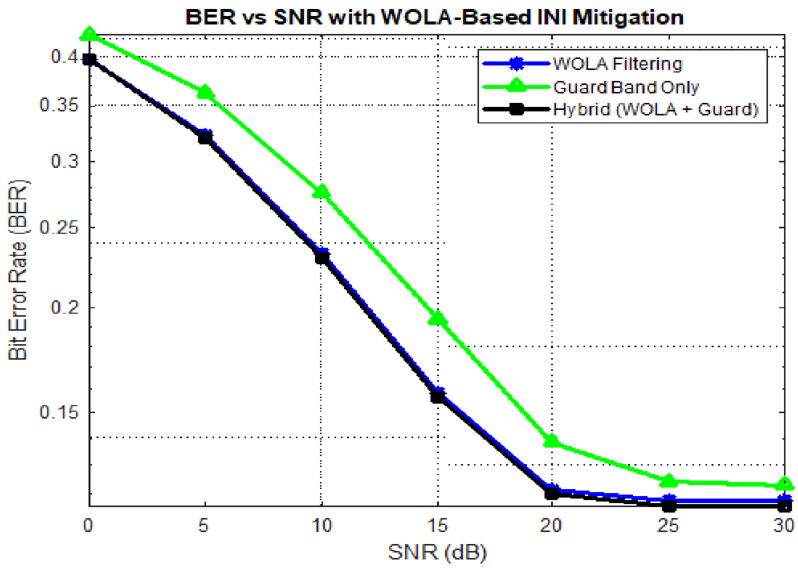


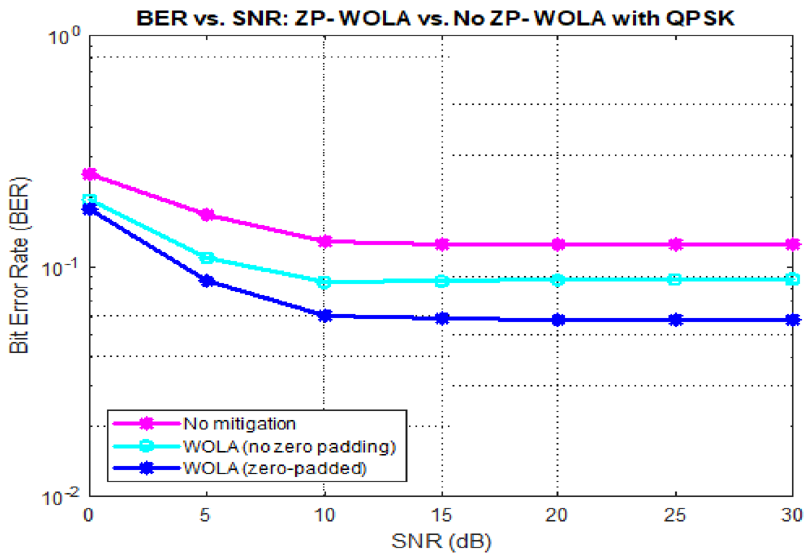
Figure 2. BER of WOLA filtering, Gard band and Hybrid mitigation

Figure 2 shows that the BER remained excessively high at moderate and high SNR values. This means that, despite increased smoothing, WOLA by itself was not able to completely prevent interference between adjacent numerologies. A big contributor to this was the 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 zero 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.

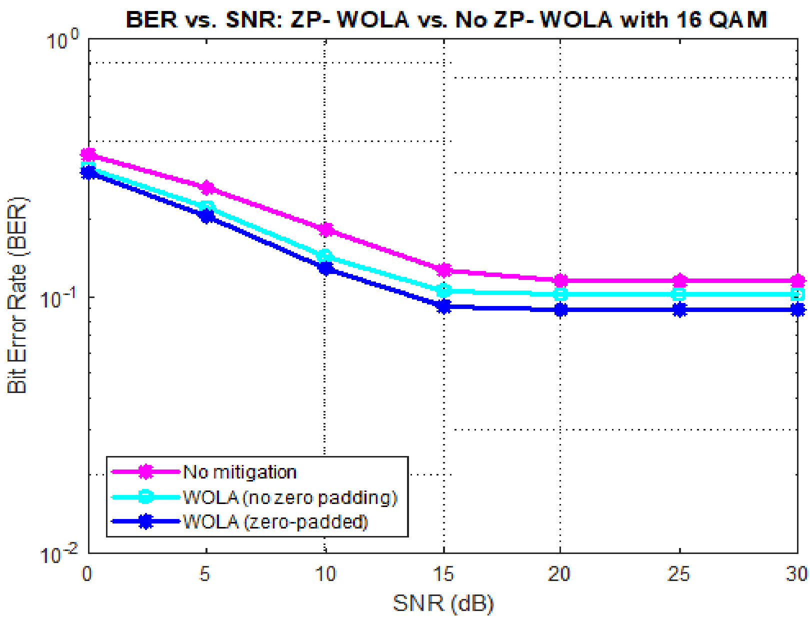
5.2 Padded WOLA filtering

As we observed from WOLA performance that it was not optimal under all conditions, we applied a modification: zero-padded WOLA, in which the zero-valued samples are filled in between each OFDM symbol before applying the WOLA window.

As Fig 3 illustrates, this padding achieves better isolation between adjacent numerologies by stretching the overlapping ends of the windowed waveform beyond the adjacent numerologies' FFT window for both QPSK and 16 QAM.



(a)



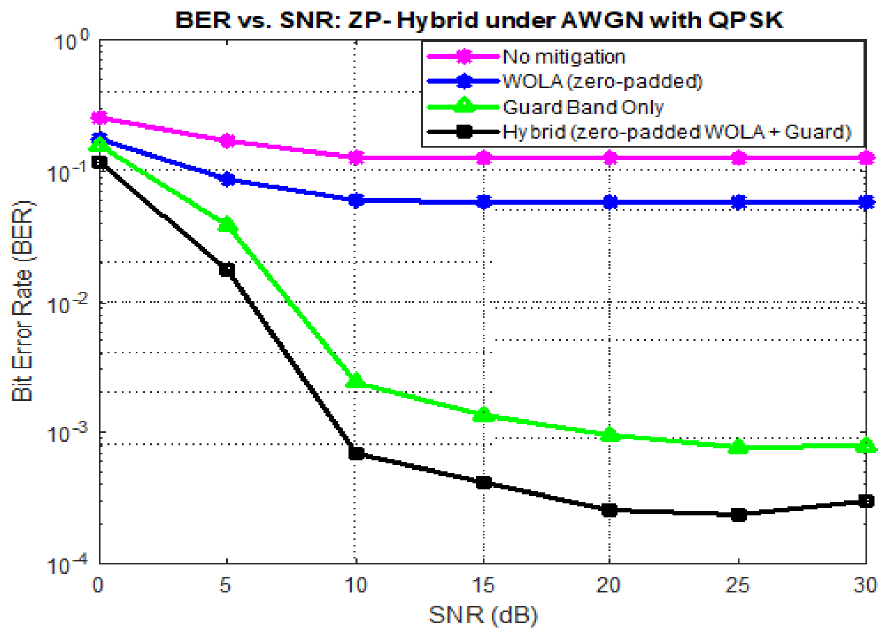
(b)

Figure 3. BER of ZP-WOLA filtering compared to the no-zero-padding WOLA mitigation method. (a) for QPSK and (b) for 16 QAM

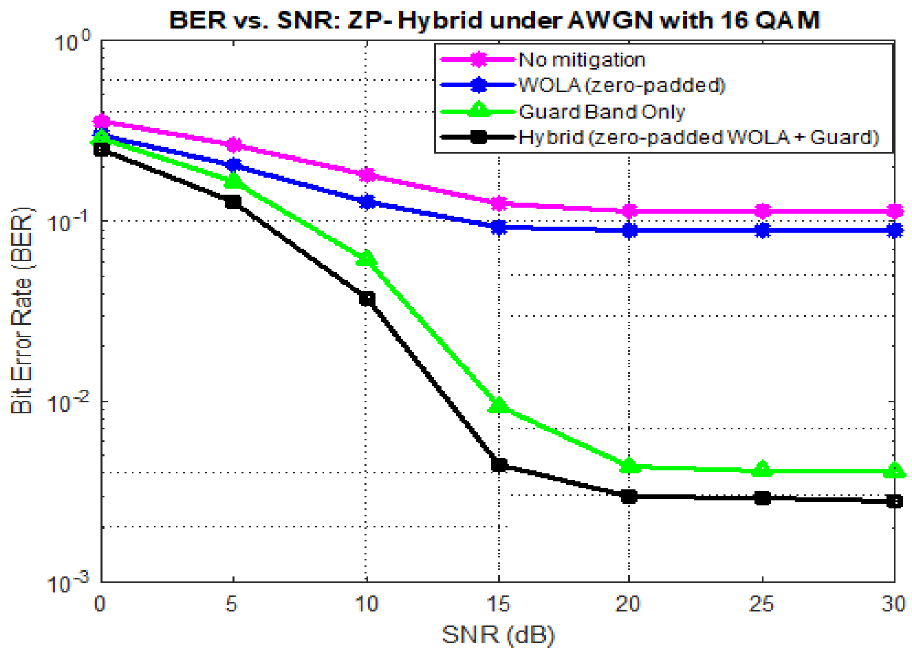
5.3 ZP-Hybrid filtering under AWGN

To reduce the persistent inter-numerology interference (INI) observed in the earlier techniques, our final proposed method integrates zero-padded WOLA filtering and 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 efficiently, 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)



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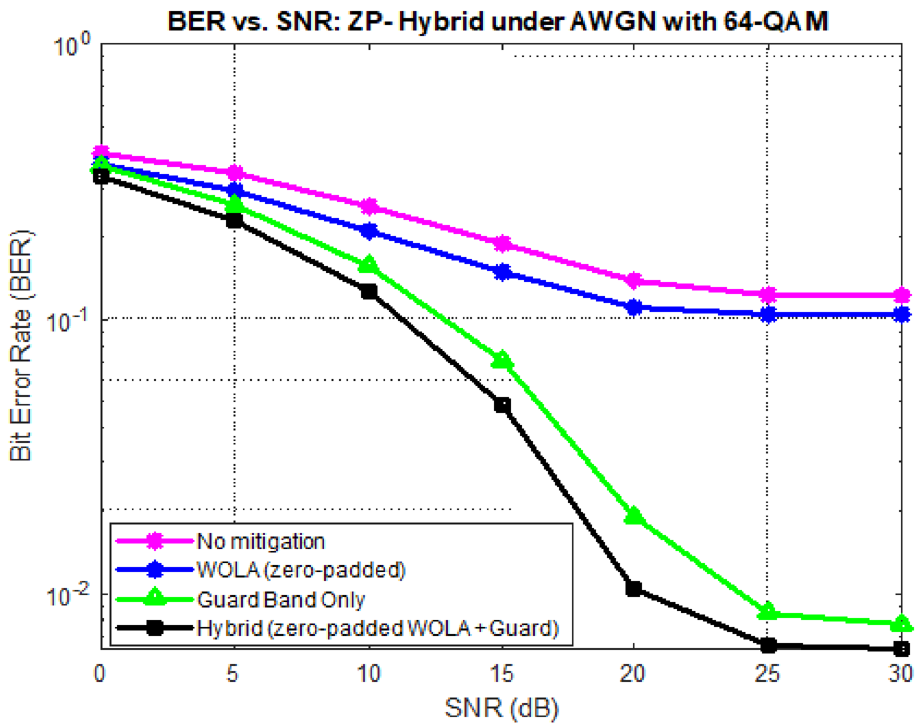


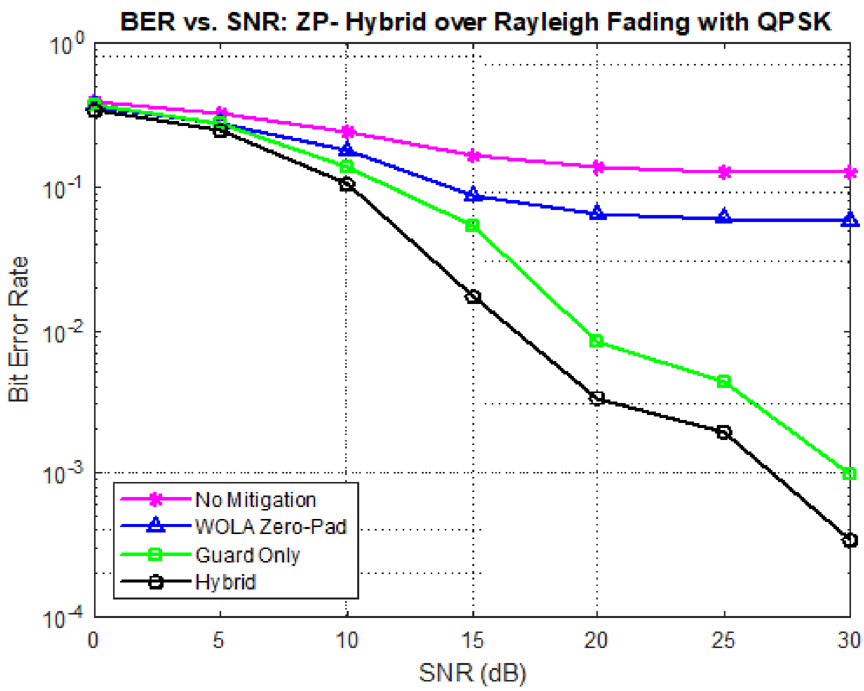
(c)

Figure 4. BER of ZP-WOLA, Gard band, and ZP-Hybrid mitigation. (a) for QPSK, (b) for 16 QAM, and (c) for 64 QAM

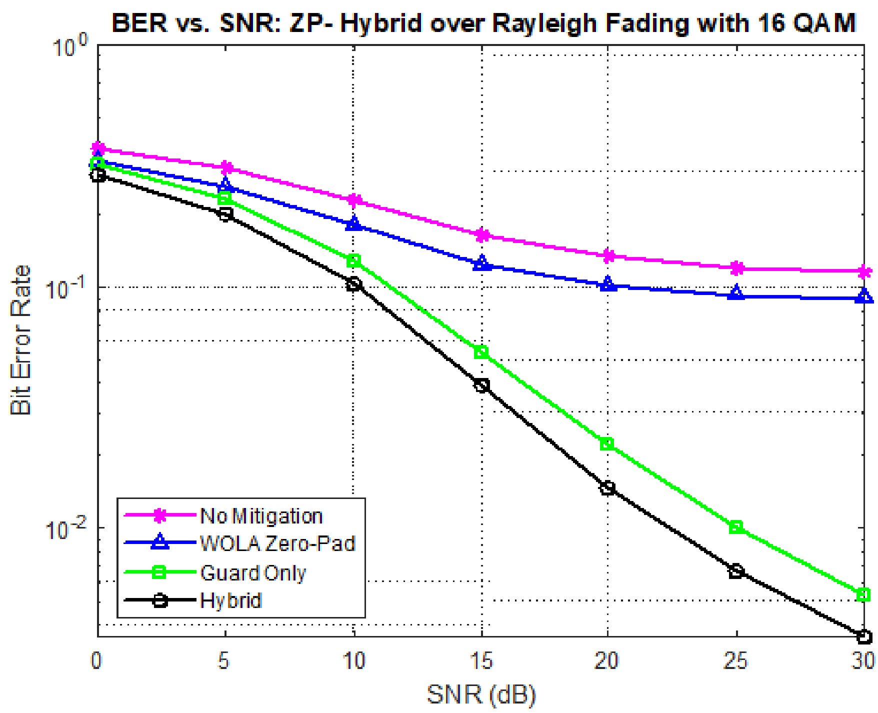
Figure 4 shows that WOLA with zero padding outperforms non-padded WOLA, with lower BER at all levels of SNR. Furthermore, in conjunction with guard band insertion, the hybrid padded WOLA solution also performs best, having the lowest BER and steeper downward slope for increasing SNR. This validates that 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.

5.4 ZP-Hybrid filtering over a 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 can be directly compared in practical fading and noise conditions.



(a)



(b)

Figure 5. BER for ZP-WOLA, Gard band, and ZP-Hybrid mitigation over Rayleigh fading. (a) for QPSK and (b) for 16 QAM

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

The results in Figure 4 illustrate that the hybrid scheme reduced the interference more effectively under fading conditions as compared to WOLA and guard band filtering.

6. Performance comparison

In assessing inter-numerology interference (INI) mitigation for multi-numerology OFDM systems, it is instructive to compare performance under multiple channel models.

In our case, 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.

The effect of a mitigation scheme on the bit-error rate (BER) can be quantified by evaluating the percentage reduction at each signal-to-noise ratio point SNRi, as given by:

$$R_i = \frac{BER_{no\ mitigation}(SNRi) - BER_{mitigation}(SNRi)}{max(BER_{no\ mitigation}(SNRi), \varepsilon)} \times 100\% \qquad \textbf{(6)}$$

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):

$$R = \frac{1}{N}\sum_{i=1}^{N} R_i \qquad \textbf{(7)}$$

Table 2 presents the mean BER reduction percentages attained by each mitigation method across two distinct channel models (AWGN and flat Rayleigh fading) for both QPSK and 16-QAM schemes:

Table 2. Average BER reduction percentages for different mitigation methods

Mitigation Method	ZP-WOLA	Guard Band	ZP-Hybrid (ZP-WOLA + 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%

The hybrid technique still held a relative advantage over stand-alone ZP-WOLA or guard band approaches. Even under fading-induced symbol losses, which reduce the performance gains. The hybrid approach always produced the lowest error floors, showing its robustness under more realistic propagation models.

7. Conclusion

The proposed approach achieves significant BER reduction across different modulation schemes and channels conditions, demonstrating that the hybrid INI mitigation model, which combines zero-padding WOLA windowing with a spectral guard band, efficiently suppresses inter-numerology interference in both time and frequency domains. 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.

Future work will examine broader numerology combinations, FFT size, and symbol duration to improve adaptability, and focus on further optimizing window parameters and evaluating performance complexity trade-offs to enhance scalability for practical 5G and beyond 5G applications.

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