Analysis of INI in 5G NR Modulation Schemes using Windowing and Pulse Shaping

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Abstract

5G and other next-generation telecommunications technologies require sufficient bandwidth, reliability, and speed. The deployment of mixed numerologies can harness the diverse use cases of 5G, including Enhanced Mobile Broadband (eMBB), Ultra Reliable Low-Latency Communication (URLLC), and Massive Machine Type Communication (mMTC) or Internet of Things (IoT). Although this sounds like a great initiative, it ushers a new challenge known as internumerology interference (INI). To address this issue, this paper proposes a novel pulse shaping technique, specifically windowing, to facilitate the implementation of mixed numerology transmission. The effectiveness of the proposed technique will be analyzed using the Error Vector Magnitude (EVM) metric. The analysis will be conducted using four modulation schemes used in 5G, namely Quadrature Phase Shift Keying (QPSK), 16 Quadrature Amplitude Modulation (16 QAM), 64 QAM, and 256 QAM.

Keywords: Error vector magnitude, Out-of-band emission, Subcarrier spacing, Windowed OFDM, Internumerology interference.

1. INTRODUCTION

In 5G NR, multiple subcarrier spacings ranging from 15kHz to 480kHz are adopted to support different deployment scenarios and requirements. Our analysis in this paper will discuss two numerologies, Numerology 1 is 15kHz while numerology 2 is 30kHz. Emphasis will be on the INI caused by numerology 2 to numerology 1 as shown in figure 2(a). Numerology 1 contributes minimal or zero interference to numerology 2 since all its subcarrier peaks coincide with the zero crossing of numerology 1 spectrum.

This analysis can be very useful when designing and optimizing OFDM systems. Windowed OFDM uses a smooth time domain window to suppress OOB emissions at the transmitter while rejecting it at the receiver. This study analyzes reduction in Error Vector Magnitude (EVM) loss for the 5G NR modulation schemes mentioned in the abstract.

The spectral leakage generated by adjacent subcarriers at the transmitter tremendously degrades system performance. This can be resolved by implementing a smoother window with a good roll-off factor although it could come at the cost of reduced spectral efficiency. Windowing is done at both the transmitter and receiver to ensure thorough spectral confinement and side-lobe suppression.

W-OFDM puts together the advantages of conventional CP-OFDM with windowing techniques to minimize out of band interference and improve system spectral efficiency thus reducing INI to a significant degree. This therefore makes windowed OFDM the transmission technique of choice. It is also worth mentioning that W-OFDM is generally less complex and has a reduced peak-to-average power ratio (PAPR) which makes it stand out.

Transmitted signals are subjected to channel conditions that may include multipath, phase noise, thermal noise, frequency offsets, fading and interference from external unwanted signals. All these factors contribute to the Error Vector Magnitude (EVM) degradation discussed in section 4 of this paper.

Figure 1(a): Shows external Interference within a 5G signal in the 3500MHz band.

Fig 1(a) illustrates a 5G signal with a 100MHz bandwidth (3400-3500 MHz) captured over the air. The white pulses circled red are captured from an external interfering source. The presence of these pulses within the signal tremendously degrades system performance to the extent that it is unusable. Both internal and external interference is undesirable and should be annihilated by all means possible.

This paper has been structured as follows:
Section 1: Introduces INI and Windowing technique. Section 2: Explains the system model. Section 3 Discuses the transmission process. Section 4: Discusses INI mitigation at the receiver. Section 5: Explains simulation results.

Abbreviations and Acronyms
3GPP: 3rd Generation Partnership Project

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5G NR: 5G New Radio
EVM: Error Vector Magnitude
SNR: Signal-to-Noise Ratio
INI: Inter-Numerology Interference
QPSK: Quadrature phase shift keying
QAM: Quadrature Amplitude Modulation
UE: User equipment
ACLR: Adjacent Channel Leakage Ratio

Multi numerology transmission is explained in fig 1(b) showing transmission of subcarriers of two different numerologies in an OFDM system.

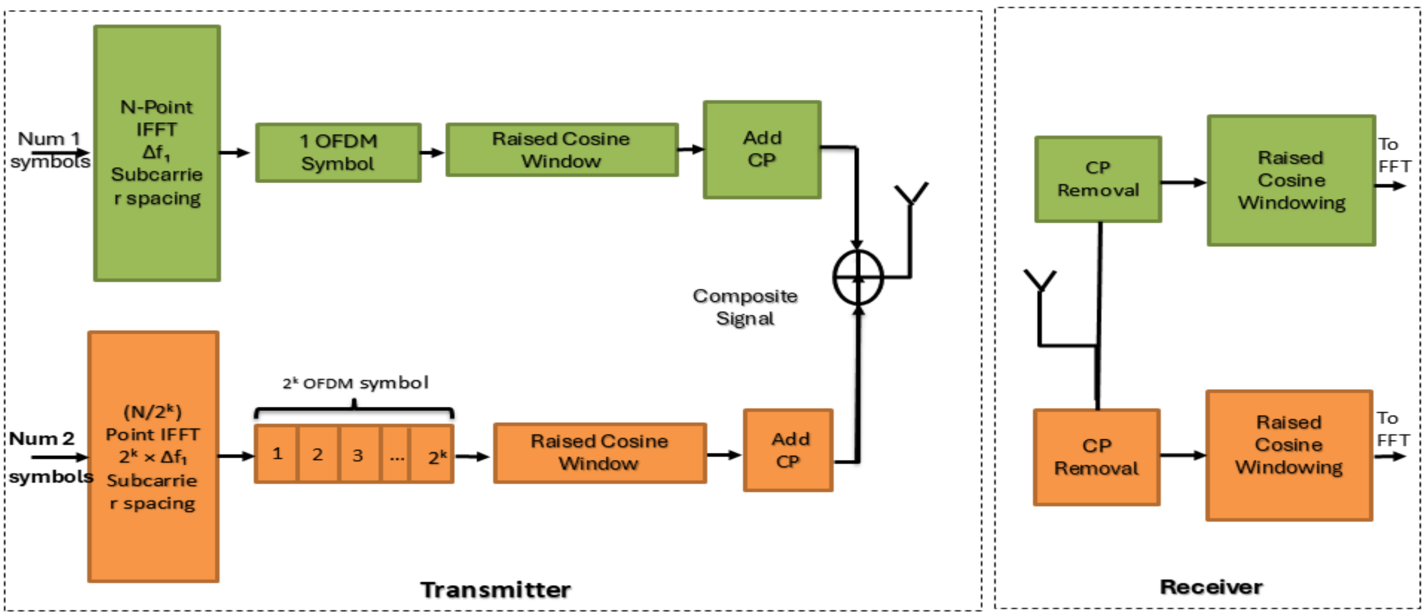

Figure. 1(b) A block diagram showing implementation of windowing for numerologies 1 and 2

The block diagram above explains the implementation of two numerologies (Numerology 1 and Numerology 2) for a 5G communication system with numerology ratio, Q = Δf2/Δf1, where Δf1 is 15kHz and Δf2 is 30kHz, Q = 2k and kϵN. Numerology 1 and numerology 2 cyclic prefix lengths is represented by NCP and MCP respectively, where MCP = NCP/Q.

The diagram enables us to analyze INI using these key components for two transmitters; one for numerology 1 and another for numerology 2, it is shown that each numerology has multiple users (u = 1, 2, ..., Q and v = 1, 2, ..., R). We also observe that the normalized power of the transmitter is shared between the two numerologies 1 and 2 respectively. Further to this, the modulated symbol vectors are passed through IFFT blocks to get time domain symbols (S1 and S2, u). The output of the IFFT blocks yields time domain symbols s1 and s2.

2. INI AT THE TRANSMITTER

Multiplexing of Numerology 1 and Numerology 2 Subcarriers

Fig 2(a) Shows subcarriers of numerology 1 and numerology 2 combined and transmitted. When this is done, it is observed that the subcarrier peaks of numerology 2 coincide with the zero crossings of

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numerology 1's out of band emissions meaning that no interference is caused to numerology 2. On the other hand, subcarriers from numerology 1 face intense interference from numerology2 subcarriers. Every alternate subcarrier of numerology 1 experiences interference due to the non-orthogonality of numerology 2 subcarriers inducing inter numerology interference (INI). In this case, Q=2. Where Q is a parameter that represents the ratio of the subcarrier spacings between numerology 1 and numerology 2. Q = 2k implies that Q is an even integer. Signal degradation in this case arises due to Inter-Numerology Interference (INI) that numerology 1 subcarriers experience due to the OOB emissions from numerology 2 subcarriers. The fraction (Q-1)/Q calculates the proportion of Numerology 1 subcarriers that suffer from INI degradation due to leakage from Numerology 2 subcarriers.

In the event that Q = 2, then (Q-1)/Q = (2-1)/2 = 1/2. This implies that half of the numerology 1 subcarriers will be affected by INI degradation, and this is clearly shown by red arrows in fig 2(a). Every other numerology 1 subcarrier is affected by numerology 2 leakage. The higher the value of Q, the more intensely numerology 1 subcarriers are affected which may cause serious errors thus downgrading system performance.

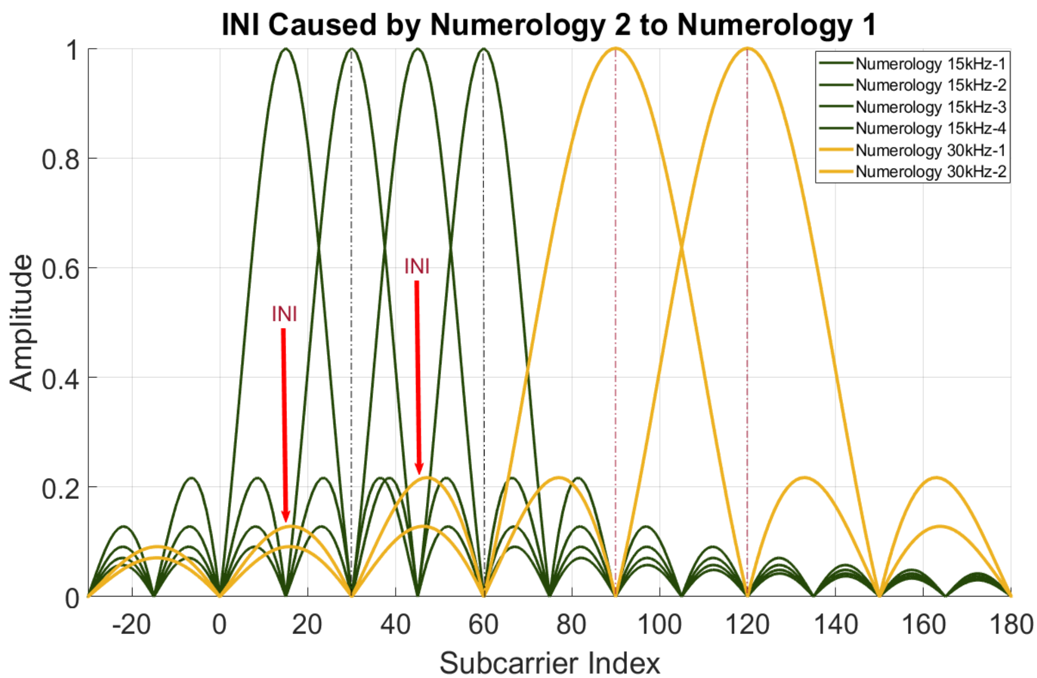

Fig. 2(a) INI caused by numerology 2 to numerology 1 at the transmitter

Generate complex modulated symbols to be transmitted

In 5G NR systems, the subcarrier modulation can be QPSK, 16 QAM, 64 QAM, or 256 QAM, depending on the application and channel conditions. $X_1 \epsilon C^{B1x1}$ is a modulated symbol vector for user 1 while $X_{2,\ u}(l) \epsilon C^{B2/Qx1}$ is the symbol of the uth OFDM symbol of user 2, with 0≤u≤Q-1. The two are defined below, where u=0,1, 2,...,(Q-1). These complex modulated symbols are used to generate the OFDM signals for User 1 and User 2, which are then transmitted over the channel.

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$$X1(k) = \begin{cases} x1(k), & 0 \le k \le B1-1 \\ 0 \quad , & B1-1 \le k \le N-1 \end{cases} \qquad (3.1)$$

X1(k) is a complex symbol vector for User 1.

$$X2, u\ (l) = \begin{cases} 0, & 0 \le l \le M - \frac{B2}{Q} - 1 \\ x2, u\ (l), & M - \frac{B2}{Q} \le l \le M - 1 \end{cases} \qquad (3.2)$$

$X_{2,\,u}$ (l) is a vector of complex numbers representing the modulated symbols for the uth OFDM symbol of User 2. The parameters used include, B1 and B2: The number of active subcarriers allocated to User 1 and User 2, respectively, N: The total number of subcarriers in the OFDM system, M: The number of subcarriers in each OFDM symbol of User 2, Q: Scaling factor that determines the number of OFDM symbols for User 2. The modulated symbol vectors are then passed through an IFFT transform.

Windowing at the transmitter

In 5G NR, windowing is used to reduce the out-of-band emissions by multiplying a designated window function that tapers to zero at the edges like the one shown in 3.3 with the OFDM symbol thus significantly reducing OOB emissions and improving the system Adjacent Channel Leakage Ratio (ACLR), which is essential for achieving 5G NR spectral mask requirements.
These attributes make W-OFDM an attractive solution for next-generation wireless communication systems, such as 5G and future wireless networks.

The transmit window to1 representing Numerology 1 is expressed with length (1 + α) NT, NT being the number of subcarriers and α as the roll- off factor. Consequently, the roll-off length N_{txroff} is expressed as αNT.

$$to2,0[n] = \begin{cases} \frac{1}{2} + \frac{1}{2}\cos\left(\pi + \frac{\pi n}{\alpha MT}\right), & 0 \le n \le \alpha MT \\ 1, & \alpha MT \le n \le MT \\ \frac{1}{2} + \frac{1}{2}\cos\left(\pi - \frac{\pi(MT-n}{\alpha M(T}\right), & MT \le n \le MT + \alpha MT \\ 0, & \text{Otherwise} \end{cases} \qquad (3.3)$$

$$to2,1\ [n] = \begin{cases} to2,0\ [n - MT], & MT \le n < MT + \alpha MT \\ 0, & \text{Otherwise} \end{cases} \qquad (3.4)$$

In Fig3(a) In below, we see reduced spectral leakage after windowing is applied. This results in reduced interference and more reliable data transmission.

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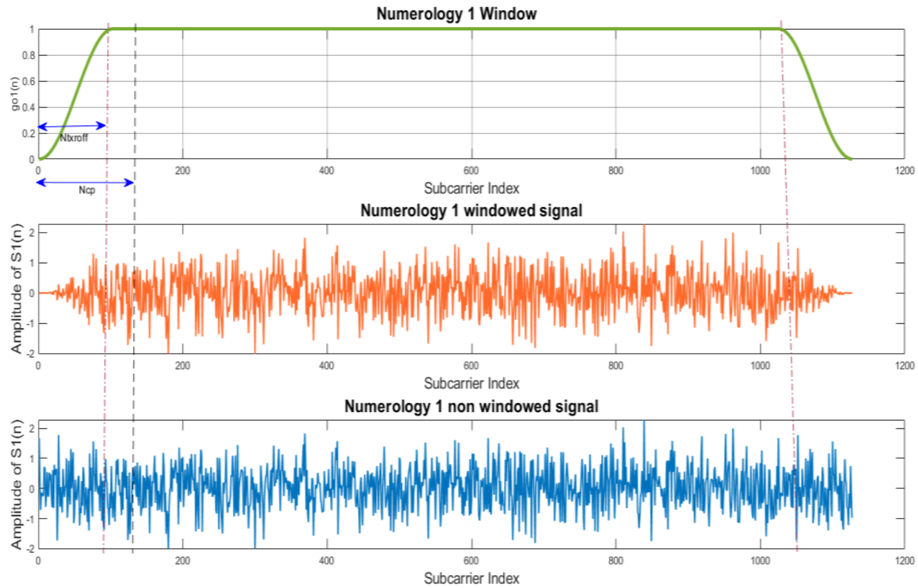

Figure 3(a): Shows the effect of windowing on signal edges

The plot above shows significant reduction at the side lobes amplitude as compared to the non-windowed one. This comes as a result of the cosine windowing function which tapers the signal to zero at the edges thus reducing the side lode amplitude to zero. It is also observed that the windowed plot yields a smoother transition between the main lobe and the side lobes. The non windowed signals have higher side lobe amplitude and more energy leakage resulting in interference with adjacent subcarriers. It is noted that windowing involves a trade-off between the width of the main lobe and side lobe amplitude. A narrower main lobe width translates to higher side lobe amplitude and a broader main lobe lower side lobes.

3. INI AT RECEIVER (UE)

The Receive window ro1 representing Numerology 1 is expressed with length (1 + α) NT, NT being the number of subcarriers and α as the roll-off factor. Consequently, the roll-off length N_{txroff} is expressed as αNT.

$$ro1\,[n] = \begin{cases} 0, & 0 \le n < Nz \\ \frac{1}{2} + \frac{1}{2}\cos\left(\pi + \frac{\pi(n-Nz)}{\beta N}\right), & Nz \le n < Nz + [\beta N] \\ 1, & Nz + [\beta N] \le n < Nz + N \\ \frac{1}{2} - \frac{1}{2}\cos\left(\pi - \frac{\pi(NT-n)}{\beta N}\right), & Nz + N \le n < NT \end{cases} \qquad (4.1)$$

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$$ro2,0\ [n] = \begin{cases} 0, & 0 \le n < Mz \\ \frac{1}{2} + \frac{1}{2}\cos\left(\pi + \frac{\pi(n-Mz)}{\beta M}\right), & Mz \le n < Mz + [\beta M] \\ 1, & Mz + [\beta M] \le n < Mz + M \\ \frac{1}{2} - \frac{1}{2}\cos\left(\pi - \frac{\pi(MT-n)}{\beta M}\right), & Mz + M \le n < MT \end{cases} \quad (4.2)$$

$$ro2,1\ [n] = \begin{cases} ro2,0\ [n - MT], & MT \le n < NT \\ 0, & \text{Otherwise} \end{cases} \quad (4.3)$$

Numerology 2 possesses two transmit windows that facilitate overlap of roll-off regions for consequent OFDM symbols. The overlap helps with spectral efficiency. The two windows from numerology 2 are ro2,0 representing the first OFDM symbol and ro2,1 for the second OFDM symbol given that Q = 2. The last M_{txroff} samples of ro2,0 and the first M_{txroff} samples of ro2,1 are overlapped.

INI analysis at the receiver

The received signal containing the desired numerology 1 signal and the (INI) generated by numerology 2 are mathematically expressed as **y = x1 + INI + n.** Where y is the received signal, x1 is the desired signal from numerology 1, INI is the Inter-Numerology Interference caused by the signal from numerology 2 and n is the additive white Gaussian noise (AWGN).

The INI experienced by numerology 1 by numerology 2 is expressed as **INI = H * P * phi * y2.**

H is a diagonal matrix representing the channel coefficients or the channel response. **P** is a diagonal matrix representing the power or gain of the interfering signal(numerology 2). **phi** is a diagonal matrix representing the phase shift or rotation of the interfering signal./ represents the interference coefficient or leakage factor **y2** the received signal from the second numerology that is causing interference to the first numerology.

The INI experienced by numerology 1 is proportional to the power of the interfering signal (P), the channel coefficient (H), the interference coefficient (α), and the signal from numerology 2 (y2).

H = diag(0.5 * ones(NT, 1)), with 0.5 representing the attenuation factor in signal power due to channel effects. **P = diag(0.8 * ones(NT, 1)),** where 0.8 represents a power scaling factor for the interfering signal**, phi = diag(0.3 * ones(NT, 1)),** with 0.3 representing a phase shift of the interfering signal.

4. SIMULATION RESULTS

Modulation analysis at Receiver

Error Vector Magnitude (EVM) is a key performance metric used to evaluate the quality of wireless communication systems by measuring the difference between the ideal and actual signal vectors in a constellation diagram. EVM = √(E / P_ref) where: E = is the error vector power, calculated as the mean squared error between the ideal and actual signal vectors and P_ref = Reference power, calculated as the mean power of the ideal signal vector.

EVM can also be calculated using SNR, EVM = √(1 / (1 + SNR)) where SNR is the signal-to-noise ratio, defined as the ratio of the signal power to the noise power. EVM is expressed in decibels: EVM (dB) = 10 * log10(EVM^2) depending on the specific system implementation and modulation scheme.

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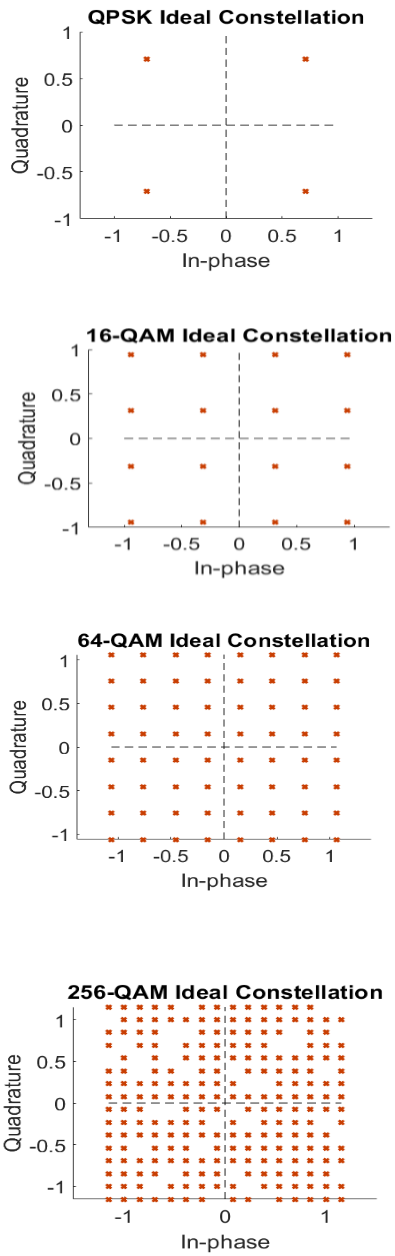
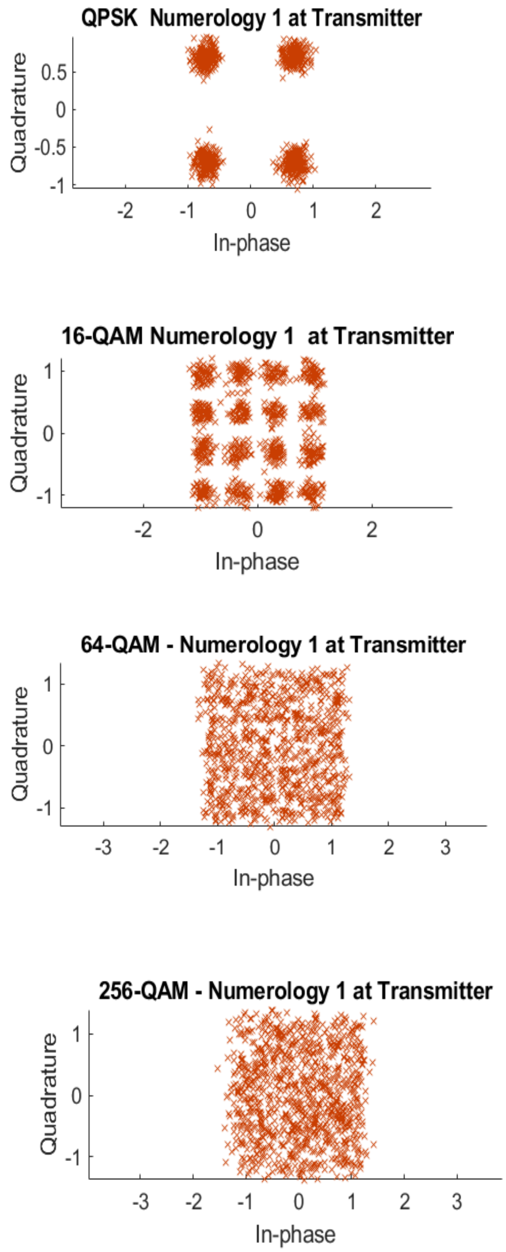
Constellation diagram comparison





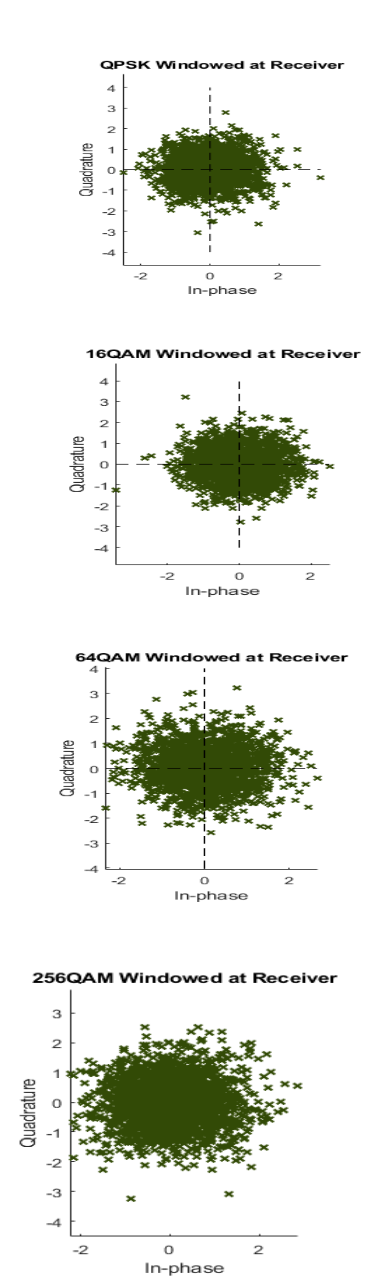


Figure 5(a): Ideal constellation points at transmitter

Figure 5(b): Constellation diagram at Transmitter after windowing

Figure 5(c) Constellation diagrams at receiver for Num 1

Fig 5(a) represents an ideal constellation with organised symbols/points. After it goes through the IFFT block and windowing is performed, we start to observe some level of distortion for QPSK, 16QAM,64QAM and 256QAM as seen in Fig 5(b). In fig 5(c) we see the received demodulated signal with a lot of distortion and spreading of the constellation points. The plots indicate that 64QAM and 256QAM points are more spread out compared to QPSK and 16-QAM, due to the increased sensitivity to noise and INI.

INI can have a greater impact on higher-order modulation types such as 64-QAM and 256_QAM resulting from sensitivity to distortion and noise. And so, if proper analysis is done, constellation

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diagrams can give good insights into the system's performance and identify potential areas for improvement. If the EVM values are higher for one numerology compared to another, it may indicate that the system is more susceptible to INI for that numerology.

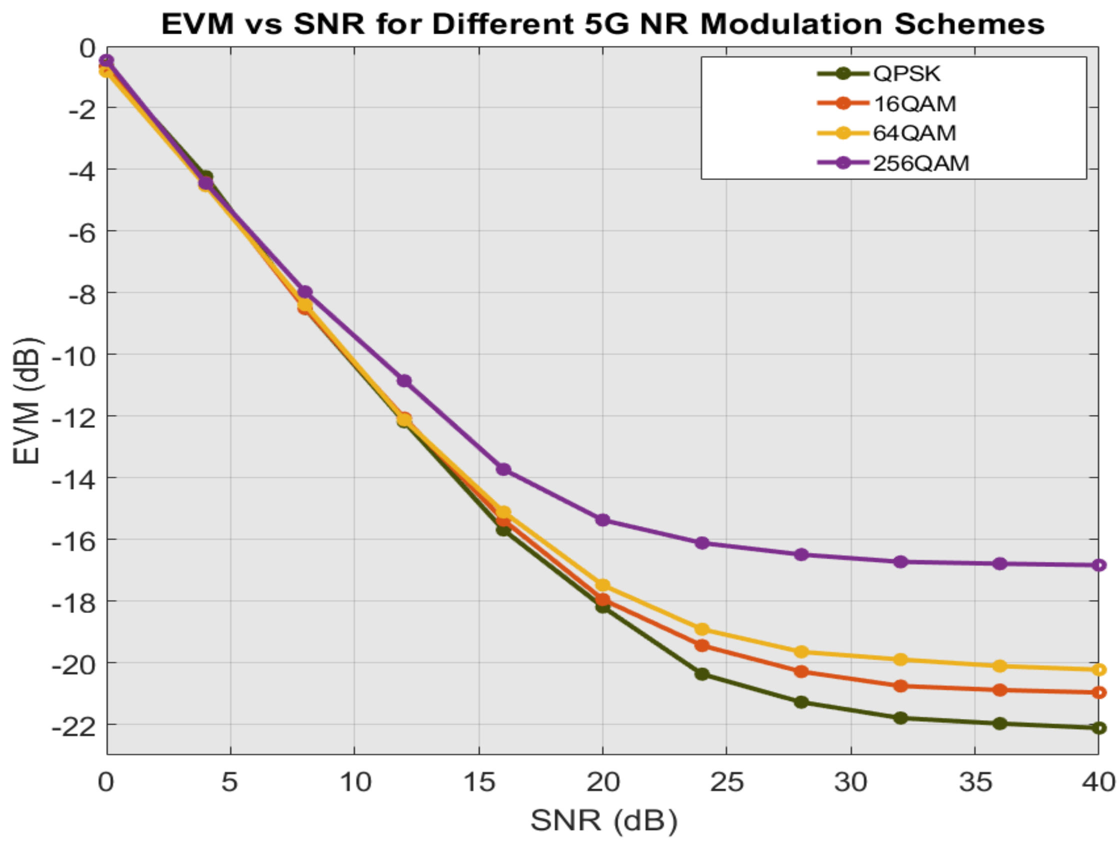

Figure 6.1: EVM vs SNR each modulation scheme.

Fig 6.1 shows a plot of Error Vector Magnitude (EVM) vs Signal-to-Noise Ratio (SNR) for different modulation schemes of a 5G NR system with two numerologies, when the symbols $X_1(k)$and $X_{2,u}(l)$ are demodulated at the receiver. From the plot, we can see that: QPSK has the best EVM performance, followed by 16QAM, 64QAM, and 256QAM. It is also observed that the EVM values decrease as SNR increases, indicating better signal quality and reduced errors. The plot also shows that EVM increases as the modulation order increases. This happens because higher-order modulation schemes are more sensitive to noise and interference. In general, the simulated 5G system EVM vs SNR curves are consistent with **3GPP standard TS 38.104** as seen in the following analysis.

For QPSK the 3GPP requirement is -15 dB (17.5% EVM) while the system simulation EVM value is around -18 dB to -20 dB, which is better than the 3GPP requirement. For 16QAM the 3GPP requirement is -18 dB (12.5% EVM) while the system gives us EVM values around -20 dB to -22 dB, which is better than the 3GPP requirement.

For 64QAM the 3GPP requirement is -22 dB (8% EVM). The system simulation gives us an EVM of around -20 dB to -22 dB, which is also around what 3GPP requires. The EVM requirement for 256QAM: is -29 dB (3.5% EVM). The system simulation gives us values between -17 dB and -21 dB, which is somewhat lower than the 3GPP requirement. If we compare these values to 3GPP's required EVM thresholds, it is evident that the system modulation schemes discussed in this paper meet the

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required EVM threshold except for 256 that is environment sensitive. Table 4(a) provides a summary of system comparison to 3GPP standards.

Table 4(a). A summary of simulated system EVM against 3GPP acceptable EVM values for the various modulation schemes.

	Modulation Scheme	EVM attained by System after Windowing	EVM standard set by 3GPP
1.	QPSK	-18 dB to -20 dB	-15 dB (17.5% EVM)
2.	16-QAM	-20 dB to -22 dB	-18 dB (12.5% EVM)
3.	64-QAM	-20 dB to -22 dB	-22 dB (8% EVM)
4.	256-QAM	-17 dB and -21 dB	-29 dB (3.5% EVM)

Comparing windowed and unwindowed EVM:

The plots below compare windowed and non-windowed system performance for the various 5G modulation schemes at the receiver. The plots in fig 6 show the effect of windowing on INI for various modulation schemes in 5G NR. Windowed simulations have much better EVM performance than the unwindowed simulations, especially at high SNR values. This is because windowing significantly reduces out-of-band emissions and interference, which consequenntly improve EVM performance. Improvement in EVM performance due to windowing may vary depending on the modulation scheme and SNR value used. This improvement may be morepronounced for higher order modulation schemes like 64QAM and 256QAM, which are sensitive to interference and noise.

EVM vs SNR performance degrades as the modulation order increases since higher-order modulation schemes get more sensitive to noise and interference, thus causing errors in the received signal.

QPSK has the best EVM vs SNR performance resulting from its robustness to noise and interference.16QAM has slightly worse performance than QPSK as a result of its higher modulation order while 64QAM has worse performance than 16QAM due to its even higher modulation order. 256QAM has the worst EVM vs SNR performance due to its highest modulation order and sensitivity to noise and interference. It is also evident that higher-order modulation schemes such as 256QAM, require higher SNR values to match the same EVM performance as lower-order modulation schemes such as QPSK.

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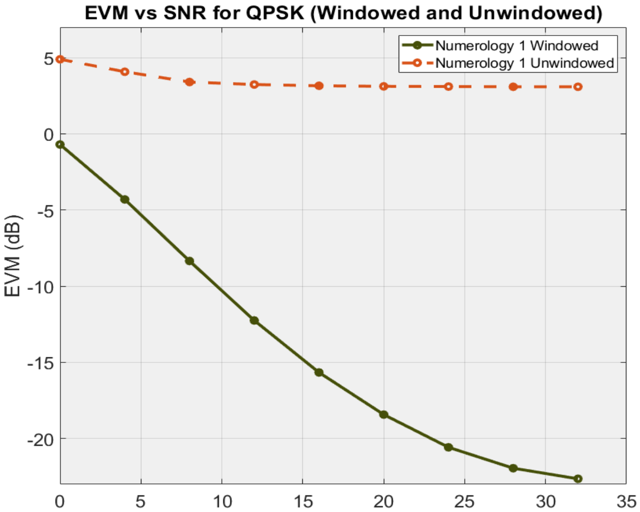

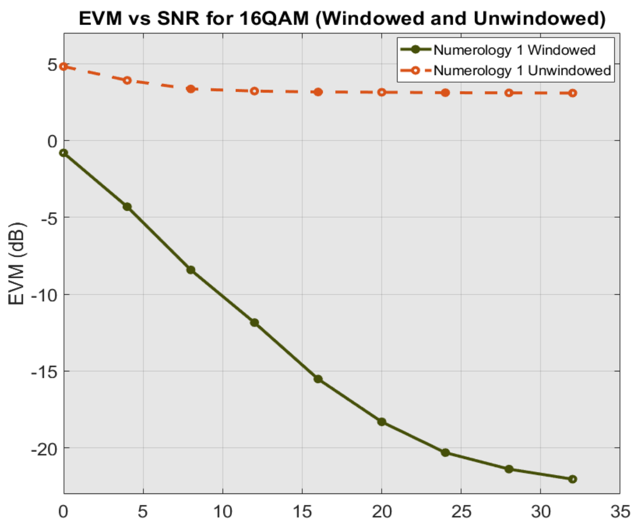

Fig6(a) Plot using QPSK

Fig 6(b) Plot using 16QAM

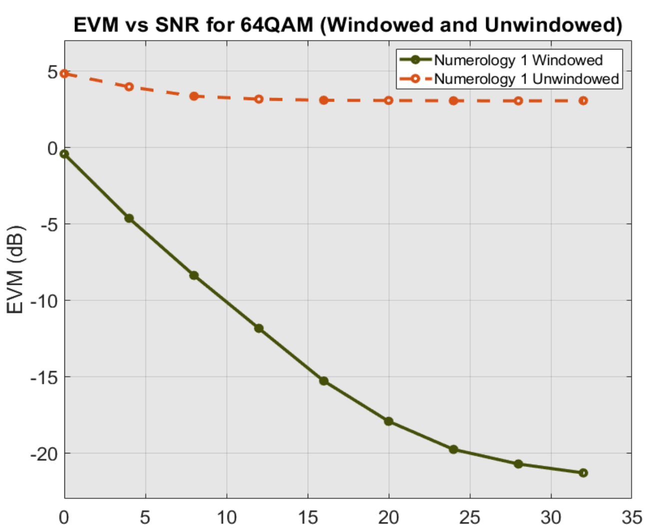

Figure 6(c): Plot using 64QAM

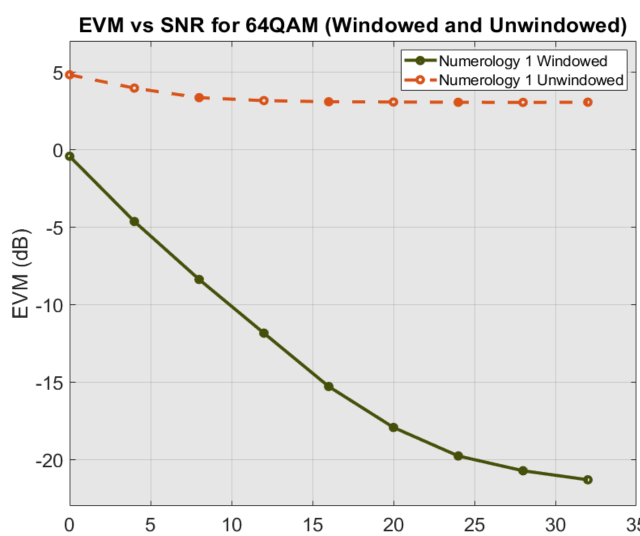

Figure 6(d): Plot using 256QAM

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5. CONCLUSION

Interference is undesirable and can distort and ruin communication systems. The simulation results obtained from using the novel pulse shaping technique discussed in this paper confirms that the system design meets the Error Vector Magnitude (EVM) performance requirements outlined in the 3GPP TS 38.104 standard for 5G NR. Notably, the simulations highlight the efficiency of windowing in reducing EVM in instances when mixed numerologies are used.

With the growing number of UEs, high throughput systems and IoTs, it is necessary to embrace the use of mixed numerologies as they support a range of services, application and users.

A good example would be one to deploy a smart city where mixed numerologies are employed to support various applications such as smart factories, public safety, and and better user experiences.

6. Appendix

Simulation Parameters:

- Number of subcarriers: 100
- Subcarrier spacing: 15 kHz (Numerology 1) and 30 kHz (Numerology 2)
- Modulation schemes: QPSK, 16QAM, 64QAM, and 256QAM
- Channel model: AWGN channel
- INI = H * P * phi * y2

Modulation Scheme | EVM Attained by System after Windowing | EVM Standard set by 3GPP

- QPSK | -18 dB to -20 dB | -15 dB (17.5% EVM)
- 16-QAM | -20 dB to -22 dB | -18 dB (12.5% EVM)
- 64-QAM | -20 dB to -22 dB | -22 dB (8% EVM)
- 256-QAM

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