Inter-Numerology Interference Analysis for 5G and Beyond

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***Abstract*—One of the defining characteristics of 5G is the flexibility it offers for supporting different services and communication scenarios. For this purpose, usage of multiple numerologies has been proposed by the 3rd Generation Partnership Project (3GPP). The flexibility provided by multi-numerology system comes at the cost of additional interference, known as inter-numerology interference (INI). This paper comprehensively explains the primary cause of INI, and then identifies and describes the factors affecting the amount of INI experienced by each numerology in the system. These factors include subcarrier spacing, number of used subcarriers, power offset, windowing operations and guard bands.**

***Index Terms*—5G New Radio, inter-numerology interference, multi-numerology systems.**

I. Introduction

5G is expected to act as a platform enabling wireless connectivity to all kinds of services. The different service classes defined for 5G include enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra-reliable and low latency communications (URLLC) [1]. These scenarios have their own specific demands causing 5G to have a wide range of requirements which dictates the need for a high degree of flexibility in the radio and network designs [2].

One of the steps taken towards achieving the required flexibility in 5G systems is the introduction of multi-numerology concept under the umbrella of 5G New Radio (5G-NR). The term numerology in 5G refers to a set of parameters like subcarrier spacing, symbol length and cyclic prefix in Orthogonal Frequency Division Multiplexing (OFDM). The diverse requirements for the different service classes in 5G cannot be supported by the uniform time/frequency resource allocation provided by 4G Long Term Evolution (LTE). This renders the use of multiple numerologies imperative in providing the flexibility required for optimized individual services in 5G. Table I provides a summary of the properties of different NR numerologies as presented in [3] and [4]. Usage of multiple numerologies significantly affects the performance of the system. These effects include spectral efficiency, scheduling complexity, computational complexity, and signaling overhead [5]. Employing multiple numerologies also introduces non-orthogonality into the system, causing interference between users belonging to different numerologies.

Interference in multi-numerology systems, also called inter-numerology interference (INI) has garnered increasing attention in recent times. An INI model is presented in [6] which describes INI as a function of frequency response of the interfering subcarrier, frequency offset between the interfering and the victim subcarriers, and the overlap in transmitter and receiver windows of the interferer and victim, respectively. Though detailed, this model is limited to windowed-OFDM system. Similarly, [7] uses adaptive windowing to minimize the interference and [8] tries to optimize the guard band and time keeping in view the power offset and requirements of the users. While these works have shed some light on the phenomenon of INI, a study which accounts for and individually explains all the factors contributing to INI is still lacking. Such a study is imperative as it would enable the development of efficient interference cancellation techniques for multi-numerology systems in 5G and beyond. In this paper, we attempt to address the above mentioned gap in the present literature by contributing the following:

- An extensive discussion on synchronization and orthogonality issues of multi-numerology systems is provided.
- The factors that affect INI are identified and their effects are explained in light of simulation results.
- This work also presents research opportunities regarding interference in multi-numerology systems.

The rest of the paper is organized as follows: Section II describes the system model used in this study and the assumptions that form its basis. Section III discusses the effects of multiple numerologies from orthogonality and synchronization perspective. This is followed by highlighting the parameters that govern INI, accompanied by simulation results and intuitive interpretation of each of them in Section IV. Section V summarizes our findings and indicates the possible future direction of research.

TABLE I: Numerology structures for data channels in 5G [3]

Δf (kHz)	T^{CP} (µs)	Slot Duration (ms)
15	4.76	1
30	2.38	0.5
60	1.19 | 4.17	0.25
120	0.6	0.125

II. System Model and Assumptions

Multi-numerology is a key concept of the 5G-NR frame structure. Our system model considers two numerologies

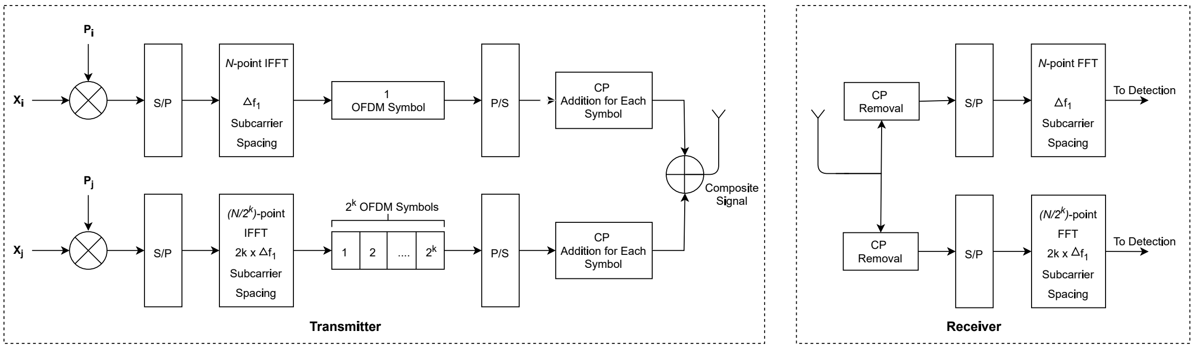


Fig. 1: Block diagram of the conventional multi-numerology implementation [9]

which is the base case for multi-numerology systems. It can be generalized to any number of numerologies by considering one pair at a time. Each numerology block consists of multiple user equipments (UEs) which are non-overlapping in the frequency domain. It is assumed that the UEs have gone through a numerology selection process based upon the user and service requirements which may lead to different power levels amongst the users. This may be achieved by algorithms such as the one presented in [5]. In our model each numerology is assumed to cater to three users where the users of a particular numerology occupy equal bandwidth. The data generated consists of binary phase shift keying (BPSK) symbols. Since choice of modulation scheme is not our primary concern for the time being, we have limited ourselves to BPSK because of its simplicity. Fig. 1 shows the block diagram of the multi-numerology implementation used in this paper. X_i and X_j are complex modulated symbols for users i and j of numerology-1 (NUM_1) and numerology-2 (NUM_2), respectively. The users indices are defined as $i = 1, 2, ..., Q$ and $j = 1, 2, ..., R$, where Q and R are number of users scheduled in the corresponding numerologies. P_i and P_j are power ratios for i^{th} and j^{th} users in each numerology. The first numerology employs subcarrier spacing Δf_1 and N-point inverse Fourier transform (IFFT) while the second numerology's subcarrier spacing and IFFT size are scaled by a factor of 2^k and $1/2^k$ respectively, where k is a positive integer. Similarly, the number of OFDM symbols for the second numerology is upscaled by 2^k as compared to first numerology. The IFFT operation is followed by addition of cyclic prefix (CP) with a certain ratio, CP_R, at the beginning of each symbol. In this study, we have narrowed down our focus on the factors affecting INI without considering noise or a wireless channel. The receiver removes CP before taking N-point and $N/2^k$-point Fast Fourier Transform (FFT) for first and second numerology, respectively. We have employed Monte Carlo method to observe and analyze the interference statistics for each used subcarrier over 500 independent trials for each scenario discussed in following sections.

III. Inter Numerology Synchronization and Orthogonality

Symbol lengths among numerologies tend to vary due to the usage of different subcarrier spacing (ScS) which in turn makes the whole system unsynchronized in the time domain. Difficulty in achieving synchronization of OFDM symbols of different numerologies is one of the major drawbacks of multi-numerology systems. However, if ScS of one numerology is integral multiple of the ScS of the other numerology, synchronization can be achieved over the so called least common multiplier (LCM) symbol duration [10]. For instance, if ScS of NUM_1, Δf_1, and that of NUM_2, Δf_2, are such that $\Delta f_2 = 2^k \cdot \Delta f_1$, then, 2^k symbols of NUM_2 can be perfectly synchronized with 1 symbol of NUM_1, i.e $2^k \cdot T_2 = T_1$, where T is the symbol duration. In this case, T_1 is the LCM symbol duration. Synchronization over LCM symbol duration can be achieved in two ways:

By using individual CPs: This is the conventional way of creating a synchronous composite signal of NUM_1 and NUM_2 in 5G where CPs are added to each symbols of each numerology before the creation of the composite signal, as shown in Fig. 2(a). In this case, duration T of the synchronous symbols can be written as

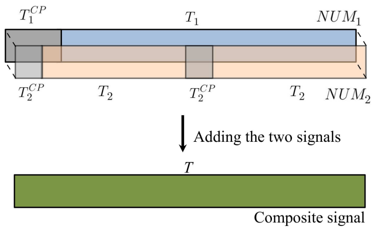
$$T = T_1 + T_1^{CP} = 2^k \cdot (T_2 + T_2^{CP}). \quad (1)$$

By using common CP: In this approach, multi symbols encapsulated OFDM (MSE-OFDM) is adopted in the numerology with shorter symbol duration (i.e NUM_2 in our case), which allows one CP to be used for 2^k concatenated OFDM symbols [11], [12]. CP size of NUM_2, $T_2^{'CP}$, is then determined from the resultant length of the concatenated 2^k symbols, which makes $T_2^{'CP} = 2^k \cdot T_2^{CP}$. In this case, a common CP can be used for both numerologies as shown in [13]. The common CP of length $T_c^{CP} = T_1^{CP} = T_2^{'CP}$, is appended after creation of the composite signal of NUM_1 and NUM_2 as show in Fig. 2(b). The duration T in this case is given by

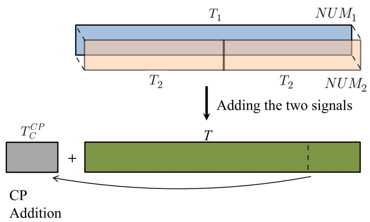
$$T = T_1 + T_c^{CP} = 2^k \cdot T_2 + T_c^{CP}. \quad (2)$$

However, due to the adoption of MSE-OFDM in NUM_2, extra FFT and IFFT blocks are required at NUM_2 receiver to facilitate proper equalization and data detection as discussed in [11] and [12].

To understand how INI affects multi-numerology signal synchronized by either of the above discussed approaches, let us first understand the coexistence of NUM_1 and NUM_2 subcarriers at the transmitter side before creation of the composite signal. We observe from Fig. 3 that NUM_1 causes



(a) Synchronization with individual CP



(b) Synchronization with common CP

Fig. 2: Synchronizing Symbols of NUM_1 and NUM_2 for k = 1

no interference at any of the NUM_2 subcarriers, while NUM_2 imparts some interference on one out of every two subcarriers of NUM_1. Number of NUM_1 subcarriers affected by INI from NUM_2 depends on the ratio $\Delta f_1/\Delta f_2$ of the two numerologies.

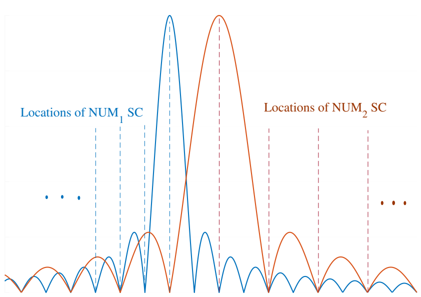
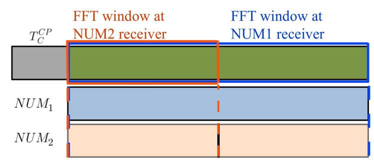


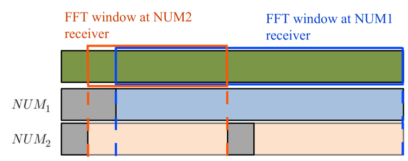
Fig. 3: Multiplexed subcarriers of NUM_1 (Δf_1 = 15 kHz) and NUM_2 (Δf_2 = 30 kHz) at the transmitter (before composite signal) with guard band = Δf_1.

At the receiver, users of each numerology concentrate on capturing and decoding their own symbols from the composite signal depending on the numerology specification (Fig. 4).

Common CP case: Fig. 4(a) summarizes what happens at NUM_1 and NUM_2 receivers when common CP is used for synchronization. FFT window at NUM_1 receiver captures a full NUM_1 symbol from the composite signal as well as two full symbols of NUM_2 as shown in Fig. 4(a) (blue window). The N-point FFT (corresponding to $2^k * (N/2^k)$-point FFT for NUM_2) at NUM_1 receiver does not disturb NUM_2 samples present in the composite signal (i.e NUM_2 subcarriers do not lose their orthogonality due to FFT process at NUM_1 receiver). Therefore NUM_2 subcarriers do not create any extra interference to NUM_1 at the receiver. On the other hand, when FFT window at NUM_2 receiver captures one symbol of NUM_2 from the composite signal, it also captures a "portion" of NUM_1 symbol (Fig. 4(a) (red window)). Thus, the FFT operation at NUM_2 receiver causes disturbance on the NUM_1 samples contained in the composite signal (i.e loss of orthogonality between subcarriers of NUM_1 at NUM_2 receiver), leading to interference from sidelobes of NUM_1 to each subcarrier of NUM_2. The zero interference from NUM_1 to each location of NUM_2 subcarriers (shown in Fig. 3) will no longer be the case. Interference analysis at the receiver was done and error vector magnitude (EVM) of each subcarrier of NUM_1 and NUM_2 was observed (Fig. 5). From Fig. 5(a), for common CP case, we observe that one out of every two subcarriers of NUM_1 has zero EVM. This shows that interference on NUM_1 is the only one that was created at the transmitter (Fig. 3) while all the subcarriers of NUM_2 are affected by INI even though they were interference-free at the transmitter.



(a) Common CP case



(b) Individual CP case

Fig. 4: Illustration of FFT-window at the receiver of each numerology (for k = 1)

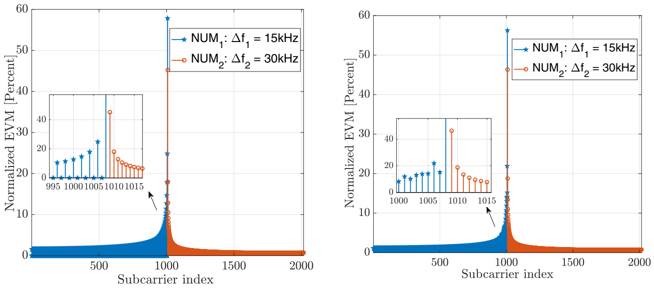
Individual CP case: From Fig. 4(b), we observe that FFT window at the receiver of each numerology captures a portion of the symbol (not the full symbol) of the other numerology contained in the composite signal. Therefore FFT process at NUM_1 receiver causes interference from NUM_2 to all subcarriers of NUM_1, and FFT process at NUM_2 receiver causes interference from NUM_1 to NUM_2. This is revealed by Fig. 5(b) where all subcarriers for each numerology are in error due to INI.

According to the above discussion, we can say that the common CP case renders the multi-numerology system partially orthogonal while in the individual CP case, the system is totally non-orthogonal. However, the rest of simulations results presented in this study are based on the conventional individual CP case.

IV. Factors Affecting INI

A. *Inter-Numerology Subcarrier Spacing Offset*

Subcarrier spacing (ScS), Δf, is one of the most crucial parameters in the multi-numerology concept. According to 3GPP 5G specification [3], four options of Δf are provided as shown in Table I. Therefore, a numerology is free to utilize any of the standardized Δf that suits its requirement. In this section we investigate how the choice of Δf among coexisting

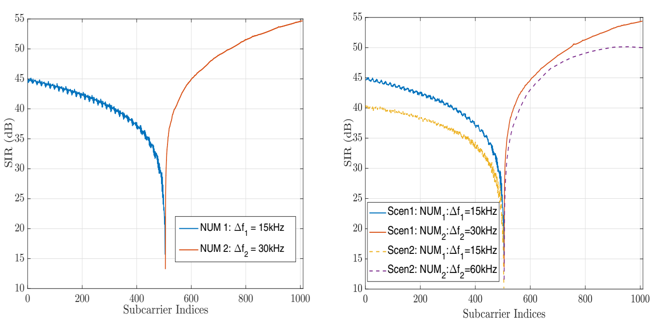


(a) Common CP case (b) Individual CP case

Fig. 5: EVM plots for the two synchronization techniques

numerologies impacts the performance of multi-numerology systems.

Signal to interference ratio (SIR) performances of two adjacent numerologies, NUM_1 with Δf_1 = 15kHz, and NUM_2 with Δf_2 = 30kHz are observed. While all other parameters are set the same for both numerologies, NUM_2 exhibits better performance than NUM_1 (Fig. 6(a)). This result is quite expected because, as explained in the previous section (Section III), it is evident that, for individual CP case, NUM_1 is a victim of interference from NUM_2 at both, transmitter and receiver, while NUM_2 receives interference from NUM_1 only at the receiver. That is to say, numerology with small Δf is more exposed to INI than the one with larger Δf.



(a) Performance of numerologies with small and large subcarriers (b) Scenarios with different subcarrier spacing offsets between numerologies

Fig. 6: SIR performances of the numerologies as a function of subcarrier spacing

Another interesting observation regarding subcarrier spacing in the multi-numerology systems is that the SIR performance of each numerology degrades as the subcarrier spacing offset (SSO) (i.e Δf_2 - Δf_1) between them increases (Fig. 6(b)). This observation again can be linked to the discussion presented in Section III. In Fig. 6(b), two scenarios are presented: Scenario-1 with $\Delta f_1/\Delta f_2$ = 15kHz/30kHz, and Scenario-2 with $\Delta f_1/\Delta f_2$ = 15kHz/60kHz.

Numerology-1: In Scenario-1, the ratio $\Delta f_2/\Delta f_1$ = 2. Recalling our discussion in Section III, only one out of two subcarriers of NUM_1 experiences interference from NUM_2 at the transmitter, that is, only half of all the subcarriers of NUM_1 are affected by INI. However, in Scenario-2, the ratio $\Delta f_2/\Delta f_1$ = 4, which causes three out of four subcarriers of NUM_1 to be affected by INI. Therefore, three quarters of all subcarriers of NUM_1 are experiencing interference from NUM_2, leading to poorer SIR performance compared to Scenario-1.

Numerology-2: The observed degradation on the SIR performance of NUM_2 can be understood by considering the signal processing at the receiver of NUM_2. FFT window at the receiver of NUM_2 captures half of the symbol duration of NUM_1 from the composite signal in Scenario-1, and only a quarter of it in Scenario-2. Therefore, during FFT operation at the receiver of NUM_2, Scenario-2 causes more disturbance on the samples of NUM_1 (and hence more severe loss of orthogonality between its subcarriers) compared to Scenario-1. This imparts higher INI from NUM_1 to NUM_2 in Scenario-2 compared to Scenario-1.

B. Number of Subcarriers

Throughput of a particular numerology can be increased by increasing its number of subcarriers. In single numerology systems larger number of subcarriers leads to the growth of peak-to-average power ratio (PAPR) problem [14]. However, in multi-numerology systems, apart from PAPR issues, different number of subcarriers used in each numerology can be evaluated to have an impact on INI as well. Increased number of subcarriers in one numerology corresponds to the proportional growth of its out of band emission (OOBE) which causes more interference to the adjacent numerology. To investigate the effect of the number of subcarriers on multi numerology system, we considered two simple scenarios shown in Fig. 7. Each user (in both numerologies) has 336 subcarriers in Scenario-1 and, number of Subcarriers for each user of NUM_2 is halved in Scenario-2.

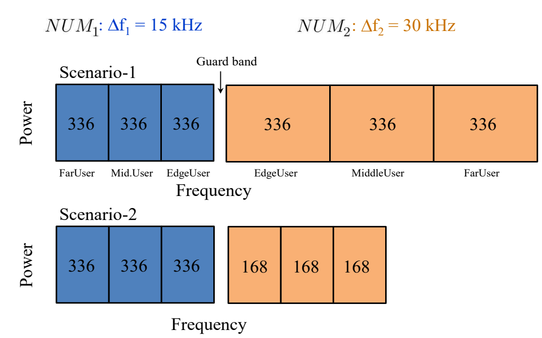
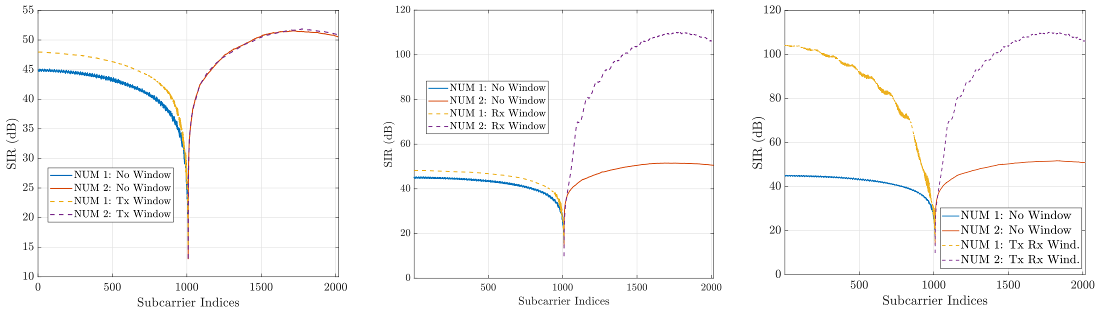


Fig. 7: Scenarios for number of subcarriers

Fig. 8 summarizes SIR performances for the two investigated scenarios. Performances of NUM_1 users improve in Scenario-2 due to the less INI they receive from NUM_2 as a result of the reduced number of subcarriers in NUM_2. Improvement in SIRs of middle and far users is higher than that of the edge user because of their larger spectral distance from NUM_2. The larger the distance of the user from the interfering numerology, the lesser the INI it receives. On the other hand, performance of each user of NUM_2 is degraded in Scenario-2. This is because, when the number of the subcarriers of each user is reduced, the users of NUM_2 get closer to NUM_1, exposing them to higher interference from it.



(a) Tx Windowing (b) Rx Windowing (c) Tx Rx Windowing

Fig. 10: SIR performance with windowing operation (roll off factor = 0.5)

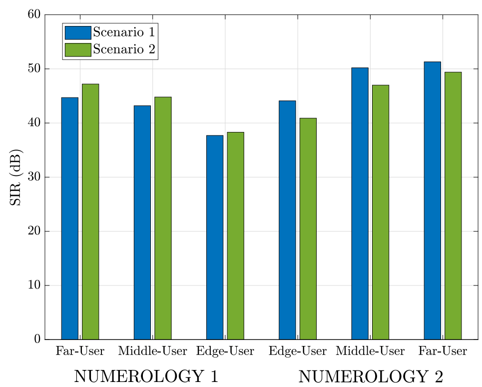
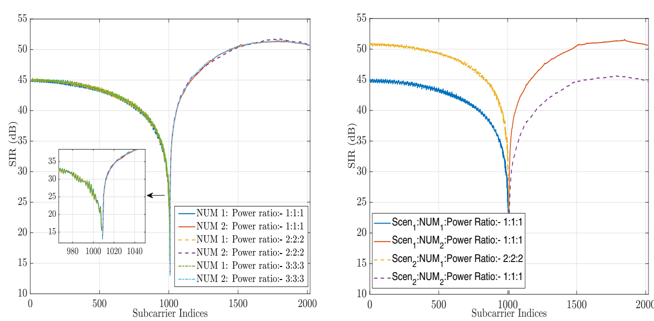


Fig. 8: SIR performance for Scenario-1 and 2, with different number of subcarriers



(a) No power offset between numerologies (b) With power offset between numerologies

Fig. 9: SIR performance of the two numerologies as a function of their power offsets.

C. Power Offset

Users can have different power requirements depending on their channel conditions and application. Power difference among the users utilizing the same numerology does not cause any interference since the orthogonality condition is maintained. However, the power offset (P_{off}) between users in two adjacent numerologies significantly contributes to the amount of INI experienced by each numerology. To illustrate this fact, let us consider an ideal case with two numerologies. In the first scenario, all users in both numerologies are assigned the same power such that P_{off} in the whole system is zero. In this case the SIR performance of each numerology remains the same regardless the actual power level assigned to the users (as long as $P_{off} = 0$) as depicted in Fig. 9(a). This is because, in this case, the amount of interference imposed on the users in the victim numerology depends solely on the spectral distance of each user from the interfering numerology.

In the second scenario, we introduce power offset between the two numerologies. Users of the same numerology are scheduled with the same power but the power levels in the two numerologies are different. We consider the result of the first scenario (with zero P_{off}) as a baseline for performance comparison. Fig. 9(b) shows that, with the power offset of 3dB between the two numerologies, the performance of NUM_2 is degraded by about 6dB.

The two scenarios discussed above give an idea about how critical the power offset issue can be in the performance of the multi-numerology systems. In more realistic scenarios, users are often expected to have different power requirements (even if they utilize the same numerology). Now, when power is assigned to each user according to its own need, power offset between numerologies will be random (i.e users in the victim numerology will have different power offsets with each user in the interfering numerology). In such cases, amount of INI experienced by each user in the victim numerology depends not only on the spectral distance of that user from the interfering numerology but also its power offset with each user of the interfering numerology. Proper scheduling technique would be required to minimize the power offsets and optimize performance of each user in the multi-numerology systems [15].

D. Windowing

High out of band emission of the OFDM waveform can be reduced by smoothing the edges of its rectangular pulse. One way of achieving this is through a windowing process where each OFDM symbol is multiplied with a smooth function, such as raised cosine. Windowing can be applied either at the transmitter or receiver, or both. Transmitter windowing reduces the possible spectral leakage to the adjacent numerology whereas receiver windowing provides a better interference rejection at the receiver [16]. Now, with reference to our discussion in Section III, for the two numerologies NUM_1, and NUM_2

shown in Fig. 3, NUM_1 receives INI from NUM_2 at both, transmitter and receiver. Therefore, applying both, transmitter windowing on NUM_2 and receiver windowing on NUM_1 should significantly improve SIR performance of NUM_1. Also, NUM_2 receives INI from NUM_1 only at the receiver. Therefore, receiver windowing on NUM_2 is expected to be sufficient enough to enhance SIR performance of NUM_2. This intuition agrees well with the simulation results presented in Fig. 10.

Simulation was conducted for NUM_1 with Δf_1 = 15 kHz and NUM_2 with Δf_2 = 30 kHz, and the raised cosine window was employed by adopting the steps discussed in [16]. Fig. 10(a) shows that transmitter windowing on NUM_1 does not cause any significant improvement on performance of NUM_2 since power leakage from NUM_1 to the subcarriers of NUM_2 at the transmitter is already zero (see Fig. 3). However, transmitter windowing on NUM_2 enhances the SIR performance of NUM_1 to some extent. Fig. 10(b) reveals the effect of receiver windowing when applied alone. Again, receiver windowing on NUM_1 only slightly improves its performance, while outstanding performance is achieved on NUM_2 with receiver windowing for the same roll off factor. Finally, Fig. 10(c) shows that combination of transmitter and receiver windowing significantly improves performance of NUM_1 compared to the case when they are applied alone. For NUM_2, the SIR performance with transmitter and receiver windowing is similar to the case when only receiver windowing is applied. In summary, better SIR performance of the numerology with small ScS can be achieved with both, transmitter windowing on the interfering numerology as well as receiver windowing at its own receiver. But for numerology with larger ScS, only receiver windowing can be enough.

E. Guard Band

Employing guard bands (GBs) between adjacent numerologies is another way of reducing the effect of INI at the expense of spectral efficiency of the system. Our simulation result for two numerologies NUM_1 with Δf_1 = 15kHz, and NUM_2 with Δf_2 = 30kHz shows that GB is effective in improving SIR performance of the edge subcarriers only. No significant improvement is observed for subcarriers far from the edges as shown in Fig. 11.

V. Conclusion

Next generations of wireless systems are geared towards ultimate flexibility in different aspects. An introduction of multi-numerology concept as a part of this flexibility has brought new problems, such as INI, that require special attention from researchers. This paper has investigated the INI problem and intuitively explained its underlying causes from signal processing point of view at the transmitter and receiver. The paper goes further and investigates the performance of multi-numerology system when coexisting numerologies flexibly adopt different parameters such as subcarrier spacing, number of subcarriers, power, etc. All the relationships observed in this study are supported by simulation results, however it will be extended to provide a thorough mathematical analysis of the INI and the factors affecting it.

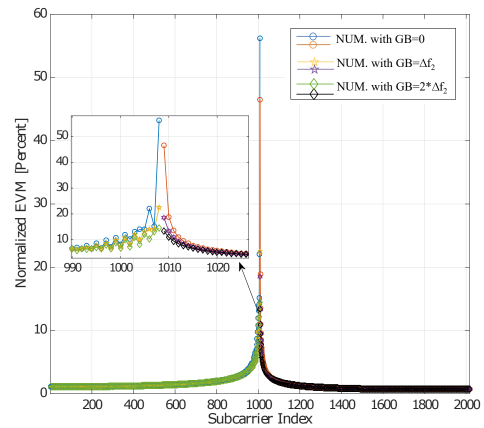


Fig. 11: EVM plot for different amounts of guard band between numerologies

References

[1] 3rd Generation Partnership Project (3GPP), "Study on scenarios and requirements for next generation access technologies; (release 14)," Technical Specification 38.913, ver 14.3.0, Aug. 2017.

[2] E. Dahlman, S. Parkvall, and J. Skold, *4G, LTE-advanced Pro and the Road to 5G*. Academic Press, 2016.

[3] 3rd Generation Partnership Project (3GPP), "NR; Physical channels and modulation (Release 15) ," Technical Specification 38.211, ver 15.1.0, Apr. 2018.

[4] ——, "NR; Base Station (BS) radio transmission and reception (Release 15) ," Technical Specification 38.104, ver 15.1.0, Apr. 2018.

[5] A. Yazar and H. Arslan, "A Flexibility Metric and Optimization Methods for Mixed Numerologies in 5G and Beyond," *IEEE Access*, vol. 6, pp. 3755–3764, 2018.

[6] X. Zhang, L. Zhang, P. Xiao, D. Ma, J. Wei, and Y. Xin, "Mixed Numerologies Interference Analysis and Inter-Numerology Interference Cancellation for Windowed OFDM Systems," *IEEE Transactions on Vehicular Technology*, 2018.

[7] B. Peköz, S. Köse, and H. Arslan, "Adaptive Windowing of Insufficient CP for Joint Minimization of ISI and ACI Beyond 5G," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2017 IEEE 28th Annual International Symposium on*. IEEE, 2017, pp. 1–5.

[8] A. F. Demir and H. Arslan, "The Impact of Adaptive Guards for 5G and Beyond," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2017 IEEE 28th Annual International Symposium on*. IEEE, 2017, pp. 1–5.

[9] A. Yazar, B. Peköz, and H. Arslan, "Flexible Multi-Numerology Systems for 5G New Radio," *arXiv preprint arXiv:1805.02842*, 2018.

[10] L. Zhang, A. Ijaz, P. Xiao, A. Quddus, and R. Tafazolli, "Subband Filtered Multi-carrier Systems for Multi-service Wireless Communications," *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 1893–1907, 2017.

[11] J.-Y. Chouinard, X. Wang, and Y. Wu, "MSE-OFDM: A new OFDM transmission technique with improved system performance," in *Acoustics, Speech, and Signal Processing, 2005. Proceedings.(ICASSP'05). IEEE International Conference on*, vol. 3. IEEE, 2005, pp. iii–865.

[12] M. Nemati and H. Arslan, "Low ICI Symbol Boundary Alignment for 5G Numerology Design," *IEEE Access*, vol. 6, pp. 2356–2366, 2018.

[13] A. T. Abusabah and H. Arslan, "NOMA for Multinumerology OFDM Systems," *Wireless Communications and Mobile Computing*, vol. 2018, 2018.

[14] H. Ochiai and H. Imai, "On the Distribution of the Peak-to-average Power Ratio in OFDM Signals," *IEEE transactions on communications*, vol. 49, no. 2, pp. 282–289, 2001.

[15] A. Yazar and H. Arslan, "Fairness-Aware Scheduling in Multi-Numerology Based 5G New Radio," *arXiv preprint arXiv:1806.04072*, 2018.

[16] E. Bala, J. Li, and R. Yang, "Shaping Spectral Leakage: A Novel Low-complexity Transceiver Architecture for Cognitive Radio," *IEEE Vehicular Technology Magazine*, vol. 8, no. 3, pp. 38–46, 2013.