Guard Band Reduction for 5G and Beyond Multiple Numerologies

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***Abstract*— The existence of inter-numerology interference (INI) is a major drawback for the flexible multi-numerology frame structure proposed for the upcoming fifth generation New Radio (5G-NR). Insertion of a guard band (GB) between adjacent numerologies has been widely used in the literature as one of the effective ways to reduce the INI. However, the conventional way of implementing GBs is inefficient in terms of spectrum usage. In this letter, we exploit the inherent INI characteristics of the scalable multi-numerology structure to propose a more spectrally efficient way of implementing GBs. It is shown through simulations that the proposed GB insertion technique enhances the GB utilization up to 50% while achieving the same bit error rate performance as the conventionally implemented GB.**

***Index Terms*— 5G new radio, guard band, INI, mixed numerologies, spectral efficiency.**

I. INTRODUCTION

FIFTH generation (5G) of wireless communication networks has changed the data-centric approach of the legacy mobile generations to a service-based wireless system in order to support several use-cases with diverse requirements [1]. The prospective use-cases have been categorized into three major service groups: enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (URLLC), and massive machine type communications (mMTC). eMBB services require high throughput and enhanced spectral efficiency, URLLC services necessitate high reliability and low latency, and mMTC services require low complexity, high energy efficiency, and extended coverage. In order to support these diverse requirements, the use of multiple numerologies has been standardised as a flexible radio access technology [2].

The introduction of mixed numerologies for the 5G New Radio (5GNR) has enhanced the degree of flexibility required to serve for a wide variety of new 5G applications. However, this flexibility brought by the mixed numerologies comes at the cost of a new form of interference known as inter-numerology interference (INI) [3]. When the numerologies with different subcarrier spacings (ScSs) are allocated adjacently over a spectrum, INI comes into the picture as a result of the non-orthogonality, unlike in Long Term Evolution (LTE) where only one numerology type is used and orthogonality is maintained. As any other form of interference, if not handled properly, INI can significantly degrade system performance especially when there is power imbalance between these subcarriers that belong to different numerologies. Moreover, the characteristics of the INI has been analyzed for different cyclic prefix (CP) configurations [4].

In order to control and reduce the INI, windowing, filtering, insertion of a guard band (GB) between interfering subbands, intelligent resource allocation and scheduling are used in the literature [5]. Insertion of GBs between adjacent subbands utilizing different numerologies is the conventional way of minimizing the effect of INI in the system. However, it reduces the spectral efficiency of the system [6]. Other alternative techniques like windowing and filtering [3] and [7] are not always possible to fully handle the interference in 5GNR, and even when possible, a GB is still required to have a sufficiently good link performance that supports high order modulation in multi-numerology systems [8]. Therefore, in most cases the usage of GBs is inevitable. Consequently, in order to simultaneously minimize the effect of INI and maintain an efficient spectrum utilization, an optimum way of implementing GBs is needed [9].

In this letter, a new and spectrally efficient way of GB implementation technique for 5G and beyond multiple numerologies is proposed. Conventionally, a GB is implemented as a set of unused contiguous subcarriers between adjacent numerologies without considering the INI characteristics. The proposed GB approach takes advantage of INI characteristics to reduce the amount of spectrum wasted. With the scalable numerology structure, the INI generated within the system is not random. It is observed that this INI is a well structured form of interference exhibiting a peculiar pattern that can be exploited to redesign the GB structure, as explained in the next sections. The proposed technique for GB design provides better spectrum utilization for multi-numerology systems. Furthermore, it is applied for both conventional and common CP because these methods impact the INI differently and thus the performance of proposed technique differs.

The rest of the letter is organized as follows. Section II describes the system model of the proposed technique. Section III provides detailed explanation of the proposed GB approach and Section IV presents simulation results and discussion of the observed performance. Section V finally concludes the letter.

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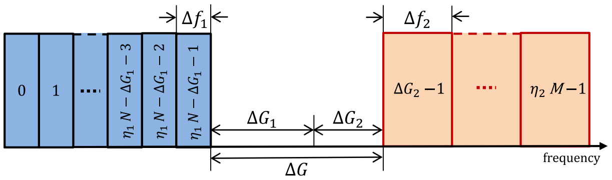


Fig. 1. Conventional guard band.

II. System Model

Consider two users, U_n and U_w with different requirements, adjacently sharing a given bandwidth B. The users are assumed to share the bandwidth with the partitions of η_1 and η_2 such that $\eta_1 + \eta_2 = 1$ as shown in Fig. 1. U_n utilizes a numerology with the narrow subcarrier spacing (ScS) of Δf_1 while U_w employs a numerology with relatively wider ScS of Δf_2 where $\Delta f_2/\Delta f_1 = Q$. As the standardized ScS for multi-numerology systems [2], the values of Δf_1 and Δf_2 can be $15 \cdot 2^z$ kHz where z is an integer value. Note that $Q = 1$ refers to the scenario when the two users are utilizing the same numerology, as in LTE.

In Fig. 1, N and M are inverse fast Fourier transform (IFFT)/FFT sizes of U_n and U_w respectively where $N = Q \cdot M$. In general, both users leave a number of unused subcarriers at the edges of the subbands to guard themselves and the adjacent user from the INI. The size of the required GB is usually determined by a number of factors such as the power offset between adjacent users, the used filter and window type, and the desired signal to interference ratio (SIR) level. Let ΔG_1 and ΔG_2 be the guards allocated in the subband of each user. ΔG is the effective GB given as $\Delta G_1 + \Delta G_2$.

Hence, at the transmitter, the symbol blocks of U_n and U_w without considering GB are generated as

$$\mathbf{X}_n = [X_n(0), X_n(1), \ldots, X_n(\eta_1 N - 1), 0 \ldots, 0]_{1\times N} \quad (1)$$

and

$$\mathbf{X}_w = [0, \ldots, 0, X_w(0), X_w(1), \ldots, X_w(\eta_2 M - 1)]_{1\times M}, \quad (2)$$

where $X_n(k)$ and $X_w(l)$ are the M-ary modulated symbols on the k^{th} and l^{th} subcarrier indices with unit power, respectively. Then, N-point and M-point IFFT operations are performed and the CPs are separately added to the time domain signals of U_n and U_w respectively. These signals are combined and transmitted over a flat fading channel. After the CP removal and N-point FFT operation, the received signal of U_n for downlink (DL) transmission at the frequency domain can be expressed as

$$Y_n(k) = X_n(k)H(k) + INI_n(k)\acute{H}(k) + W(k), \quad (3)$$

where $H(k)$ and $\acute{H}(k)$ are the channel samples with the distribution of $\mathcal{CN}(0,1)$ for Rayleigh fading and $W(k)$ is the noise sample with the distribution of $\mathcal{CN}(0, N_0)$. Here, $INI_n(k)$ represents the total interference on the k^{th} subcarrier that is caused by the subcarriers of U_w. At the DL transmission, $H(k)$ and $\hat{H}(k)$ have the same channel sample due to the combination of the signals before the channel. Also, the received signal of U_w can be written similarly to (3). Lastly, to demodulate the symbols, one-tap frequency domain equalization is deployed.

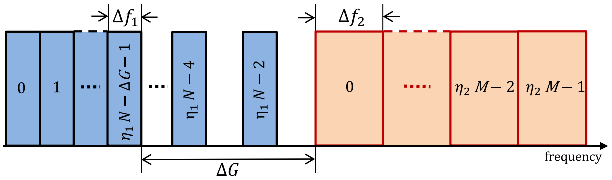


Fig. 2. Proposed guard band.

III. Proposed Guard Band Technique

For the mixed numerologies, a GB is conventionally inserted between subbands of the different numerologies to reduce the effects of the INI as shown in Fig. 1. With the proposed technique, this GB is utilized further thanks to exploiting the characteristics of the INI as illustrated in Fig. 2. For this, the placement of the subcarriers in the ΔG region is performed as

$$X_{\mathrm{n}}^{\mathrm{GB}}(k) = \begin{cases} X_{\mathrm{n}}^{\mathrm{GB}}(k), & \{\eta_1 N - \Delta G \leq k \leq \eta_1 N - 1 : \frac{k}{Q} \in \mathbb{Z}\} \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where $X_n^{GB}(k)$ is the M-ary modulated symbol of U_n to be carried by k^{th} subcarrier.

Referring to the INI analysis presented in [3] and [4] without considering the channel, the interference power on the subcarrier of U_w at p index is given as

$$I_w(p) = \frac{1}{N \cdot M} \sum_{k=0}^{\eta_1 N - 1} \frac{\rho_n(k) \left| \sin\left[\left(\frac{\pi}{Q}(k-p) \right) \right] \right|^2}{\left| \sin\left[\frac{\pi}{N}(k - p - \eta_1 N) \right] \right|^2},$$
$$\text{for} \quad \{0 \leq p \leq \eta_2 N - 1 : p/Q \in \mathbb{Z}\}, \quad (5)$$

where $\rho_n(k)$ is the k^{th} subcarrier power of the interfering numerology (i.e., U_n). Here, the relationship between the l and p indices is $l = p/Q$. The term $k - p$ in (5) is the spectral distance between the interfering subcarrier at k and the victim subcarrier at p. With further examination of (5), it can be observed that for some values of k such that $k/Q \in \mathbb{Z}$, the term $\sin(\pi(k-p)/Q)$ is zero. This means that the U_n subcarriers occupying these particular indices contribute zero interference to the total INI experienced by the victim subcarrier at p. Therefore, some subcarrier indices within the GB can be utilized by U_n subcarriers without affecting the SIR performance of U_w. Here, the interference power of U_n on the k^{th} subcarrier can be obtained as

$$I_n(k) = |INI_n(k)|^2 = \frac{1}{N \cdot M} \sum_{p=0}^{\eta_2 N - 1} \rho_w(p) \Psi(p,k), \quad (6)$$

where

$$\Psi(p,k) = \frac{\left| \sin\left[\frac{\pi}{Q}\left(1 + (1-Q)C_p\right)(p-k) \right] \right|^2}{\left| \sin\left[\frac{\pi}{N}(p - k + \eta_1 N) \right] \right|^2} + (Q-1) \frac{\left| \sin\left[\frac{\pi}{Q}\left(1 + C_p\right)(p-k) \right] \right|^2}{\left| \sin\left[\frac{\pi}{N}(p - k + \eta_1 N) \right] \right|^2}. \quad (7)$$

The subcarrier power of U_w on the p index and the CP ratio are given as $\rho_w(p)$ and C_p respectively.

Fig. 2 summarizes the proposed way of GB insertion in the multi-numerology systems as explained above for Q = 2. Here, ΔG_1 is only used between the subbands of two users while ΔG is same for conventional and proposed techniques. With the proposed approach, $\lfloor \Delta G/Q \rfloor$ Hz of the allocated ΔG can be saved and consequently, spectrum utilization of the system can be improved, where $\lfloor . \rfloor$ is the floor function. Therefore, compared to the conventional GB approach, the occupied bandwidth is increased by $\lfloor \Delta G/Q \rfloor$ and the improved spectrum utilization ξ can be given as

$$\xi = \frac{(B - \Delta G) + \lfloor \Delta G/Q \rfloor}{B}. \tag{8}$$

From (8), it can be observed that for the special case of $Q = 1$, the whole portion of the band reserved as GB can be used and thus the maximum bandwidth efficiency is attained. For the case of multiple numerologies, the portion of the GB that can be utilized by the proposed technique decreases with increasing Q. This signifies that the maximum amount of GB is saved when numerologies that constitute a minimum Q are scheduled adjacent to each other.

The critical challenge of the proposed technique is that, although a number of U_n subcarriers that are inserted to utilize some indices within the GB region do not cause any interference to the adjacent band as explained above, they themselves experience relatively high INI as they are closer to the adjacent numerology. In order to ensure a reliable communication and to not degrade the average bit error rate (BER) performance of U_n, a low order modulation is recommended for the symbols transmitted by these subcarriers. Low order modulations such as quadrature phase shift keying (QPSK) are robust against low SIR communication links. Note that, in this case, modulated symbols carried by subcarriers outside the GB region can still utilize higher order modulation formats such as M-ary quadrature amplitude modulation (QAM).

As another alternative for enhancing BER performance of the narrow numerology edge subcarriers within GB region, the multi-numerology symbol alignment-based technique known as common CP discussed in [4] can be employed. For this structure, Q symbols of U_w are concatenated and aligned within the one symbol duration of U_n, where U_n can also consists of the concatenated symbols. Then, the same sized CPs are added to concatenated symbols of U_n and U_w. Due to common CP structure, it is observed that one out of every Q subcarriers of U_n does not experience INI from U_w subcarriers with common CP [4]. These U_n subcarriers that receive zero INI from U_w are the same subcarriers that do not cause interference to U_w subcarriers. Therefore, one can conclude that with common CP symbol alignment, there is a number of narrow numerology subcarriers (whose indices k satisfy $k/Q \in \mathbb{Z}$) which are completely orthogonal with all U_w subcarriers. Therefore, for the proposed GB insertion technique, utilizing these subcarriers within the GB region does not affect the performance of either user, regardless of the used modulation order.

In order to analyze the BER performance of the proposed technique, an uplink (UL) transmission is considered. This is because, in the UL, $\acute{H}(k)$ and $H(k)$ are independent from each other, as the signals of U_n and U_w pass through different independent channels, unlike in the DL where they experience the same channel. Here, (5) is still valid for the UL while the proposed technique is still applicable. Thus, the instantaneous signal to interference plus noise ratio (SINR) can be obtained as

$$\gamma_k = \frac{|X(k)|^2 |H(k)|^2}{|INI_n(k)|^2 |\acute{H}(k)|^2 + |W(k)|^2}. \tag{9}$$

Then, the average approximate SINR can be obtained by taking the expected value of the numerator and denominator of the γ_k separately as [10]

$$\overline{\gamma}_k = \frac{E_b}{\mathbb{E}\left[|INI_n(k)|^2\right] + N_0} \tag{10}$$

where E_b is the energy per bit and $\mathbb{E}[|INI_n(k)|^2]$ is the average power of $INI_n(k)$ that can be obtained from (6). Owing to the fact that the interference power on each subcarrier is different, the overall BER of the proposed technique for BPSK under Rayleigh fading channel can be calculated as

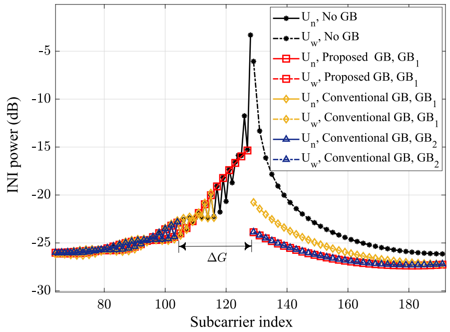
$$P_b = \frac{1}{K} \sum_{k=\eta_1 N - \Delta G}^{\eta_1 N - 1} \frac{1}{2} \left(1 - \sqrt{\frac{\overline{\gamma}_k}{\overline{\gamma}_k + 1}} \right) \tag{11}$$

where K is the total number of used subcarriers on the GB whose indices k satisfy $k/Q \in \mathbb{Z}$.

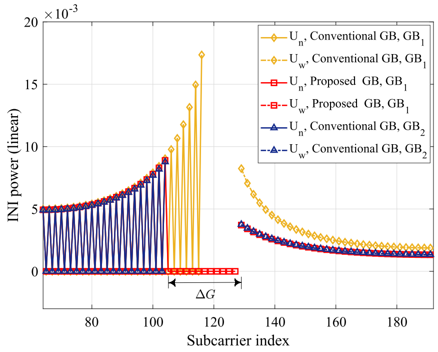
IV. SIMULATION RESULTS AND DISCUSSION

In this section, the INI and BER performances of the proposed GB technique is analyzed via Monte Carlo simulations. We assume that two users U_n and U_w equally share the available bandwidth such that $\eta_1 = \eta_2 = 0.5$. For simplicity, we consider that the GB is allocated within U_n subband (i.e., $\Delta G_2 = 0 \implies \Delta G = \Delta G_1$). Two different scenarios are considered in computer simulations: Conventional CP and common CP. For these scenarios, two different GB values as $GB_1 = 12 \cdot \Delta f_1$ and $GB_2 = 24 \cdot \Delta f_1$ are selected where $\Delta G = GB_2$. The system parameters are taken as $N = 256, \Delta f_1 = 15$ kHz, $Q = 2$, and $C_p = 1/16$. Unless otherwise stated, rectangular windowing, conventional CP, and DL transmission are considered throughout the simulations.

Fig. 3 justifies the claim made in Section III that placing U_n subcarriers properly within the GB region does not degrade the performance of the adjacent wide numerology user U_w. When conventional and proposed techniques have the same amount of the GB, the conventional technique creates around 3 dB more INI to U_w. Due to the subcarriers on ΔG that experience more INI with the proposed technique, low order modulations are used for the conventional CP scenario. Furthermore, as explained in the previous section, the proposed technique with $Q = 2$ can utilize the half of the GB, but this utilization decreases with the larger values of Q. On the other side, if common CP as being alternative to conventional CP is deployed, the subcarriers on the ΔG region do not experience any interference, and they can be used for higher order modulations. Thus, for both conventional and common CP



(a) Conventional CP.



(b) Common CP.

Fig. 3. INI experienced by each numerology for the conventional and common CP scenarios.

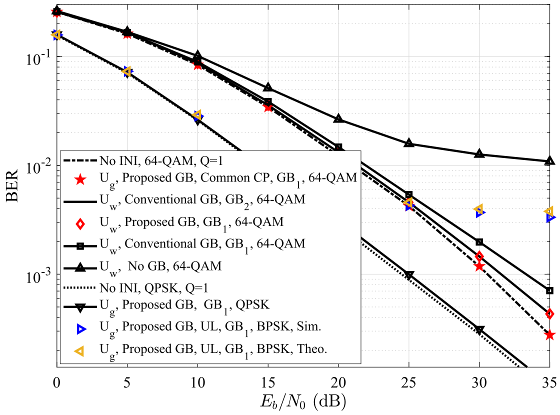


Fig. 4. BER performance of the proposed technique for the comparison.

scenarios, the proposed technique becomes more advantageous as the required GB increases.

The BER performance of the proposed technique is analyzed in Fig. 4. Firstly, the BER results of QPSK and 64-QAM for $Q = 1$, which corresponds to the case where interference does not exist in the system, are obtained for the evaluation. Here, U_g only represents the used subcarriers on ΔG. As we have discussed earlier, the U_g subcarriers occupying the indices within the GB region experience the interference caused by the subcarriers of U_w. Therefore, with low order modulation such as QPSK, U_g can exhibit a BER performance very close to $Q = 1$ case. Compared to UL transmission, the INI effects are diminished in DL transmission due to the fading channel as in [11]. Since there is no interference on these subcarriers with the common CP, U_g can use higher order modulations without any BER performance loss. While the BER performance of U_w is the same for both, proposed and conventional GB, the size of GB needs to be adjusted based on the required SIR value. As seen from the figure, if the GB decreases the BER performance of U_w also decreases for the conventional GB. In the case of not using GB, the BER performance of U_w degrades significantly. Also, the theoretical and simulation BER results are in agreement for the UL transmission as shown in the figure.

V. CONCLUSION

In this letter, a spectrally efficient approach of allocating a guard band in the multi-numerology system has been proposed. This approach exploits the characteristics of the INI distribution among subcarriers of the adjacent numerologies and can recover up to fifty percent of the spectrum wasted as GB, while maintaining the performance of each numerology. The best performance of the proposed GB technique has been obtained when numerologies with the minimum ScS ratio are scheduled adjacent to each other and common CP is used. Also, the spectrum utilization obtained with the proposed technique increases when the required guard band is wider, especially to use the high order modulation. For future work, the INI characteristics exploited in this letter will be investigated to develop better scheduling and resource allocation techniques for multi-numerology systems.

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