

The Impact of Adaptive Guards for 5G and Beyond

Ali Fatih Demir*, *Student Member, IEEE*, Hüseyin Arslan*[†], *Fellow, IEEE*

*Department of Electrical Engineering, University of South Florida, Tampa, FL, 33620

[†]School of Engineering and Natural Sciences, Istanbul Medipol University, Istanbul, TURKEY, 34810
e-mail: afdemir@mail.usf.edu, arslan@usf.edu

Abstract—The next generation communication systems are evolving towards an increased flexibility in different aspects. Enhanced flexibility is the key in order to address diverse requirements. This paper presents the significance of adaptive guards considering a windowed-OFDM system which supports a variety of services operating asynchronously under the same network. The windowing approach requires a guard duration to suppress the out-of-band emissions (OOBE), and the guard band is required to handle the adjacent channel interference (ACI) along with the windowing. The guards in both time and frequency domains are optimized with respect to the use case and power offset between the users. To fully exploit and further increase the potential of adaptive guards, an interference-based scheduling algorithm is proposed as well. The results show that the precise design that facilitates such flexibility reduce the guards significantly and boost the spectral efficiency.

Index Terms—5G, ACI, OFDM, OOBE, scheduling, windowing.

I. INTRODUCTION

The next generation communication systems including 5G are expected to support high flexibility and a diverse range of services, unlike the previous standards. The IMT-2020 vision defines the use cases into three main categories as enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra-reliable low-latency communications (URLLC) featuring 20 Gb/s peak data rate, $10^6/\text{km}^2$ device density, and less than 1 ms latency, respectively [1]. The applications which require larger bandwidth and spectral efficiency fall into eMBB category, whereas the ones that have a tight requirement for device battery life falls into mMTC. Usually, the industrial smart sensors or medical implants [2] need to operate several years without maintenance, and hence low device complexity and high energy efficiency are crucial for these mMTC services. Furthermore, the mission-critical applications such as remote surgery [3] or self-driving vehicles are represented in URLLC. Therefore, a flexible air interface is required to meet these different requirements.

Orthogonal frequency-division multiplexing (OFDM) is the most popular multi-carrier modulation scheme which is currently being deployed in many standards

such as 4G LTE and the IEEE 802.11 family [4]. A major disadvantage of OFDM systems is their high out-of-band emissions (OOBE). The OFDM signal is well localized in the time domain with a rectangular pulse shape, which corresponds to a sinc shape in the frequency domain. The sidelobes of the sines cause significant OOBE and should be reduced to avoid adjacent channel interference (ACI). Especially, the frequency localization is important to allow asynchronous transmission across adjacent sub-bands and coexistence with other waveforms/numerologies in the network [5]. However, a signal cannot be limited in both domains simultaneously due to the Heisenberg's uncertainty principle [6]. Hence, a better spectrum confinement is realized with the cost of expansion in the time domain. Typically, OOBE is reduced by various windowing/filtering approaches, and numerous waveforms are proposed for the upcoming 5G standard to provide better time-frequency concentration [1], [5], [7]–[10]. These filtering and windowing operations require additional period which extends the guard duration between the consecutive OFDM symbols. Also, extra guard bands are needed in between adjacent channels to control the ACI along with the windowing/filtering that handles the OOBE. The forthcoming generations must optimize the guards in both time and frequency domains to boost the spectral efficiency.

This paper presents the significance of adaptive guards considering an OFDM-based system which supports a variety of services operating asynchronously under the same network. The OOBE is reduced with a transmitter windowing operation that smooths the inherent rectangular pulse shape of OFDM. This technique retains the main design of the OFDM receivers and provides backward compatibility for the existing systems. The guard band and the window parameters that control the guard duration are jointly optimized regarding the use case and the power offset between the users. Although various windowing approaches are proposed towards better spectral concentration [11]–[14], this study also reduces the need for guards by grouping the users with similar power levels and SIR requirements. Hence, the potential of adaptive guards is further increased and exploited with an interference-based scheduling algorithm.

The rest of the paper is organized as follows. Section II describes the system model and explains the methodology in detail. Section III presents optimization of guards regarding the user requirements. Section IV proposes the interference-based scheduling strategy along with the utilization of adaptive guards. Finally, Section V summarizes the contributions and concludes the paper.

II. SYSTEM MODEL

Consider a multiuser OFDM-based system where asynchronous numerologies operate in the network. The users which have different use cases (i.e., requirements) and power levels perform transmitter windowing to control their OOB levels and reduce interference to the users serving in adjacent bands. The guard duration that is designated for the multi-path channel is fixed and sufficient to handle the inter-symbol interference (ISI). An additional guard duration is required to perform windowing. Several windowing functions have been evaluated in detail [15] with different tradeoffs between the width of the main lobe and suppression of the side lobes. The optimal windowing function is beyond the scope of this study, and the raised-cosine (RC) window is adopted due to its computational simplicity and common use in the literature [11]–[13]. The RC window function [11] is expressed as follows:

$$g[n] = \begin{cases} \frac{1}{2} + \frac{1}{2} \cos\left(\pi + \frac{\pi n}{\alpha N_T}\right) & 0 \leq n \leq \alpha N_T \\ 1 & \alpha N_T \leq n \leq N_T \\ \frac{1}{2} + \frac{1}{2} \cos\left(\pi - \frac{\pi n}{\alpha N_T}\right) & N_T \leq n \leq (\alpha + 1) N_T \end{cases} \quad (1)$$

where α is the roll-off factor ($0 \leq \alpha \leq 1$) and N_T is the symbol length of the RC function. The roll-off factor (α) controls the taper duration of the window. As α increases, the OOB decreases at the price of increased guard duration to perform windowing. The transmitter windowing operation is illustrated in Fig. 1. First, the cyclic prefix (CP) that is allocated to deal with the multi-path channel is further extended on both edges, and then the extended part from the beginning of the OFDM symbol is appended to the end. The transition parts (i.e., ramp-ups and ramp-downs) of adjacent symbols are overlapped to decrease the additional time-domain overhead resulting from the windowing operation.

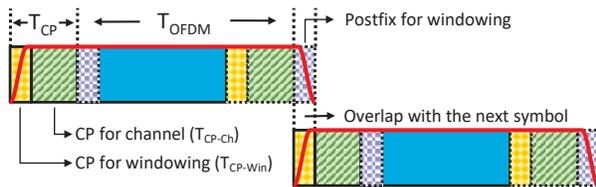


Fig. 1. Transmitter windowing operation and the guard durations.

The windowing operation is not sufficient to handle the OOB, and non-negligible guard bands are still needed. However, the amount of guard band (GB) or the length of guard duration (GD) to perform windowing depends on the power offset and the required signal to interference ratio (SIR) level of the users in adjacent bands. As an example, the leaked energy from the near user can be more powerful than the in-band energy of the far user in its adjacent band (i.e., the well-known near-far problem). The power control mechanism is a solution for this power offset problem. Nonetheless, it prevents near users to deploy higher order modulation schemes. Thus, the power control needs to be relaxed with an adaptive design to improve the spectral efficiency.

The required guards in both time and frequency domains are tightly related to the use case as well. For example, the guard units and other extra overheads decrease the spectral efficiency, which is especially critical for the eMBB type of communications. Hence, the guards are reduced with an expense of interference on the adjacent bands. On the other hand, the reliability and latency are extremely important for mission critical communications where errors and retransmissions are less tolerable. Thus, a strict OOB suppression is more feasible for URLLC applications. In addition, mMTC operates at the low power level to preserve energy and might suffer from the ACI seriously in an asynchronous heterogeneous network.

As a result of these discussions, the threshold for allowed interference level (θ) on adjacent bands should be adaptive considering the power offset (PO) and the use case. Fig. 2 presents how GB is inserted regarding θ to achieve the desired SIR level when there is a PO between the users in adjacent bands. Throughout the numerical evaluations in the paper, T_{CP-Win} (i.e., GD) and GB are adaptive, and these guards are optimized in Section III. The rest of the parameters belong to the windowed-OFDM (W-OFDM) system are fixed and summarized in Table I.

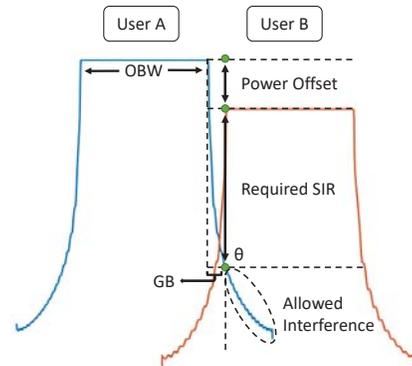


Fig. 2. Guard band allocation considering the interference threshold (θ) in the adjacent band. (OBW stands for occupied bandwidth and θ is represented in dB w.r.t. the power of “user A” throughout the paper)

TABLE I
SIMULATION PARAMETERS

Parameter	Value
FFT Size	1024
CP _{channel} Size	256
Subcarrier Spacing (Δf)	15 kHz
Occupied Bandwidth (OBW)	15.36 MHz
T_{OFDM}	66.7 μs
$T_{CP-channel}$	16.68 μs
# OFDM Symbols	300
Window Type	Raised Cosine

III. OPTIMIZATION OF THE ADAPTIVE GUARDS

The ACI is handled by windowing and allocating guard band between adjacent users as described in Section II. Since windowing operation suppresses the OOB with a penalty of additional guard duration, the procedure converges to the utilization of guard duration (GD) and guard band (GB) to achieve desired interference threshold (θ). Fig.3 presents the required GB and GD for selected θ . Each α value in the figure corresponds to a GD to perform windowing, and a GB to deal with the remaining interference power for a given θ .

An excessive amount of resources is needed to solve the problem only with GB or GD. As a result, the spectral efficiency, which is defined as the information rate that can be transmitted over a given bandwidth, decreases significantly. Therefore, GB and GD must be jointly optimized to boost the efficiency of the communication system. This hyper-parameter optimization has been performed by a grid search algorithm through a manually specified subset of the hyper-parameter space [16]. The spectral efficiency (η) is proportional to the multiplication of efficiencies in the time and frequency domains which are expressed as follows:

$$\eta_{time} = \frac{T_{OFDM}}{T_{OFDM} + T_{CP-Ch} + T_{CP-Win}} \quad (2)$$

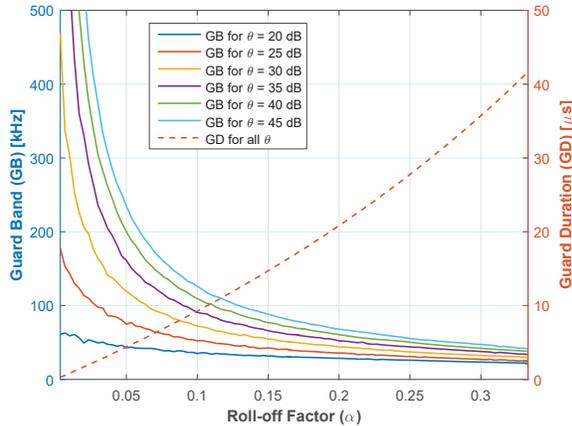


Fig. 3. Required GB and GD to achieve selected θ levels.

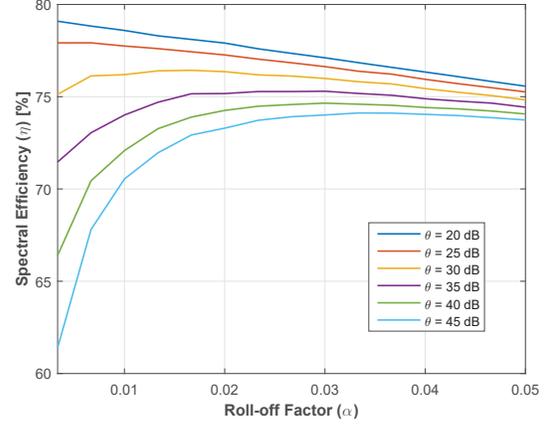


Fig. 4. Spectral efficiency (η) of the GB and GD pairs that achieves selected θ . (Please note that each α corresponds to a GB-GD pair as shown in Fig. 3)

$$\eta_{freq} = \frac{OBW}{OBW + (GB \times 2)} \quad (3)$$

Since T_{OFDM} , T_{CP-Ch} , and OBW are fixed parameters, the degrees of freedom that can be selected independently becomes only T_{CP-Win} (i.e., GB) and GD. The problem that seeks for the optimal GB and GD pair can be formulated as follows:

$$(GB, GD) = \arg \max_{GB, GD} (\eta_{time} \times \eta_{freq}), \quad (4)$$

$$\text{subject to: } PO + SIR \leq \theta. \quad (5)$$

The spectral efficiency of the W-OFDM system for selected θ values is presented in Fig. 4. Each α value in the graph corresponds to a GB-GD pair for a given θ and the peak value of each curve provide the optimal pair. These optimal pairs are listed in Table II along with the associated parameters. The results show that the need for windowing decreases as θ decreases, and hence the desired ACI level can be achieved only with a few guard carriers. In addition, the spectral efficiency increases with the decrease in θ . The variation in required guards clearly affirms that the adaptive design improves the spectral efficiency significantly instead of designing the system considering the worst case (e.g., $\eta_{\theta=45 dB} = 74.11\%$ whereas $\eta_{\theta=20 dB} = 79.33\%$).

TABLE II
THE OPTIMAL GUARDS FOR SELECTED θ

Interference Threshold (θ) [dB]	Max. Spectral Efficiency (η) [%]	Roll-off Factor (α)	Required Guard Duration [μs]	Required Guard Band [kHz]	Required Guard Carriers
20	79.33	0.0000	0.00	64.48	5
25	77.92	0.0067	0.55	153.06	11
30	76.43	0.0167	1.40	226.07	16
35	75.30	0.0300	2.57	235.51	16
40	74.65	0.0300	2.57	303.95	21
45	74.11	0.0333	2.86	333.96	23

IV. INTERFERENCE-BASED SCHEDULING

The optimization results in Section III reveal that the spectral efficiency (η) decreases as the interference threshold (θ) increases. Since θ depends on the users operating in the adjacent bands, the potential of adaptive guards can be increased further along with the utilization of an interference-based scheduling algorithm. Assuming that the base station or the user equipment has all necessary information, θ is determined as follows:

$$\theta_i = \max(SIR_{i-1} + PO_{i-1}, SIR_{i+1} + PO_{i+1}), \quad \forall i \quad (6)$$

where i is the indicator of the available consecutive bands. If the users with similar power levels and SIR requirements are grouped together, the average θ in the network decreases. As a result, the need for guards is reduced, and the spectral efficiency increases.

Consider an exemplary scenario with eight users, where the users have different power levels and SIR requirements as shown in Tables III and IV. The power offset (PO) pairs in the tables are provided regarding the users in adjacent bands. The users are assigned to the bands in two different ways. In the first scenario, a random scheduling has been realized (Fig. 5), whereas the ACI based scheduling strategy is utilized in the second scenario (Fig. 6). To compare and present the impact of the adaptive guards, a fixed guard assignment strategy is implemented in the random scheduling scenario as well. The guards are selected regarding the worst case scenario (i.e., $\theta = 45$ dB) in the fixed assignment scenario.

The comparison of required guards for the fixed guard assignment with random scheduling, the adaptive guard assignment with random scheduling, and the adaptive guard assignment with interference-based scheduling scenarios is summarized in Table V. The results show that the amount of guard duration (GD) and guard band (GB) decreased by 57% and 19%, respectively when the fixed guards are replaced with the adaptive guards. In addition, the amount of GD and GB decreased further by 35% and 16%, respectively when the random scheduling is replaced with the interference-based scheduling strategy.

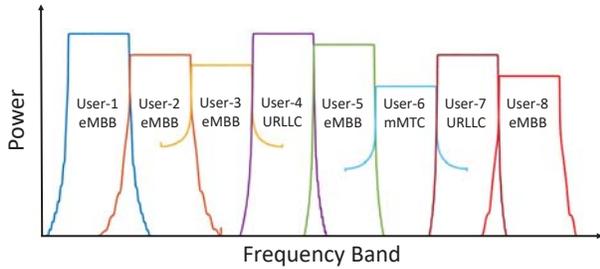


Fig. 5. Random scheduling of eight users which have different requirements.

TABLE III
THE REQUIREMENTS OF RANDOMLY SCHEDULED USERS

Band	1	2	3	4	5	6	7	8
User	1	2	3	4	5	6	7	8
Req. SIR [dB]	20	20	20	25	20	25	35	20
Rx Power [dBm]	0	-10	-15	0	-5	-25	-10	-20
Power Offset [dB]	10	-10, 5	-5, -15	15, 5	-5, 20	-20, -15	15, 10	-10
Intf. Thr. (θ) [dB]	30	25	15	35	45	20	40	25

TABLE IV
THE REQUIREMENTS OF INTERFERECE-BASED SCHEDULED USERS

Band	1	2	3	4	5	6	7	8
User	7	4	1	5	2	3	8	6
Req. SIR [dB]	35	25	20	20	20	20	20	25
Rx Power [dBm]	-10	0	0	-5	-10	-15	-20	-25
Power Offset [dB]	-10	10, 0	0, 5	-5, 5	-5, 5	-5, 5	-5, 5	-5
Intf. Thr. (θ) [dB]	15	45	25	25	25	25	30	15

TABLE V
THE COMPARISON OF REQUIRED GUARDS FOR DIFFERENT SCENARIOS

Scenario	Required Guard Duration [μ s]	Required Guard Band [kHz]
Fixed Guards Random Scheduling	22.88	2337
Adaptive Guards Random Scheduling	9.95	1891
Adaptive Guards Intf-based Scheduling	6.46	1579

V. CONCLUSIONS

This paper presented the importance of adaptive guards considering a windowed-OFDM system which supports a variety of services operating asynchronously under the same network. The guards in both time and frequency domains are optimized taking the use case and power offset into account. Furthermore, the need for guards is reduced with an interference-based scheduling algorithm. Such a scheduling strategy is especially critical when the power offset between the users operating in adjacent bands is high. The results show that the precise design that facilitates such flexibility considering the user requirements improve the spectral efficiency significantly. Although the computational complexity increases compared to conventional OFDM-based systems, the computation of the optimal GB and GD is an

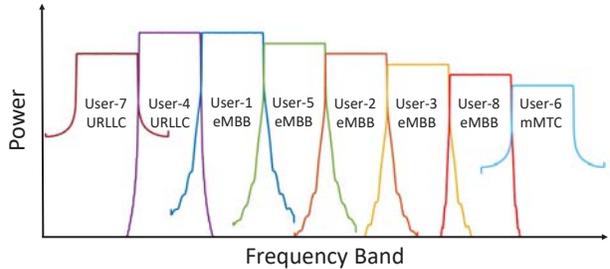


Fig. 6. Interference-based scheduling of eight users which have different requirements.

offline process that requires a one-time solution. Hence, a lookup table method can be adopted to reduce the complexity. This study will be extended by optimizing the guards and scheduling the users under various channel conditions and impairments. Also, the proposed methodology is applicable to the filtered-OFDM systems. The next generation communications systems are evolving towards an increased flexibility in different aspects. Enhanced flexibility is the key especially to address diverse requirements, and definitely, the guards should be a part of the flexibility consideration as well.

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