Adaptive Filtered OFDM with Regular Resource Grid

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***Abstract*—This paper proposes a simple, but efficient solution to avoid a potential problem for filtered OFDM (F-OFDM) that may violate regular resource grid structure. F-OFDM is an extension of OFDM by additional per-subband filtering and a well-localized filter can be utilized to significantly lower the out-of-band radiation that can mitigate interference in asynchronous access. Even with the filtering, additional guard bands that carry no data may be needed between the subbands for different users to keep the interference level sufficiently low. The required guard bandwidth may vary since various aspects should be taken into account such as interference power, modulation format or quality of service requirement. If the subbands are simply shifted to add the guard bands, the regular resource grid will be destroyed. One option to keep the regular resource grid while supporting flexible guard bands is to define several filters, each of which is optimized for each possible guard bandwidth. But this is rather complex. We propose a much simpler solution allocating the guard bands inside the filter bandwidth, which is kept independent of guard bandwidths. We show through detailed analytical and numerical analysis that the proposed solution performs even better than the more complex one in practically relevant interference scenarios.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) has been adopted for different wireless standards such as WiFi, WiMax and Long Term Evolution (LTE). With the use of cyclic-prefix (CP), OFDM provides numerous advantages such as the efficient implementation through fast Fourier transforms (FFT) to combat severe multipath fading for broadband signals and its good affinity with multiple-input multiple-output (MIMO) systems. On the other hand, it is also widely recognized that CP-OFDM suffers from various disadvantages. The high out-of-band (OOB) radiation poses the need to use large guard bands and makes the usage of narrow band whitespaces not possible and in the cases of asynchronous users or high mobility users the accumulated ICI degrades the overall system performance. In addition, the CP-OFDM numerology has to be always fixed for the whole band i.e., parameters like CP length or subcarrier spacing cannot be changed within the same band.

Moreover, future 5G systems are expected to address a wider range of scenarios and applications such as machine type communications (MTC) and high mobility, supporting higher frequency bands and coexistence with other systems like, e.g., Device to Device (D2D), wireless backhaul [1], [2], [3], [4].

Filtered OFDM (F-OFDM) is well suited for 5G systems as it allows for flexibility in several respects as a well-localized filter in frequency domain decouples the transmission of different users or services on neighboring subbands, e.g., [5], [6], [7]. The numerology of the subcarrier spacing as well as the symbol and cyclic prefix (CP) duration can be adapted within one band to optimize each transmission to the corresponding channel conditions and requirements. Nevertheless, depending on the specific filter design, the isolation between subbands may not be perfect and additional guard bands may be needed [8], [9], [10], [11], [12]. The width of the required guard bands highly depends on the specific circumstances including modulation scheme, power of neighboring users and filter shape. In order to have an efficient system, such guard bands should be chosen flexibly for any particular transmission.

The remaining part of this paper is organized as follows. In Section II we provide an overview of F-OFDM. Then, in Section III we describe the problem of flexible guard bands while keeping a regular resource grid. A performance analysis including analytical and simulation results is provided in Section IV. Conclusions and future work are given in Section V.

II. Filtered OFDM

Filtered OFDM can be seen as a compromise between no filtering as for pure OFDM and subcarrier filtering as done for Filter-Bank Multicarrier (FBMC) [13], as the filtering is applied to a subband consisting of a group of subcarriers as shown in Fig. 1 [14]. The whole system bandwidth is separated into subbands of certain width, each subband is filtered separately and the sum of these filtered subbands is transmitted depending on the allocated frequency resources.

The choice of the particular filter is quite flexible [12], but what is common to most proposals in the literature is the aim at minimum OOB radiation with almost constant passband. The actual performance of the different filters for F-OFDM higly depends on the considered scenario and the particular filter design. The example filter considered here keeps the CP as used in OFDM and applies a filter with much longer filter impulse response compared to the CP length, but still much shorter than the ones usually used for FBMC. As the filter tails exceed the CP length, there will be certain ISI even for flat channels, but by design of the filter this can be kept rather small.

Here the tradeoff between time and frequency localization gets obvious. The shorter the filter impulse response is, the broader the corresponding spectrum will be and that leads to higher out-of-band radiation and lower robustness to asynchronous systems [14]. On the other hand the ISI may be minimized or even avoided by zero padding without loosing too much in terms of efficiency. When the filter is longer, ISI cannot be completely avoided unless very long guard times are used, but on the other hand, the OOB radiation can be made much lower.

For the concrete filter design, basically any well-known tool can be used, depending on the constraints the filter should fulfill, like satisfying the Nyquist criterion or simply minimizing the maximum power of the side lobes. For the example, we assume in this paper applying a lowpass filter with raised cosine windowing with filter length of half a symbol duration similar to [15], [9].

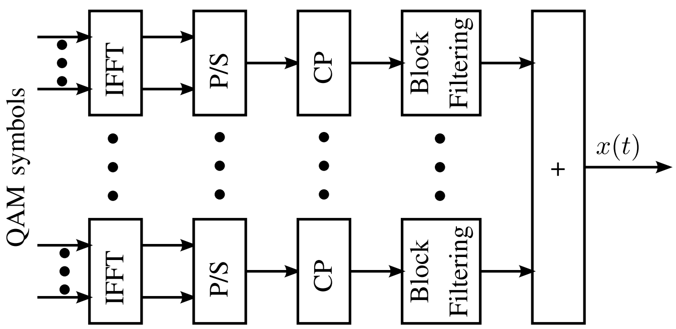

Fig. 1. F-OFDM block diagram.

III. Problem statement

A. Insertion of guard subcarriers

In a classical OFDM system like LTE downlink the subcarriers are orthogonal to each other as long as the signals are recieved synchronously and the channel is static and therefore does not introduce inter-carrier interference (ICI). In case of a time-varying channel the ICI depends on the Doppler spread and may degrade the performance. But also asynchronity between different users in uplink or different subcarrier spacing on different subbands introduce ICI. In such cases, F-OFDM can significantly reduce the interference between different subbands.

Basically, the filtering of a subband of an OFDM system does not violate the orthogonality between the subcarriers within one subband but can theoretically completely avoid ICI between subbands if the filter would be a perfect bandpass filter. In practice, perfect bandpass filters are not suitable as they would require an infinite length of the filter impulse response. Therefore, filters are used that show a compromise between filter length and OOB suppression. This leads to filters that do not perfectly suppress the ICI, but keep it at a reasonable level.

Nevertheless, even if the OOB radiation is reasonable for a setup with equal power users, the interference may become unacceptable if the interfering user has much higher power. This situation can occur if no proper power control is applied, e.g., as expected for IoT applications. In such a case, additional guard bands may be needed to achieve an acceptable level of interference.

The width of the required guard bands highly depends on the specific circumstances including modulation scheme, power of neighboring users and filter shape. In order to have an efficient system, such guard bands should be chosen flexibly for any particular transmission [8], [12].

B. Regular resource grid

Many communication systems use a regular resource grid, meaning that the entire resource space is divided into several subblocks of mostly same size. One example is LTE, where a slot is divided into a number of physical resource blocks (PRBs), each of them containing 14 symbols and 12 subcarriers. Based on these blocks, many signaling information refers to one or more resource blocks rather than to individual symbols or subcarriers. The main reason for this is obvious: to define all parameters or to signal the channel quality on a per subcarrier basis would lead to a vast amount of signaling overhead. So the granularity of the measurements and signaling plays a crucial role for the efficiency of a system.

On the other hand, some granularity is needed as certain parameters should be adapted to the specific condition on a certain subband. The most efficient way would be to go for a regular resource grid, as any kind of irregular grid would lead to the need for extra signaling of the position of a certain subband within the entire resource space. Therefore, it is highly desirable to keep a regular resource grid also in future systems.

C. Impact of guard bands on regular resource grid

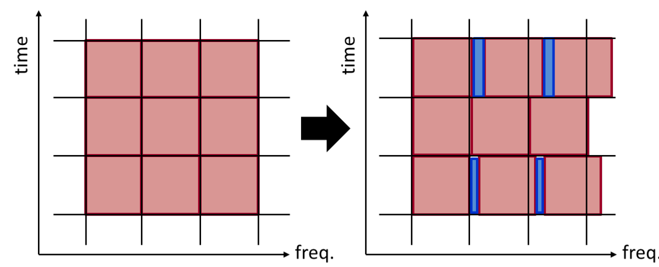

Fig. 2. Guard bands violating regular resource grid.

It is often proposed to go for a limited number of filters to be used for the subbands in order to keep the system complexity and possible extra signaling low. Therefore, it may be reasonable to choose a limited set of filters covering a certain set of numbers of resource blocks similar to the PRB in LTE. The problem that may then occur is that when introducing the guard bands between the subbands, the subbands will be shifted apart in frequency domain and therefore violate the regular resource grid as illustrated in Fig. 2. As already discussed in Section III-B, the resulting irregular grid leads to a tremendously increased overhead for signaling the shifted subband locations. In the next section we discuss new approaches to address this issue and also provide analytical and numerical analysis in detail.

IV. Proposed regular resource grid with guard bands for F-OFDM

To circumvent the violation of the regular grid by introducing guard SCs that we discussed in Section III, one can allocate guard bands within the regular resource grid as illustrated in Fig. 3. To implement this, we further consider two approaches: either to define multiple filters, each of which

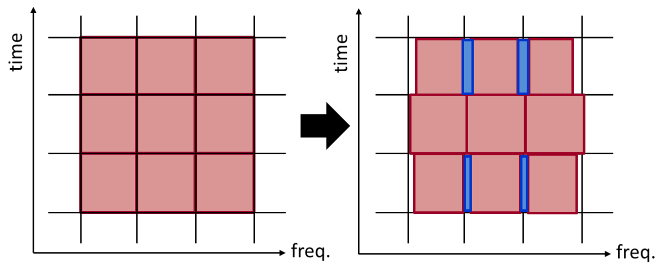

Fig. 3. Guard bands keeping regular resource grid.

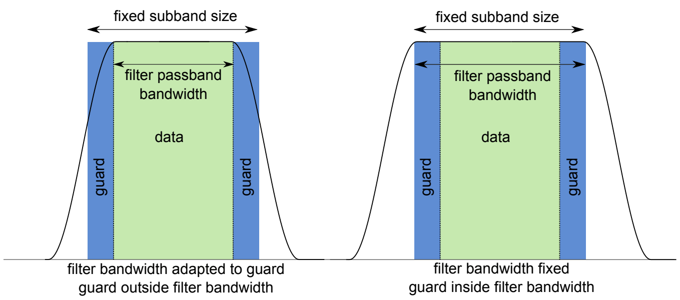

Fig. 4. Two approaches to keep regular resource grid.

referring to one subband size tailored with a pair of particular passband and guard bandwidths where allocating the guard band outside the filter passband bandwidth, or to keep the filter fixed with a constant passband bandwidth independent of the guard bandwidth where allocating the guard band within the filter passband bandwidth. These two approaches are illustrated in Fig. 4.

The first approach would make the system much more complex as more filters would have to be defined and possibly signaled, whereas the latter keeps the system simple but may lead to a degradation of the OOB suppression. In the following sections we will investigate this effect in more detail and it will be shown that the latter approach performs better in practically relevant interference scenarios regardless of the simplicity.

A. Analytical analysis

1) Interference due to out-of-band radiation: The interference can be calculated by a simple formula considering the spectrum of the data, the filter shape, and the allocated guard subcarriers. Let us denote the continuous signal in the interfering subband in the frequency domain as $D(f)$ and the filter shape in frequency domain without any shift with respect to the data signal as $G(f)$. In an OFDM system without filtering, the Inter-Band Interference (IBI) of a band starting at frequency f_1 to the neighboring band of width F can be calculated as:

$$\text{IBI} = \int_{f_1-F}^{f_1} |D(f)|^2 \, df \,. \tag{1}$$

Fig. 5 a) illustrates the calculation of the effective interference in the case of no filtering and no guards between users showing the signal spectrum $D(f)$. The gray area in Fig. 5 indicates the total amount of interference affecting the data-carrying subcarriers of the user of interest illustrated as dotted line.

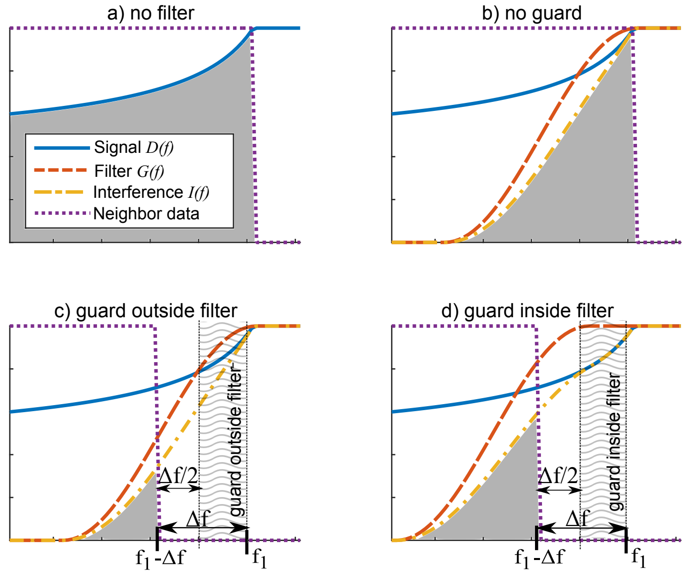

Fig. 5. Guard bands keeping regular resource grid

In case of filtering per subband, but without any guard band between the subbands this will become

$$\text{IBI} = \int_{f_1-F}^{f_1} |D(f) \cdot G(f)|^2 \, df \,. \tag{2}$$

As $G(f)$ usually takes values smaller than 1 outside the intended band, the overall interference will be reduced.

The calculation of the effective interference in the case of no guards between users is illustrated in Fig. 5 b) showing the signal spectrum $D(f)$ and the filter shape $G(f)$ of the interfering user as well as the resulting interference $I(f) = D(f) \cdot G(f)$.

Now, if additional guard bands are allocated between the subbands, the data carrying subcarriers of the neighboring user will be shifted apart from the other user by the guard bandwidth Δf as shown in Fig. 5 c) and the interference reads as:

$$\text{IBI} = \int_{f_1-F+\Delta f}^{f_1-\Delta f} |D(f) \cdot G(f)|^2 \, df, \tag{3}$$

and therefore it significantly lowers the interference, as indicated by the smaller gray area in Fig. 5 c), as compared to the case without guard in Fig. 5 b).

Note that the guard band is allocated outside the filter $G(f)$ in Fig. 5 c) and the overhead by the guard band is shared by the two neighboring users. For ease of exposition we also assume, without loss of generality, that the guard band is equally shared, i.e., $\Delta f/2$ is used by each user, although any different proportion of sharing the guard band is possible. As the guard band is allocated outside the filter, different filters $G(f)$ would be needed in this approach when the guard band bandwidth is changed. This makes the system design more complex.

The guard band could also be allocated inside the subband and therefore inside the filter passband as depicted in Fig. 5 d), where the filter shape $G(f)$ is shifted by half the guard bandwidth $\Delta f/2$ towards the neighboring user, as compared

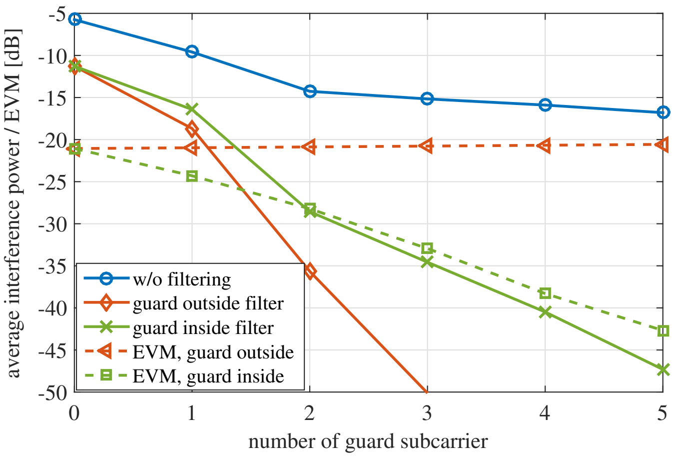

Fig. 6. Interference to neighboring subband versus number of guard subcarrier

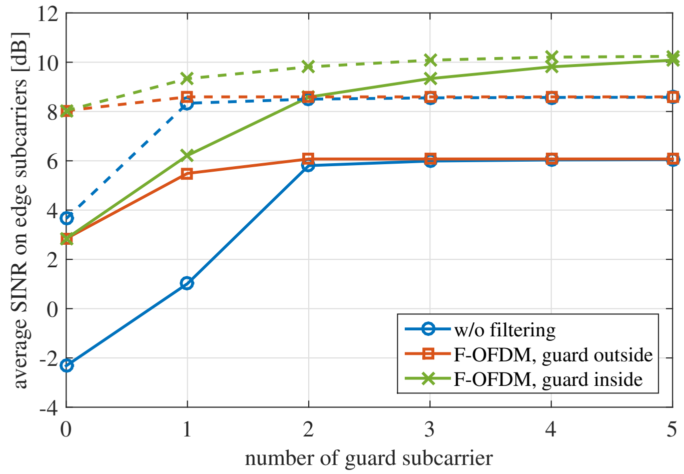

Fig. 7. SINR of edge subcarriers versus number of guard subcarrier for SNR=10 dB, outmost SC (solid) and second outmost SC (dashed)

to Fig. 5 c). In other words the edge of filter passband is fixed in the middle of the two neighboring users and only the guard band $\Delta f/2$ inside the fixed passband is changed in Fig. 5 d) whereas in Fig. 5 c) the filter passband has to be changed additionally, as explained earlier. The signal spectrum $D(f)$ in Fig 5 d) is the same as Fig 5 c), but due to the shifted filter, the shape of the interference spectrum is different. In this case the interference can be calculated as

$$\mathrm{IBI} = \int_{f_1-F+\Delta f}^{f_1-\Delta f} |D(f) \cdot G(f-\Delta f/2)|^2 \, df \, . \tag{4}$$

This will increase the interference slightly as can be observed in Fig. 5 d) as compared to Fig. 5 c), but it enables to keep the system simple. Although the relevant interference is only sampled at certain frequencies corresponding to the subcarrier locations, the relative performance will be similar to the overall power in that domain unless the system is fully synchronized.

In Fig. 6 the average interference is plotted versus the guard bandwidth in terms of number of subcarriers. It can be clearly observed that filtering significantly lowers the interference. OFDM without any guard shows the worst performance, but filtering itself may not be the only solution as introducing guards also lowers the interference without any filtering. The best results are obtained by a combination of filtering and insertion of guards, where the solution to put the guards outside the subband shows the best performance. But even when putting the guards inside the subband and inside the filter, the performance is still significantly improved while keeping the system much simpler. Especially for small guards, which are expected to be the most relevant and most likely case, the loss of the new proposed scheme is rather small. So there is a tradeoff between low interference and simple system design that should be taken into account.

2) In-band distortion due to filtering: In addition to the interference from neighboring users, also the inband distortion introduced by the filter can degrade the performance. In order to achieve a good OOB suppression with reasonably short filters, also the edge subcarriers of the passband are affected and attenuated. To illustrate that, also the average Error Vector Magnitude (EVM) is plotted in Fig. 6. For the case of guards outside the filter, the EVM does not change when the guard is increased as the passband stays the same. But if the guard is located inside the filter passband bandwidth, the most distorted subcarriers of the passband are not used to transmit data but rather act as guard subcarriers. Consequently, the inband distortion measured by the EVM decreases for the case of guard inside the filter as the number of guard SC increase.

3) SINR calculation based on OOB radiation and inband distortion: In summary, we have two effects: One is the interference coming from neighboring interferers and the other one is the inband distortion due to the nonperfect passband. So although the interference is higher if the guard is inside the filter, the inband distortion decreases. Furthermore, both effects are most significant at the edges of a band, so that the SINR of the edge subcarriers will be significantly lower than in the middle of a subband. The effect of both aspects to the SINR on the edge subcarrier can be observed in Fig. 7. Here we show the average SINR for the two outmost subcarriers for the same setups as before. It can be clearly seen that in case of the guards inside the band the combination of inband distortion and interference leads to even better SINR than in case the guard is outside the filter. The simulation results in the next section confirm these observations.

It should be noted that such observations depend of course on the specific filter design, but the basic results will hold for other filters as well.

B. Simulation results

In this section we will show and discuss simulation results for different ways to include guard SCs. The two users are allocated resources next to each other in the frequency domain, only separated by 2 guard SCs, which are located either inside (as shown in Fig. 5 d)) or outside the filter (as shown in Fig. 5 c)). The subband size is 48 SCs for both users, in the state-of-the-art (SoA) case the guard SCs are outside the subband, for the new proposal they are inside, i.e., they are contained in the subband of 48 SCs. We consider half a symbol transmission timing misalignment between the two users to account for a worst case timing offset. The power ratio of the two users' signals observed at the receiver denoted as ΔP is varied as a parameter in order to investigate how the performance of the

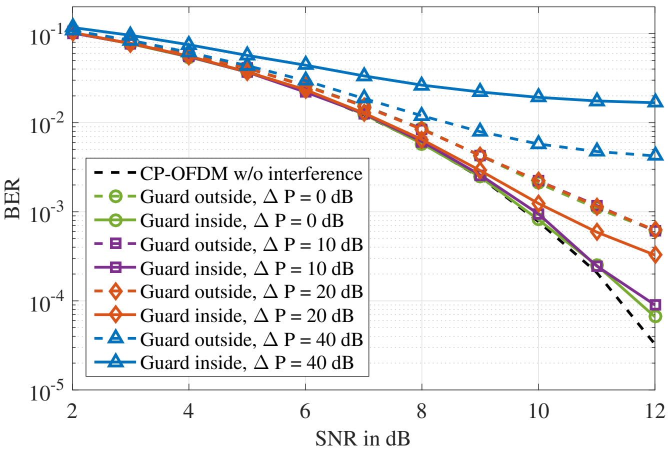

Fig. 8. Uncoded BER performance of F-OFDM on an AWGN channel with 2 guard SCs and QPSK modulation.

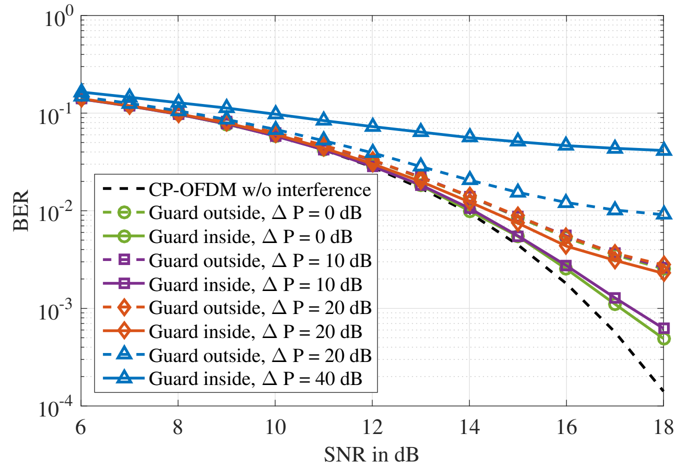

Fig. 9. Uncoded BER performance of F-OFDM on an AWGN channel with 2 guard SCs and 16QAM modulation.

user of interest is affected by the different relative strengths of the interfering signal.

Fig. 8 compares the SoA and new approaches in terms of uncoded bit error rate (BER) performance of F-OFDM versus SNR on an AWGN channel using QPSK modulation. As a reference the single user performance of CP-OFDM without interferer is also plotted. We can observe that the new approach (guard SCs inside subband) outperforms the SoA (guard SCs outside subband) for the interference power of up to 20 dB higher than the user of interest although the new approach keeps the system design simpler. For extremely high interference of 40 dB higher than the user of interest the performance of the new approach degrades and the SoA performs slightly better, but overall the performance is not satisfactory for such strong interference. This observations are aligned with the analytical analysis in Section IV-A as we further elaborate below.

The observations can be understood by considering the two effects of the OOB suppression and inband distortion that are introduced by the filtering, as we discussed in Section IV-A. The new approach experiences the lower inband distortion because the edge SCs that are distorted by filtering are used as the guard SCs located inside the passband and do not carry data. That leads to the better performance of the new approach although the amount of interference from the neighbor user is slightly increased (cf. Figs. 5 c) and d)). High interference exceeding a certain level, however, starts dominating the overall degradation and thus, the performance is better for the SoA, which experiences lower interference from the neighboring user.

The observations and conclusions that are made for QPSK basically remain the same for 16QAM as illustrated in Fig. 9 with slightly more pronounced differences in performance for 16QAM due to its increased sensitivity to the interference as compared to QPSK.

Figs. 10 and 11 show the performance versus SNR over an EPA channel with mobility of 3 km/h where QPSK and 16QAM modulations are used, respectively. For a fading channel frame error rate (FER) evaluation makes more sense than uncoded BER and we apply LTE compatible turbo codes

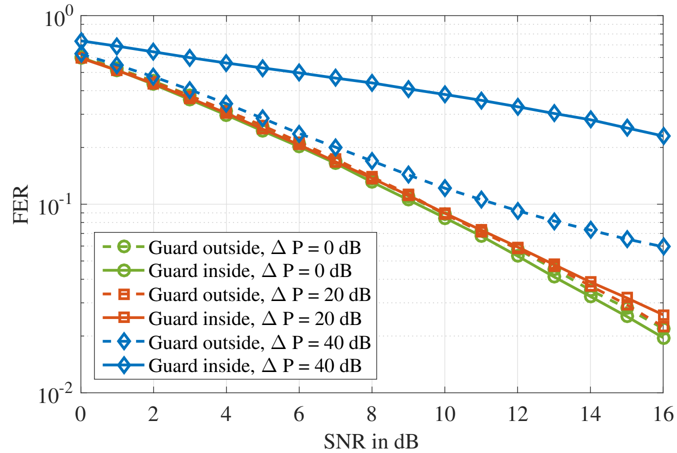

Fig. 10. FER performance for F-OFDM with different number of guard subcarriers, EPA channel, 3 km/h, QPSK, $R_c = 0.32$, 2 guard SCs.

with code rates of 0.32 and 0.55, respectively, for QPSK and 16QAM. We can make the observations in FER performance similar to the uncoded BER over an AWGN channel with the smaller performance differences between the SoA and new approaches.

Therefore, despite its system design simplicity our new approach allocating guard SCs within a constant passband is an attractive solution to accommodate diverse services by adaptive F-OFDM with regular resource grid, which may be seen as a candidate for future mobile communications systems.

V. Conclusions

In this paper a simple, but efficient solution was proposed for the problem of flexible guard bands for F-OFDM while at the same time keeping a regular resource grid and avoiding the design of a large set of filters, each of which is optimized for possible size of the guard band. All these aspects are highly relevant for practical system design to keep it simple but not sacrificing the performance significantly.
The main point of the new proposal is to allocate the guard band between subbands of different users inside the filter

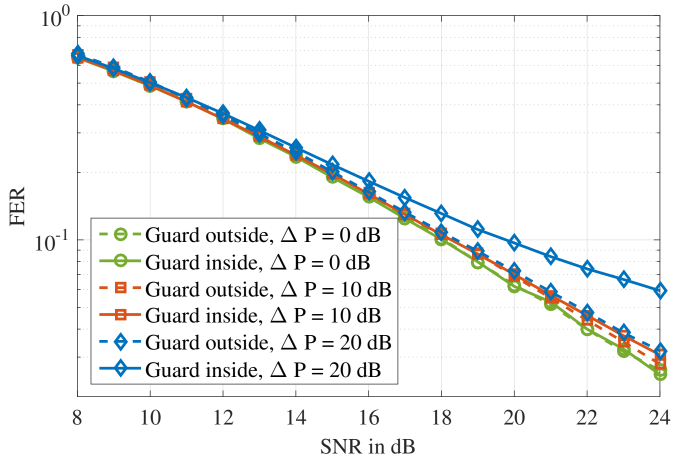

Fig. 11. FER performance for F-OFDM with different number of guard subcarriers, EPA channel, 3 km/h, 16-QAM, $R_c = 0.55$, 2 guard SCs.

passband, meaning to transmit no data on the outer edge subcarriers while the number of unused subcarriers depends on the system parameters and may be different for each subband. It was shown by analysis and simulations that the new approach performs even better than other proposed solutions in practically relevant interference scenarios.

Although results were shown for a specific filter design proposed in the literature, the results for other filter designs and respective conclusions are expected to be similar. Therefore, despite its system design simplicity our new proposal appears an attractive practical solution to accommodate diverse services by adaptive F-OFDM with regular resource grid, which may be seen as a candidate for future mobile communications systems. In the future, other filter designs as well as related techniques like pre-distortion of the data signal will be studied.

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