Efficient Fast-Convolution Implementation of Filtered CP-OFDM Waveform Processing for 5G

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***Abstract*—This paper investigates the use of effective and flexible fast-convolution (FC) filtering scheme for multiplexing OFDM resource blocks (RBs) in a spectrally well-localized manner. The scheme is able to effectively suppress interference leakage between adjacent RBs, thus supporting asynchronous operation and independent waveform parametrization of RBs. This is considered as an important feature in 5G waveform development for effectively supporting diversified service characteristics. Our approach is applicable for cyclic prefix or zero prefix based OFDM and the corresponding OFDM based single-carrier (SC-FDMA) waveforms. It is also possible to generate and process traditional Nyquist pulse shaping based single-carrier waveforms and filter bank multicarrier waveforms using the same FC processing engine, accommodating different waveforms simultaneously in different RBs. Our case study is based on proposed numerology for 5G cm-wave communications utilizing flexible time-division duplexing principle. While using RBs of 160 OFDM subcarriers, it is enough to deactivate 3 to 5 subcarriers out of each RB as guardbands to effectively suppress interference leakage between RBs.**

I. Introduction

Orthogonal frequency-division multiplexing (OFDM) is the most important multicarrier technique and it is extensively utilized in modern broadband radio access systems. This is due to the simple and robust way of channel equalization, high flexibility and efficiency in allocating spectral resources to different users, as well as simplicity of combining multiantenna schemes with the core functionality [1]. However, OFDM has one major limitation in challenging new spectrum use scenarios, like opportunistic dynamic spectrum access, heterogeneous wireless system coexistence, and asynchronous multiple access in general: limitations in spectral containment, which lead to strong out-of-band emission in the transmitter and high sensitivity to interferences from asynchronous spectral components in the receiver.

An alternative scheme is offered by the filter bank based methods of waveform processing and channelization filtering [2], [3], [4], [5]. The transmitted waveforms generated by these methods are spectrally well-contained and the unused portions of the spectrum are inherently clean. The filter bank processing on the receiver side is able to suppress interferences from unused parts of the frequency band. Naturally, there are limitations in the reachable levels of attenuation, mostly determined by the analog RF imperfections, notably power amplier non-linearity on the transmitter side.

A relatively widely studied filter bank based waveform is filter bank multicarrier/offset-QAM (FBMC/OQAM, also known as OFDM/OQAM) [2], [3], [5]. While reaching high spectral containment, it keeps many of the important features of OFDM. On the other hand, FBMC/OQAM exhibits higher algorithmic and computational complexities, it requires more complicated pilot/training symbol structures, and it has difficulties in certain multi-antenna transmission schemes.

FBMC schemes provide good spectrum localization for each subcarrier, but this is actually not required, since resource allocation and adaptive coding and modulation schemes are commonly applied with a group of subcarriers, or resource block (RB) as the basic unit. Recently, various filtered OFDM (F-OFDM) schemes utilizing filtering at resource block level have been proposed for future wireless communications [6], [7], [8]. In the existing studies, window based time-domain filtering [6], [8], and more effective uniform polyphase filter bank structures [7] have been considered. In [8], also the possibility of effective FFT-based filtering was briefly mentioned.

In this paper we propose an efficient fast-convolution (FC) based scheme for RB-filtered OFDM as a candidate waveform for 5G system development. Our focus is on cyclic prefix (CP) based OFDM, but it is equally applicable to OFDM with zero prefix (ZP). This is an extension of our earlier studies on exploiting the FC filtering approach for advanced multicarrier and single-carrier waveforms in flexible and efficient manner [9], [10]. Next in Section II, the fast-convolution filter bank (FC-FB) idea is introduced and its application to F-OFDM is presented. In Section III, the proposed numerology for 5G cm-wave communications is explained. Section IV contains a performance analysis of the proposed FC-F-OFDM system using the proposed cm-wave numerology. Finally, concluding remarks are given in Section V.

II. Fast-Convolution Filter Banks

This paper uses a special implementation scheme for multirate filters and filter banks which is based on fast-convolution processing. Here the main idea is that a high-order filter can be implemented effectively through multiplication in FFT-domain, after taking DFT's of the input sequence and the filter impulse response. The time-domain output signal is finally obtained by IDFT. In practice, efficient implementation techniques, like FFT/IFFT, are used for the transforms, and overlap-save processing is applied for long sequences. The application of

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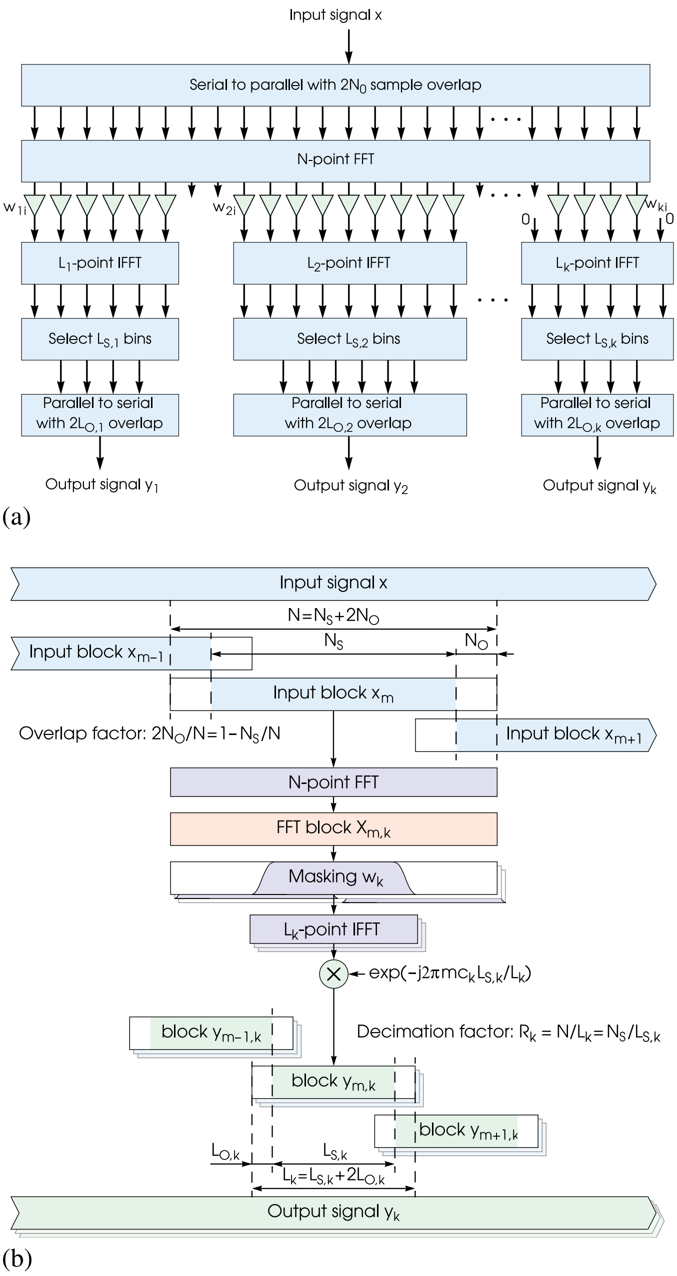


Fig. 1. (a) Fast-convolution based flexible analysis filter bank (AFB) structure. (b) Overlap-save processing flow and used notation for processing block lengths.

FC to multirate filters has been presented in [11], and FC implementations of channelization filters have been considered in [12], [13], [14]. The authors have introduced the idea of FC-implementation of nearly perfect-reconstruction filter bank systems and detailed analysis and FC-FB optimization methods are developed in [15]. In [9] FC approach has been applied for filter bank multicarrier waveforms and in [10] for flexible single-carrier waveforms. These papers demonstrate the flexibility and efficiency of FC-FB in communication signal processing.

A. Fast-Convolution Filter Bank

Figure 1 shows the structure of FC-based flexible analysis filter bank, for a case where the incoming high-rate, wideband signal is to be split into several narrowband signals with adjustable frequency responses and adjustable sampling rates. The figure shows also the overlap-save processing flow, along with the notation used for processing block lengths. It is assumed that the subband output signals are oversampled by the factor of 2. We also note that different subbands may be overlapping. The dual structure of Figure 1 can be used on the transmitter side as a synthesis bank combining multiple low-rate, narrowband signals into a single wideband signal [16].

Figure 1 includes sampling rate reduction by factors

$$R_k = N/L_k = N_S/L_{S,k} \qquad (1)$$

where k is the subband index. In other words, the sampling rate conversion factor is determined by the IFFT size, and can be configured for each subband individually. The IFFT size determines the maximum number of frequency bins, i.e., the bandwidth of the subband. Based on (1), the input and output block lengths are related through the decimation factor. The input and output block lengths have to exactly match, taking into account the sampling rate conversion factor. Consequently, it is required that $L_k/N = L_{S,k}/N_S$. We can see that the configurability of the output sampling rate depends greatly on the choice of N and N_S. Later discussions focus on uniform filter banks, and the subband index k is dropped for clarity.

There are two key parameters which have an effect on the spectral characteristics of the FC-FB scheme: (1) The IFFT (short transform) length L defines how well the filter frequency response can be optimized. Increasing the value of L helps to reduce the inband interference and out-of-band power leakage, because a higher number of FFT-domain weights are used for shaping the transition bands. (2) The FC-overlap factor $1 - N_S/N = 1 - L_S/L$: In FC based multirate signal processing there is an inherent cyclic distortion effect because it is usually not reasonable to make the overlapping part of the processing block big enough to absorb the tails of the filter impulse response. This effect can be reduced by increasing the overlap factor. But increased overlap means also higher computational complexity. In [15] these effects were analyzed using a periodically time variant model for FC and effective tools for frequency response analysis and FC filter optimization were developed.

B. FC Filter Design

In our approach, FC design is done in FFT-domain by defining/optimizing the weight coefficients. Generally, the FFT-domain weights consist of two symmetric transition bands with non-trivial weights. All passband weights are set to 1, and all stopband weights are set to zero. The number of stopband weights is selected to reach a feasible subchannel oversampling factor, typically 2. Figure 2 shows the weights for two example cases with different bandwidths.

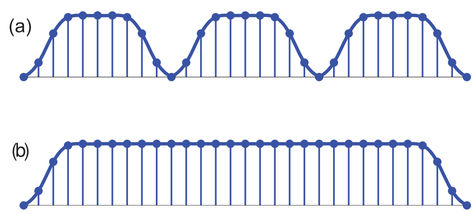


Fig. 2. Examples of FFT-domain weight masks. (a) Filter bank with three narrow subchannels. (b) Single subchannel with wider bandwidth. The stopband zero-bins needed for 2x oversampling are not shown.

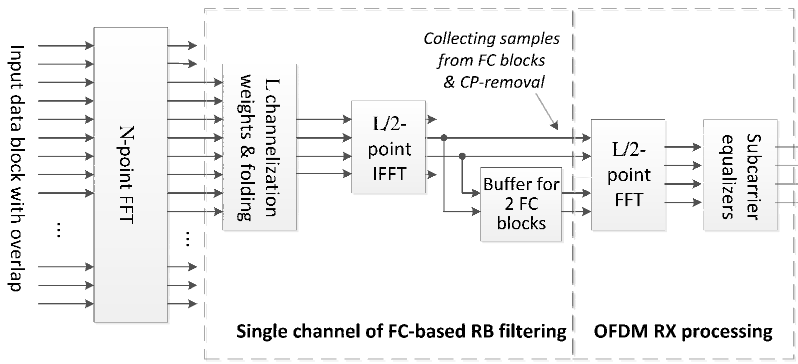


Fig. 3. FC-FB based processing for F-OFDM receiver. Processing structure for one filter channel (group of RBs) is shown. The long N-point FFT is common for all filter bank channels.

For FBMC or single-carrier waveform generation and processing, the weights can be derived by sampling the square-root raised-cosine (RRC) function. For channelization filtering purposes, raised-cosine (RC) shape provides better performance with the same transition bandwidth. In [15] it was shown that optimizing the FFT-domain weight values gives in many cases significant improvement in terms of the key performance metrics, in-band interference (IBI) and adjacent channel leakage ratio (ACLR), compared to direct RRC or RC designs. Typically, the transition bandwidth is 3 to 7 FFT bins and, especially if RRC or RC symmetry is imposed, there are only a few free parameters to be optimized. Consequently, standard non-linear optimization methods can be utilized.

One important feature of the FC-FB structure is that the transition band shape optimized for a basic narrowband design case can be used for constructing filters with arbitrary bandwidths. The bandwidth can be increased by adding an even number of 1-valued bins in the passband and equal number of zero-valued bins in the stopbands, symmetrically on both sides. With this scheme, while the bandwidth is increased and the transition bands maintain the same shape, the roll-off is reduced correspondingly. Also the IFFT length grows proportionally to the bandwidth, and the subchannel oversampling factor is always 2. Naturally, it is possible to optimize the transition band weights separately for each bandwidth, but the benefit is usually small. With fixed transition band weights, adjusting the subchannel bandwidths is quite straightforward in the FC-FB structure.

C. FC based Filtered OFDM

The main idea of this paper is to apply FC-filter banks for resource block level filtering, while utilizing normal CP-OFDM or SC-FDMA waveforms for the resource blocks. The main application is in cellular uplink scenarios, in which the different user equipments (UEs) utilize different resource blocks for their transmissions. UEs may utilize single-channel FC-filtering, or corresponding time-domain filtering to shape their spectra. For good isolation of different users' RBs, a few subcarriers at the edges of the RB are deactivated as guardbands. Good spectral isolation allows to relax the tight synchronization requirements of traditional uplink multiuser OFDMA. Furthermore, it becomes possible to parametrize the waveforms differently for different UEs, e.g., using different subcarrier spacings, CP-lengths, and/or frame structures. On the base-station side, a FC-based analysis filter bank is used for separating the resource blocks of different UEs. Concerning cellular downlink scenarios, synchronization is not an issue, but the F-OFDM idea would still make it possible to parametrize individually different users' signals.

With FC-FB, it is easy to adjust the filtering bandwidth for the RBs individually. This is very useful in RB-filtered OFDM because there is no need to realize filter transition bands and guardbands between equally parametrized synchronous RBs. Let L_{RB} denote the number of subcarriers per RB (a few of which may be deactivated for guardbands) and let n_{RB} denote the number of contiguous resource blocks operating synchronously. Then a FC filter can be realized for a group of $n_{RB}L_{RB}$ subcarriers, such that the filter transition bands appear only at the edges of the group of RBs. This helps to minimize the effect of transition band overhead on spectrum efficiency. In the extreme case, the group of RBs could cover the full carrier bandwidth, and FC filtering would implement tight channelization filtering for the whole carrier.

Figure 3 shows a block diagram of a FC-F-OFDM base-station receiver. In the basic model of FC processing, the short transform (IFFT) length is chosen as $L = 2n_{RB}L_{RB}$ to reach 2x-oversampled OFDM signal. Defining L_G as the number of guard subcarriers between active subcarriers of adjacent RBs, we have for each group of RBs (see Figure 4):

- Number of non-zero FFT-domain weights: $L/2 + L_G = n_{RB}L_{RB} + L_G$
- Number of non-trivial FFT-domain weights for the two guardbands: $2L_G$
- Number of 1-valued FFT-domain weights: $n_{RB}L_{RB} - L_G$

The 2x oversampled model is needed only when considering the FFT weighting scheme. Non-oversampled signal is sufficient for OFDM receiver processing after channelization. Down-sampling by the factor of two can be done effectively in the FFT-domain, by folding the weighted FFT bin values, following the folding model of the sampling theorem. After folding, the needed IFFT length for FC is $L/2$, which is equal to the number of subcarriers in the group of resource blocks.

Due to the overlap-save principle applied in FC processing, the samples needed for the FFT of the OFDM receiver come typically out in 2 or 3 consecutive FC processing blocks (with high FC-overlap and long CP, even more blocks are needed). The CP removal takes place also in this context: The relevant samples obtained from consecutive FC blocks are assembled as the input data to the FFT.

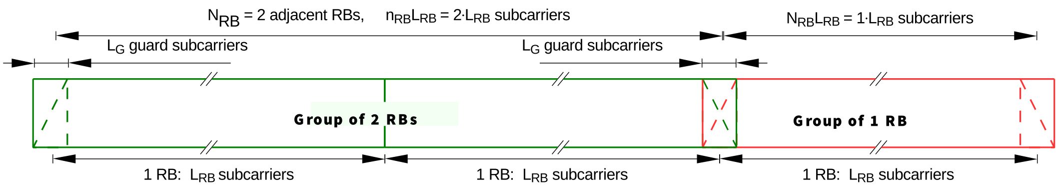


Fig. 4. Resource block structure in FC-F-OFDM.

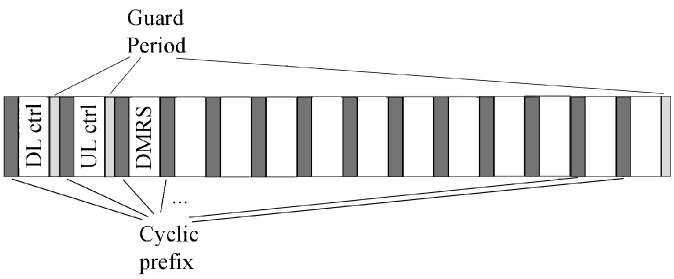


Fig. 5. Flexible TDD subframe structure.

Channel equalization is implemented in the same way as in basic CP-OFDM through subcarrier weight coefficients. It is important to notice that the channel equalizer is able to compensate even quite significant non-ideality of the passband frequency responses of the resource block filters of the transmitter and receiver. Therefore, flatness of the passband response is not a critical criterion in the RB filter design. As suggested in [17] for FBMC/OQAM, channel equalization coefficients could be combined with FC channelization weights. However, this would actually increase the computational complexity, because the channelization weights are real-valued and only few of them are non-trivial, but the modification would cause all nonzero coefficients to take non-trivial complex values.

III. Flexible TDD Frame Structure and Numerology

A. Subframe Structure

We consider the subframe structure introduced in [18], [19]. The design criteria are low latency, low complexity and high throughput. The flexible time-division duplexing (TDD) principle is utilized. The structure of the subframe is shown in Figure 5, consisting of 14 OFDM symbols. The first one is downlink (DL) control, the second is uplink (UL) control, and the rest 12 are for data. These 12 OFDM symbols are either all for UL or all for DL. One of these is the demodulation reference signal (DMRS). The frame structure includes three guard periods (GP) enabling link direction switching.

The placement of DMRS in the beginning of the subframe enables efficient pipeline processing in the receiver. Time multiplexed physical control channels also enable small latency in both link directions [18]. The same subframe structure is used in both link directions. As a result, interference covariance matrix can be estimated from the DMRS symbol, and the cross link interference can be efficiently mitigated by minimum mean-square error based interference rejection combining (MMSE-IRC).

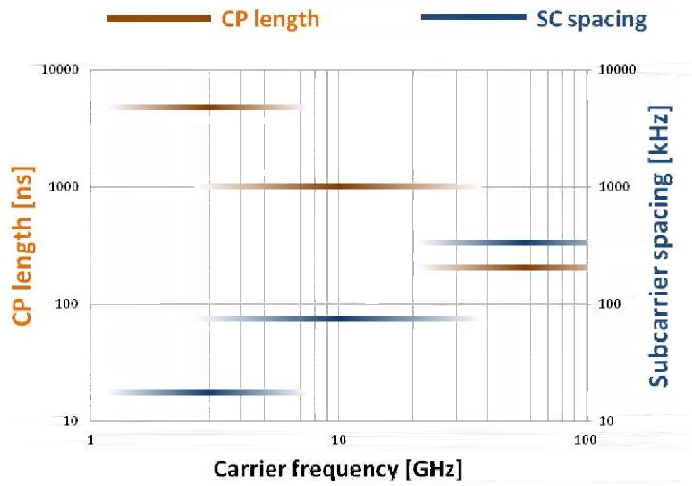


Fig. 6. Harmonized OFDM principle.

TABLE I. Numerology example for cm-wave frequency range.

Parameter	Value
Subcarrier spacing	75 kHz
OFDM symbol length	13.33 μs
Total CP & GP duration	13.33 μs
Subframe length	0.2 ms
FFT size	2048
Used subcarriers	1280
Carrier bandwidth	100 MHz

B. Numerology

We use the principle of harmonized OFDM [19], in which the FFT size is kept almost constant, but subcarrier spacing and CP length are functions of carrier frequency, as shown in Figure 6. As the carrier frequency increases, the channel delay spread tends to decrease. This means that the CP can be shortened with increasing carrier frequency. On the other hand, phase noise (PN) increases with carrier frequency, and increasing subcarrier spacing mitigates PN. Decreasing CP length means that overhead does not get too high. A more detailed CP overhead analysis can be found in [20].

Next, we give an example numerology targeted especially for the cm-wave area. In order to reuse LTEs functional blocks, we use a sample clock frequency of 153.60 MHz, which is 5 times the LTE clock frequency. With 75 kHz subcarrier spacing and total CP & GP duration of 13.33 μs, we get a subframe length of 0.2 ms, which is short enough for 1 ms latency. All parameters are shown in Table I.

IV. CASE STUDY OF FC-F-OFDM WITH CM-WAVE NUMEROLOGY

In our case study we consider utilizing FC-F-OFDM waveform for the uplink data payload of the flexible TDD structure presented in the previous section. We assume that resource blocks consist of $L_{RB} = 160$ subcarriers. In the full-band case, there is just a single group of resource blocks with 1280 carriers. For the guardbands between groups of RBs, we consider two choices, $L_G = \{3, 5\}$. The FFT-domain filtering weights are optimized for both cases separately. The number of active subcarriers in a group of RBs is then $n_{RB} \cdot 160 - L_G$. The used 100 MHz carrier bandwidth corresponds to about 1333 subcarriers, so at the carrier edges the guardbands are significantly wider, providing enhanced ACLR characteristics. The CP length is $N/16 = 2048/16 = 128$ samples at the carrier sampling rate.

The FC-overlap factor of 3/8 was found to be the most interesting choice. Among the alternative values, the overlap of 1/2 gives somewhat improved performance but also significantly higher computational complexity. On the other hand, the overlap of 1/4 gives lower complexity but significantly reduced performance. The overlap of 3/8 means that for a group of RBs with $n_{RB} \cdot 160$ subcarriers, $n_{RB} \cdot 100$ useful samples are obtained from each FC block. With the CP-length of $n_{RB} \cdot 10$ low-rate samples, a 12-symbol subframe consists of $n_{RB} \cdot 2040$ low-rate samples, and 21 FC blocks need to be processed per subframe.

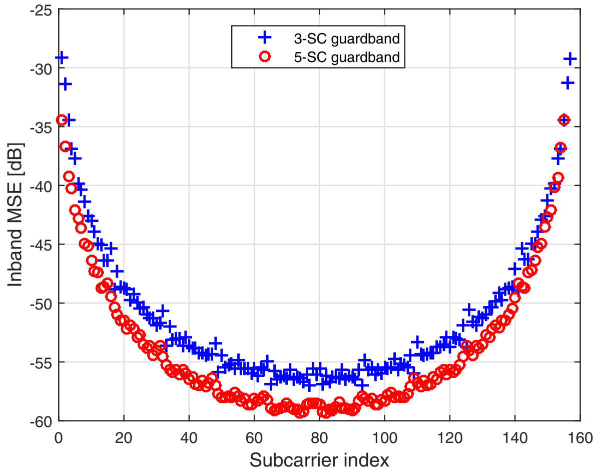
To reduce the time-domain overheads, filtering tails (due to relatively long effective filter impulse response) are truncated on both sides to 128 samples, i.e, to the same length as the CPs. This is the additional overhead due to filtering, in comparison to the basic CP-OFDM scheme. However, in the flexible TDD frame structure, these filtering tails can, at least partly, be included in the guard periods needed for link direction switching.

Next we evaluate the FC-F-OFDM performance in terms of in-band interference (IBI) and out-of-band power leakage characteristics.

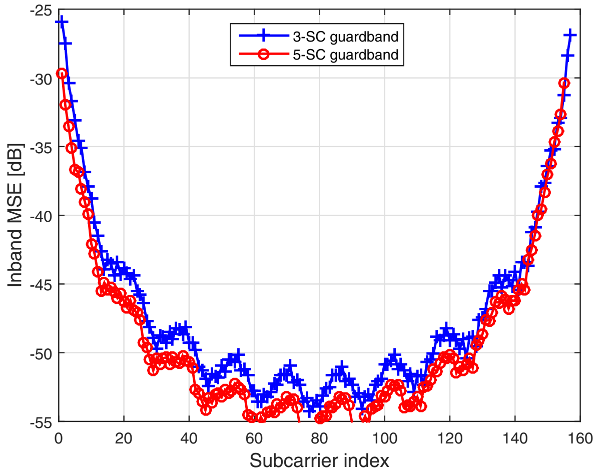
A. Inband Interference

The IBI is measured by the mean-squared error (MSE) in the equalized subcarrier symbols in reference to the symbol energy, and without channel noise. Figure 7 shows first the inband MSE for the active subcarriers of a single isolated resource block, for both guardband widths. It can be seen that the IBI is significant in a few subcarriers close to the edges of the RB. Anyway, the worst-case inband MSE is at the level of -28 dB or -34 dB with 3 or 5 subcarrier guardbands, respectively.

Figure 7 shows also a more practical case were relevant additional interference sources are included: (i) Adjacent resource blocks are active and introduce interference to the target RB. (ii) The adjacent RBs are not synchronized to the target one: There is a relative timing offset of half of the OFDM symbol interval and relative frequency offset of quarter of the subcarrier spacing between them (reduced spacing on one side and increased spacing on the other). (iii) A two-path channel is included, with delay spread equal to the CP length and tap magnitudes $\{1, 0.5\}$. The worst-case inband MSE is still at the level of -26 dB and -29 dB with 3 or 5 subcarrier guardbands, respectively. Finally, Figure 8 shows the inband subcarrier MSE plots for isolated groups of 1, 2, 4, or 8 RBs with 5 subcarrier guardbands. It is seen that the worst case IBI is quite similar for different FC-filtering bandwidths and the number of active subcarriers experiencing somewhat significant IBI is the same in all cases. For example, 3 edge subcarriers have an IBI above -40 dB in all cases.



(a)



(b)

Fig. 7. Inband interference in FC-F-OFDM with 160 subcarrier RB, 3 or 5 subcarrier guardbands, and FC-overlap factor of 3/8. (a) Isolated RB, ideal channel, no noise. (b) With interference leakage from adjacent non-synchronized RBs, two-tap channel with delay spread equal to CP length, no noise.

B. Out-of-Band Interference

Figure 9 shows the power spectral density (PSD) plots for FC-F-OFDM with filtering for groups of 1, 2, 4, and 8 RBs. It can be seen that the spectral characteristics, especially the transition band shape, remain practically the same when the FC-filter bandwidth is adjusted for different sizes of RB groups. With 5 subcarrier guardbands, the out-of-band PSD is at the level of -42 dB at the first active subcarrier of an adjacent RB group. With 3 subcarrier guardband, the corresponding value is -36 dB. Since the guardbands at the edges of the carrier are wider, the PSD level outside the 100 MHz carrier band is below -60 dB with respect to the passband.

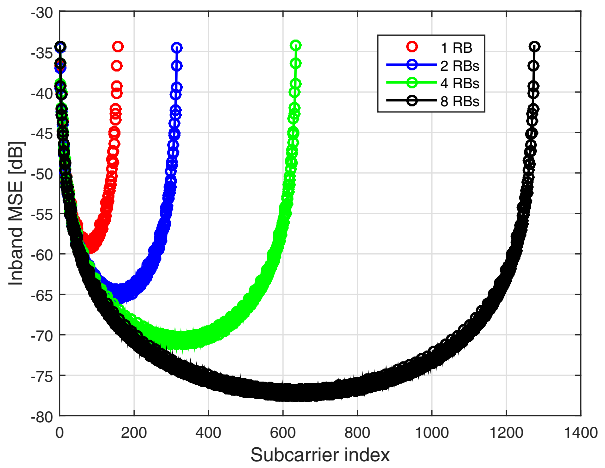


Fig. 8. Inband interference in FC-F-OFDM with filter bandwidths of 1, 2, 4, and 8 RBs of 160 subcarriers. FC-overlap factor of 3/8, 5 subcarrier guardbands, noise-free, ideal channel, isolated RB case.

C. Computational Complexity

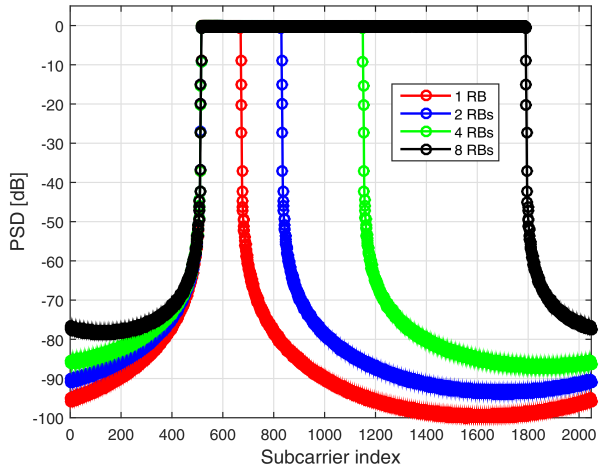
Table II shows basic complexity metrics for FC-F-OFDM in comparison to basic CP-OFDM. The results are shown for (i) a single RB of 160 subcarriers, (ii) 8 RBs which are all isolated from each other using FC-FB, and (iii) full-band transmission case, in which FC-filtering is used to realize only tight filtering for the whole carrier. First the numbers of needed FFT/IFFT transforms for 12 OFDM symbol data block are shown. CP-OFDM uses 12 transforms of length 2048 in all cases. With the FC-overlap of 3/8, FC-F-OFDM needs 21 long transforms of length 2048 in all cases. Additionally, FC-F-OFDM needs for each filtering channel 21 short transforms for FC and 12 short transforms for OFDM processing. For 1-RB channel, the short transform length is 160, in the fullband case the length is 1280.

Table II shows also the relative multiplication rates for FC-F-OFDM versus CP-OFDM, both for transmitter and receiver sides. On the transmitter side, practically all the multiplications come from the transforms. The FC weight coefficients have a very small effect. On the receiver side, a complex coefficient (4 real multiplications) is needed for each active subcarrier as equalizer. The equalizer complexity is the same for FC-F-OFDM and CP-OFDM. The most effective algorithms found in the literature [21], [22] use 16388, 8980, and 660 real multiplications for transforms with the lengths of 2048, 1280, and 160, respectively. In general, the multiplication rate of FC-F-OFDM compares favorably with time-domain filtering solutions for F-OFDM reported in the literature [6], [7], [8].

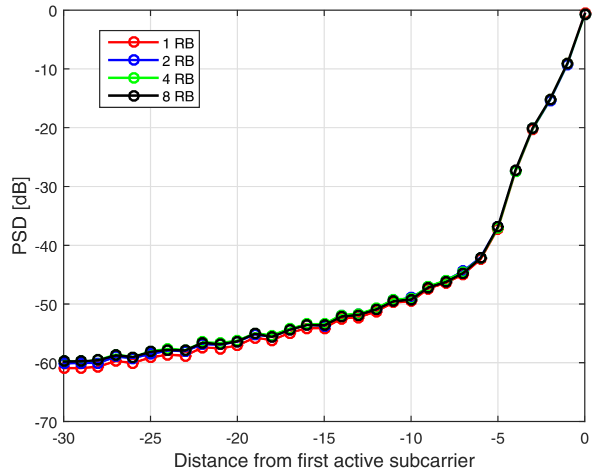
V. Concluding Remarks

This paper demonstrated how to use fast-convolution based filter processing for efficient realization of the resource block filtered CP-OFDM (or ZP-OFDM) scheme. In comparison to the basic CP-OFDM, the complexity increase can be seen affordable, while considering other computationally extensive processing modules, such as the channel decoder. The main benefit of FC-F-OFDM is its high flexibility with affordable complexity compared to reported time-domain filtering solutions. The scheme allows to realize filtering for suppressing interference leakage between resource blocks which are operated asynchronously or are otherwise susceptible to interference leakage effects. Yet the scheme also allows to operate contiguous synchronous resource blocks without filtering guardbands in between.

The presented FC-FB parametrization and filter design should be considered as preliminary. There are various possibilities to search for improved tradeoff between spectral efficiency, spectral purity, inband interference, and implementation complexity. The tradeoff involves the choice of system numerology, guardband width, FC-overlap factor, and weight mask optimization. Another future study topic is the choice of uplink waveform with low peak-to-average power ratio (PAPR). The SC-FDMA scheme can be directly applied with RB filtering, but a more straightforward approach would be to use basic single carrier transmission with FC-based RRC-type pulse-shaping with adjustable roll-off [10].



(a)



(b)

Fig. 9. Power spectra for FC-F-OFDM with filter bandwidths of 1, 2, 4, and 8 RBs of 160 subcarriers. FC-overlap factor of 3/8, 5 subcarrier guardbands. (a) Spectrum over the whole FFT bandwidth. (b) Zoom to the transition band region. The spectrum analysis is done using a PHYDYAS filter bank [5] with frequency resolution corresponding to the OFDM subcarrier spacing.

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TABLE II. COMPLEXITY COMPARISON FOR FC-F-OFDM VS. CP-OFDM.

Needed transforms per data block of 12 CP-OFDM symbols			
	1 RB	8 independent RBs	Full-band
CP-OFDM	$12 \times C_{2048}$	$12\times C_{2048}$	$12\times C_{2048}$
FC-F-OFDM	$21 \times C_{2048} + 33 \times C_{160}$	$21 \times C_{2048} + 8 \times 33 \times C_{160}$	$21 \times C_{2048} + 33 \times C_{1280}$

Relative multiplication rate in TX/RX with CP-OFDM as reference			
	1 RB	8 independent RBs	Full-band
FC-F-OFDM	1.87/1.83	2.64/2.25	3.26/2.73

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