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Fast-Convolution Filter Bank Approach for Non-Contiguous Spectrum Use

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Abstract: Fast-convolution processing, consisting of an FFT, frequency-domain weights, and an IFFT, offers an effective and very flexible way for implementing multirate filters and filter banks. In recent years, fast-convolution filter banks (FC-FBs) have been considered for channelization filtering in software defined radios and recently also for implementing nearly perfect reconstruction transmultiplexers. FC-FB provides an alternative way of implementing filter bank multicarrier systems with good spectral containment and high flexibility in tuning the subchannel bandwidths and center frequencies. These features make FC-FBs a particularly interesting choice for multicarrier transmission in challenging radio scenarios like dynamic spectrum access, cognitive radio, and fragmented spectrum use. This paper develops an FC-FB based transmission scheme of the FBMC/OQAM type with the main parameters of the 5 MHz LTE system. The main application in mind is the development of broadband data communication service to the evolution of TETRA standards for the Professional Mobile Radio (PMR). In this development, a challenging coexistence scenario is commonly considered, since the idea is to use the spectral slots in the PMR band between the active narrowband TETRA channels for broadband communication.

Keywords: Cognitive Radio, OFDM, Peak-to-average power ratio, Spectral shape

1. Introduction

Multicarrier modulation has most of the key elements needed in the challenging new spectrum use scenarios, like opportunistic dynamic spectrum access, cognitive radio, and heterogeneous wireless system coexistence. Characteristic to these situations is the need to adjust the spectral characteristics of the transmitted signal, notably bandwidth and center frequency, to the available unused slots of radio spectrum. To support high data rates, it is often desirable to combine multiple non-contiguous spectrum slots in the transmission. In multicarrier systems, this can be achieved by activating only those subcarriers that are within the available frequency slots. One important example case of such fragment spectrum use is the high data rate services to be developed for the Professional Mobile Radio (PMR), which is utilized, e.g., by safety organizations [1]. Currently, PMR supports voice and narrowband data services, based on the family of TETRA standards in Europe and many countries outside Europe, as well as APCO25 in North America.

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 doing channel equalization, high flexibility and efficiency in allocating spectral resources to different users, as well the simplicity of combining multi-antenna schemes with the core functionality [2]. However, OFDM has one major limitation in the mentioned co-existence scenarios: limitations in spectral containment, which leads to high sensitivity to interferences from asynchronous spectral components, e.g., in fragmented spectrum use. The traditional channel filtering approach is commonly used for isolating the used frequency band from adjacent channels. However, in case of dynamic and/or fragmented spectrum use, the needed channel filtering becomes difficult to implement. Various techniques to reduce the level of sidelobes in the OFDM spectrum are available in the literature [3, 4, 5, 6, 7]. However, each of them has its limitations in terms of overheads in the transmission capacity and/or implementation complexity versus efficiency of sidelobe suppression.

An alternative scheme for the considered scenarios is offered by the filter bank based methods of waveform processing and channelization filtering [8]. Actually, it is possible to combine both functions in filter bank based implementations:

1. The waveforms generated for transmission are spectrally well-contained and no other measures are needed to clean the unused portions of the spectrum allocated for dynamic/fragmented use.
2. The filter bank processing on the receiver side is able to suppress the interferences in the unused parts of the allocated spectrum.

Naturally, there are limitations in the reachable levels of attenuation, mostly determined by the analog RF imperfections, notably power amplifier nonlinearity on the transmitter side and nonlinearity of the active stages of the receiver chain, as well as I/Q imbalance effects on both sides.

A relatively widely studied filter bank based waveform is FBMC/OQAM (filter bank multicarrier/offset-QAM, more commonly known as OFDM /OQAM) [9, 10]. While reaching high spectral containment, it keeps many of the important features of OFDM. Even though FBMC/OQAM has its limitations in terms of conceptual and implementation complexity and difficulties with certain multi-antenna transmission schemes, it has received increasing interest in the mentioned challenging spectrum use scenarios. There are also filter bank based single carrier transmission schemes with high flexibility and reduced peak-to-average power ratio (PAPR), similar to the OFDM based SC-FDMA adopted for the LTE uplink [11].

This paper focuses on a special implementation scheme for multirate filter banks which is based on fast-convolution (FC) processing. The basic idea of fast convolution is that a high-order filter can be implemented effectively through multiplication in frequency domain, after taking DFT's of the input sequence and the filter impulse response. Eventually, the time-domain output is obtained by IDFT. Commonly, efficient implementation techniques, like FFT/IFFT, are used for the transforms, and overlap-save processing is adopted for processing long sequences. The application of FC to multirate filters has be presented in [12], and FC implementations of channelization filters has been considered in [13, 14, 15]. The authors have introduced in [16] the idea of FC implementation of nearly perfect-reconstruction filter bank systems and detailed analysis and FC-FB optimization methods are developed in [17]. These papers demonstrate the greatly increased flexibility and efficiency of FC-FB in communication signal processing, in comparison with the commonly used polyphase implementation structure.

After introducing the ideas of FBMC/OQAM and FC-FB in Section II, a case study of FC-FB design, with parameters of the 5 MHz LTE system, is presented in Section III. The resulting spectral characteristics are presented, and the implementation complexity is compared with basic OFDM and polyphase FBMC/OQAM scheme.

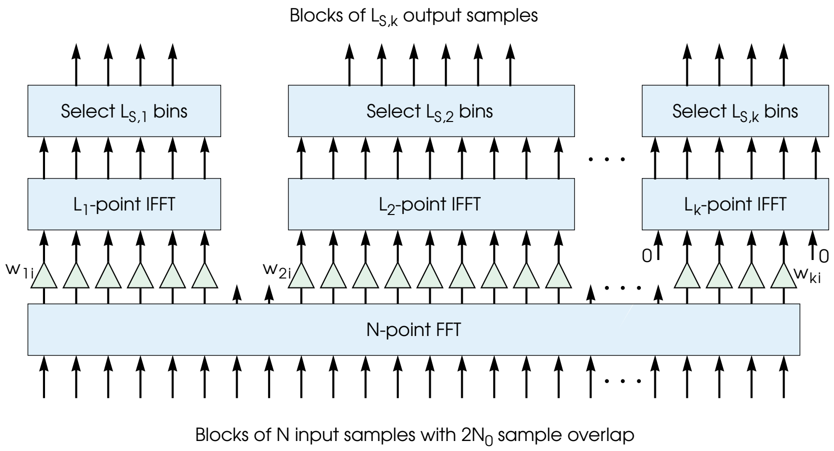

Figure 1: Fast convolution based flexible analysis filter bank using overlap-save processing.

2. Fast-Convolution Filter Banks

The structure of FC-based flexible analysis filter bank (AFB) is illustrated in Fig. 1. The general idea of the structure is a multirate version of fast convolution [13, 12]. We consider 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. We are interested in cases where the output signals are critically sampled or oversampled by a small factor. We also note that different subbands may be overlapping. The dual structure of Fig. 1 can be used for combining multiple low-rate, narrowband signals into a single wideband signal, following the frequency-division multiplexing principle.

Figure 1 includes sampling rate reduction by factors

$$R_k = N/L_k = N_S/L_{S,k} \tag{1}$$

where k is the subband index and the notation used for the lengths of the overlap-save processing blocks is indicated in Fig. 2. In other words, the sampling rate conversion factor is determined by the IFFT size, and can be configured for each subband individually. Naturally, the IFFT size determines the maximum number of frequency bins, i.e., the bandwidth of the subband. It is also possible to increase the subband output sampling rate by increasing the IFFT size by adding zero-valued bins outside the wanted subband frequency range. In communication applications, a subband would contain a communication waveform with the specific symbol rate, and the output sampling rate is normally chosen as its (small) integer multiple.

Regardless of the specific processing applied for each subband, the decimation factor of the structure of Fig. 1 is given by (1) [12]. This means that the length of the FC output block is reduced by the same factor, and so is also the length of the overlapping part in the overlap-save processing. The input and output block lengths have to exactly match, taking into account the sampling rate conversion factor. It follows that in (1), both N/L_k and $N_S/L_{S,k}$ have to be integers. For example, if $N_S = 3N/4$, L_k has to be a multiple of 4, or if $N_S = 4N/5$, L_k has to be a multiple of 5. If f_s is the input sampling rate, the possible output sampling rates are multiples of $4f_s/N$ and $5f_s/N$, respectively. So the configurability of the output sampling rate depends greatly on the choice of N and N_S.

There are two key parameters which have an effect on the spectral characteristics of the FC-FB scheme:

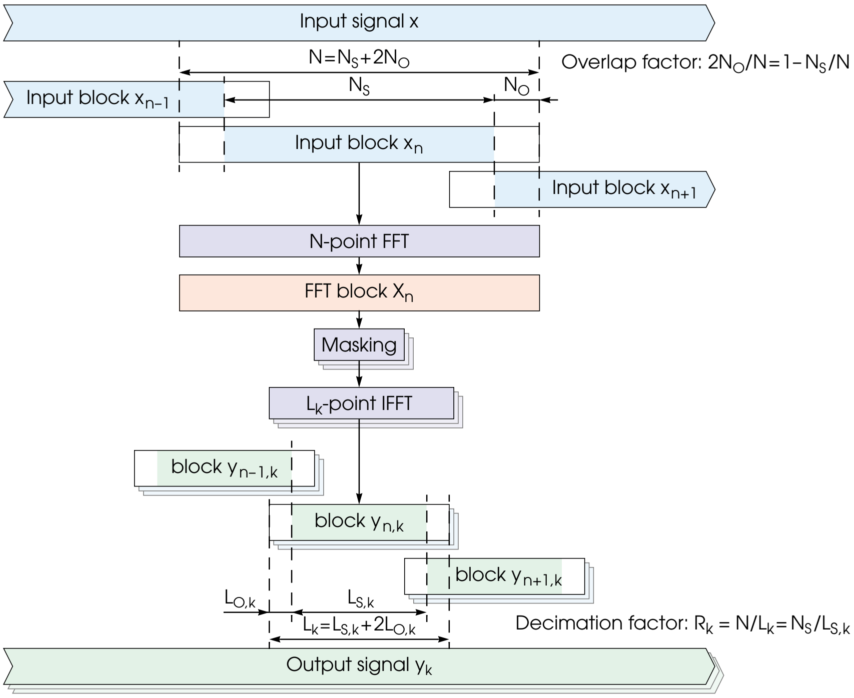

Figure 2: Overlap-save processing.

- The IFFT size L is defining how well the filter frequency response can be optimized. In general, increasing the value of L helps to improve the stopband attenuation.

- The overlap factor $1 - L_S/L$: In FC based multirate signal processing there is an inevitable cyclic distortion effect because the overlapping part of the processing block cannot be made big enough to absorb the tails of the filter impulse response. Naturally, this effect can be reduced by increasing the overlap factor.

In [17] these effects were analyzed using a periodically time variant model for FC processing and effective tools for frequency response analysis and FC filter optimization were developed.

The FC-FB model can be used for generating and demodulating different kinds of communication waveforms. In our approach, the basic design is done for a filter channel with roll-off of one. The frequency-domain weights consist of two symmetric transition bands and all stopband bins are set to zero. Figure 3(a) shows an FBMC/OQAM type multiplex of subchannels, which is constructed using such basic filters. The subchannel spacing is half of the overall bandwidth, which is equal to the IFFT length. Therefore, the subchannels are oversampled by two, which is also necessary for staggered, OQAM type subchannel processing. OQAM subcarrier signal model, in turn, is necessary for reaching (near) orthogonality of overlapping subcarriers in FB systems.

The transition band shape should be of the square-root Nyquist filter type. The root-raised-cosine (RRC) model can be used straightforwardly for constructing such transition bands. However, depending on the FC parameters, optimization of the weights may give significant improvement in the spectral characteristics [17].

One important feature of the FC-FB structure is that the transition band shape optimized for the basic case can be used for constructing filters with arbitrary bandwidths. In Figure 3(b) a filtered multi-tone (FMT) [18] type multiplex of non-overlapping subchannels is shown and Figure 3(c) shows a single-carrier transmission channel. In these cases, the normal QAM

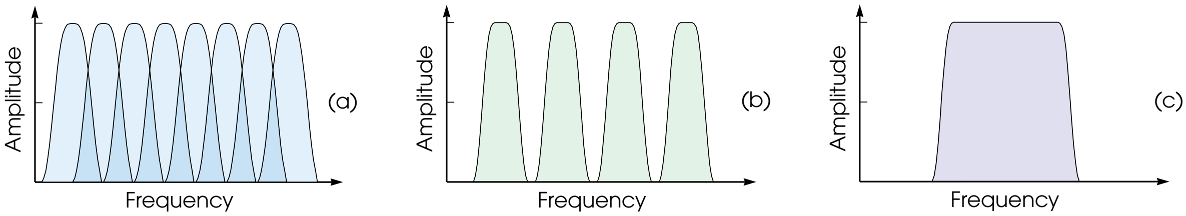

Figure 3: Examples of different waveforms which can be implemented using the FC-FB structure. (a) FBMC/OQAM type multiplex of eight subchannel, (b) FMT type multiplex of four subchannels, (c) and single-carrier transmission channel.

modulation can be used. The subchannel bandwidths and center frequencies can be independently tuned, with the resolution of the FFT bin spacing. Different types of multiplexes can be combined in a single FC-FB structure. It is also possible to use different transition band shapes for different multiplexes, if so desired. The flexibility of the scheme can be used also for coarse frequency offset compensation by shifting the set of frequency bins connected to the subchannel processing functions. For time synchronization purposes, a linearly frequency-dependent phase response can be introduced to each subcarrier for timing offset correction.

3. 5 MHz LTE Case

In this section, we explore the spectral characteristics of the FC-FB approach. We choose a parametrization based on 5 MHz LTE with $M = 512$ subcarriers, out of which 300 active subcarriers are used [2]. Actually, the scheme includes 150 active subcarriers on both sides of the unused DC-subcarrier. The 300 active subcarriers are scheduled in resource blocks of 12 subcarriers, i.e., there are 25 resource blocks (RBs). We consider the non-contiguous scenario where a spectral gap of 1 RB (12 subcarriers) is reserved for narrowband legacy transmissions. Without loss of generality, we assume that this gap is next to the DC subcarrier. In time domain, the resource blocks have the length of 0.5 ms, i.e., 3840 samples at the used sampling rate of 7.68 MHz. The RBs are scheduled to different users in 1 ms sub-frames of 2 RBs. Especially in the uplink, the minimum transmission burst length is 1 ms, consisting of 7680 samples. In the basic LTE transmission scheme, 14 OFDM symbols are transmitted during one sub-frame. In the extended cyclic prefix (CP) mode, designed to accommodate longer channel delay spreads, 12 OFDM symbols are transmitted during one sub-frame.

Here the approach for selecting the main parameters of the FC-FB scheme is to use the same sampling rate, the same subcarrier spacing, and the same parameters for the RBs as in the 5 MHz LTE system. Consequently, the FFT length can be determined as $N = ML/2$ where L is the IFFT length and the subcarrier spacing is $L/2$ FFT bins. (For clarity of the discussion, we focus here on the analysis bank of the receiver.) The choice of the FFT length, together with the overlap factor, defines the time interval of each processing block and has a significant effect on the performance of the scheme with fast-fading channels. However, this depends greatly on the used channel equalization structure, and the analysis of the fading sensitivity is left as a topic for future studies. On the other hand, increasing the FFT length gives better changes to shape the spectrum to improve spectral containment. In any case, we assume that the FFT length should be shorter than the RB length and we are looking for a good trade-off between the spectrum control and fading sensitivity. A third element in the tradeoff is implementation complexity. Increasing the overlap factor improves the spectral containment for a given IFFT length but it also increases the computational complexity as the ratio of the useful part of FFT to the FFT length is reduced.

The general results of [17] indicate that using IFFT length of 16 gives a reasonable compromise between the mentioned effects. This choice leads to the FFT length of 4096. Figure 4 shows a comparison of the spectrum leakage to the 12 subcarrier spectral gap in the 5 MHz LTE case with different overlap factors $1 - L_S/L$ for $L_S = 9$, $L_S = 12$, and $L_S = 16$. Since FC-FB is a periodically time-varying process, the spectrum leakage varies with time within the FFT block. The figure shows the mean-squared distortion for each sample within the useful part of the IFFT block and for the 2nd to 11th subcarrier within the RB-wide gap. Since the FB subchannels have a roll-off of one, the first and 12th subcarrier are significantly overlapping with the active subcarriers at the edges, and are not included in the plots. In the experiment, it is assumed that all the 288 active subcarriers are transmitting offset-QPSK waveforms with equal power levels, and the interference level is relative to the active subcarrier power. We can see that the interference level is considerably higher during the first and last subcarrier symbols of the used part of the IFFT block. The average spectrum leakage levels over the output blocks are shown in Table 1. Figure 5 shows the inband interference in an active subcarrier due to the imperfections of the FC processing. Again, the interference dominates in the first and last samples of the IFFT block. All these results are obtained through a simulation model of the FC-FB filter bank system, and they are consistent with the results obtained through the analytical model.

Figure 6 shows a comparison of the average spectrum leakage level in different multicarrier systems, including basic CP-OFDM, CP-OFDM with raised-cosine windowing, polyphase filter banks with impulse response lengths of $KM = 3M$ and $KM = 4M$ using the FB design of [19, 8], as well as FC-FB with the three different overlap factors. The OFDM case represents LTE without any additional methods for spectrum control. The good spectral containment of FB schemes is clearly visible, as well as the nature of the tradeoffs of different FB schemes from the spectrum control point of view. Raised-cosine windowing is the most basic scheme, apart from the channel filtering approach, for enhancing the spectral characteristics of OFDM. Here we have assumed that 6 OFDM symbols are transmitted in each RB and that the normal CP length of LTE is used. Instead of extending the CP's, the extra time intervals are used for smooth, RC-shaped transitions between the symbols.

FBMC uses OQAM subcarrier modulation and the subcarrier signals are sampled at twice the OFDM symbol rate. The 1 ms sub-frame consists of 15 OQAM symbols or 30 subcarrier samples. Each 4096-point FFT is used to produce 9, 12, or 14 subcarrier samples with the overlap factors of $7/16$, $4/16$, and $2/16$, respectively. Therefore, 3 or 4 FFT blocks are needed per sub-frame. However, in continuous transmission, the FFT blocks are not confined to RB or sub-frame boundaries. We can see that in the downlink transmission, the FBMC approach allows to increase the number transmitted bits per RB by the factor of $15/14$.

However, since uplink users are not perfectly synchronized in time and frequency, guard bands need to be inserted between the RBs of different users and guard intervals are needed

Table 1: Average interference levels in dB in the subcarriers of 1 RB wide spectrum gap.

	SC 2/11	SC 3/10	SC 4/9	SC 5/8	SC 6/7
$L_S = 9$	-64.2	-71.4	-74.4	-75.9	-76.5
$L_S = 12$	-48.7	-57.3	-61.9	-64.7	-66.0
$L_S = 14$	-43.2	-51.0	-55.4	-58.2	-59.6

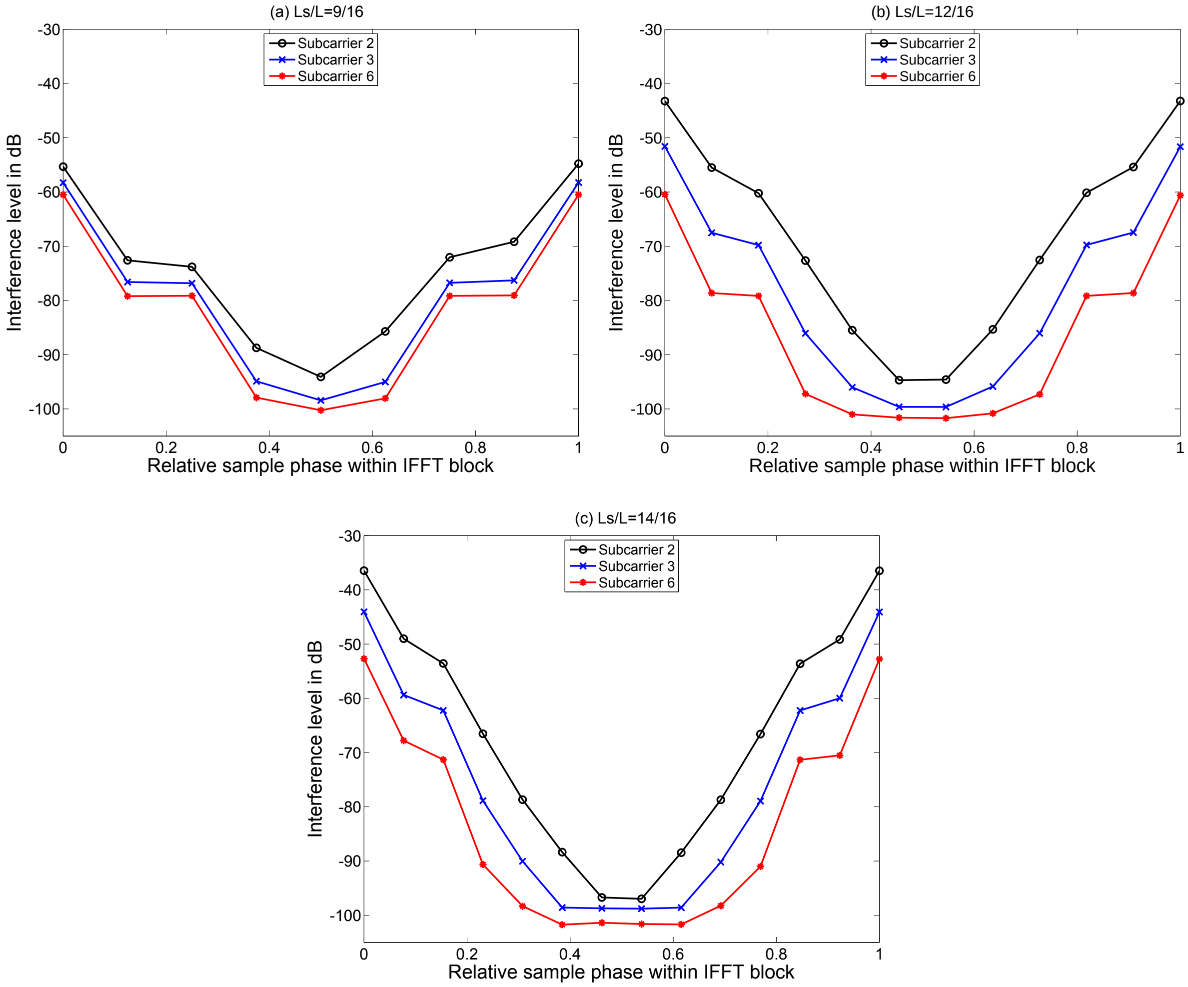

Figure 4: Interference level in 12 subchannels (1 RB) wide spectral gap for 512 subcarriers out of which 300 are in use for $N = 4096$ and $L = 16$. (a) Optimized design with $L_S = 9$. (b) RRC-design with $L_S = 12$. (c) RRC-design with $L_S = 14$.

between different users' transmission bursts exploiting the same subcarriers. Using just one subcarrier subband between different user's groups of subcarriers, the users are well isolated even if they are not synchronized in time as long as the relative frequency offset is small compared with the subcarrier spacing of 15 kHz. One subcarrier guard band can be implemented systematically, e.g., by leaving the upper edge subcarrier of each user's transmission block to be unused.

To maintain spectrum control in the uplink, some subcarrier symbols in the beginning and at the end of the transmission burst must be set to zero and also the symbol pulses may have to be truncated. With the overlap factors of $7/16$, $4/16$, and $2/16$, it is possible to include 11.5, 12, or 14 OQAM symbols in each subcarrier of a sub-frame long transmission burst without the need for impulse response truncation. (Here 0.5 OQAM symbols mean just the real or imaginary part of the complex symbol, or effectively half the number of bits mapped to each complex symbol.) Depending on how well different uplink users are synchronized in time, additional guard intervals may be needed for the transition intervals. With this model of guard bands and guard intervals, the overheads in transmission capacity depend on the users data rates and also on the scheduling approach, as well as on the tolerable level of spectral leakage through the choice of the overlap factor.

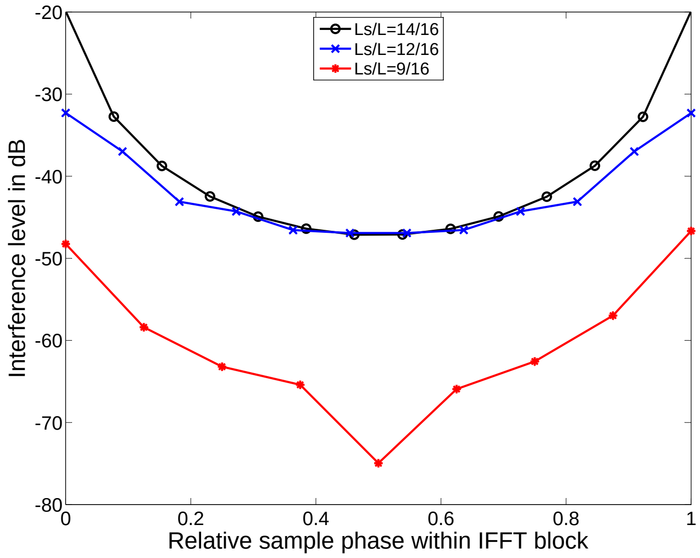

Figure 5: Inband interference level in an active subcarrier in the middle of a transmission block for the three cases of Figure 4.

Table 2: Computational complexity of different multicarrier schemes in terms of number of multiplications / number of additions. The values are given per detected symbol.

	CP-OFDM	FBMC $K = 3$	FBMC $K = 4$	FC-FBMC $\frac{L_S}{L} = \frac{14}{16}$	FC-FBMC $\frac{L_S}{L} = \frac{12}{16}$	FC-FBMC $\frac{L_S}{L} = \frac{9}{16}$
$M_{act} = 300$	$14/43$	$45/100$	$52/106$	$29/86$	$34/100$	$45/134$
$M_{act} = 60$	$55/207$	$209/482$	$243/516$	$99/343$	$116/400$	$154/534$

Table 2 shows a comparison of the computational complexity of different multicarrier transmission schemes based on the number of multiplications and additions needed in the receiver analysis bank processing [5]. Also a single-tap subcarrier equalizer is included for each of the schemes. With the considered parameters, all the needed FFT and IFFT lengths are powers of two, and the complexity of the split-radix algorithm has been used as the basis. The possibilities of reducing the FFT complexity through FFT pruning is not considered here. The results are given for the case where all the 300 subcarriers are active, and also for the case where 60 subcarriers (5 RB's) are active. We can see that the complexity of the FC-FB scheme is significantly lower than that of the polyphase FBMC implementation. The difference is pronounced when the number of active subcarriers is reduced. The complexity of the FC-FB with smaller overlap factor is about double the complexity of the basic OFDM scheme.

4. Concluding Remarks

In this paper, we have explored the characteristics of fast-convolution based filter bank schemes in fragmented spectrum use cases, considering the spectral properties and implementation complexity. FC-FB is a promising scheme with high flexibility and potential for somewhat reduced complexity in comparison with the polyphase FB structures.

Sufficiently high overlap factor in the FC processing, like 7/16 in the example case, results in a safe design where both inband interference and spectrum leakage are at low level. The computational complexity of such a design seems to be similar or somewhat lower than in

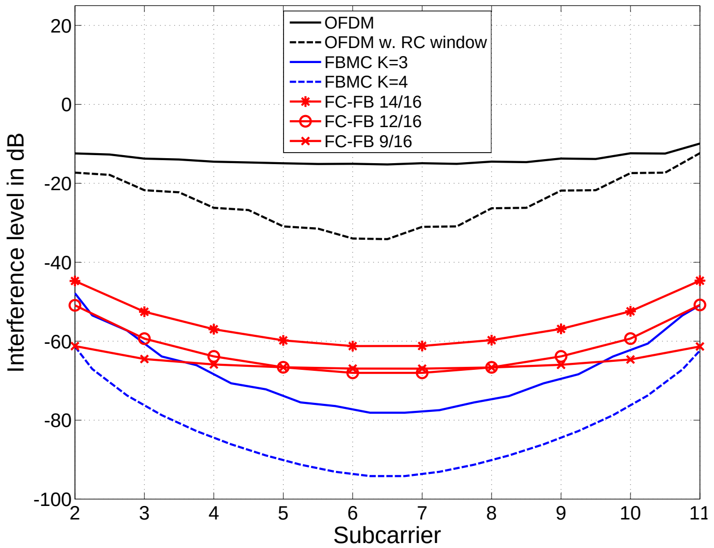

Figure 6: Average interface levels in 12 subcarriers for different multicarrier systems.

polyphase FBMC/OQAM implementation, but the FC-FB solution offers much higher flexibility. With careful choice of the FC processing parameters and careful filter optimization, it may be possible to reduce the overlap factor significantly, leading to reduced computational complexity. This is an important topic for future studies. Another crucial issue is to evaluate the performance of the proposed scheme with fast-fading channels, considering alternative channel equalization and synchronization structures.

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