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Channel Estimation Andequalization For Fbmc Systems

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ABSTRACT
The main concern of the paper is to analyze physical layer succeeding OFDM,i.e., a multi-carrier system applying filter banks omitting severe out-of-band leakage of OFDM.First standard Filter bank structure was considered and reduced to another structure with polyphase elements of the prototype filter. The generated waveforms are spectrally well-contained, with very small power leakage to adjacent frequencies, and are thus good candidates for opportunistic and heterogeneous spectrum use scenarios. On the side of receiver, the filter bank approach can be used for simultaneously processing multiple channels with individually tunable bandwidths, different center frequencies, and timing offsets, providing asynchronous multi-user operation. Generallythese implementations are compared with traditional polyphase designs in terms of different spectral characteristics and computational complexity.
KEYWORDS: FBMC, Channel Estimation, Equalization, BER.

I. INTRODUCTION

Multicarrier modulation has most of the key elements required with in the challenging new spectrum use eventualities, like timeserving dynamic spectrum access, cognitive radio, and heterogeneous wireless system coexistence. Characteristic to those situations is compelled to adjust the spectral characteristics of the transmitted signal to the available unused slots of radio spectrum. To support high data rates, it is typically fascinating to mix multiple non-contiguous spectrum slots with in the transmission. In multicarrier systems, this will be achieved by activating solely those subcarriers that are among the obtainable 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, supported by the family of terrestrial trunked radio (TETRA) standards in Europe and lots of countries outside Europe, in addition as APCO25 in North America.Orthogonal frequency-division multiplexing (OFDM) isthat the most vital multicarrier technique and it is extensively utilized in trendy broadband radio access systems. This is due to the straightforward and sturdy means of channelequalization, highflexibilityandefficiencyinallocatingspectralresourcesto completely differentusers,additionally assimplicityofmixingmulti-antenna schemes with the core practicality [2]. However, OFDM has one major limitation with in the mentioned co-existence scenarios: limitations in spectral containment, that cause high sensitivity to interferences from asynchronous spectralelements.

An alternative theme for the thought of situations is obtainable by the filter bank based strategies of waveform processing and channelization filtering [3]. Actually, it is possible to combine both functions in filter bank based implementations. First, the waveforms generated for transmission are spectrally well-contained and no other measures are needed to clean the unused parts of the spectrum allotted for dynamic/fragmented use. Second, the filter bank processing on the receiver side is in a position to suppress the interferences from the unused components of the allocated spectrum. Naturally, there are limitations within the approachable levels of attenuation, largely determined by the analog RF imperfections, notably power amplifiernonlinearityonthetransmitterside.A relatively widely studied filter bank basedwaveform is FBMC/OQAM (filter bank multicarrier/offset-QAM, also called as OFDM/OQAM) [4] [5]. While reaching high spectral containment, it keeps several of the vitaloptions of OFDM. Even although FBMC/OQAM has its limitations in terms of conceptual and implementation complexness, it has received increasing interest with in the mentioned difficult spectrum use scenarios. Another well-known FBMC scheme is filtered multi-tone (FMT) [6], [7]. FBMC/OQAM reaches maximal spectral efficiency by using significantly overlapping subcarriers, typically with the roll-off of 1, and the orthogonality is reached through offset-QAM modulation of subcarriers. FMT uses non-overlapping subcarriers, and comparatively little roll-off is chosen to succeed in good spectral efficiency. The main good thing of FMT is that basic QAM modulation may be utilized in subcarriers,thatpermitsadditionaldirectapplicationofpilotbased synchronization and channel estimation schemes, likewise the multi-antenna configurations developed for OFDM. On the other hand, offset-QAM modulation introduces various challenges in developing effective pilot schemes and in applying certain multi-antenna configurations, like Alamouticoding.

In this paper, we present optimized FBMC/OQAMand FMTdesignsbasedonfast-convolution(FC)processing,which has recently been introduced in the waveform processing context [8], [9]. It can be used for efficient implementation of different FBMC schemes with greatly increased flexibility and improved support for asynchronous multi-user operation [10], [11]. After introducing the main ideas of FC filter bank (FC- FB) in Section II, FC-FB based implementations are presented and analyzed in Section III in terms of spectral properties and computationalcomplexity.

II. FAST-CONVOLUTION FILTERBANKS

This paper uses a special implementation theme for multi-irate filters and filter banks that relies on fast-convolution (FC) processing. Here the main idea is that a high-order filter may be implemented effectively through multiplication in frequency domain, once taking DFTs of the input sequence and the filter impulse response. The time domain output signal is finally obtained by IDFT. In practice, efficientimplementationtechniques,likeFFT/IFFT,areused for the transforms, and overlap-save processing is applied for processing long sequences. The application of FC to multi-rate filters has been presented in [12], and FC implementations of channelization filters are thought about in [13], [14], [15]. The authors have introduced the thought of FC-implementation of nearly perfect-reconstruction filter bank systems and careful analysis and FC filter bank (FC-FB) optimization strategies are developed in [9]. These papers demonstrate the flexibility and efficiency of FC-FB in communication signal processing.

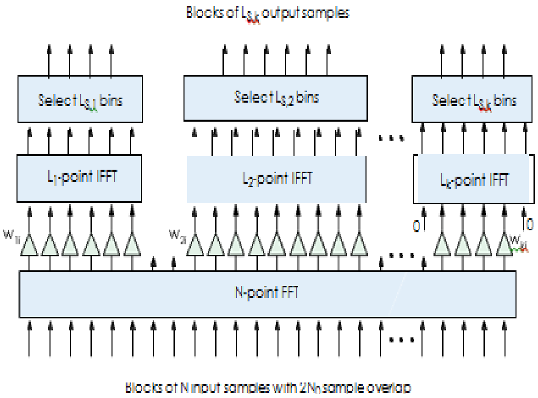

Fig.1.Fastconvolutionbasedflexibleanalysisfilterbankusingoverlap-save processing.

$N = N_S + 2N_0$, $L = L_S + 2L_0$.

Figure 1 show the structure of FC-based flexible analysis filter bank, for a case where the incoming high-rate, wideband signal is to be divided into several narrowband signals with suitable frequency responses and adjustable sampling rates. It is assumed that the output signals are oversampled by the factor of two. We also observe that different subbands may be overlapping. The dual structure of Figure 1 will be used on the transmitter side as a synthesis bank combining multiple low-rates,narrowbandsignalsintoasinglewidebandsignal.Figure 1 includes sampling rate reduction by factors

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

Where$k$ is the subband index. In alternative way, the sampling rate conversion factor is determined by the IFFT size, and may be designed for each subband individually. The IFFT size tells 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 need to specifically match, taking under consideration ofthesamplingrateconversionfactor.Consequently, it is required that 1 $L_{S,k}/L$ = 1 N_S/N . We will see that the configurability of the output sampling rate depends greatly on the choice of N and N_S. Later discussions focus on uniform filterbanks,andthesubbandindex$k$isdroppedforclarity.There are two key parameters those have an effect on the spectral characteristics of the FC-FB scheme:

The IFFT (~~s~~hort transform~~)~~ length L defines how wellthefilterfrequencyresponsecanbeoptimized.In- creasing the value of L helps to improve the stopband attenuation, because a higher number of FFT-domain weightsareusedforshapingthetransitionbands.

The overlap factor 1 L_S/L: In FC based multi-rate signal processing there is an inevitable cyclic distortion effect because the overlapping part of the processing block cannot be made big enough toabsorbthe tails of the filter impulse response. This effect can be reduced by increasing the overlap factor. But increased overlap means also higher computational complexity.

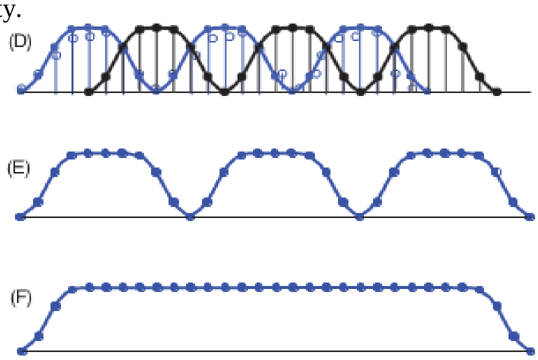

Fig.2. Examples of FFT-domain weight masks for different waveforms whichcanbeimplemented usingtheFC-FBstructure.(a)FBMC/OQAMtype- multiplexofsixsubchannels,(b)FMT-typemultiplexofthreesubchannels,(c) and single-carrier transmission channel.

In [9] these effects were analyzed using a periodically time variantmodelforFCandeffectivetoolsforfrequencyresponse analysisandFCfilteroptimizationweredeveloped.

III. FILTER BANK SYSTEM-POLYPHASE APPROCH

Filter Bank Based Multicarrier Communications. Exponentially modulated filter banks (EMFB) modified DFT (MDFT) filter banks and OFDM with offset QAM (OFDM/OQAM or FBMC/OQAM) among others, are complex filter bank structures that can produce complex I/Q baseband signals for transmission, making them suitable for FBMC systems in spectrally efficient radio communications. In FBMC communications, the filter banks are used in the trans-multiplexer (TMUX) configuration with the synthesis filter bank (SFB) in the transmitter and the analysis filter bank (AFB) in the receiver. Figure 3 shows the filter banks in this configuration as fundamental part of a complete FBMC/OQAM transmission/reception systemThis FB technique builds on uniform modulated filter banks in which a prototype filter $p[m]$ of length $L_p$is shifted in frequency to generate subbands which cover the wholesystem bandwidth.

Thetransmitter contains a synthesis filter bank (SFBand the receiver contains an analysis filter bank (AFB). In the structure of the figure, the FFT (Fast Fourier Transform) is present as in OFDM. It is augmented, to complete a filter bank, by the PPN (Polyphase Network) which consists of a set of digital filters, whose coefficients, globally, form the impulse response of the so-called prototype low-passfilter.

OFDM exhibits large ripples in the frequency domain, which imposes the orthogonality constraint between all the sub-carriers. On the contrary, the filter bank frequency response has negligible amplitude beyond the center frequency of the adjacent sub-carriers. In fact, the filter bank divides the trans- mission channel of the system into a set of sub-channels and any sub-channel overlaps with its immediate neighbors only. Then, in order to make two groups of contiguous subchannels independent, it is sufficient to leave a single empty subchannel between them.

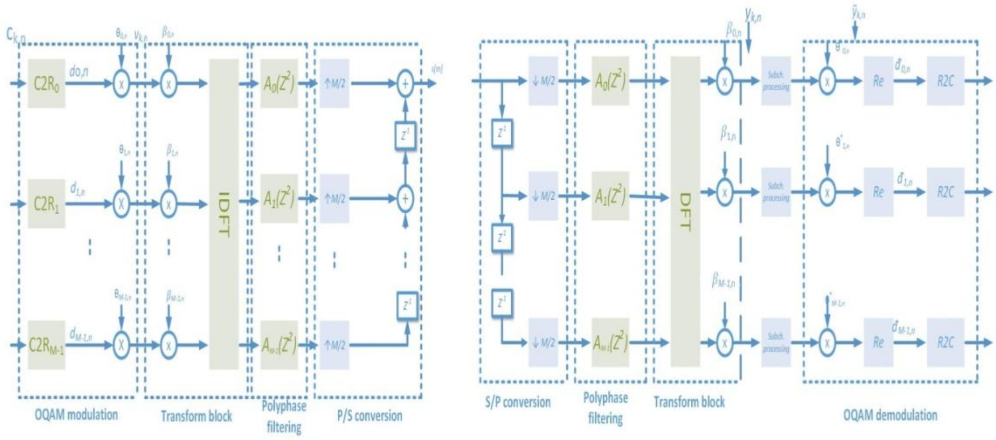

Figure 3: (a) Synthesis and (b) analysis filter banks for complex FBMC trans-multiplexer (TMUX) with per-sub channel processing

The main processing blocks in the direct form representation are OQAM pre-processing, synthesis filter bank, analysis filter bank, and OQAM post-processing. The transmission channel typically omitted when analyzing and designing TMUX systems because the channel equalization problem is handled separately. The synthesis and analysis filter banks are naturally the key componentsThe field of filter banks is very broad and even modulated filter banks can be divided into differenttypesdependingonthechoiceoftheprototypefilters,modulationfunctions,anddesired properties. The number of subchannels is twice the up-sampling and down-sampling factors indicating 2x oversampled filter banks if input and output signals are complex-valued. However, if input and output signals are purely real/imaginary-valued then the presented TMUX is equivalent to a critically sampled TMUX. This is because the samplerate (counted in terms of real-valued samples) of the SFB output and AFB input is equal to the sum of the sample rates of the subchannel signals. An extra delay Z^{-D}, with depending on the length of the prototype filter ($L_p = KM + 1 - D$), has to be includedeither to the SFB output of AFB input. Our TMUX system transmits OQAM symbols instead of QAM symbols. The pre- processing block, which utilizes the transformation between QAM and OQAM symbols,the first operation is a simple complex-to-real conversion, where the real and imaginary parts of a complex-valued symbol $c_{k,l}$are separated to form two new symbols $d_{k,2l}$and $d_{k,2l+1}$(this operation can also be called as staggering).The order of these new symbols depends on the subchannel number, i.e., the conversion is different for even and odd numbered subchannels. The complex-to- real conversion increases the sample rate by a factor of 2. The second operation is the multiplication by $\theta_{k,n}$sequence.A possible choice is$\theta_{k,n}=j^{(k+n)}$.

IV. FBMC/OQAM AND FMT DESIGNCASES

The FC-FB model can be used for generating and de- modulating different kinds of communication waveforms. In our approach, the basic design is done for a filter channel with roll-off of 1. The FFT-domain weights carries with two symmetric transition bands and all stopband bins are set to zero. Figure 2(a) shows an FBMC/OQAM-type multiplex of subchannels, which is designed using such basic filters. The subchannel spacing is half of the total bandwidth, which is equal to the IFFT length. Therefore, the subchannels are oversampled by two, which is additional need for staggered, OQAM-type subchannel process. OQAM subcarrier signal model, in turn, is important for reaching (near) orthogonality of overlapping subcarriers in FB systems. The transition band shape should be of the squareroot Nyquist filter type. The root-raised-cosine model may be used straightforwardly for constructing such transition bands. However, relying on the FC-FB parameters, optimization of the weights could provide importantimprovement with inthespectralcharacteristics[9].One necessary feature of the FC-FB structure is that the transition band shape optimized for the basic case can be used for constructing filters with discretionary bandwidths. In Figure 2(b) a filtered multi-tone (FMT) [6], [7] type multiplex of non- overlapping subchannels is shown and Figure 2(c) shows a single-carrier transmission channel. In these cases, the normal QAM modulation can be used. The subchannel bandwidths and center frequencies can be independently tuned, with the resolutionoftheFFTbinspacing.

In our case study, we consider a non-contiguous multi- carrier system design case with main parameters similar to the MHz variant of the 3GPP LTE system [2]: 128 subcarriers, out of which 72 may be active, and 15 kHz subcarrier spacing are assumed [8]. The particular scenario includes a spectrum gap of 12 subcarriers (one LTE resource block), implemented by deactivatingthecorrespondingsubcarriers. The gapisincluded for accommodating legacy narrowband services in the same frequency band, in co-existence with broadband data communications. In all the following designs, the weight coefficient optimization procedure explained in [9] is utilized. Complex weight coefficients are used for improved spectral characteristics[9].

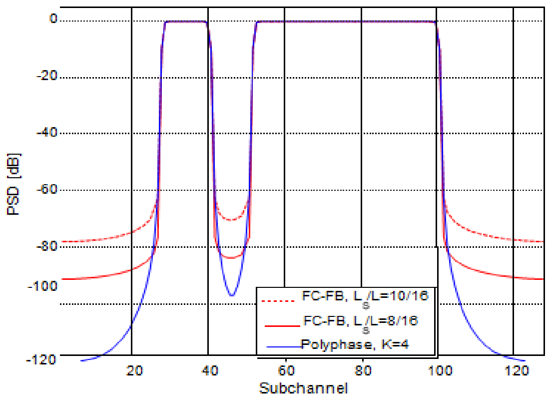

Fig.3.Non-contiguousFBMC/OQAMspectraforpolyphaseimplementation (polyphase filter bank with overlap factor $K = 4$) and FC-FB based implementationwith$L$=16anddifferentFC-FBoverlapfactors$1-L_S/L$.

For the FBMC/OQAM solution, we choose [8]L =16,L_S= 8, 10, resulting in FFT bin spacing of δ_f=15/8kHz.The long transform length becomes N =128 L/2=1024.Theresultingpowerspectraareshownin Figure3.Alsothepowerspectraldensity(PSD)ofabasicpolyphasedesign[3]is included in the figure. For spectrally efficientFMT, thesub-channel roll-off should be relatively small, like0.25orsmaller. In the FC-FB design, each transitionband shouldconsistofatleast3FFTbinsinordertoreachreasonablein-band interference and stop-band attenuation.Apracticalparameterization for such a design with 15kHzsubcarrierspacing,withhighestFFTbinspacing,andlowesttransformlengths is: N = 2560, L = 32, L_S= 12, 16, 20 .Figure4shows the resulting power spectra with these parameters.Inthecenterofthegap,thepowerlevelisatabout -73, -63,and-58dBwithrespecttotheactivesub-carrierforL_S=12,16,and20,respectively.

Figure5showstheinbandinterferencewith the same overlap factors. The interferenceissignificantlyincreasedattheedgesymbolswhentheoverlapfactorisreduced.Theworst-caseinbandMSEvaluesare -43, -34, and -28 dB for L_S= 12, 16, and 20, respectively.Eventhe L_S= 20 case might be considered feasible,exceptforhigh-order constellations, but it is excluded fromthelatercomparison. Also polyphase implementations forFMT[7]were designed with the same parameters fortwoprototypefilterorders,1600and1920(correspondingtopolyphaseoverlap factors K = 10 and K= 12, respectively) andinband MSElevelof –35dB.TheresultingPSDsareshowninFigure6.Wecanseethatthelowerfilterorderissufficientfor reaching −60 dB PSD level in the spectral gap.In order to evaluate the computational complexity of FC- FB based implementation of FBMC/OQAM and FMT wave- forms, we recall that the structure includes a long FFT/IFFT transform of length N , short transform of length L, and L 1 nontrivial complex weight coefficients for each subchannel.

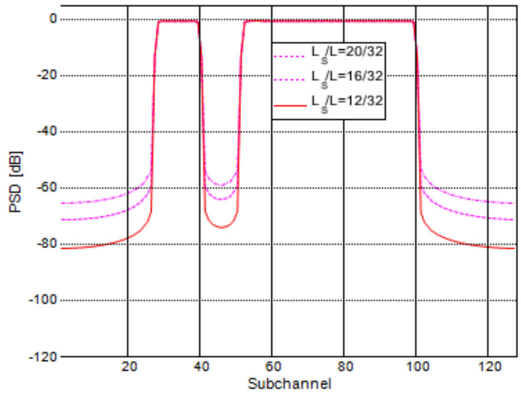

Fig.4. Non-contiguous FMT spectra for FC-FB based implementation with L = 32 and different FC-FB overlap factors 1−L_S/L.

In the FMT case, the folding (due to 2x oversampling) can be implemented easily in the FFT domain, and the short transform length can be reduced to L/2 on the transmitter side.

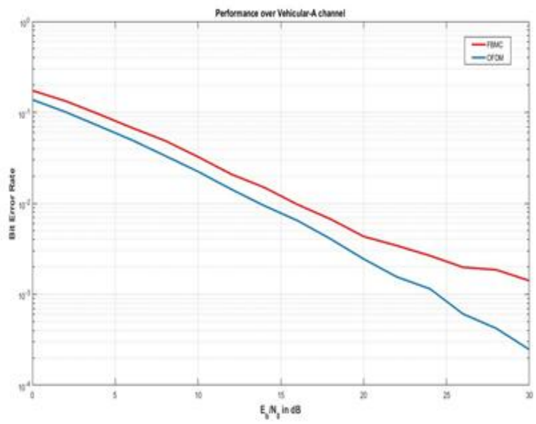

Fig.5. BER comparison of OFDM and FBMC systems

The same can be done on the FMT receiver side after channel equalization, which can be done in FFT domain by adjusting the weights based on the estimated channel (so- called embedded equalizer [16]). In the FBMC/OQAM case, implementing the folding process in FFT-domain is more complicated,andisleftasatopicforfuturestudies.

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Table I. Characteristics ofDifferent FBMC/OQAM and FMT ImplementationStructures.

Scheme	Complexity 12 sub-carriers TX/RX		Complexity 72 sub-carriers TX/RX		Maximal transform length	Inband interf. [dB]	Out-of-band interference in 1 RB gap [dB]	
	Adds	Mults	Adds	Mults			Edge	Centr.
Polyphase FBMC/OQAM, K=4	513/523	257/269	86/96	43/55	128	-50	-62.0	-96.7
FC-FB FBMC/OQAM, L=16, L_S=8	620	170	141	45	1024	-58	-76.0	-83.4
L=16, L_S=10	497	136	128	40	1024	-40	-62.4	-70.5
Polyphase FMT, Order 12x 160	513/523	364/376	86/96	61/73	128	< -50	-71.9	-76.5
Order 10x 160	460/470	310/322	77/87	52/64	128	< -50	-63.1	-68.2
FC-FBFMT, L=32,L_S=12	1698	301	311	64	2560	-43	-67.8	-73.6
L=32, L_S=16	1273	226	233	48	2560	-34	-58.6	-63.4

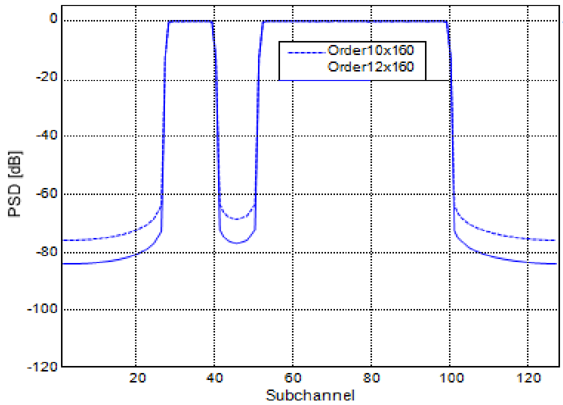

Fig.6.Non-contiguous FMT spectra forpolyphase implementations with different filterorders.

Table I shows a comparison of the spectral characteristics and computational complexity of alternative FBMC/OQAM and FMT schemes, including the presented FC-FBdesigns as well as traditional polyphase designs. Two cases, with 12 or 72 subcarriers are included in the complexity comparison. In the FC-FB implementations, the channel equalization is implemented utilizing the FFT-domain weight coefficients, but in the polyphase cases three-tap subcarrier equalizers are included [3]. The implementation complexity is evaluated in terms of the needed number of real multiplications and additions per processed QAM symbol. The complexities of DFTs and IDFTs for power-of-two lengths are based on the split- radix algorithm, for other cases, the most effective algorithms in terms of multiplication rate are assumed. It should be noted that in the FMT case, the length of the long transform is not a power oftwo.

V. CONCLUDINGREMARKS

FC-FB can be used for efficient implementationof FBMC/OQAM and FMT waveforms, with a potential for reduced computational complexity compared to traditional polyphase implementations, especially in case of low number of active subcarriers. Furthermore, FC-FB implementationpro- vides highly increased flexibility for multimode/multi-standard operation based on non-uniform FC-FB configurations. Efficient techniques are available for timing offset and frequency offset compensation. Therefore, the synchronization requirements can relaxed and the synchronization overheads can be reduced,forexample,incellularuplinkorad-hocscenarios.When comparing the two waveforms, in the studied case FBMC/OQAM provides 25 % higher spectral efficiency than FMT. FMT has higher complexity both in polyphase and FC- FB implementations. Notably, FC-FB implementation of FMT with small roll-off leads to significantly higher processing block length than what is needed in FBMC/OQAM.

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