

Channel Equalization in Fast-Convolution Filter Bank based Receivers for Professional Mobile Radio

Markku Renfors and Juha Yli-Kaakinen

Dept. of Electronics and Communications Engineering, Tampere University of Technology, Finland
markku.renfors@tut.fi and juha.yli-kaakinen@tut.fi

Abstract—Fast convolution processing has recently been proposed as an efficient approach for implementing filter bank multicarrier systems with good spectral containment and high flexibility in adjusting the subchannel bandwidths and center frequencies. These features make fast convolution filter banks (FC-FBs) a particularly interesting choice for multicarrier transmission in challenging radio scenarios like dynamic spectrum access, cognitive radio, and fragmented spectrum use. In this contribution, the target is to compare the performance of the time-domain equalizer with the frequency-domain equalizer implemented through subcarrier processing in LTE-like multicarrier systems. It is shown that integrating the equalization functions with the FC-FB processing leads to an efficient overall implementation in terms of performance and computational complexity.

I. INTRODUCTION

Multicarrier modulation offers 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 fragmented 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 terrestrial trunked radio (TETRA) standards in Europe and many countries outside Europe, as well as APCO-25 in North America.

Orthogonal frequency-division multiplexing (OFDM) is extensively utilized in modern broadband radio access systems. This is due to the simple and robust way of doing channel equalization, to its high flexibility and efficiency in allocating spectral resources to different users, as well as the ability to combining multi-antenna schemes with the core functionality [2]. However, OFDM has major limitations in the mentioned co-existence scenarios: spectral inefficiency due to the requirement for using guard intervals when transmitting, high sensitivity to frequency offsets, bad spectral containment which leads to high sensitivity to interferences from asynchronous spectral components in fragmented spectrum use.

A more sophisticated multicarrier scheme that has been shown to constitute an attractive alternative to OFDM is

offered by the filter bank (FB) based methods of waveform processing and channelization filtering [3], commonly referred to as filter bank-based multicarrier (FB-MC) [4]. 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 in-phase/quadrature (I/Q) imbalance effects on both sides [5].

A relatively widely studied filter bank-based waveform is FBMC/OQAM (filter bank multicarrier/offset-QAM, more commonly known as OFDM/OQAM) [6], [7]. 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 (MIMO) transmission schemes, it has received increasing interest in the mentioned challenging spectrum use scenarios.

A particularly flexible and effective scheme for FBMC/OQAM implementation, based on fast-convolution processing, has been recently introduced by the authors in [8]–[10]. In this work, the target is to exploit the new opportunities provided by the fast-convolution filter bank (FC-FB) signal processing in channel equalization. The proposed embedded equalization concept utilizes the frequency-domain weights of the FC-FB structure also for channel equalization. Integrating the channel equalization function with the FC-FB processing structure leads to efficient overall implementation, especially in cases where the channel is highly frequency selective within the subcarrier bandwidths and multi-tap subcarrier equalizers would be needed.

The outline of this paper is as follows. The basic idea of the FC-FB is first summarized in Section II and the proposed FC-FB based embedded channel equalizer is then briefly described in Section III. In Section IV, the target broadband PMR scheme is parameterized and two filter bank configurations are introduced as the implementation alternatives. The computational complexity of the these implementations is evaluated

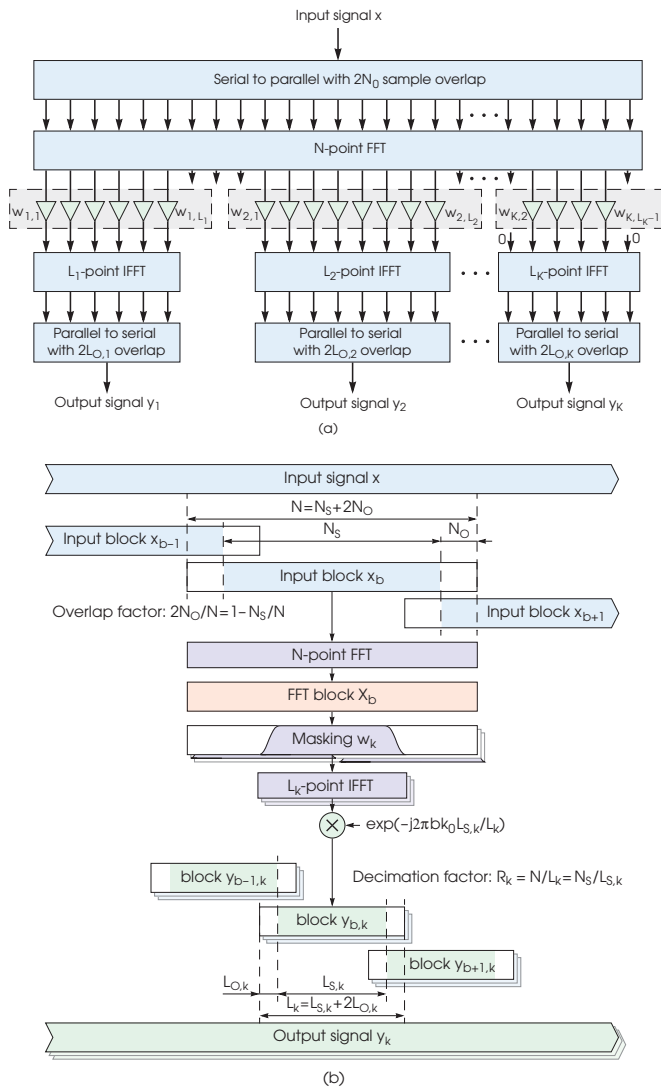


Fig. 1. Fast convolution based flexible analysis filter bank using overlap-save processing. (a) Multirate fast-convolution structure. (b) Processing flow.

in Section V. In Section VI, the equalization performances of these two realizations are compared in terms of numerical simulations and these comparisons validate the feasibility of the proposed scheme in scenarios of high frequency and time selectivity. Finally, the conclusions are drawn in Section VII.

II. FAST-CONVOLUTION FILTER BANKS

The basic idea of fast convolution (FC) is that a high-order filter can be implemented effectively through multiplication in frequency domain, after taking discrete Fourier transforms (DFT) of the input sequence and the filter impulse response. Eventually, the time-domain output is obtained by inverse DFT (IDFT). Typically, efficient implementation techniques, like fast Fourier transform/inverse fast Fourier transform (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 been presented in [11], and FC implementations of channelization filters have been considered in [12]–[14]. The authors have

introduced in [8] the idea of FC-implementation of nearly perfect-reconstruction filter bank systems and detailed analysis and FC-FB optimization methods are developed in [9], [15]. The timing offset compensation in FC processing is demonstrated in [16] whereas FC-FB based transmission scheme of the FBMC/OQAM type with the main parameters of the 5 MHz long time evolution (LTE) system is developed in [10]. 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.

The overlap-save processing of FC analysis filter bank is represented in Fig. 1. We consider a case where the incoming high-rate, wideband signal is to be split into several narrowband signals with adjustable frequency responses and possibly also adjustable sampling rates. We are interested in cases where the output signals are oversampled by a small factor (typically two). We also note that different subbands may be overlapping. The most essential constraint in the parametrization is that the overlapping factors of different subchannels have to be the same and equal to the overlapping factor on the input (high-rate) side, $1 - L_{S,k}/L_k = 1 - N_S/N$. The dual structure of Fig. 1(a) can be used for combining multiple low-rate, narrowband signals into a single wideband signal, following the frequency-division multiplexing principle.

In FC processing, the subchannel bandwidths and center frequencies can be independently tuned, with the resolution of the FFT bin spacing. Different types of multiplexes (FBMC/OQAM, filtered multitone (FMT) [17], or single carrier) can be combined in a single FC-FB structure. The transition band shapes can be adjusted by the frequency-domain weights $w_{k,n}$ (cf. Fig. 1) and it is also possible to use different shapes for different multiplexes, if so desired. The flexibility of the scheme can be used also for frequency offset compensation by either shifting the set of frequency bins connected to the subchannel processing functions or by shifting the frequency-domain mask in addition to supplementary modulation [18].

In Fig. 1, the decimation factor of subchannel k is equal to the ratio of the FFT length and IFFT length. In the rest of this paper, we focus on the uniform FBMC/OQAM case, where all the subchannels have the same IFFT lengths and the subchannels oversampling factor is two.

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

- 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 $1 - L_S/L = 1 - N_S/N$: 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. However, increase in the overlap factor increases the computational complexity as well.

In [9] these effects were analyzed using a periodically time variant model for FC processing and effective tools for fre-

quency response analysis and FC filter optimization were developed.

III. CHANNEL EQUALIZATION

Here we consider a subchannel-wise channel equalization structure where the channelization weights of the fast-convolution filter bank structure are also used for channel equalization purposes. This frequency-domain equalization scheme is referred to as an embedded equalizer. The frequency-sampled subcarrier-wise equalization model of [19] is employed. This model approximates closely a linear fractionally-spaced equalizer and the conceptual model of the receiver front-end includes the following elements [20], [21]:

- Pulse-shape matched filter: The FC-FB realizes the root raised cosine (RRC) type pulse shaping filter through the weights $w_{k,n}$'s. Here, n is the FFT bin index and k in subchannel index.
- Channel matched filter $H_{k,n}^*$, where $H_{k,n}$ is the subchannel frequency response at the corresponding FFT bin.
- Folding effect (aliasing) due to resampling at the symbol rate.
- Linear equalizer with mean squared error (MSE) criterion.

The resulting frequency-domain weights can be determined as [21]:

$$\hat{w}_{k,n} = \frac{H_{k,n}^* w_{k,n}^*}{|H_{k,n} w_{k,n}|^2 + |H_{k,\tilde{n}} w_{k,\tilde{n}}|^2 + 1/\sigma},$$

where σ is the signal-to-noise ratio and \tilde{n} is the FFT bin index folding on top of FFT bin n in subchannel k .

In order to construct the embedded equalizer, the channel estimate should be available at all the FFT bins of the active subchannels. In scattered pilot based estimation, the channel estimates at the pilot positions can be evaluated, e.g., using auxiliary pilot or pair-of-pilots techniques [22]. Naturally, piecewise constant or piecewise linear interpolation can be used to approximate the channel estimate with a frequency resolution of a fraction of the subcarrier spacing if the channel is not highly frequency selective within the subbands. The same embedded equalizer model can be used for FBMC/OQAM, FMT, and single carrier waveforms.

The weights of the FC-FB structure must be constant over each processing block of $L_S/2$ OQAM symbols (5 symbols with the used parametrization). The coefficients can be updated for each processing block.

As a benchmark for the comparisons, we consider the polyphase filter bank structure, using the PHYDYAS prototype filter design [23] with overlapping factor of $K = 4$, together with 3-tap frequency-sampling based subcarrier equalizers with MSE criterion [22].

IV. PERFORMANCE OF EMBEDDED EQUALIZER IN LTE-LIKE BROADBAND PMR SCHEME

We focus here on a 5 MHz LTE-like multicarrier system utilizing the FBMC/OQAM waveform and using FC-FB

based receiver implementation. The 5 MHz bandwidth case is suitable for broadband PMR, and the LTE system is a good candidate for possible broadband PMR system deployment in new frequency bands. As the dominating broadband cellular network standard, LTE is a natural reference for advanced multicarrier system development for PMR, and a high level of commonality with LTE is expected from the new system. The 5 MHz LTE uses the sampling rate of $f_s = 7.68$ MHz with $M = 512$ subcarriers (out of which $M_{\text{used}} = 300$ active subcarriers are used) and subcarrier spacing of $\Delta_f = 15$ kHz [2]. The 300 active subcarriers are scheduled in resource blocks of 12 subcarriers, i.e., there are 25 resource blocks (RBs).

While all FBMC/OQAM subcarriers can be used in the synchronous downlink, one subcarrier wide guardbands are needed in asynchronous frequency-division multiple access (FDMA) operation in the uplink. For example, the highest subcarrier of each contiguous set of resource blocks allocated to a user could be left unused, as a guardband. FBMC/OQAM allows to transmit 15 multicarrier symbols in a subframe of two slots (1 ms), instead of 14 in basic LTE, which compensates the additional overhead in data transmission capacity due to the guardbands in asynchronous FDMA operation.

The performance of the embedded channel equalization is evaluated with *Vehicular A* and *3GPP Hilly Terrain* channel models for the static and mobile users. Since the broadband PMR system is expected to be used also in large macrocells, channel models with relatively wide delay spreads, like the *Hilly Terrain*, are important to be taken into consideration in the system development. For such channels, the LTE version with extended cyclic prefix (CP) should be considered as the reference. This variant of LTE transmits 6 + 6 multicarrier symbols per subframe, but otherwise the main parameters are the same as described above.

The following two filter bank configurations are under consideration:

- Polyphase filter bank: PHYDYAS prototype [23] with overlapping factor of $K = 4$ and 3-tap frequency-sampling based equalizer with MSE criterion [19].
- FC filter bank: In the 5 MHz case, short transform length of $L = 16$, the long transform length of $N = 512L/2 = 4096$, and $L_S = 10$ useful subcarrier samples (5 OQAM symbols) per processing block are used. The weights of the FC-FB structure were optimized using the methods presented in [9] and EMPhAtiC deliverable D2.1 [24].

V. COMPUTATIONAL COMPLEXITY

The FC-FB structure has potential for reduced computational complexity, in terms of multiplication and addition rates, in comparison to the commonly used polyphase filter bank structure [9]. In the following, we assume that the FFT and IFFT lengths are powers of two and that the implementation uses the split-radix algorithm taking $B(\log_2(B) - 3) + 4$ real multiplications for length- B FFT or IFFT.

In the FC-FB receiver implementation, the following elements are needed in the 5 MHz case: (i) one FFT of length $N = 4096$, (ii) M_{used} IFFTs of length $L = 16$, and (iii) $M_{\text{used}} = 300$ sets of weight coefficients each containing

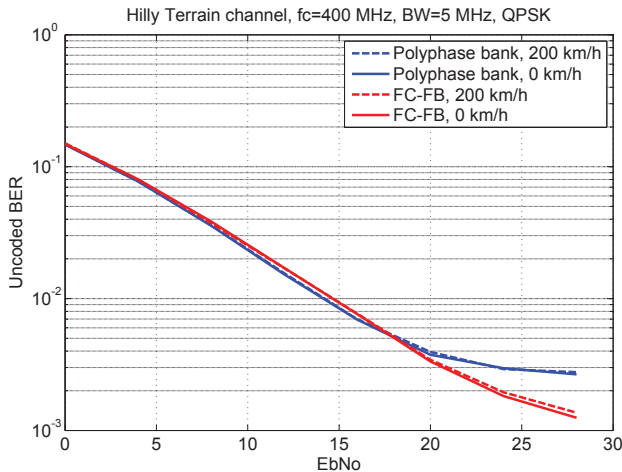


Fig. 2. Performance of the polyphase and fast-convolution filter banks in the case of *Hilly Terrain* channel model for a static user and a user with 200 km/h mobility. Perfect channel knowledge and QPSK modulation is assumed.

$L - 1 = 15$ non-trivial coefficients. There is a need for using arbitrary complex coefficients as weights, instead of fixed basic weight coefficients which, depending on the specific parametrization and design, could also take real values. From each processing block, $M_{\text{used}}L_S/2 = 1500$ data symbols are detected.

The polyphase receiver implementation with same number of subbands requires (i) one FFT of length $M = 512$, (ii) KM real coefficients in the polyphase filter structure, and (iii) $3M_{\text{used}}$ complex weights as 3-tap subcarrier equalizers. The multiplication rate of the polyphase filter is double due to complex input and each complex equalizer coefficient is assumed to take four real multiplications. The equalizer taps are implemented at the subcarrier symbol rate, otherwise the mentioned processing functions need to be implemented two times for each symbol interval to produce M_{used} complex symbols.

The needed number of real multiplications per detected symbol is about 41. This compares favorably with the multiplication rate of the polyphase implementation with 3-tap subcarrier equalizers [25], [26], which takes about 53 real multiplications per detected symbol with the polyphase filter bank overlap factor of $K = 3$, or about 60 multiplications per detected symbol with polyphase filter bank overlap factor of $K = 4$. The arithmetic complexity of the FC-FB based implementation depends greatly on the overlap factor. As another example, if the IFFT length is 24, the FFT length is 6144, and the overlap factor is $6/24$, then the multiplication rate is reduced to 36 real multiplications per detected symbol.

The above calculations include only the multiplications in the data symbol path. Additional computations are needed for channel estimation and calculation of the equalizer weight coefficients. It was assumed that the weights are recalculated for each IFFT bin for each FFT processing block, which naturally leads to relatively high complexity. To reduce the complexity, methods based on interpolation over each set of weight coefficients and between FFT processing blocks should be developed.

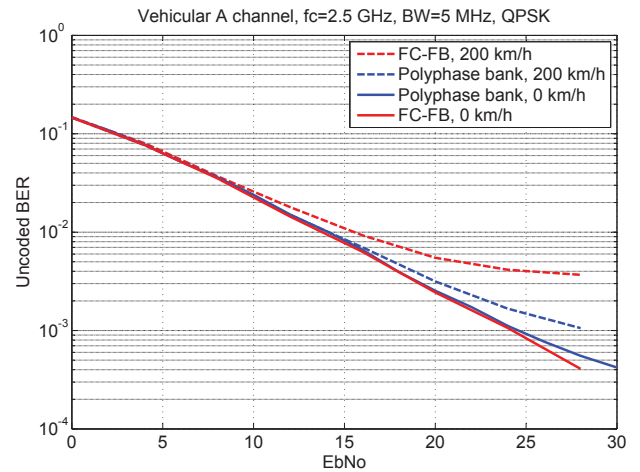


Fig. 3. Performance of the polyphase and fast-convolution filter banks in the case of *Vehicular A* channel model for a static user and a user with 200 km/h mobility. Perfect channel knowledge and QPSK modulation is assumed.

VI. NUMERICAL RESULTS FOR EMBEDDED EQUALIZER

The examples here are for the 5 MHz LTE-like synchronous downlink case with $M_{\text{used}} = 300$ active subchannels, assuming perfect channel knowledge. In the FC-FB case, the instantaneous channel response in the middle of each 5-symbol FFT processing block is used. In the polyphase case, the channel is updated for each OQAM half-symbol.

Figures 2 and 3 show the performance of both configurations for QPSK modulation in the case of *Hilly Terrain* and *Vehicular A* channel models for both the static user and the user with 200 km/h mobility. As can be seen from these figures, the embedded FC-FB equalizer works well even in the case of high mobility with the used parameters and PMR frequency band ($f_c = 400$ MHz). In the 2.5 GHz frequency band, the limitations due increased block length of FC-FB are visible with high mobility, but the effect is not severe. Figure 4 shows the simulation results also for the case where the subcarrier width has been increased by a factor of four. It can be seen that the embedded equalizer is able to handle high frequency selectivity significantly better than the 3-tap equalizer.

VII. CONCLUSION

We have demonstrated the feasibility of the embedded equalization concept, which is integrated with the fast-convolution filter bank processing structure. It shows good equalization performance in channels which exhibit high level of frequency selectivity at the subcarrier level. The extended length of processing blocks turned out not to be a serious problem even with relatively high mobility.

It was demonstrated in [9] and [10] that FC implementation of FBMC/OQAM has significantly lower arithmetic complexity than the traditional polyphase filter bank structure. Furthermore, the embedded equalization model saves significant number of multiplications in comparison to multi-tap subcarrier equalizers.

The future work topics include channel estimation for the highly frequency selective channels like the *Hilly Terrain*

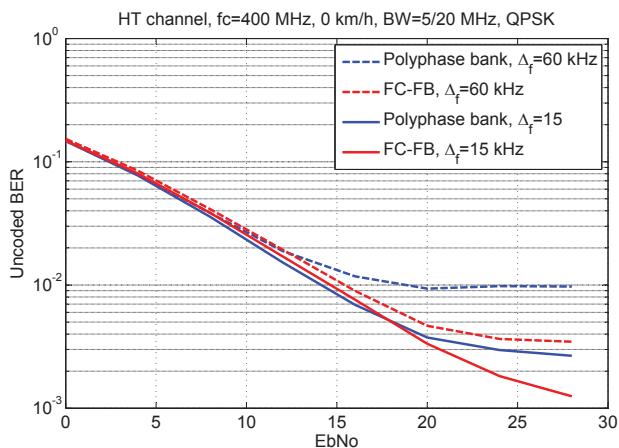


Fig. 4. Performance of the polyphase and fast-convolution filter banks in the case of *Hilly Terrain* channel model for subcarrier spacing of $\Delta_f = 15$ kHz and $\Delta_f = 60$ kHz. Perfect channel knowledge and QPSK modulation is assumed.

model, as well as integrating the carrier and symbol timing synchronization functions with the fast-convolution filter bank processing structure

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