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A GENERALIZED OVERSAMPLED STRUCTURE FOR COSINE-MODULATED TRANSMULTIPLEXERS AND FILTER BANKS*

Luiz C. R. de Barcellos,[1] *Paulo S. R. Diniz,*[1] *and Sergio L. Netto*[1]

Abstract. In this paper, a new structure, called the channel split-and-add method, for designing oversampled transmultiplexers and filter banks is presented. The proposed method is based on an initial design with an additional number of bands. The band number is then reduced to the desired value by the proper combination of adjacent and/or nonadjacent bands (subchannels). With the proposed approach it is always possible to perform the filtering tasks at the lowest data rate of the system. An example illustrates the design flexibility achieved with the proposed structure.
Key words: Oversampled filter banks, transmultiplexers, digital filtering, multicarrier systems.

1. Introduction

Transmultiplexers (TMUXes) are key building blocks in multicarrier communications systems [15], [6]. These modulation systems are efficient for data transmission through channels with moderate and severe intersymbol interference (ISI). The TMUXes excite the physical channel utilizing several nonoverlapping narrowband subcarriers. If the subcarriers are narrow enough, they will be nearly flat, allowing the use of simple equalizers. The current interest in the design of selective and flexible multicarrier systems has sparked a growing interest in oversampled TMUX theory, where the ratio between the number of channels and the sampling-rate change can assume nonstandard values. For any value of this ratio, the computational complexity should be reduced to allow the processor to deal with other tasks or to allow the implementation of more selective subfilters.

The orthogonal frequency division multiplex (OFDM) is the simplest and most widely used implementation of a memoryless TMUX. The main attractive fea-

* Received February 7, 2005; revised October 4, 2005.
[1] Programa de Engenharia Elétrica-COPPE/DEL-Poli/UFRJ, P.O. Box 68504, Rio de Janeiro, RJ, 21941-972, Brazil. E-mail for Netto: sergioln@lps.ufrj.br; E-mail for Barcellos: barcellos@lps.ufrj.br; E-mail for Diniz: diniz@lps.ufrj.br

tures of the OFDM system are its elimination of the ISI and its intrinsic low computational complexity. An OFDM system utilizes an inverse discrete Fourier transform (IDFT) in the transmitter and a DFT at the receiver, enabling the use of the computationally efficient fast Fourier transform algorithms. In order to avoid ISI in transmissions through frequency-selective channels, some redundancy (cyclic prefix) must be included at the transmitter, reducing the data rate. In addition, because the OFDM system is memoryless, the TMUX subfilters have very poor selectivity, resulting in substantial intercarrier interference (ICI).

Oversampled TMUX structures, like their filter bank counterparts, present an interpolation/decimation factor lower than the number of channels. An oversampled TMUX may be useful when there is severe channel distortion in some specific band. In such a case, maximally decimated TMUXes would cause loss of information for the respective signal. However, an oversampled TMUX, by spreading the input signal in different channels, may be able to recover it, even after one signal component is destroyed by the channel. The purpose of this work is to propose a flexible and computationally efficient oversampled TMUX structure with memory, where the oversampling factor and the number of subcarriers can be more freely chosen. As a result, the proposed structure enables the design of low-complexity TMUXes with frequency-selective subcarriers with a more general desirable redundancy [10], [11], avoiding loss information in the end by performing a proper channel combination in the middle. This technique fills the gap left by the design of the critically sampled high-resolution cosine-modulated transmultiplex (CM-TMUX) proposed in [3], for instance, which is based on a (multistage) cascade structure for the prototype filter.

For any value of the ratio between the upsample factor and the number of subcarriers, the computational complexity should be reduced. However, when employing some efficient structures proposed in the literature, depending on this ratio, the filtering operation may not be performed at the lowest sample rate of the TMUX system, and the bandwidth of the subcarriers may not be uniform. The latter occurs when the upsampling factor is not a multiple of the number of subcarriers, forcing some subcarriers to present overlapping in the spectrum repetition. In this paper, we introduce a new computationally efficient structure for oversampled TMUXes and filter banks. The design is based on a proper combination of adjacent or nonadjacent subchannels. The result is a more flexible design scheme that allows one to perform all filtering tasks at the lowest data rate of the system.

This paper is organized as follows. Section 2 presents the TMUX system and comments on its relation to filter banks. Section 3 discusses the implementation of oversampled TMUXes when the ratio between the interpolation factor M' and the number of subchannels M is an integer number. Section 4 discusses in detail the case where this ratio is a noninteger. Section 5 proposes the channel split-and-add method, which enables the derivation of efficient structures for noninteger $\frac{M'}{M}$. Section 6 defines some parameters related to TMUX design using the proposed

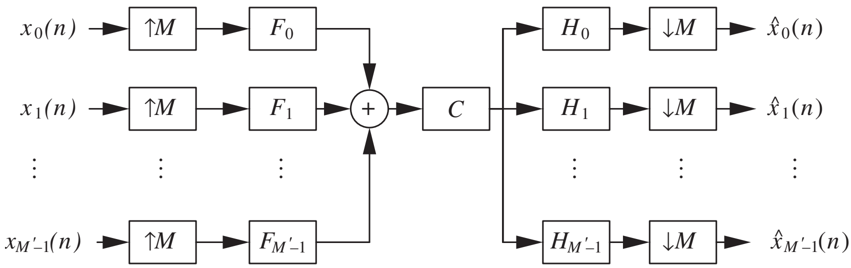

Figure 1. Block diagram of an M'-channel TMUX.

method, and in Section 7 an illustrative design example is presented. Finally, Section 8 gives our concluding remarks.

2. Transmultiplexer and filter bank systems

A filter bank system consists of an analysis filter bank where a single input signal is split into several subbands and subsequently downsampled to remove redundancy of the narrowband subband signals. If the original full-rate signal needs to be recovered, these subband signals should be applied to a synthesis filter bank consisting of upsamplers and subband filters. It is well known that a TMUX transceiver is obtained by interchanging the analysis and synthesis filter banks [3], where the synthesis filter bank is the transmitter and the analysis filter bank is the receiver.

In the TMUX, signals coming from various sources are interpolated, filtered by synthesis filters, and added together to compose a single signal that is transmitted on a single channel C [12], [16]. The received signal is split by the analysis filters into M' subchannels, where each subchannel output consists of an estimated version of the corresponding input source. Figure 1 depicts the block diagram for such a system. There are some ways to design the filters of the bank such that if the channel C presents an ideal transfer function (namely, a delay), then the output signals may be equal to the source signal, resulting in a perfect reconstruction (PR) condition system. If a small amount of distortion is allowable, the design constraints can be relaxed so that a nearly perfect reconstruction (NPR) condition is achieved. The ISI and ICI figures of merit serve as good indicators of the NPR condition. For uniformly distributed TMUXes, where all subcarriers have the same bandwidth, it is possible to employ a CM-TMUX design technique, the design of which is based on a single prototype filter [12]. Once the prototype is designed, the synthesis and the analysis filters can be obtained by modulating the prototype filter with a proper cosine function. The prototype filter of order N_p is of the form

$$H_p(z) = \sum_{n=0}^{N_p} h_p(n) z^{-n},\ h_p(N_p - n) = h_p(n). \tag{1}$$

The band edges are determined by the roll-off factor and the 3-dB point of the amplitude response, which must be located approximately at $\omega = \pi/(2M')$. The roll-off factor gives us the stop band edge

$$\omega_s = \frac{(1+\rho)\pi}{2M'}. \tag{2}$$

The analysis and the synthesis filters are given by

$$h_k(n) = 2h_p(n) \cos\left(\frac{(2k+1)(n - N_p/2)\pi}{2M'} + (-1)^k \frac{\pi}{4}\right) \tag{3}$$

and

$$f_k(n) = 2h_p(n) \cos\left(\frac{(2k+1)(n - N_p/2)\pi}{2M'} - (-1)^k \frac{\pi}{4}\right), \tag{4}$$

respectively, for $k = 0, 1, \ldots, M' - 1$. By using the preceding equations in the filter bank structure, the ISI and ICI figures of merit can be estimated by using the following expressions [16]:

$$\mathrm{ISI} = \max_k \left(\sum_n (\delta(n) - t_k(n))^2 \right) \tag{5}$$

$$\mathrm{ICI} = \max_k \left(\sum_{l=0, k \neq l}^{M-1} |[\mathbf{T}(e^{j\omega})]_{kl}|^2 \right), \tag{6}$$

where $\delta(n)$ is the ideal impulse, $t_k(n)$ is the impulse response for the kth channel output, and the term $[\mathbf{T}(e^{j\omega})]_{kl}$ is the crosstalk term [16], that is, the transfer function between the input of the kth channel and the output of the lth channel.

3. Change of sampling rate

The TMUX and filter bank systems require splitting and reconstructing signals whose rates are different at internal nodes of the systems. For example, in the TMUX transmitter, the sampling rate of the sources is lower than the sampling rate of the transmitted signal through the main channel C. This change of sampling rate is denoted by the expansion operation in the TMUX transmitter side. However, when the signal reaches the receiver part of the TMUX, it is decomposed into several signals by distinct filtering operations followed by sampling rate reduction, eventually with no aliasing effects, because of the filtering process. Ideally, the outputs are good estimates of the original input signals, and the output signals have the same sampling rate as the sources. The main idea behind the TMUX transceiver is to excite the main C channel with narrowband subcarriers, which in most applications have the same bandwidth. If all subcarriers are nonoverlapping in frequency, then it is straightforward to use the maximum change of sampling rate factor, where the decimation and interpolation factors are equal to the number of channels. In this special case, with uniformly distributed subcarriers, it is possible to use efficient structures, namely, CM-TMUX, FRM-CM-TMUX, or butterfly-based structures [3]. The key to generating a low computational complexity structure is to perform all the signal filtering at the lower sampling rate nodes of the system, as depicted in Figure 2. In this figure, the number of channels is equal to M', and the matrix $\mathbf{E}^{\alpha}(z^M)$ of dimension $M' \times M$ represents the polyphase decomposition of the analysis filter bank, where M is the downsampling factor. The polyphase matrix of the analysis bank is then given by

$$\mathbf{E}^{\alpha}(z^M) = \begin{bmatrix} H_{0,0}(z^M) & H_{0,1}(z^M) & \dots & H_{0,M\text{-}1}(z^M) \\ H_{1,0}(z^M) & H_{1,1}(z^M) & \dots & H_{1,M\text{-}1}(z^M) \\ \vdots & \vdots & \ddots & \vdots \\ H_{M'\text{-}1,0}(z^M) & H_{M'\text{-}1,1}(z^M) & \dots & H_{M'\text{-}1,M\text{-}1}(z^M) \end{bmatrix}. \tag{7}$$

The terms $H_{k,l}(z^M)$ are the lth polyphase components of the kth analysis filter, and are given by

$$H_{k,l}(z) = \sum_n h_k(Mn + l)z^{-n}. \tag{8}$$

Therefore, a single subfilter is composed by adding the properly delayed elements of the corresponding row of the matrix $\mathbf{E}^{\alpha}$. These delays are shown in Figure 2, and the subfilter transfer functions are given by

$$H_k(z) = \sum_l H_{k,l}(z^M)z^{-l}. \tag{9}$$

For the synthesis filter bank, the polyphase components are denoted by $F_{k,l}(z^M)$. The index α is the ratio between M and M' given by

$$\alpha = M'/M. \tag{10}$$

For a zero-redundancy TMUX, $M = M'$ and thus α is equal to 1. Note that it is possible to move the decimators to the input tapped delay line because the matrix $\mathbf{E}^{\alpha}$ is a function of z^M, i.e., the filtering coefficients of each polyphase term are separated by M samples. When using an efficient CM structure, a single prototype filter described using a specific polyphase decomposition allows the use of a single modulating (DCT-IV) matrix for the entire system in order to implement the various subfilters in the matrix $\mathbf{E}^{\alpha}(z^M)$. The efficient structure requires that M' be a multiple of M. Therefore, the parameter α should be an integer if an efficient polyphase structure is used.

In general, for any oversampled or critically sampled (zero-redundancy)

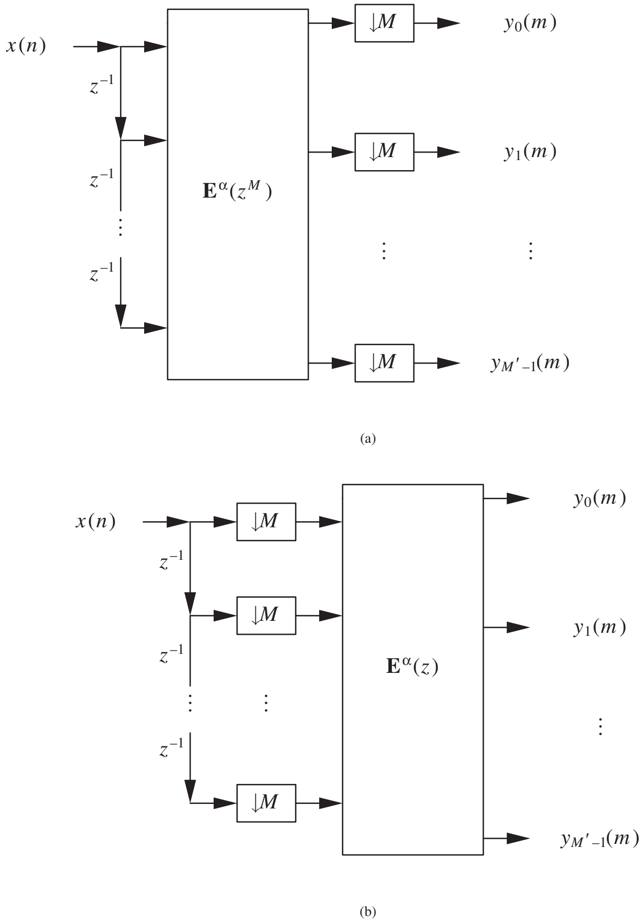

Figure 2. Changing the place of decimators of an analysis filter bank: (a) after, (b) before.

TMUX such that the number of channels M' is a multiple of the upsampling factor M, an efficient structure is realizable. In these cases, the filtering operations are performed at the lowest sampling rate inside the system. For any α factor integer greater than 1, it is possible to design a zero-redundancy ($\alpha = 1$) TMUX, and then employ the resulting polyphase matrix for the oversampled case as follows:

$$\mathbf{E}^{\alpha}(z) = \mathbf{E}^{1}(z^{\alpha})\mathbf{S}(z), \tag{11}$$

where

$$\mathbf{S}(z) = \frac{1}{\sqrt{\alpha}}\left[\mathbf{I}_M \quad z^{-1}\mathbf{I}_M \quad \dots \quad z^{-(\alpha-1)}\mathbf{I}_M\right]. \tag{12}$$

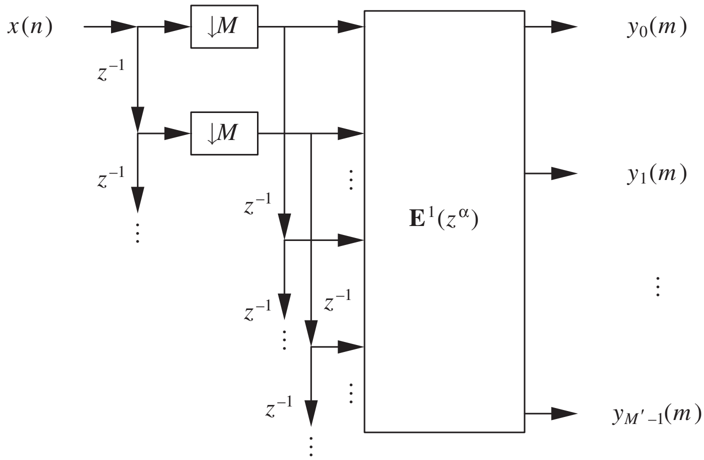

Figure 3. Alternative representation for the case when α is an integer.

The resulting structure is depicted in Figure 3. This figure is equivalent to the one in Figure 2b by replacing the matrix $\mathbf{E}^{\alpha}(z)$ by $\mathbf{E}^{1}(z^{\alpha})$. In fact, when transforming the zero-redundancy TMUX into the oversampled case for α integer, it is required to change the scaling factor of the filter bank structure (to the adequate value of $\sqrt{\alpha}$ in equation (12)) and also the values of the decimation and interpolation factors.

As an example, in Figures 4 and 5 we show the spectrum decomposition of the signals on a TMUX system with six subcarriers, with sampling rate change equal to three ($M' = 6$ and $M = 3$), for a CM-TMUX design. From those figures, we note that when the receiver estimates the signal $\hat{x}_i(n)$, it will use only 50% of the original bandwidth of the corresponding source. In the case of a 6-channel system, with a TMUX upsampled by $M = 2$, it would use only 33.3% of the original signal bandwidth. Note that the number of channels, $M' = 6$, is a multiple of both 2 and 3, so that α is an integer, and an efficient structure is available in these two cases. We conclude that for any of the source signals, some part of its spectrum will be lost or unusable. The first integer value of α in which an efficient oversampled structure exists is 2; thus, the oversampled CM-TMUX will lose at least 50% of the bandwidth on each subcarrier.

4. Filter banks for noninteger α

There are some ways in which we can reduce the loss of bandwidth of the channels of a filter bank. If we use a noninteger relation between M' and M, we can still use the efficient cosine-modulated filter bank (CMFB) structure, but the loss of

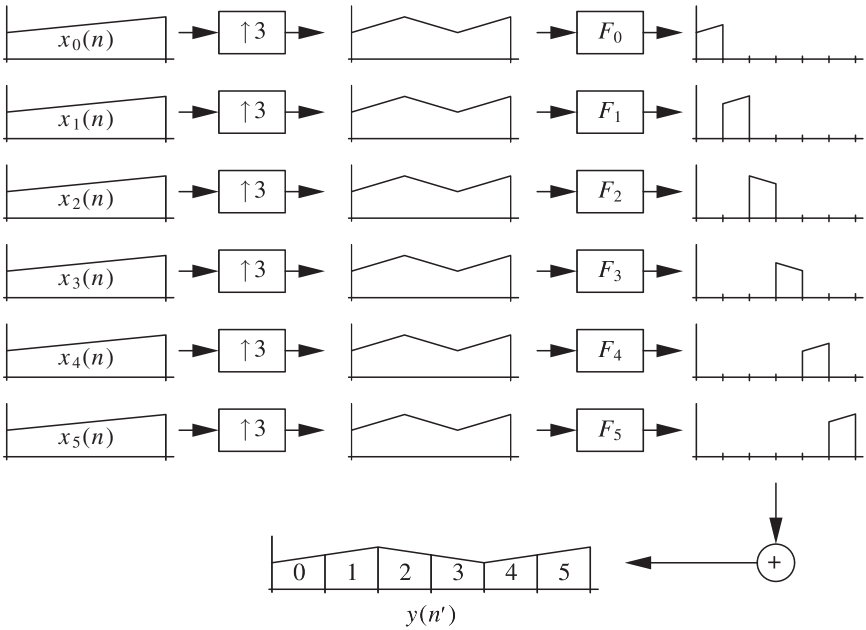

Figure 4. Signal representation of a 6-channel TMUX synthesis bank with resampling factor of 3.

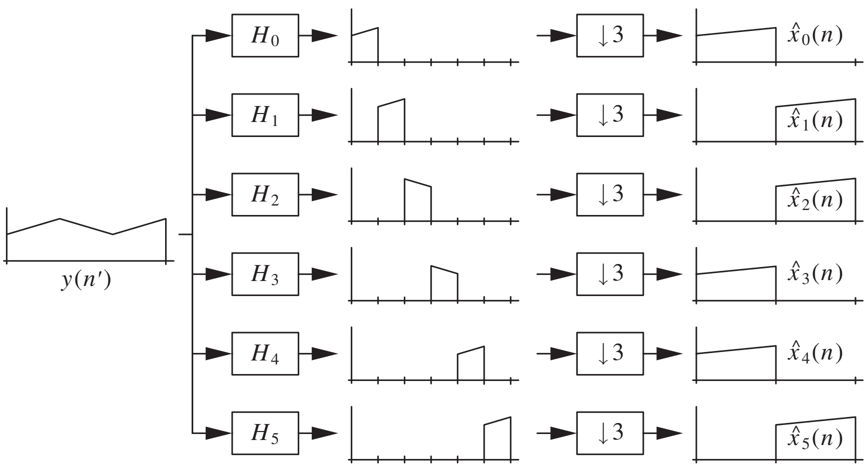

Figure 5. Signal representation of a 6-channel TMUX analysis bank with upsampling factor of 3.

bandwidth will not be equal for all the channels. Also, the processing will not be performed at the lowest sample rate of the system, but at an intermediate rate. For the case when M' is not a multiple of M, it is possible to obtain the structure in

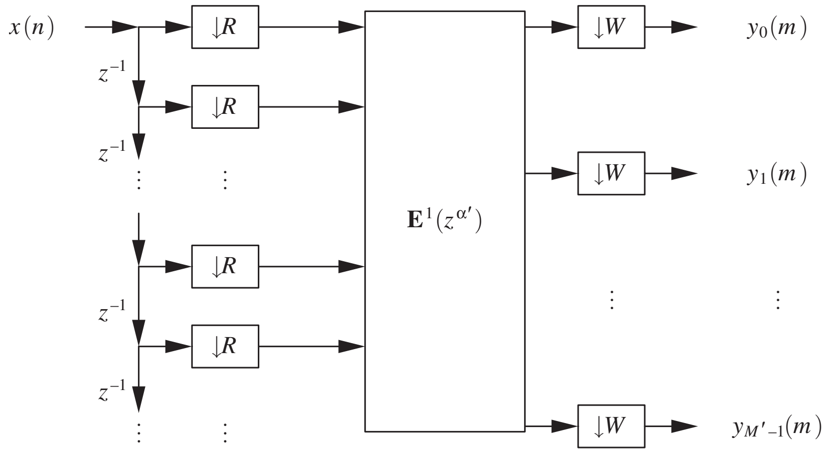

Figure 6. Representation of an analysis filter bank with noninteger α factor.

Figure 6 if we have

$$\alpha' = \frac{M'}{R} \tag{13}$$

and

$$W = \frac{M}{R}, \tag{14}$$

where the key point is to find a value of R that divides M' and M simultaneously such that α' and W become integer values, and then split the resampling operation into two stages. In such a scheme, because M' will not necessarily be a multiple of W, the polyphase decompositions that lead to the efficient CMFB structure generally will not allow the W-factored decimators to be moved to the matrix input. Thus, the processing must work with an intermediate sampling rate, reducing the performance of the system when compared to the integer-α case.

Analyzing the reconstruction in the frequency domain of the signals on a TMUX system for a noninteger α, one can verify the nonuniformity among the subchannel bandwidths. As an example, the TMUX case of 6 channels resampled by a factor of $M = 4$ is depicted in Figures 7 and 8. In such a case, $R = 2$, such that $\alpha' = 3$ and $W = 2$. From these figures we note that some channels will have 66.7% of band occupation whereas others will have only 33.3% of band occupation. In this case, we have an average bandwidth occupation of $10/18 \approx 56\%$; in the previous case, where $M = 3$ such that $\alpha = 2$, one gets only $9/18 = 50\%$ bandwidth occupation. It is also important to notice that the second and the fifth channels ($x_1(n)$ and $x_4(n)$, respectively) may present twice the channel gain, as their responses appear as a double sideband in the composition of the output signal $y(n')$. This will happen only if the responses of both sides

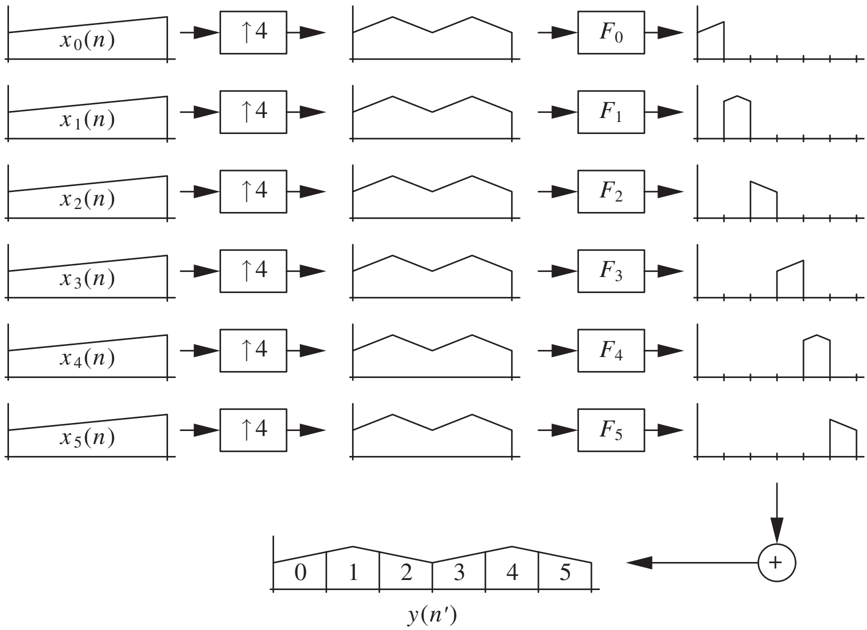

Figure 7. Signal representation of a 6-channel TMUX synthesis bank with resampling factor of 4.

are in phase. In general, some of those bands will add and others will cancel or partially cancel, so the use of such bands is restricted (the in-phase composition also depends on the choice of the phase of the last stage decimators). Also, from the explanation above, not all the channels will have the same correction factor, as any nonoverlapping channel (e.g., channel $x_0(n)$ in the example above) will have a constant factor RW, as opposed to the integer-α case, in which there is a constant factor of $1/\sqrt{\alpha}$. Overall, the noninteger α case represents a trade-off between the processing performance and the average band occupation on a filter bank or TMUX structure.

5. The channel split-and-add method

When working with a noninteger value of α, it is possible to reduce the computational load of the system by changing the number of channels within the system. In this case, the idea is to find a structure in which the new number of channels M'' is a multiple both of M' and M, thus forcing a new parameter $\alpha'' = M''/M$ to be integer. Because we are adding more channels than in the other cases, the information (signal) that comes from one of the sources can be transmitted over two or more of those channels. However, because the resampling

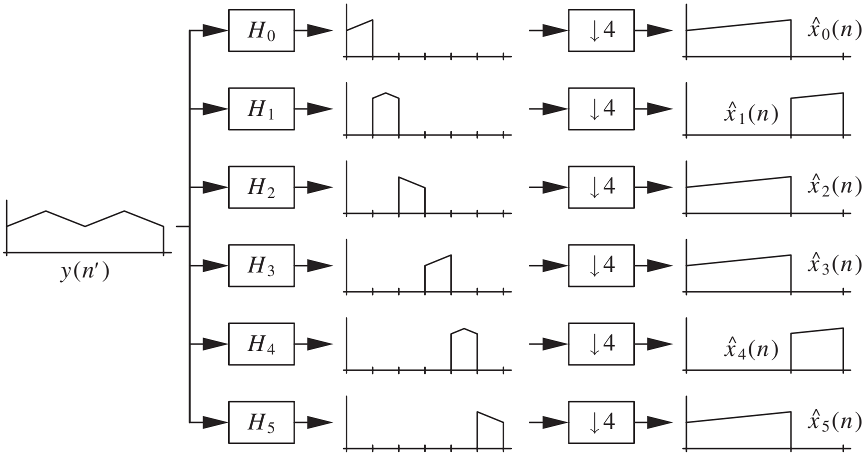

Figure 8. Signal representation of a 6-channel TMUX analysis bank with resampling factor of 4.

factor is less than the number of channels M', it is possible to arrange the new M'' subchannels in such a way that the bandwidth occupation becomes higher. In addition, we must ensure that each of the subchannels carrying information of one source is working on a different subband of the particular channel, thus properly splitting the source signal. Using this technique, the average occupation factor can be increased considerably.

The main disadvantage of this approach is that the specifications for the required subchannel filters become more demanding. This can be overcome by using improved design methods, as for instance, by choosing nonadjacent channels to compose the response of a particular channel and/or by using a least-squares or weighted least-squares (WLS)-Chebyshev algorithm in such a way that the individual stopbands compensate each other. Notice, however, that although the initial subchannels present narrow bandwidths, after a proper combination procedure, all resulting channels have adequate bandwidths for the corresponding input signal.

The channel split-and-add method described above is represented in Figure 9, which illustrates a particular case where each filterbank channel is formed as the sum of two adjacent subchannels. However, the combination technique is in fact more general and can even be applied to nonadjacent channels. This general case will be illustrated in Design 2 of Section 7.

Revisiting the TMUX case where $M' = 6$ and $M = 4$, it is now possible to employ a structure with $M'' = 12$ channels, such that $\alpha'' = \frac{M''}{M} = 3$ is an integer number, adding the (adjacent or not) channels two by two to form the desired 6 channels. The choices for M'' include any (minimum or not) common multiple of M' and M, in such a way that the scheme of Figure 2 can be used, and the processing is performed once again at the lowest sampling rate of the system.

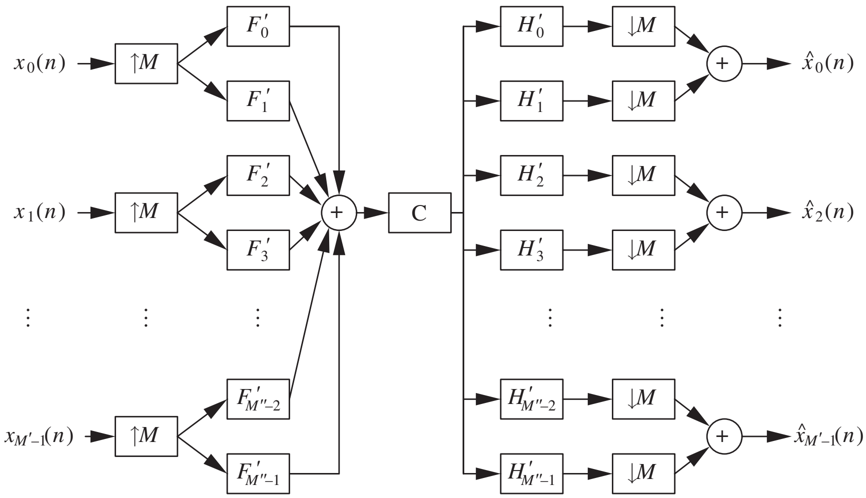

Figure 9. Block diagram of an M-channel TMUX as sum of two adjacent channels.

The spectrum composition of the signal of an $M'' = 12$-channel, resampled by 4, TMUX system is shown in Figures 10 and 11. In these figures, we note that the occupation factor is low, only 30%, if one sees the system as a 12-channel TMUX. However, by adding the channels two by two, the bandwidth occupation factor of the effective 6-channel TMUX becomes 60%.

6. Design comments

The resulting occupation factor is a multiple of the bandwidth of the individual subchannels only when none of the bands of a particular composing channel overlaps. In general, there will be $\alpha'' = M''/M$ groups of $\alpha' = M''/M'$ overlapping channels that should not be added together. In our particular example, according to Figure 11, there are three groups of 4 subchannels each, given by

$$G_1 = \left\{x_0'(n) \quad x_5'(n) \quad x_6'(n) \quad x_{11}'(n)\right\} \tag{15}$$

$$G_2 = \left\{x_1'(n) \quad x_4'(n) \quad x_7'(n) \quad x_{10}'(n)\right\} \tag{16}$$

$$G_3 = \left\{x_2'(n) \quad x_3'(n) \quad x_8'(n) \quad x_9'(n)\right\}. \tag{17}$$

By using a convenient heuristic method, it is always possible to combine properly the M'' subchannels without overlap to form the desired M channels. The best combination depends on the requirements of the application at hand; for instance, signal strength or tolerance against noise on determined frequency bands, minimum ICI, etc.

When employing the channel split-and-add method, it is always possible to

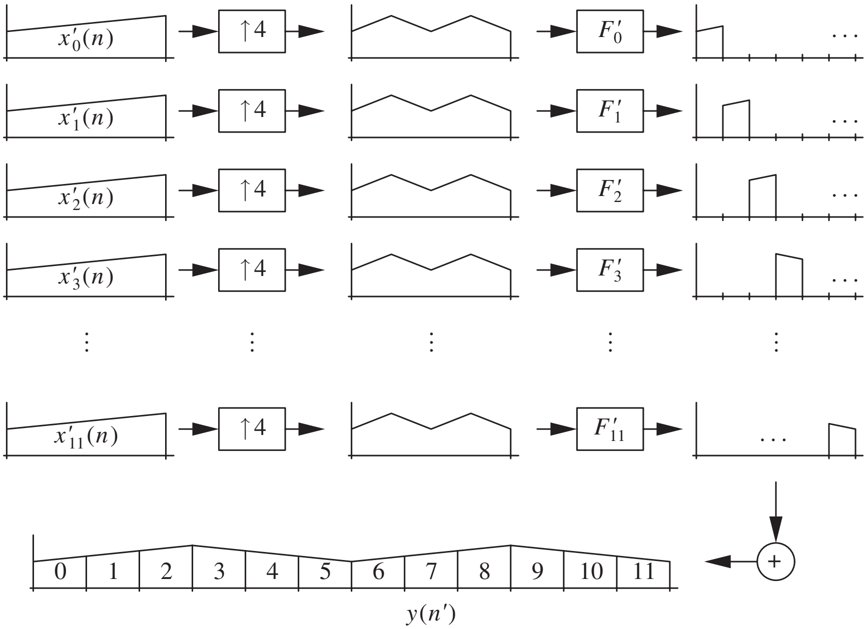

Figure 10. Signal representation of a 12-channel TMUX synthesis bank with resampling factor of 4.

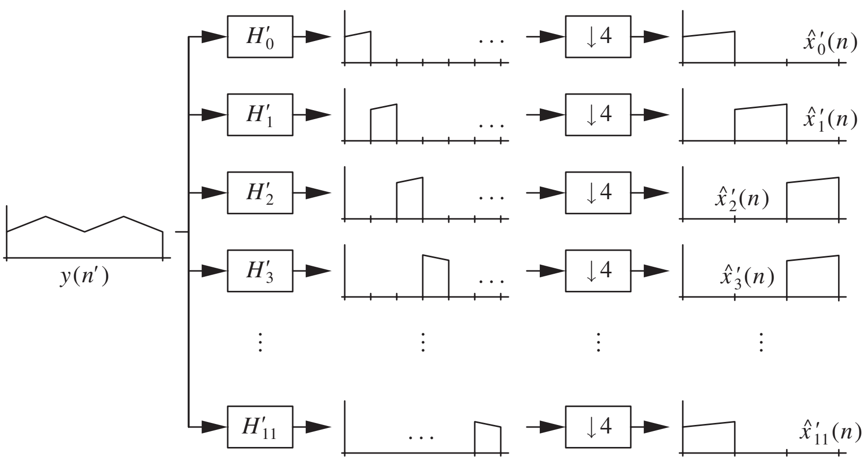

Figure 11. Signal representation of a 12-channel TMUX analysis bank with resampling factor of 4.

find an efficient structure for the system, based on the CMFB or any other filter bank structure. However, it is important to understand how the proposed method changes the specifications of the composing filters. For instance, when using a

Table 1. Prototype filter characteristics for the numerical example

	N	ω_p	ω_s	A_p (dB)	A_r (dB)
Design 1	587	0.0806π	0.0917π	0.198	-82.6
Design 2	1223	0.0403π	0.0458π	0.188	-86.5

CMFB structure, the 3-dB and cutoff frequencies for the new prototype filters should be properly defined as

$$\omega_{3\text{dB}} = \frac{\pi}{2M''} \tag{18}$$

$$\omega_s = \frac{(1+\rho')\pi}{2M''}, \tag{19}$$

respectively. Also, the minimum stopband attenuation, A'_r, and the maximum passband ripple, A'_p, must be redefined as

$$A'_r = \frac{A_r M'}{M''} \tag{20}$$

$$A'_p = \frac{A_p M'}{M''} \tag{21}$$

in such a way that the desired specifications are satisfied by the resulting filter bank.

7. Numerical example

This example consists of a 6-channel TMUX system with a resampling factor of 4. For this design, we require a minimum stopband attenuation of $A_r = 80$ dB and a maximum passband ripple of $A_p = 0.2$ dB. The roll-off factor is 0.1.

In Design 1, a CM-TMUX prototype filter is determined using the approach for noninteger α discussed in Section 4 with $R = 2$. The prototype filter is designed using a Remez algorithm with $\omega_{3\text{db}} = \pi/12$, and is characterized in Table 1, where N is the prototype filter order. Then the corresponding CMFB, with a constant multiplying factor (taking into account the value of $\sqrt{RW}$ on both the analysis and synthesis banks), will have the response depicted in Figure 12. For Design 1, the responses of the analysis filters after the decimation by a factor of 4 are shown in Figure 13. From this figure, we note the overlapping effect that attenuates the signal in channel 1 and amplifies the signal in channel 4. In addition, it is easy to determine that the average spectrum occupation is (1/3 on channels 1 and 4, and 2/3 on the other channels) $10/18 \approx 56\%$.

The values of ICI, ISI, and computational effort (CE) for the Design 1 TMUX are presented in Table 2. The CE figure is the number of filter coefficients mul-

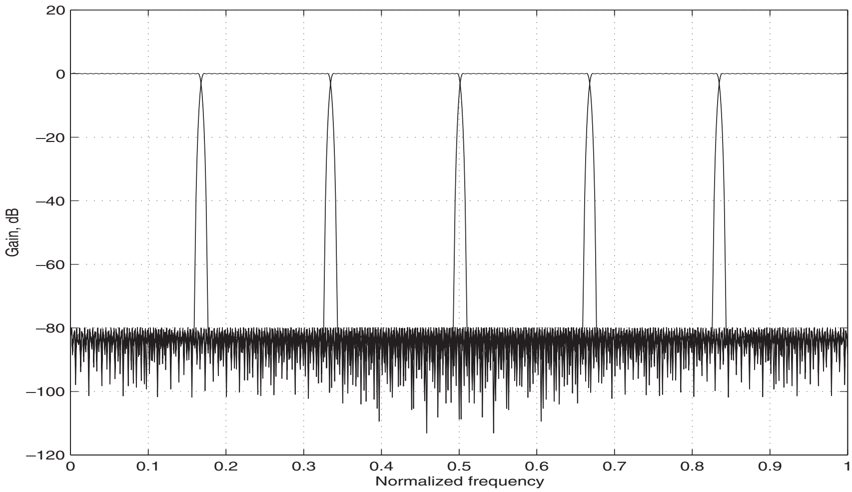

Figure 12. CMFB response for Design 1.

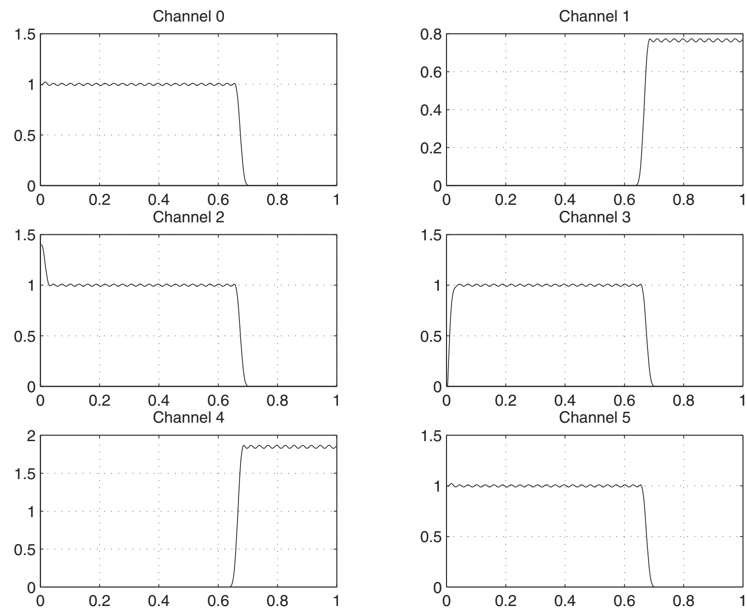

Figure 13. Responses of analysis filters for Design 1 after decimation by a factor of 4.

tiplied by W, because W is the factor that cannot exchange position with the polyphase structure. In the case of Design 1, $W = 2$.

Table 2. TMUX characteristics for the numerical example

	ISI (dB)	ICI (dB)	CE
Design 1	−70.5	−76	1174
Design 2	−71.3	−73	1224

Table 3. The subchannel split-and-add combination for Design 2

Channel	Subchannels
$x_0(n)$	$x'_0(n) + x'_7(n)$
$x_1(n)$	$x'_1(n) + x'_8(n)$
$x_2(n)$	$x'_2(n) + x'_6(n)$
$x_3(n)$	$x'_3(n) + x'_{11}(n)$
$x_4(n)$	$x'_4(n) + x'_9(n)$
$x_5(n)$	$x'_5(n) + x'_{10}(n)$

Now, we obtain the Design 2 TMUX using the channel split-and-add method described in Section 5 with $M'' = 12$ channels. In this case, as described in Section 6, the new specifications for the prototype filter are $A'_p = 0.197$ dB and $A'_r = -86$ dB. The roll-off ρ factor can be the same as before, if the nonadjacent channels are to be added together. The resulting prototype filter designed with a Remez algorithm is also characterized in Table 1.

For $M'' = 12$ with a resampling factor of $M = 4$, the three groups of overlapping signals are as given in Section 6. Hence, a possible choice of composing channels, two-by-two, where no adjacent subchannels are added together, is as presented in Table 3.

The responses of the 12-channel filter bank are depicted in Figures 14 and 15, before and after decimation by a factor of $M = 4$, respectively. The corresponding responses for the 6-channel bank after adding up the above subchannels two-by-two, as determined in Table 3, are shown in Figures 8 and 17, before and after decimation by a factor of $M = 4$.

From Figure 17 we note that by adding the subchannels, a uniform occupation rate of 66.7% is achieved for all channels. Also, as the auxiliary parameter α'' is an integer number, the CE for the resulting TMUX is given by the number of coefficients of the prototype filter, as shown in Table 2. Figure 17 also illustrates that the peaks and notches seen in Figures 13 and 15 tend to cancel each other when the original subchannels are added properly. The practical effect of such peaks and notches is minimal, as can also be inferred from the resulting ISI and ICI values shown in Table 2.

The channel split-and-add method may also take advantage of the combined low stopband energy and attenuation levels yielded by the WLS-Chebyshev

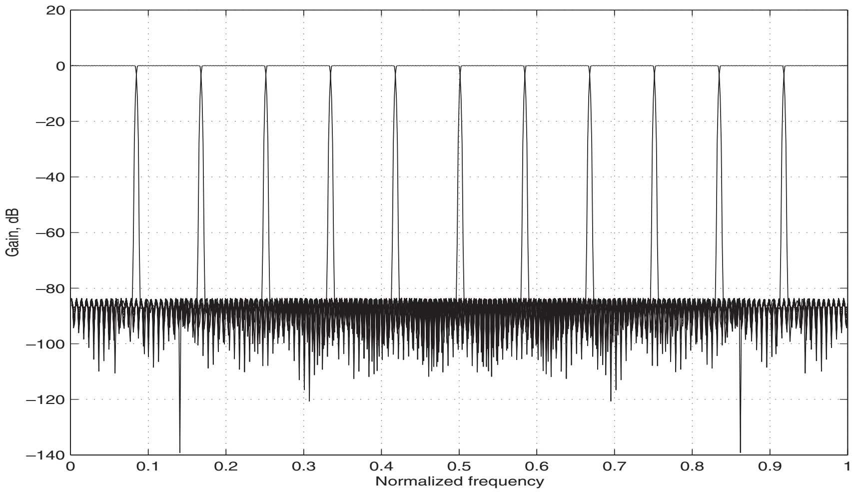

Figure 14. $M'' = 12$-channel CMFB response for Design 2.

method [1], [4], [5], [14]. With such a design, bands that are separated in the frequency domain cause little effect on other bands. Therefore, specifications of the modified prototype filter can be made more similar to the original specifications, reducing the CE required to implement the complete TMUX structure.

In addition, one may combine the channel split-and-add method with the frequency-response masking (FRM) approach [7], [8], including its optimized versions [9], [13], giving more flexibility on the choice of the interpolation factor for the FRM-based filter, as illustrated in [2].

8. Conclusions

A new method for designing filter banks has been proposed. By using this method, it is possible to reduce the computational complexity and to increase the occupation percentage of the channel bands on an oversampled filter bank. The method also gives the designer the choice of working with efficient structures, and making the bandwidth of the channels uniform for unusual relations of the number of channels and the change of sample rate factor. The choice of a new signal distribution inside the system represents an overhead because it raises the computational complexity and constrains even further the specifications of the original filter bank (namely, minimum attenuation and cutoff frequency parameters). Nevertheless, this method is suitable for generalizing the structure of some special CM-TMUX designs.

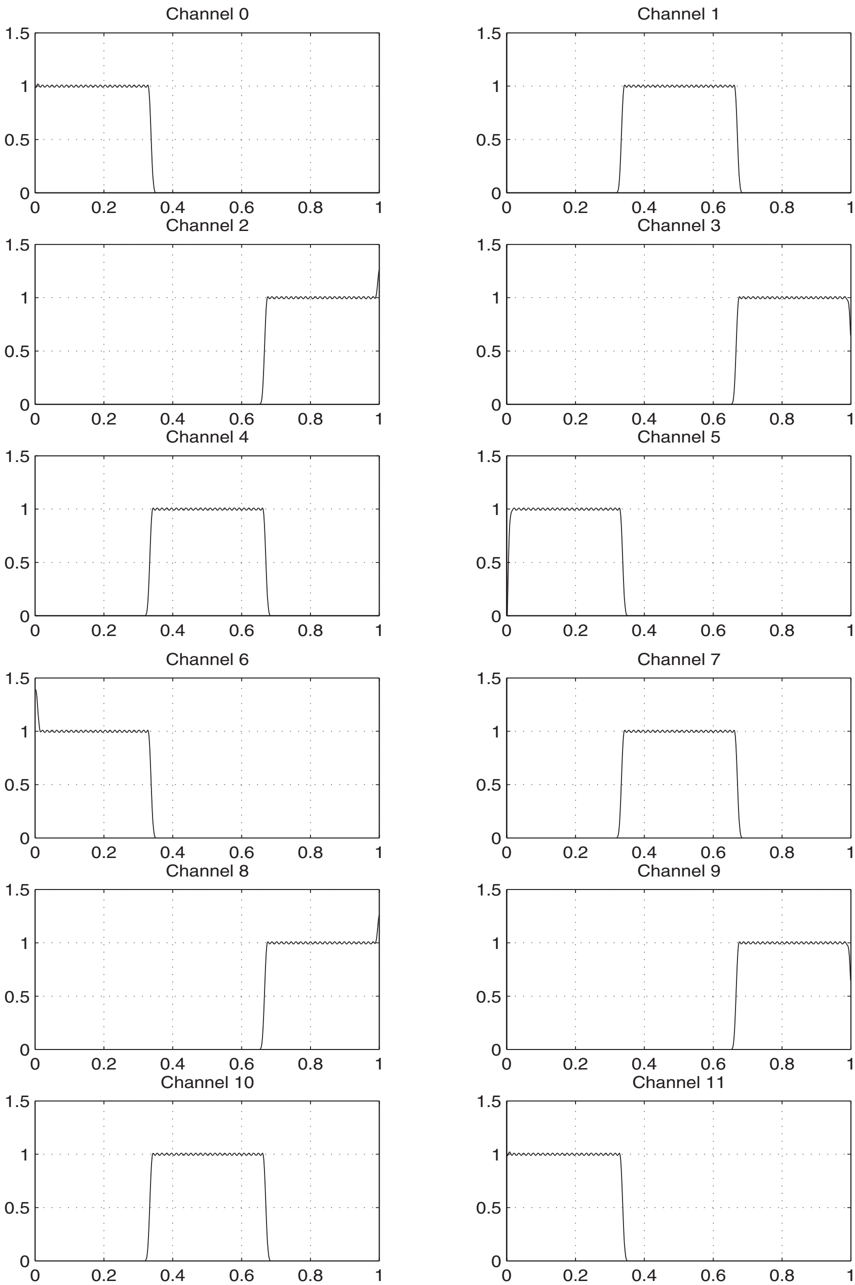

Figure 15. Responses of $M'' = 12$ individual analysis filters for Design 2 after decimation by a factor of 4.

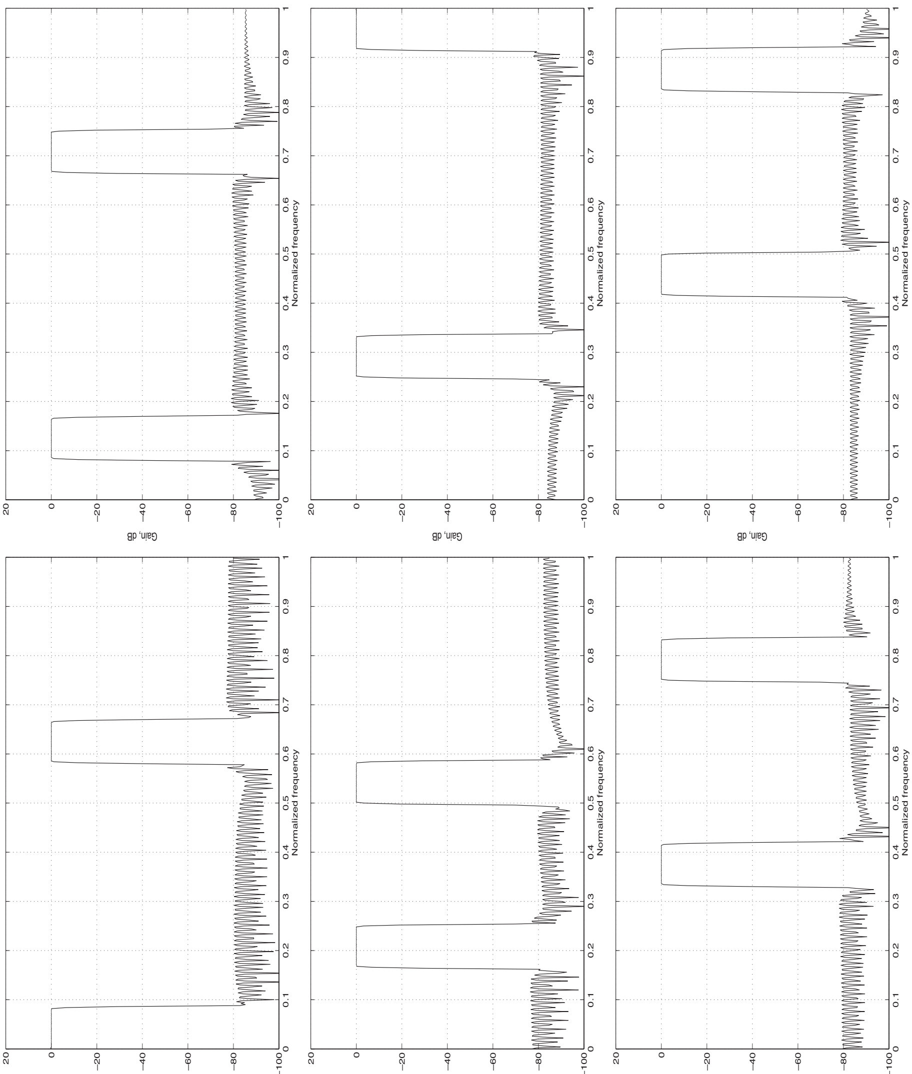

Figure 16. $M' = 6$-channel CMFB res ponse for Design 2.

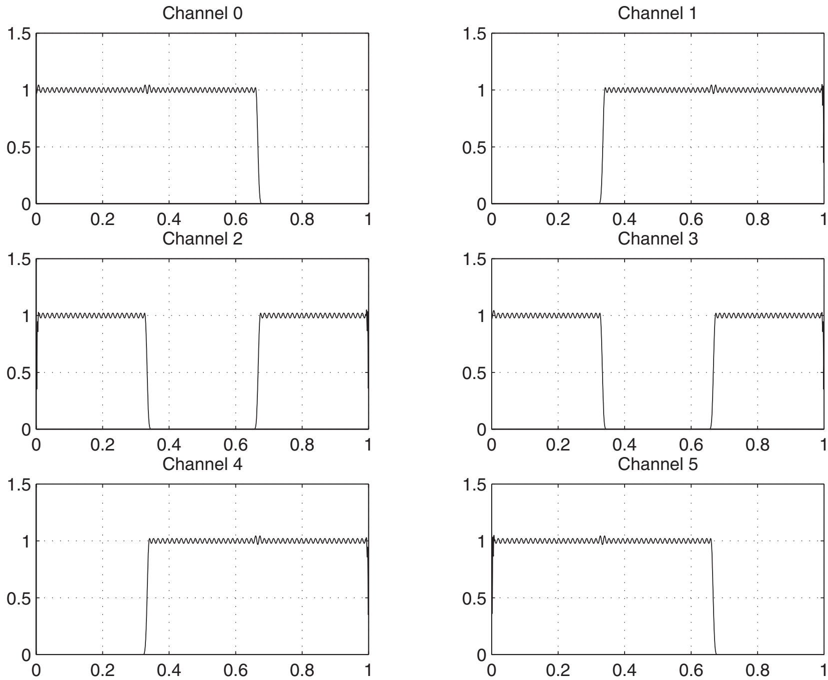

Figure 17. Responses of $M' = 6$ individual analysis filters for Design 2 after decimation by a factor of 4.

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