A Tree-Structured Non-Uniform Filter Bank for Multi-Standard Wireless Receivers

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***Abstract*— A new approach to implement computationally efficient reconfigurable filter banks for multi-standard wireless receivers is presented in this paper. Based on the concepts of tree-structured quadrature mirror filter bank (TQMFB) and coefficient decimation approach, a reconfigurable and efficient tree-structured non-uniform filter bank (TNFB) is proposed in this paper. The proposed filter bank is designed to extract channels of non-uniform bandwidths with reduced complexity when compared to TQMFB. Each stage of the proposed filter bank consists of a modal filter and a complementary delay to obtain the low-pass and high-pass channels respectively. Design examples show that the proposed TNFB offers an average multiplication rate reduction of 69% over the TQMFB.**

I. INTRODUCTION

In recent years, the software defined radio (SDR) concept accelerated the migration of traditional hard-wired radio platforms to flexible software definable platforms that can support multiple communication standards [1, 2]. A first order estimate of the resources required to implement the SDR receiver shows that the channelizer is the most computationally intensive part in the digital front end of an SDR [3]. This is because the channelizer needs to operate at the highest sampling rate as it comes directly after the analog-to-digital converter. The channelizer accomplishes the task of extracting individual narrow-band radio channels from the digitized wideband input signal with the help of digital filter banks [4, 5]. The channelizer must be reconfigurable to operate for different communication standards. Therefore to implement efficient SDR receivers, it is vital to have reconfigurable low complexity filter bank channelizers [3].

Efficient implementations of a channelizer using discrete Fourier transform (DFT) filter banks (DFTFBs) are available in literature [5]. A uniform N-channel channelizer can be realized using DFTFB by implementing one low-pass filter and a corresponding modulator such as N-point DFT. Thus instead of implementing N separate channel filters, a single low-pass filter followed by DFT is only required [3]. The limitation of the DFTFB is that the channel filters have fixed equal bandwidths corresponding to the specification of a given standard and hence can not be efficiently used for multi-standard receivers. Also if the number of channels required is less, DFTFB based channelizer is very expensive. In [6], a reconfigurable tree-structured quadrature mirror filter bank (TQMFB) has been proposed for SDR channelization. The TQMFB is composed of a tree of quadrature mirror filter banks. Each stage of the tree splits the input signal into a set of quadrature high and low frequencies. The desired channel is obtained at an appropriate stage along the tree corresponding to the bandwidth of the channel-of-interest. However the TQMFB can only extract signals whose channel spacing is related by a factor-of-two because of uniform splitting of input signal into equal low and high frequency bands. This factor-of-two relation of channel spacing imposes constraints on TQMFB for multi-standard channelization.

In this paper, we propose a reconfigurable non-uniform tree-structured filter bank. Similar to the TQMFB, it splits the input signal frequency into a set of low and high frequencies, but need not be of equal bandwidths. This is achieved because, in the proposed tree-structured non-uniform filter bank (TNFB), the low-pass filters are designed based on our recently proposed coefficient decimation (CD) approach proposed [7]. The basic idea of CD approach is as follows. If every M^{th} coefficient of a finite impulse response (FIR) filter $h(n)$ (called modal filter) is kept unchanged and all other coefficients are replaced by zeros, we get $h'(n)$, that has a multi-band frequency response:

$$h'(n) = h(n).c_M(n) \qquad (1)$$

$$\text{where } c_M(n) = \begin{cases} 1; \textit{for } n = kM, & k = 0,1,2...M-1 \\ 0; \textit{otherwise} \end{cases}$$

The frequency response of $h'(n)$ is scaled by M with respect to that of $h(n)$ and the replicas of the frequency spectrum are introduced at integer multiples of $2\pi/M$. By changing the value of M, different numbers of frequency response replicas located at different centre frequencies can be obtained. In the sequel, we call this coefficient decimation (CD) method as *CDM-1*. The passbands of the multi-band response obtained using *CDM-1* will have identical widths as that of the modal filter [7]. If all the coefficients of the coefficient decimated filter obtained using *CDM-1* are grouped together after discarding the in-between zeros, a decimated version of the original frequency response is obtained whose passband width is M times that of the original modal filter. This method is referred as *CDM-2* in the sequel. Thus by using the low-pass filters based on *CDM-2* in the proposed TNFB in all the stages along the tree, it is possible to obtain different passband widths by changing the value of M. The high-pass channels in all the stages along the proposed TNFB tree are obtained using complementary delays i. e complimenting the low-pass channel output using appropriate delays. At each stage of TNFB, low-pass filters based on *CDM-2* extract different low-pass channels, whose bandwidths are variable or not uniform, and the complementary delays extract the corresponding high-pass channel. Thus the proposed TNFB has the ability to perform non-quadrature, non-uniform bandwidth channel extraction at a lower complexity compared to the TQMFB.

The rest of the paper is organized as follows. In Section II, the proposed TNFB is presented. Section III illustrates the function of the proposed FB as a low complexity alternative to TQMFB with design examples. Section IV has our conclusions.

II. Proposed Tree-Structured Non-Uniform filter bank

In this section, we present the proposed reconfigurable non-uniform tree structured filter bank. The basic architecture of the proposed FB is similar to the TQMFB as shown in Fig. 1. However each stage of the proposed FB (as shown using dotted lines in Fig. 1) consists of an N-tap low-pass filter based on *CDM-2* (modal filter) and a complementary delay to obtain the low-pass and high-pass frequency band of the input signal respectively. The high-pass filter output can be obtained by subtracting the output of the low-pass modal filter from a suitable delayed version of the input by using complementary delays as shown in Fig. 1.

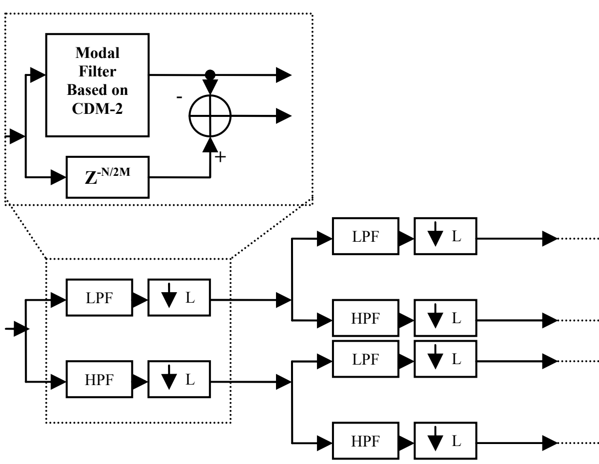

Figure 1. Architecture of the proposed TNFB.

The value L is the downsampling factor and $L = 2$ when the TNFB is employed to split the input signal into two equal low-pass and high-pass bands as in TQMFB. The low-pass filter based on the *CDM-2* approach can have multiple frequency responses which forms the basis of extraction of channels of non-uniform bandwidths in proposed TNFB. The CD approach [7] allows the modal filter to be reconfigured without changing the values of coefficients. Thus each stage of the TNFB can be employed for extracting channels of non-uniform bandwidth. This can be generalized as follows. The same modal filter specifications are employed for all the stages of TNFB. Let f_p and f_s be the passband and stopband edges respectively and M_1, M_2 etc be the M values for first, second and successive stages respectively. Then the first stage low-pass output channel will have passband and stopband edges as $M_1.f_p$ and $M_1.f_s$ respectively. The high-pass channel will be the complementary of the low-pass channel. Similarly the second stage low-pass channel will have passband and stopband edges as $M_2.f_p$ and $M_2.f_s$ respectively and so on. Thus the passband widths at the successive stages are not the same, which makes the proposed TNFB ideally suitable for SDR channelizers. However the passband widths at successive channels can be made the same as in TQMFB by making M_1, $M_2 = M$. The uniform and non-uniform channel extractions are explained in more details in Section III.

The passband width of the low-pass channel at each stage can be independently adjusted by decimating the modal filter at each stage by appropriate M values. The high-pass channels obtained using complementary delays can also be easily changed. As a result of this, the proposed TNFB can be easily reconfigured.

The steps to design the proposed TNFB are as follows:

Step 1: Let the specification of the modal filter are peak passband ripple, δ_p, peak stopband ripple, δ_s, passband edge, f_p and stopband edge, f_s respectively. Using the formula advanced by Bellanger [8], the filter-length N is given by:

$$N = \frac{-2\log_{10}(10\delta_p\delta_s)}{3(f_s - f_p)} - 1 \tag{2}$$

Step 2: Non-uniform bandwidth channels can be extracted when the coefficients of the modal FIR filter are decimated by M according to *CDM-2*. Choose an M value so that a desired frequency response corresponding to the communication standard is obtained at each stage.

Step 3: Based on the selected M for the modal FIR filter, we can obtain the complementary delay, D,

$$D = Z^{-\frac{N}{2M}} \tag{3}$$

Note that while N is fixed, the value of the delay is directly proportional to $1/M$. The delay changes with M as different M^{th} coefficients are grouped together for each decimated frequency response. Hence to avoid in-between delays, the original delay have to be scaled by $1/M$.

III. Design Examples

In this section, we compare the performances of the proposed TNFB and TQMFB [6]. Two design examples of extracting multiband frequency channels are presented. The first example would be on extraction of channels of uniform bandwidths, where performances of TQMFB and proposed TNFB will be compared. The second example is a scenario where channels of non-uniform bandwidths need to be extracted, which is practically impossible using TQMFB.

A. *Design Example I*

In this example, extraction of channels of uniform bandwidths by the proposed TNFB is illustrated and compared with TQMFB. Let the bandwidth of the input signal be 12.8 MHz and sampling frequency be 25.6 MHz. The passband (f_p) and stopband (f_s) frequency edges for the low-pass filter of TQMFB are fixed as 0.4986 and 0.5 and that of the modal filter in proposed TNFB are fixed as f_p=0.080 and f_s=0.0825 (All frequency edges normalized to 0.5 i. e. half the Nyquist frequency). The passband and stopband attenuation specifications are fixed as 0.1 dB and -30 dB respectively for illustration. For obtaining the specified passband and stopband attenuations using the *CDM-2* approach in the proposed TNFB, the modal filter specifications must be more stringent. This is because when the modal filter coefficients are decimated using *CDM-2*, the passband and stopband attenuations reduce. Hence the passband and stopband attenuation specifications of the modal filter in TNFB are fixed slightly higher as 0.05 dB and -55 dB respectively. The length of the prototype low-pass filter in TQMFB and that of modal filter in TNFB are 1200 and 2200 using (2).

Let the two channels of interest for this example be: CH1: 0 - 200 kHz and CH2: 0 - 3.2 MHz. The general tree-structured architecture for both TQMFB and the proposed TNFB is as shown in Fig. 2. Due to space constraints, only a part of the subband decomposition along with the tree structure is shown in Fig. 2, where all the numerals are in MHz.

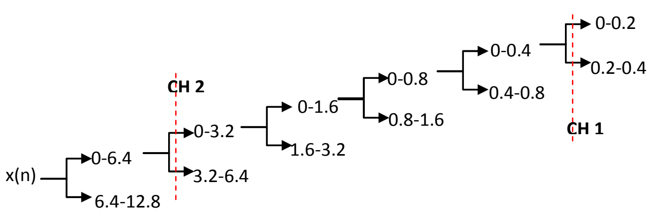

Figure 1. Tree-structure for 2-channel channelizer in design example 1.

From Fig. 2, it can be seen that CH1 is extracted at the sixth stage of the tree whose bandwidth is 200 kHz. CH2, whose bandwidth is 3.2 MHz, is extracted at the second stage of decomposition. In this design example, the modal filter of the proposed TNFB is selected to be a decimated frequency response of M = 6. Fig. 3 (a) represents the frequency response of the modal filter and Fig. 3 (b) represents the frequency response for the case M = 6, which is employed for this design example. Thus effectively the passband (f_p) and stopband (f_s) frequency edges of the modal filter are 0.48 and 0.495 respectively as shown in Fig. 3 (b). Also effective modal filter length is 2200/6 = 367 for each stage. However the length of each low-pass filter in TQMFB is 1200.

Table I shows the comparison of the proposed FB with TQMFB in terms of multiplication rate. The number of multiplications is given by,

$$No.\ of\ multiplications = \sum_{i=1}^{6} L_i F_{si} \tag{4}$$

where i is stage number, L_i is length of the filter and F_{si} is sampling frequency at stage i. From Table I, it is clear that, the proposed FB offers multiplication rate reduction of 69.2% over the TQMFB.

TABLE I. MULTIPLICATION RATE COMPARISON

	TQMFB	Proposed TNFB
L_i	1200	367
No. of Multiplications	30240	9322
Savings in terms of No. of Multiplications (%)		69.2%

Thus from Table I, it is evident that even though the modal filter in the proposed TNFB has higher order to start with when compared to the prototype filter in TQMFB, the effective filter order and thus the multiplication rate is lower for the proposed TNFB.

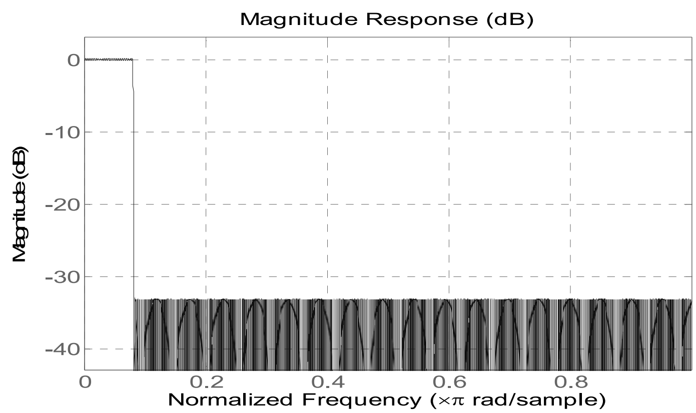

Figure 3 (a). Frequency Response of original Modal FIR filter.

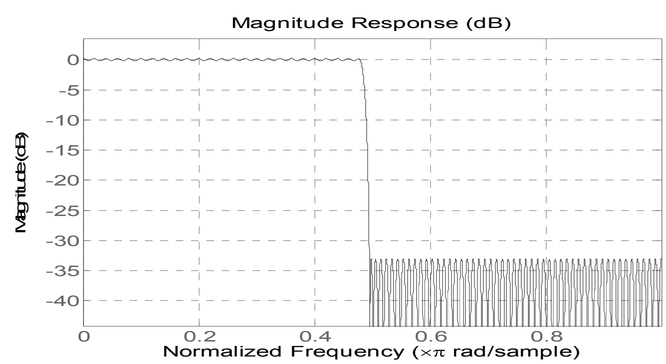

Figure 3 (b). Decimated Frequency Response of Modal FIR filter when M=6.

In Fig. 4, the CH1 and CH2 signals extracted using the TQMFB and the proposed TNFB are shown. Fig. 4 (a) shows CH1 extracted at the sixth stage and Fig. 4 (b) shows the CH2 extracted at the second stage. The solid line represents the TQMFB and the dotted line represents the TNFB in Fig. 4. It can be noted that there is slight difference in the passband and stopband ripples between TNFB and TQMFB, because the proposed TNFB has been over-designed to obtain the required specifications.

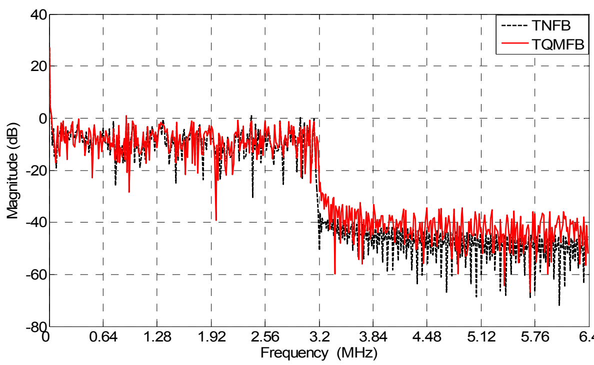

Figure 4 (a). Output response of CH2 (3.2 MHz) extracted using TQMFB and the proposed TNFB.

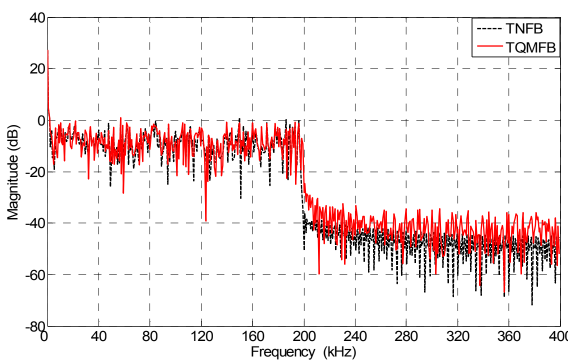

Figure 4 (b). Output response of CH1 (200 kHz) extracted using TQMFB and the proposed TNFB.

B. *Design Example II*

In this section, we present the extraction of channels of non-uniform bandwidth using the proposed TNFB. Let the bandwidth of the input signal be 6.4 MHz, sampling frequency be 12.8 MHz and the channels of interest be: Ch1: 1.1 - 6.4 MHz, Ch2: 0.55 - 1.06 MHz, Ch3: 90 - 212 kHz and Ch4: 0 – 90 kHz. The TQMFB can not be employed for this design example. The structure of the proposed TNFB for simultaneously extracting the four channels, Ch1 to Ch4, is shown in Fig. 5.

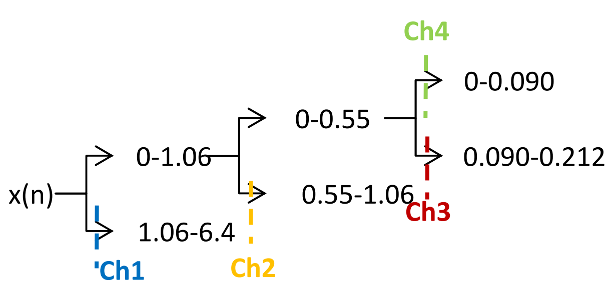

Figure 5. Proposed TNFB architecture for 4-channel channelizer in design example 2.

The modal filter specifications are same as in design example 1 in all the stages. However in the first stage, the modal filter is decimated by $M = 2$, in the second and third stages, the modal filter is decimated by $M = 6$ and $M = 5$ respectively. When the modal filter is decimated by $M = 2$, the passband and stopband edges of the modal filter become $f_p = 0.080\text{x}2 = 0.16$ and $f_s = 0.0825\text{x}2 = 0.165$. With the sampling rate of 12.8 MHz, the low-pass filter at stage-1 of the proposed TNFB can extract 0 – 1.06 MHz (0 - f_sx12.8/2 MHz) and the complementary high-pass channel will be corresponding to 1.06 – 6.4 MHz. Thus the Ch1 can be obtained as high-pass channel output at stage-1. Similarly Ch2 can be obtained as high-pass channel at stage-2 and Ch3 and Ch4 can be obtained as high-pass can low-pass channels respectively from the stage-3. The number of multiplications involved in this design example (according to (2)) = 2200/2 x 12.8 + 2200/6 x 2.12 + 2200/5 x 0.424 =15044. From this design example, it can be seen that the proposed TNFB can be used for extraction of non-uniform channels. It is not possible using TQMFB or DFTFB. Hence the proposed TNFB is ideally suited for multi-standard wireless receivers.

IV. Conclusion

In this paper, we have proposed a reconfigurable tree-structured non-uniform filter bank. The proposed filter bank (FB) follows the architecture of tree-structured quadrature mirror filter bank (TQMFB). However the low-pass filters are designed using coefficient decimation (CD) approach proposed by us in [7]. The high-pass filters are replaced by complementary delays. From the design example, it can be seen that the proposed FB offers multiplication rate reduction of 69% over the TQMFB. The proposed filter bank is also able to perform extraction of channels which have non-uniform bandwidths. By changing the value of M in the low-pass filter designed using the CD approach, the proposed FB is able to change its bandwidth requirements and adjust accordingly to different specifications and thus easy to reconfigure.

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