Area Efficient Reconfigurable Fast Filter Bank for Multi-
Standard Wireless Receivers

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ABSTRACT— This brief presents a reconfigurable fast filter bank (RFFB) with less gate counts for wireless communication applications such as spectrum sensing and channelization. RFFB offers fine control over subband bandwidth without any reimplementation. This is accomplished with an improved modified frequency transformation-based variable digital filter (MFTVDF) at the first stage of the multistage implementation that offers unbridged control over the cutoff frequency on a wide frequency range thereby improving the cutoff frequency range which inturn results in fine control over subband bandwidth. RFFB offers less gate counts among other filter banks.

KEYWORDS— Fast filter bank (FFB), Transition bandwidth (TBW), variable digital filter (VDF).

I. INTRODUCTION

Concerned scholars and development groups are showing their attraction to communication advances by enhancing the multi-standard terminals that simultaneously support voice calls, positioning and navigation activities, high quality video and audio streaming, and large size data transmission. Multi-standard oriented systems operate with a set of integrated technologies. They can be performed in different hardware units and connected by buses. A multi-standard wireless receiver (MSWR) enables different air interfaces with the digital signal processing.

Generally, filter bank is used to perform several operations for MSWRs. The filter bank must be dynamically reconfigurable to support multiple communication standards with different channel bandwidth and center frequency specifications. Various filter bank design approaches exist. The discrete Fourier transform filter bank (DFTFB) is a modulated filter bank that consists of a low-pass prototype filter followed by DFT operation [1], [2] and widely used for various communication applications but they fail to provide nonuniform sub-band bandwidth and fixed center frequency for each sub-band. An improved DFTFB using coefficient decimation method (CDM) [3] allows changing sub-band bandwidths using a fixed-coefficient filter but it fails to have fine control over sub-band bandwidth because the decimation factor in the CDM is restricted to be integers. Also, center frequency of sub-bands in CDM-DFTFB is fixed.

The fast filter bank (FFB) [6] is a low complexity alternative to DFTFB and is suitable for applications requiring sharp transition bandwidth (TBW). However, the FFB has the drawbacks of uniform subband bandwidth. Several improvements in FFBs are suggested, particularly multiresolution FFB in [8] also has only coarse control over sub-band bandwidth by changing the filter bank resolution.

In order to have fine control over subband bandwidth, a new approach of reconfigurable fast filter bank is designed by combining FFB and a variable digital filter (VDF). A VDF that offers wide cutoff frequency range is desired. The reconfigurable FFB (RFFB) is designed by replacing fixed-coefficient low-pass subfilter in the first stage of FFB with the MFT-VDF. The subfilters in RFFB have higher order than FFB that can be reduced by varying the subfilters TBW. The RFFB provides fine control over the sub-band bandwidth on the desired bandwidth range. This makes RFFB suitable for multi communication standards with different channel bandwidth.

II. SECOND ORDER TRANSFORMATION VDF

Consider a FIR filter of order 2N with symmetric coefficients which is referred to as prototype filters. This prototype is implemented in taylor form by expressing transfer function as

\[
H(z) = \sum_{n=0}^{N} a_n z^{-N \left[ \frac{2z-1}{2} \right]}
\]

where the coefficients \(a_n\) are related to the impulse response coefficients \(h_n\) of \(H(z)\).
The second transformation is given by

$$\frac{z + z^{-1}}{2} = \sum_{k=0}^{N-1} A_k \left( \frac{z + z^{-1}}{2} \right)^k$$  \hspace{1cm} (2)$$

where parameters $A_k$ are the transformation coefficients which controls the relationship between $H(z)$ and second-order transformation based VDF, $H_2(Z)$. Substituting (2) in (1) we get

$$H_2(Z) = \sum_{n=0}^{N-1} a_n Z^{-(N-n)} \left[ \sum_{k=0}^{N-1} A_k Z^{-k} \left( \frac{1 + z^{-2}}{z} \right)^k \right]^n$$  \hspace{1cm} (3)$$

Fig.1  a) second order transformation VDF,  b) second order transformation

By substituting $z = e^{j\omega_c}$ and $Z = e^{j\Omega_c}$ in equation 2, the following expression is obtained,

$$\cos \omega_c = \sum_{k=0}^{N-1} A_k \left( \cos \Omega_c \right)^k$$  \hspace{1cm} (4)$$

$\omega_c$ and $\Omega_c$ are considered as cut-off frequency of $H(z)$ and $H_2(Z)$ respectively.

By expanding (4) the $\Omega_c$ and TBW are given by

$$\Omega_c = \cos^{-1} \left( -\frac{A_1 \pm \sqrt{A_1^2 - 4A_2(A_0 - \cos \omega_c)}}{2A_2} \right)$$  \hspace{1cm} (5)$$

$$\text{TBW} = \frac{A_1 \sin \Omega_c + A_2 \sin \Omega_c}{\sin \omega_c}$$  \hspace{1cm} (6)$$

If the constraints are met

$$A_0 + A_1 + A_2 = 1$$  \hspace{1cm} (7a)$$
0 \leq A_1 \leq 1$$  \hspace{1cm} (7b)$$
A_1^2 - 4A_2(1 - A_1 - A_2 - \cos \omega_c) \geq 0$$  \hspace{1cm} (7c)
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Fig. 2 a), b) Schematic diagrams of VDF

![Schematic diagrams of VDF](image)

Fig. 3 Simulated result of VDF

![Simulated result of VDF](image)

Fig. 4 Summary of the result

<table>
<thead>
<tr>
<th>Device Utilization Summary</th>
<th>Used</th>
<th>Available</th>
<th>Utilization</th>
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<tr>
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</tr>
<tr>
<td>Number of 4 Input LUTs</td>
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<td>Logic Distribution</td>
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<td></td>
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</tr>
<tr>
<td>Number of occupied Slices</td>
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<tr>
<td>Number of Slices containing only related logic</td>
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<td>766</td>
<td>100%</td>
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<tr>
<td>Number of Slices containing unrelated logic</td>
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<td>0%</td>
</tr>
<tr>
<td>Total Number of input LUTs</td>
<td>1,135</td>
<td>12,288</td>
<td>9%</td>
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<tr>
<td>Number used as logic</td>
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<tr>
<td>Number used as a route-thru</td>
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<tr>
<td>Number used as Shift registers</td>
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<tr>
<td>Number of bonded DFFs</td>
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<td>40%</td>
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No pertinent information was found.
The cut-off frequency and TBW are controlled by the parameters $A_0, A_1, A_2$. In frequency transformation VDF $A_1$ is fixed to unity which reduces complexity. By restricting $A_1$ to unity the variation over the cut-off frequency range is limited which leads to limited control over the subband bandwidth of the filter bank. As MSWR applications require fine control over the subband bandwidth, the VDF that allows wider cutoff frequency range is required to have fine control over the subband bandwidth.

III. DESIGN OF RFFB

The RFFB is designed to provide fine control over the sub-band bandwidth. The reconfigurable FFB (RFFB) is designed by replacing fixed-coefficient low-pass subfilter in the first stage of FFB with the MFT-VDF. The linear phase VDF that offers fine control over cutoff frequency range is desired. Therefore RFFB retains the linear phase property which is required for most of the communication applications. Let the design specification of RFFB with $L$ subbands are maximum and minimum subband bandwidth, desired TBW, pass band ripple, and stop band attenuation. The structure of RFFB with $k = \log_2(L)$ stages is shown in fig.5. The design of RFFB is described as follows.

3.1 First stage- MFT VDF

The low-pass VDF in the first stage is designed using modified second-order frequency transformation with transfer function $H_2(Z)$ in the form given by (3). The range over which cutoff frequency of $H_2(Z)$ can be varied is decided by parameters $A_1$ and $A_2$, while the order of the prototype filter of $H_2(Z)$ is decided by its TBW, pass-band ripple, and stop-band attenuation specifications. Expanding $D(Z)$ in (3),

$$D(Z) = A_0Z^{-2} + A_2(\frac{1+z^{-2}}{2})^2 + A_2\left[\left(\frac{1+z^{-2}}{2}\right)^2\right]$$

From the constraints given in (8) substitute $A_0 = 1 - A_1 - A_2$ in (9) then $D(Z)$ becomes

$$D(Z) = A_1\left[\left(\frac{1+z^{-2}}{2}\right)^2\right] - Z^{-2} + Z^{-2} - A_2\left[Z^{-2} - \left(\frac{1+z^{-2}}{2}\right)^2\right]$$

In this way, only two multipliers are needed instead of three multipliers, to implement $D(Z)$. In frequency transformation based variable filters, $A_1$ is fixed to unity. In the MFT-VDF, we have relaxed the constraint that $A_1 = 1$ so that $H_2(Z)$ allows a much wider cutoff frequency range. The design steps for the first stage of RFFB are as follows.

1) Based on desired $BW_{\text{min}}$ and $BW_{\text{max}}$, the lower and upper cutoff frequencies of $H_2(Z)$, $f_{c1}$ and $f_{c2}$, respectively, are calculated as $M/2$ times $BW_{\text{min}}$ and $BW_{\text{max}}$, respectively.

2) For a desired range from $\Omega_{c1} = 2\pi f_{c1}$ to $\Omega_{c2} = 2\pi f_{c2}$, corresponding value of $A_1$ and range of $A_2$ are calculated. For a given $A_1$ ($0 \leq A_1 \leq 1$) and $\omega_c$, corresponding range of $A_1$ and $\Omega_c$ are obtained through iterative procedure. In this case $A_1$ ($0 \leq A_1 \leq 1$) is restricted to sum of reciprocals of power-of-two values to keep the multiplier complexity same as [11]. In case where multiple combinations of $\omega_c$, $A_1$, and $A_2$ provide same cutoff frequency range from $f_{c1}$ to $f_{c2}$ is selected to provide better TBW performance as per (6) in order to reduce the order of the MFT-VDF, $H_2(Z)$. 

Fig.5 Reconfigurable fast filter bank

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3) As the TBW of the $H_2(Z)$ is not constant over the frequency range from $f_{c1}$ to $f_{c2}$ as shown in (6), $TBW_0$ of the prototype filter of $H_2(Z)$ is chosen such that the maximum TBW over the range of $f_{c1}$ to $f_{c2}$ is equal to or narrower than $M^*TBW_d$. Based on these parameters, $H_2(Z)$ is designed and interpolated by $M$ to get multiband original $(O_1)$ and complementary $(C_1)$ response. When $H_2(Z)$ is interpolated by $M$, the multiband responses $O_1$ and $C_1$ is obtained with sub-band bandwidths and TBWs smaller by a factor of $M$ as shown in Fig. (b) and (c), respectively. For a given cutoff frequency, $f_c$, of $H_2(Z)$, where $f_{c1} \leq f_c \leq f_{c2}$, bandwidth of subband in the original response, $O_1$ is given by

$$BW_{o1} = \frac{2}{M^4} f_c$$

(10)

Bandwidth of subband in the complementary response, $C_1$, is given by

$$BW_{c1} = \frac{2}{M^4} (1 - f_c)$$

(11)

When $f_c = f_{c2}$, $BW_{o1} = BW_{max}$ and $BW_{c1} = BW_{min}$, when $f_c = f_{c2}$, $BW_{o1} = BW_{min}$ and $BW_{c1} = BW_{max}$. For desired $\Omega_c = 2\pi f_c$, corresponding value of $A_2$ is obtained by rewriting (4)

$$A_2 = \left( \frac{\cos \omega_c - A_0 - A_1 \cos \Omega_c}{\cos \Omega_c^2} \right)$$

(12)

In this way, by controlling $\Omega_c = 2\pi f_c$ of $H_2(Z)$ using $A_2$, fine control over sub-band bandwidth from $BW_{min}$ to $BW_{max}$ is achieved. By combining adjacent sub-bands and varying $A_2$, RFFB offers fine control over center frequency of fixed bandwidth sub-bands. All sub-bands in multiband responses $O_1$ and $C_1$ are individually extracted using subfilters in remaining $(k - 1)$ stages.

3.2 Remaining Stages–Fixed-Coefficient Digital Sub-Filters

The remaining stages of the RFFB consist of fixed coefficient subfilters, $H_{ij}(Z)$, where $1 \leq i \leq (k - 1)$ and $0 < j \leq (2^i - 1)$, arranged in a tree structure similar to uniform FFB. The design steps for remaining stages are as follows.

1) The $(k-1)$ subfilters, $H_{ij}(Z)$, $1 \leq i \leq (k-1)$ and $j = 0$ are fixed-coefficients even-order low-pass filters which shall be known as subprototype filters. The cutoff frequency of all these subprototype filters is fixed and equal to 0.5 in the normalized frequency scale. The pass band ripple $\delta p$ and stop band attenuation $\delta s$ of the filter bank and all subprototype filters are kept same.

2) The transition bandwidths $TBW$, of the subprototype filters, $H_{io}(Z)$, $1 \leq i \leq (k-1)$, are given by

$$TBW_i = 1 - \left( \frac{f_{c2} + TBW_d}{2} \right)$$

(13)

where $f_{c2}$ is maximum cutoff frequency of the $H_2(Z)$. Based on these parameters, $H_{io}(Z)$, where $1 \leq i \leq (k-1)$, are designed and then interpolated by the factor $M/2^i$.

3) The remaining subfilters, $H_{ij}(Z)$, where $1 \leq i \leq (k-1)$ and $1 \leq j \leq (2^i - 1)$, are obtained by modulating the corresponding interpolated sub prototype filters, $H_{io}(Z(M/2^i))$. 

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The RFFB with MFT-VDF in the first stage, provides uniform bandwidth subbands of bandwidth \( \frac{2}{L} \) as well as nonuniform bandwidth sub-bands with bandwidth varying from \( BW_{\text{min}} \) to \( BW_{\text{max}} \), where \( BW_{\text{min}} \leq \frac{2}{L} \). It can be observed from (10) and (11) that higher the value of \( f_{c2} \) (= \( f_c \)), wider is the range over which sub-band bandwidths can be varied. As \( f_{c2} \) is inversely proportional to TBW according to (13), wider sub-band bandwidth variation range comes at the cost of narrow TBW subfilters in remaining \((k-1)\) stages. As the \( f_{c2} \) in the RFFB is higher than that in uniform FFB, where \( f_{c2} = 0.5 \), the fixed-coefficient subfilters in the remaining stages of our RFFB have narrow TBWs (which means higher order, i.e., more gate count complexity) than that of the uniform FFB for a given \( TBW_{\text{d}} \), \( \alpha_{p} \), and \( \alpha_{s} \). This is the penalty in terms of number of gate counts incurred while achieving fine control over sub-band bandwidths. So \( f_{c2} \) is varied to change TBW, thereby reduces the order of the subfilters. As \( H_2(Z) \) is a linear phase VDF and all subfilters in remaining stages have linear phase, the RFFB retains the linear phase property of the FFB in [6] which is required for most of the communication applications.

IV. DESIGN EXAMPLE
Consider the desired specifications of the RFFB as: \( L = 16, BW_{\text{min}} = 0.06, BW_{\text{max}} = 0.2, TBW_{d} = 0.03, \alpha_{p} = 0.1 \) dB and \( \alpha_{s} = -50 \) dB. Then, for \( M = 8 \) and \( k = \log_2(L) = 4 \), the required values of \( f_{c1} \) and \( f_{c2} \) are 0.24 (= 0.06*8/2) and 0.8 (= 0.2*8/2) respectively. For desired values of \( f_{c1} \) and \( f_{c2} \) \( A_2 \) is 0.4375, \( A_2 \) varies between \(-0.2 \) and \( 1.5 \), and \( \omega_c = 0.2 \). Note that multiplication with \( A_2 \) can be performed by addition and shift operations only. \( H_2(Z) \) is designed using the prototype filter of order 80 with \( \omega_c = 0.4, TBW_0 = 0.065, \alpha_p = 0.1 \) dB, and \( \alpha_s = -50 \) dB. The orders of the subfilters \( H_{10}(Z), H_{20}(Z), H_{30}(Z) \) with 0.5 cutoff frequency, TBWs obtained using (10), maximum pass-band ripple of 0.1 dB and minimum stop-band attenuation of \(-50 \) dB are \( 40, 16 \) and \( 6 \) respectively.

The RFFB provides fine control over subband bandwidth by varying \( A_2 \) from \(-0.2 \) to \( 1.5 \). Fig.7 shows frequency responses of subband 9 as the bandwidth varies between 0.06 and 0.2.

![Fig.7 Variable bandwidth responses for subband 9](image-url)

V. IMPLEMENTATION COMPLEXITY
As RFFB can be used as a uniform as well as nonuniform filter bank, its complexity is higher than uniform FFB. The CDM-DFTFB, consisting of a prototype filter of order 1000 (\( f_c = 0.0225 \), \( TBW = 0.003 \), CDM factor range 3–10) followed by 16 point FFT, has a gate count 99% higher than the RFFB.

The nonuniform FFBS, with desired specifications can also be designed using either one of the following VDF in the first stage of FFB: 1) programmable filter of order 36 as in variable cut-off linear phase digital filters. 2) two VDFs each of order 50 as in frequency transformation for linear phase cut-off filters. 3) VDF consisting of 9 subfilters each of order 56 adjustable bandwidth FIR filters. The remaining stages in all three approaches are identical to RFFB. Note that all three approaches are based on the idea of employing VDF in the FFB. The complexity comparison shows that the filter bank based on VDFs in 2 and 3 require higher gate counts of 42% and 74%, respectively, compared to the RFFB. The 16-sub-band uniform FFB, i.e., \( BW_{\text{min}} = BW_{\text{max}} = 0.125 \), consists of fixed-coefficient subfilters of order 36, 16, 10, and 6 are obviously lesser when compared to subfilter order 80, 40, 16, and 6 in RFFB. Reduction in the orders of subfilters are achieved by varying its TBW which leads to reduction in the gate counts.
VI. CONCLUSION

An area efficient RFFB with a MFT-VDF which allows fine control over the subband bandwidth is designed with lower order subfilters i.e. lesser gate counts in subfilters when compared to other filter bank approaches [3],[11],[12]. Possible future work is to control the center frequency of subbands by combining adjacent subbands.

REFERENCES