Research Inventy: International Journal Of Engineering And Science
Vol.5, Issue 4 (April 2015), PP 47-53
Issn (e): 2278-4721, Issn (p):2319-6483, www.researchinventy.com

\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 unabridged 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 fails 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

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

where the coefficients a_n are related to the impulse response coefficients h_n of H(z).

The second transformation is given by

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

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

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

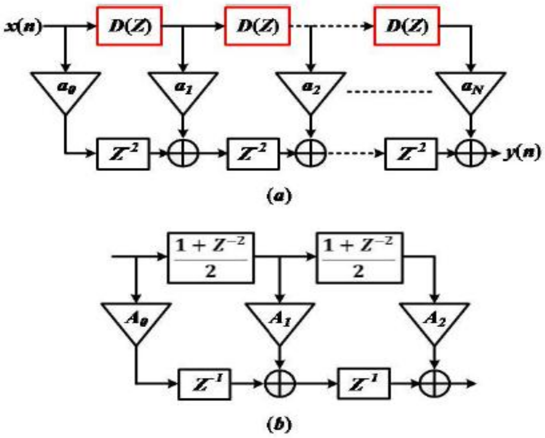


Fig.1 a)second order transformation VDF, b)second order transformation

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

$$\cos\omega_c = \sum_{k=0}^{2} A_k (\cos\Omega_c)^k \tag{4}$$

ω_c and Ω_c are considered as cut-off frequency of H(z) and $H_2(Z)$ respectively.

By expanding (4) the Ω_c and TBW are given by

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

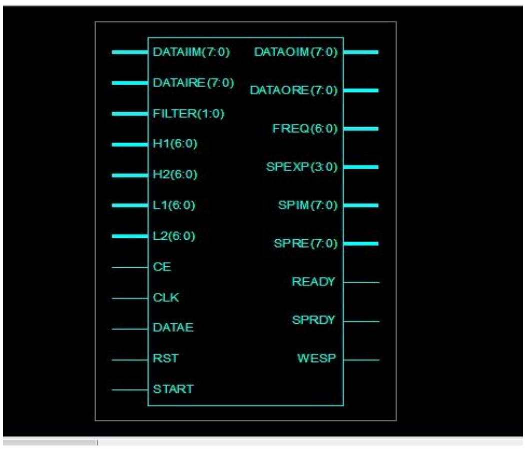
$$\text{TBW} = \left(\frac{A_1 \sin\Omega_c + A_2 \sin\Omega_c}{\sin\omega_c}\right) \tag{6}$$

If the constraints are met

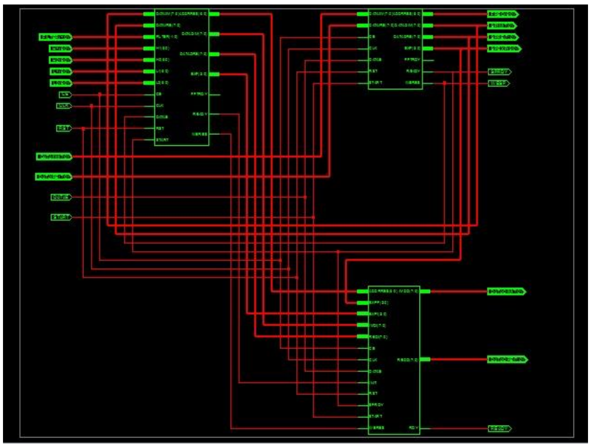
$$A_0 + A_1 + A_2 = 1 \tag{7a}$$

$$0 \leq A_1 \leq 1 \tag{7b}$$

$$A_1^2 - 4A_2(1 - A_1 - A_2 - \cos\omega_c) \geq 0 \tag{7c}$$



(a)



(b)

Fig.2 a), b) Schematic diagrams of VDF

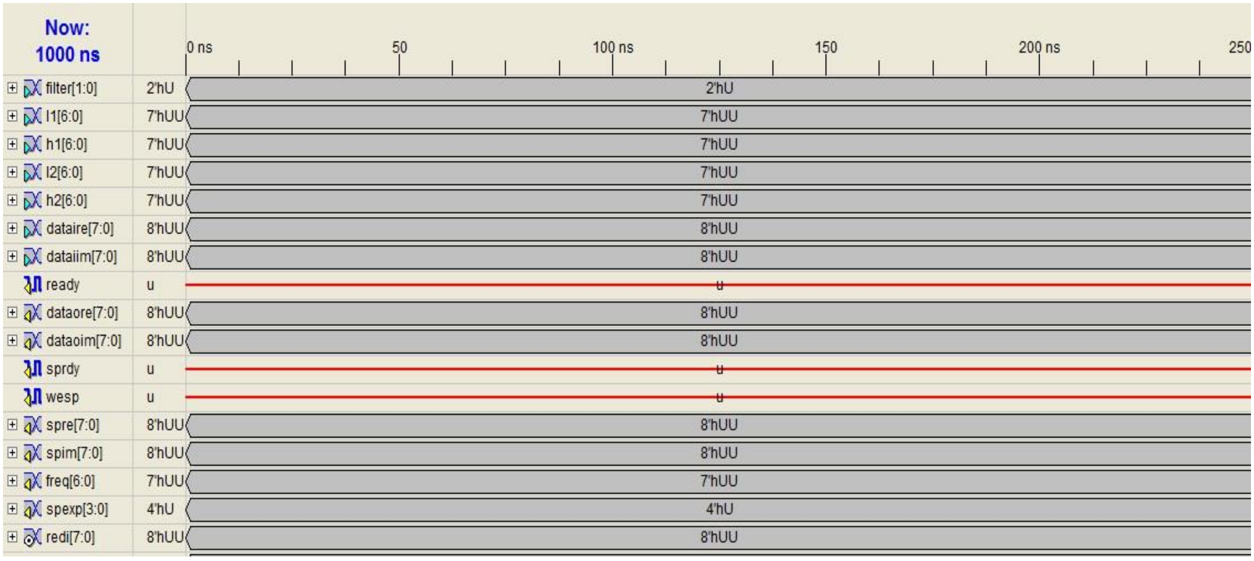


Fig.3 Simulated result of VDF

FFT_FIR_FILTER Project Status			
Project File:	fft_fir_filter.ise	**Current State:**	Placed and Routed
Module Name:	FFT_Filter2	• **Errors:**	No Errors
Target Device:	xc4vlx15-12sf363	• **Warnings:**	281 Warnings
Product Version:	ISE 8.2i	• **Updated:**	Sun 7. Dec 09:22:56 2014

FFT_FIR_FILTER Partition Summary
No partition information was found.

Device Utilization Summary				
Logic Utilization	**Used**	**Available**	**Utilization**	**Note(s)**
Number of Slice Flip Flops	672	12,288	5%	
Number of 4 input LUTs	1,105	12,288	8%	
Logic Distribution				
Number of occupied Slices	766	6,144	12%	
Number of Slices containing only related logic	766	766	100%	
Number of Slices containing unrelated logic	0	766	0%	
Total Number 4 input LUTs	1,135	12,288	9%	
Number used as logic	1,105			
Number used as a route-thru	22			
Number used as Shift registers	8			
Number of bonded IOBs	97	240	40%	

Fig.4 Summary of the result

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 susband 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

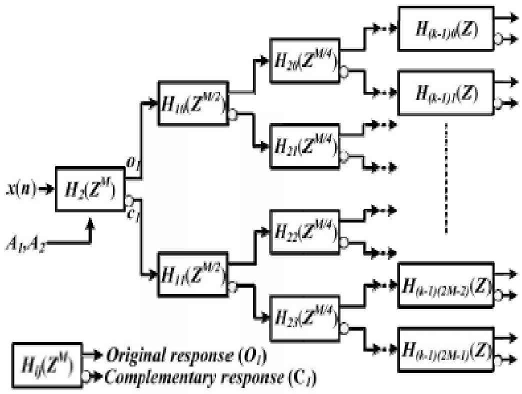


Fig.5 Reconfigurable fast filter bank

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),

$$\mathrm{D(Z)} = \mathrm{A_0 Z^{-2}} + \mathrm{A_1 Z^{-1}}\left(\frac{1+\mathrm{Z}^{-2}}{2}\right) + \mathrm{A_2}\left(\frac{1+\mathrm{Z}^{-2}}{2}\right)^2 \qquad (8)$$

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

$$D(Z) = \mathrm{A_1}\left[\left(\frac{\mathrm{Z}^{-1}+\mathrm{Z}^{-3}}{2}\right) - \mathrm{Z}^{-2}\right] + \mathrm{Z}^{-2} - \mathrm{A_2}\left[\mathrm{Z}^{-2} - \left(\frac{1+\mathrm{Z}^{-2}}{2}\right)^2\right] \qquad (9)$$

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_{min} and BW_{max}, the lower and upper cutoff frequencies of $H_2(Z)$, f_{c1} and f_{c2}, respectively, are calculated as *M/*2 times BW_{min} and BW_{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 ωc, corresponding range of A_1 and Ω_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 ω_C, A_1, and A_1 provide same cutoff frequency range from f_{c1} tof_{c2} is selected to provide better TBW performance as per (6) in order to reduce the order of the MFT-VDF, $H_2(Z)$.

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 rangef_{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 ($O1$) and complementary ($C1$) response.

When $H_2(Z)$ is interpolated by M, the multiband responses $O1$ and $C1$ 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, $O1$ is given by

$$\mathrm{BW}_{\mathrm{o1}} = \frac{2}{\mathrm{M}} \mathrm{f_c} \tag{10}$$

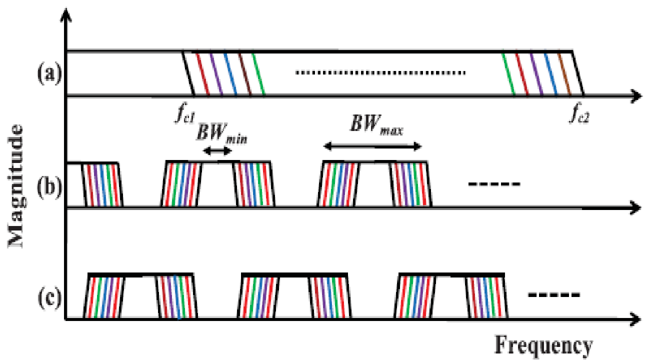


Fig.6 Frequency response of first stage a) Response of VDF, b) Original response O1, c) Complementary response C1

Bandwidth of subband in the complementary response, $C1$, is given by

$$\mathrm{BW}_{\mathrm{c1}} = \frac{2}{\mathrm{M}}(1 - \mathrm{f_c}) \tag{11}$$

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

$$\mathrm{A_2} = \left(\frac{\cos\omega_c - A_0 - A_1 \cos\Omega_c}{(\cos\Omega_c)^2}\right) \tag{12}$$

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 f ixed bandwidth sub-bands. All sub-bands in multiband responses $O1$ and $C1$ 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, $H_{ii}(Z)$, $1 \leq i \leq (k-1)$ 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 ∂p and stop band attenuation ∂s of the filter bank and all subprototype filters are kept same.

2) The transition bandwidths TBW_i of the subprototype filters, $H_{i0}(Z)$, $1 \leq i \leq (k-1)$, are given by

$$\mathrm{TBW_i} = 1 - \left(\mathrm{f_{c2}} + \frac{\mathrm{TBW_d}}{2}\right) \tag{13}$$

where f_{c2} is maximum cutoff frequency of the $H_2(Z)$.Based on these parameters, $H_{i0}(Z)$, 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, $H_{i0}\left(Z(M/2^i)\right)$.

The RFFB with MFT-VDF in the first stage, provides uniform bandwidth subbands of bandwidth (2/L) as well as nonuniform bandwidth sub-bands with bandwidth varying from BW_{min} to BW_{max}, where ($BW_{min} \leq$ (2/L) $\leq BW_{max}$). 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_d , ∂_p, and ∂_p . 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_i , 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_{min}= 0.06, BW_{max}= 0.2, TBW_d= 0.03, ∂_p = 0.1 dB and ∂_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_1 is 0.4375, A_2 varies between −0.2 and 1.5, and ωc = 0.4. Note that multiplication with A_2 can be performed by addition and shift operations only. $\boldsymbol{H_2(Z)}$ is designed using the prototype filter of order 80 with ω_c= 0.4, TBW_0 = 0.065, ∂_P = 0.1 dB, and ∂_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 suband 9 as the bandwidth varies between 0.06 and 0.2.

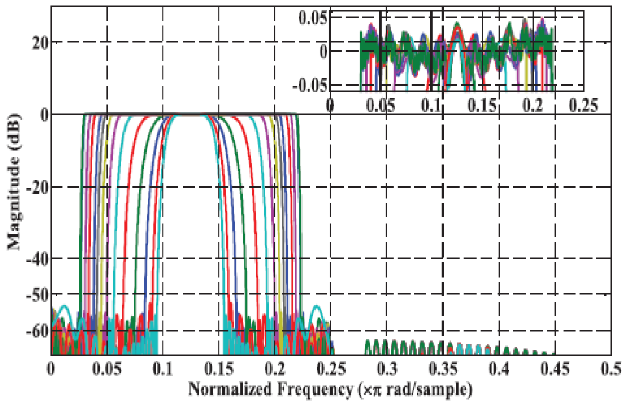


Fig.7 Variable bandwidth responses for subband 9

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_{min}= BW_{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.

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