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FILTER BANK DESIGN USING MULTIPLE PROTOTYPE APPROACH FOR VARIABLE GRANULARITY BANDS

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Abstract- In this paper, a multiple prototype based filter bank is proposed for variable granularity bands. This method makes use of channel combiners for variable granularity bands from a cosine modulated filter bank. In the proposed method, the filter bank is generated from proper choice of prototype filters and different bandwidth combinations are generated from different prototypes, where M determines the granularity of the uniform bandwidth from individual prototypes. The condition for generation of variable granularity bands from multiple prototype filters is also defined. The method is found to have less complexity and distortions as compared to a single prototype approach using channel combiners. The method allows different combinations of the uniform filter banks to generate the filter banks with variable granularity for integer powers of two. Simulations are done to obtain varying bandwidth channels, and analyzed for different input signals with different fidelity parameters. The results are found to be comparable with existing methods.

Index terms*:* Multi Prototype, Variable Granularity, Channel Combiners, Cosine modulation, Filter Banks.

I. INTRODUCTION

Multirate filter banks find wide applications in various fields including subband coding, image coding and transmultiplexer designs [1]. There are some simple and efficient methods to generate a uniform multirate filter banks. However, in several applications uniform filter banks does not provide the required bandwidth allocation. For example, in multimode systems, the simultaneous transmission of different data (text, image, audio) require variable granularity bandwidth allocation which can be accomplished using non uniform transmultiplexers which are dual of non uniform filter banks.

The design of non uniform filter banks is an extensively researched area mainly due to the lack of simple and efficient methods. The conventional methods for the design of non uniform filter banks (NUFB) are very difficult and are not fully efficient. Some have exploited the advantage of constructing NUFB from uniform filter banks due to its simplicity in design [2]-[10]. Uniform linear phase filter bank can be implemented with DFT, cosine modulation and multiplier less lattice structures for perfect reconstruction filter bank [11]- [13]. In [8], a non uniform filter bank with integer sampling factors is discussed. This is obtained from cosine modulated uniform filter banks. A non uniform filter bank based multimode transmultiplexer structure is proposed in [14] and they have used Farrow structures. A Tree structure based non uniform filter bank is designed in [9] which has limitations in the combinations used for building NUFB due to the propagation delays in successive stages. A flexible frequency band reallocation network using Cosine Modulated filter banks is proposed in [8] and [15] where they have used channel switches and combiners for frequency allocation and reallocation. Filter bank has also been exploited for transceiver systems for single and multicarrier systems [16]-[19]. Most of the literature mentions NUFB design using a single prototype approach due to its simplicity in design. The works done in multiple prototype approach is limited. In [20], Del Re et.al presented a multiple prototype based NUFB design where they mainly aim at alias cancellation. In [21], they have presented a NUFB using multiple prototypes which can perform integer as well as rational sampling.

In this paper, a NUFB with variable granularity is implemented, based on multiple prototype approach, using cosine modulation considering amplitude distortion and aliasing error. This makes use of channel combiners which perform addition operation of adjacent channels/subbands in a uniform filter bank which are generated using cosine modulation. The method makes use of multiple prototypes to reduce distortions and complexity occurring in single prototype based approach with channel combiners. The prototype filters can be optimized using different techniques existing in literature [22]-[24]. Each prototype is optimized using the same filter length so that it does not increase the complexity of the system during addition of filter coefficients. The rest of the paper is organized as follows. Section II discusses cosine modulated filter banks and Section III, general conditions required for non uniform filter banks with variable granularity. Section IV gives an introduction to channel/subbands combination technique using a single prototype approach, and its limitation, and then multiprototype based method is discussed. In Section V, the relevant results and design examples are discussed and analyzed. Finally Section VI concludes the work done.

II. COSINE MODULATED FILTER BANK

Cosine Modulation has been widely used for designing Uniform Filter Banks (UFB) and Non uniform filter banks (NUFB) and is derived by cosine modulation of a single prototype filter. It is a simple, maximally decimated and computationally efficient filter bank. The closed form expressions for obtaining the analysis and synthesis filters $h_k(n)$ and $f_k(n)$ for an *M*-channel Cosine Modulated Filter Bank (CMFB) are given by (1) and (2) [1], [8].

$$h_k(n) = 2h_p(n)\cos\left[(2k+1)\frac{\pi}{2M}\left(n-\frac{N}{2}\right)+\theta_k\right] \tag{1}$$

$$f_k(n) = 2h_p(n)\cos\left[(2k+1)\frac{\pi}{2M}\left(n-\frac{N}{2}\right)-\theta_k\right] \tag{2}$$

Where, $h_p(n)$ is the prototype filter with length N, $0 \le k \le M-1,\ 0 \le n \le N-1$ and θ_k is the phase term. Filter banks will have perfect reconstruction if the prototype filters are linear phase FIR and the analysis filters are chosen according to (3) as in [8].

$$f_k(n) = h_k(N-1-n) \tag{3}$$

Also phase term θ_k must be chosen such that, $\theta_{k+1} = \theta_k \pm \frac{\pi}{2},\ 0 \le k \le M-2$. The orthogonality condition on the phase term reduces aliasing error. The phase term is represented as $\theta_k = (-1)^k \frac{\pi}{4}$. The prototype filters are designed with user specified filter length N and attenuation A_s. The cutoff frequency of the prototype filter is chosen to be $\omega_c = \pi/2M$ as in [22].

III. NON UNIFORM FILTER BANKS

Nonuniform filter banks have variable granularity spectral bands. They are preferred in applications such as audio coding and subband adaptive filtering. Efficient structures and design methods for perfect reconstruction nonuniform filter banks are therefore desirable. Compared with the uniform filter banks, further investigation is required for nonuniform perfect reconstruction filter banks. The decimation ratios are not the same for all the subbands as in uniform filter banks. They are constrained by the relation given in (4) [25],

$$\sum_{k=0}^{M-1} \frac{1}{d_k} = 1 \tag{4}$$

The above condition has to be satisfied so that the average sampling rate is preserved at the output of the analysis filter bank. The decimators have to be chosen satisfying the compatibility test for the perfect reconstruction condition to exist. The compatibility test is required because each alias frequency in the output should occur at least twice for aliasing to be canceled. The compatibility test is stated as an algorithm to be performed on the different decimator values in [25]. The set of decimators are ordered as $d_0 \le d_1 \le ... \le d_{M-1}$, then if $d_{M-2} \ne d_{M-1}$ the set is not compatible. This implies that every decimator must be a factor of some other decimator. Another necessary condition is that no two decimators can be coprime. This arises from the equivalence between perfect reconstruction and the biorthogonality relation.

IV. MULTIPLE PROTOTYPE COSINE MODULATED FILTER BANK FOR VARIABLE GRANULARITY

a. RELATED WORK

An M – channel Cosine Modulated Filter Bank structure is used for generating analysis and synthesis filters for uniform bandwidth allocation [1], [8]. The same can be used for generating non uniform bandwidth allocation using various techniques. Channel combiners are sometimes used for generating NUFB from Uniform filter Bank. We have exploited the advantage of using channel combiners for non uniform bandwidth allocation using a single prototype approach in [26]. Performance analysis of channel combiners in multiprototype and single prototype was presented in [27]. Channel combiners add the frequency responses at specific locations of the uniform filter bank to produce a non uniform bank as shown in Figure 1. In this approach, the adders can create small amplitude distortions at the 3dB frequency response. The prototype filter is optimized to have 3dB amplitude response at $\frac{\pi}{2M}$ which is the cutoff frequency. Hence the analysis filters have their cut off frequencies at $\frac{n\pi}{2M}$, where $1 \le n \le M$. If adjacent subbands are not combined exactly at 3dB, amplitude distortion will be introduced around the 3dB as dips or bumps. This effect is illustrated in Figure 2. Thus it is a necessary condition that when the adjacent subbands are combined together to generate the non uniform band they must combine exactly at the 3dB amplitude response to eliminate the above distortions.

For a single prototype approach, using channel combiners, the frequency response of the analysis filters of the variable granularity is given by

$$\bar{H}_i(z) = \sum_{m=P}^{P+p_i-1} H_m(z) \tag{5}$$

where, $P = \sum_{l=0}^{i} p_{l-1},\ P_{-1} = 0$ (6)

$H_m(z)$ is the frequency response of the uniform filter bank. Here, $0 \le i \le L-1$ and p_i is the number of granularity bands that has to be combined to get the required granularity for the different users. The granularity p_i can be an odd or even number, but constrained by the compatibility set.

Suppose, we require a combination of wideband and narrowband the single prototype filter approach will require more combinations. This would increase the distortion caused due to adders especially when the filter order is low. The residual error will also increase proportionally when the combinations increase. Hence, we go for alternative methods where we use channel combiners and at the same time reduce these adder distortions.

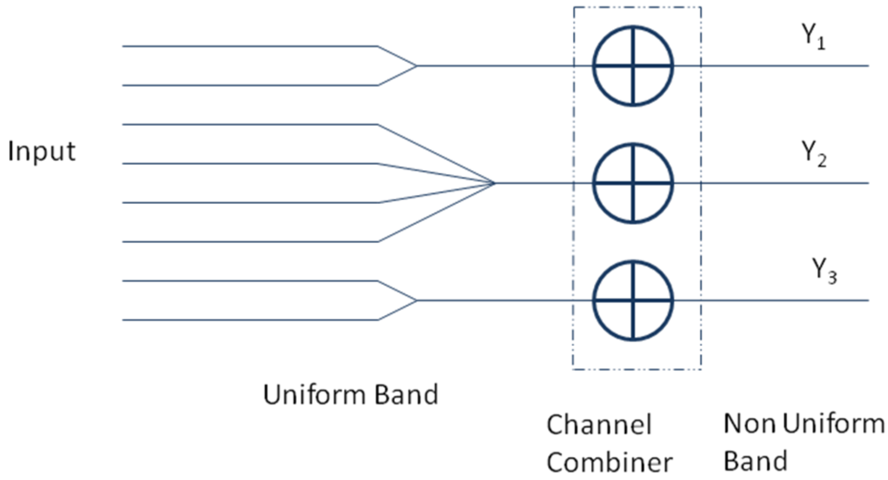


Figure 1 Channel Combiners are used for generating non uniform bandwidth from uniform bandwidth

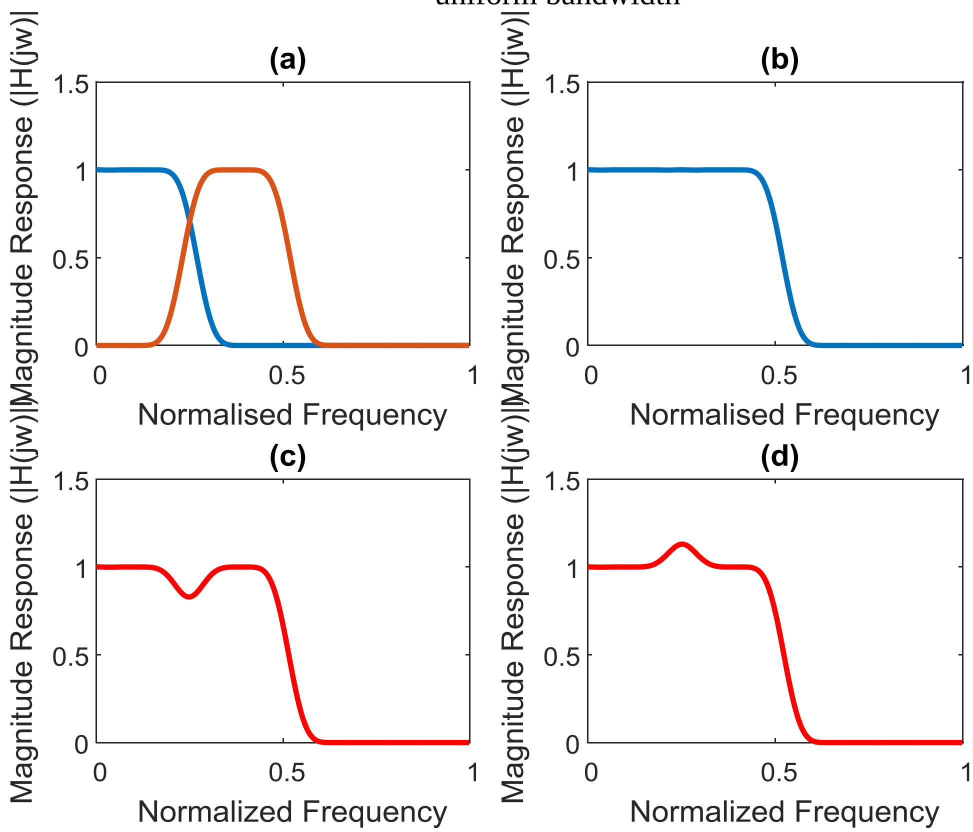


Figure 2 Frequency Response when adjacent subbands are combined (a) Adjacent uniform subbands (b) Addition of subbands at 3dB (c) and (d) Addition at points before and after 3dB creates distortions in the form of dips and bumps.

A Multiple Prototype Approach is addressed in this paper for variable granularity. The analysis and synthesis filter coefficients are generated using cosine modulation. Here, multiple prototype filters are predesigned initially and depending on the granularity band requirement the prototype filters are combined and the variable granularity band filter bank is configured. The prototype optimization is done using an iterative method described in [22]. The iterative method optimizes the 3dB cut off frequency of the prototype filter at $\omega_c = \pi / 2M$. The smallest granularity band possible will be that of the bank generated using the largest M (number of channels/subbands). Since the number of combinations is reduced in the multiprototype filter banks, the distortions introduced are reduced.

b. MULTI PROTOTYPE APPROACH:

In the multiprototype approach, the analysis and synthesis filter coefficients are calculated and stored for multiple prototype filters. Consider two banks generated from prototypes $h_{p1}(n)$ and $h_{p2}(n)$ with M_1 and M_2 as the number of channels/subbands in each filter bank. Then the impulse responses of the generated analysis and synthesis filters are given by :

Bank 1:

$$h_{1,k}(n) = 2h_{p1}(n)\cos\left[(2k+1)\frac{\pi}{2M_1}\left(n-\frac{N}{2}\right)+(-1)^k\frac{\pi}{4}\right]$$
$$f_{1,k}(n) = 2h_{p1}(n)\cos\left[(2k+1)\frac{\pi}{2M_1}\left(n-\frac{N}{2}\right)-(-1)^k\frac{\pi}{4}\right] \tag{7}$$

Bank 2:

$$h_{2,k}(n) = 2h_{p2}(n)\cos\left[(2k+1)\frac{\pi}{2M_2}\left(n-\frac{N}{2}\right)+(-1)^k\frac{\pi}{4}\right] \tag{8}$$
$$f_{2,k}(n) = 2h_{p2}(n)\cos\left[(2k+1)\frac{\pi}{2M_2}\left(n-\frac{N}{2}\right)-(-1)^k\frac{\pi}{4}\right]$$

The multiple prototype filters are optimized independently with reduced distortion unlike the method proposed in [20], [21]. This reduces the complexity of the design approach. Different prototype filters of variable granularity are designed independent of each other and combined with proper choice of filter banks. If $\theta_{1,k}$ and $\theta_{2,k}$ are the phase terms associated with the different filter banks, the phase difference has to be $\frac{\pi}{2}$ in order to reduce distortions. The phase terms are related by (9) to satisfy matching conditions for the filter bank design with multiple prototype filters.

$$e^{-j\theta_{1,k}} + e^{-j\theta_{2,k}} = 0 \tag{9}$$

where $\theta_{q,k} = \pm(-1)^k \frac{\pi}{4}$, $q = 1,2,3...Q$, Q is the number of prototypes designed.

The prototype filters designed to achieve variable granularity bands have to satisfy certain necessary conditions. This condition reduces the aliasing error and amplitude distortion while combining the different prototype to implement filter banks of variable granularity.

(i) All the prototype filters have to be of the same length N.

(ii) The prototype filters should satisfy near perfect reconstruction (NPR) conditions, bandlimiting and power complementary as in [22].

$$\left|H\left(e^{j\omega}\right)\right| \approx 0 \quad |\omega| > \frac{\pi}{M} \tag{10}$$

$$|H(e^{j\omega})|^2 + |H(e^{j(\pi/M-\omega)})|^2 \approx 1, 0 \le \omega \le \pi / M \tag{11}$$

(iii) The phase terms relative to adjacent filters must differ by $\frac{\pi}{2}$.

(iv) The prototype filters should satisfy the linear phase conditions $f_p(n) = h_p\left(N-1-n\right)$

The multiple prototypes can be optimized independently. The filter banks with variable granularity band are implemented by alternatively selecting the analysis and synthesis filter coefficients to satisfy the phase conditions. The flowchart for the design of multiprototype filter is shown in Figure 3.

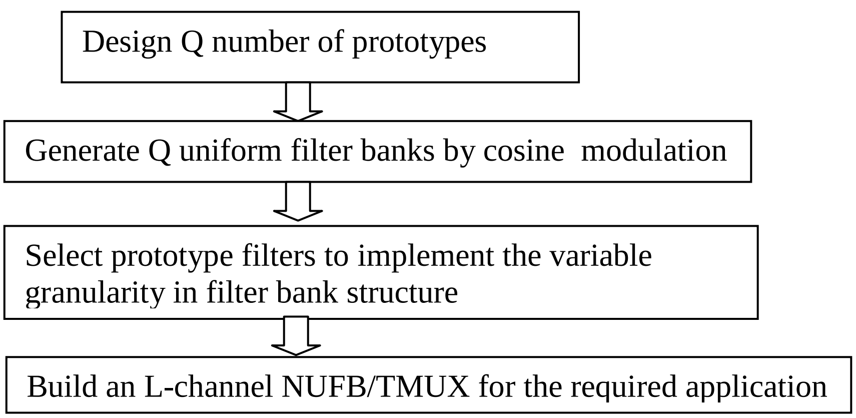


Figure 3 Flow chart for variable granularity bands using multiple prototype filters

Thus the selected prototype filters ensures there are no bumps or dips while combining to reduce amplitude distortions. In the absence of aliasing, reconstructed signal is given by

$$Y(z) = \bar{T}\left(z\right)X\left(z\right) \tag{12}$$

Where, $T(z)$ is called the distortion transfer function. For variable granularity bands the distortion transfer function is represented as

$$\overline{T}(z) = \sum_{i=0}^{L-1} \overline{H}_i(z)\overline{F}_i(z) \tag{13}$$

Since the analysis and synthesis filters are chosen to satisfy the linear phase conditions as in (14)

$$F(z) = z^{-N} H\left(z^{-1}\right) \tag{14}$$

Thus the distortion function maintains linear phase property, where $z = e^{-jw}$.

$$\overline{T}(z) = e^{-jwN} \sum_{i=0}^{L-1} |\overline{H}_i\left(e^{-jw}\right)|^2 \tag{15}$$

The distortion function maintains the linear phase property, so that the system is free of phase distortions. The system satisfies the perfect reconstruction property, if the summation of the decimations term is equal to 1. The prototype filter of our choice support power complementary condition such that the $\sum_{k=0}^{L-1} \frac{1}{d_k} |H_k(e^{-j\omega})|^2 = c$, where $c > 0$. Thus non uniform filter bank with variable granularity preserves Near Perfect Reconstruction.

The procedure followed for implementation of a multiprototype variable granularity filter bank is summarized below:

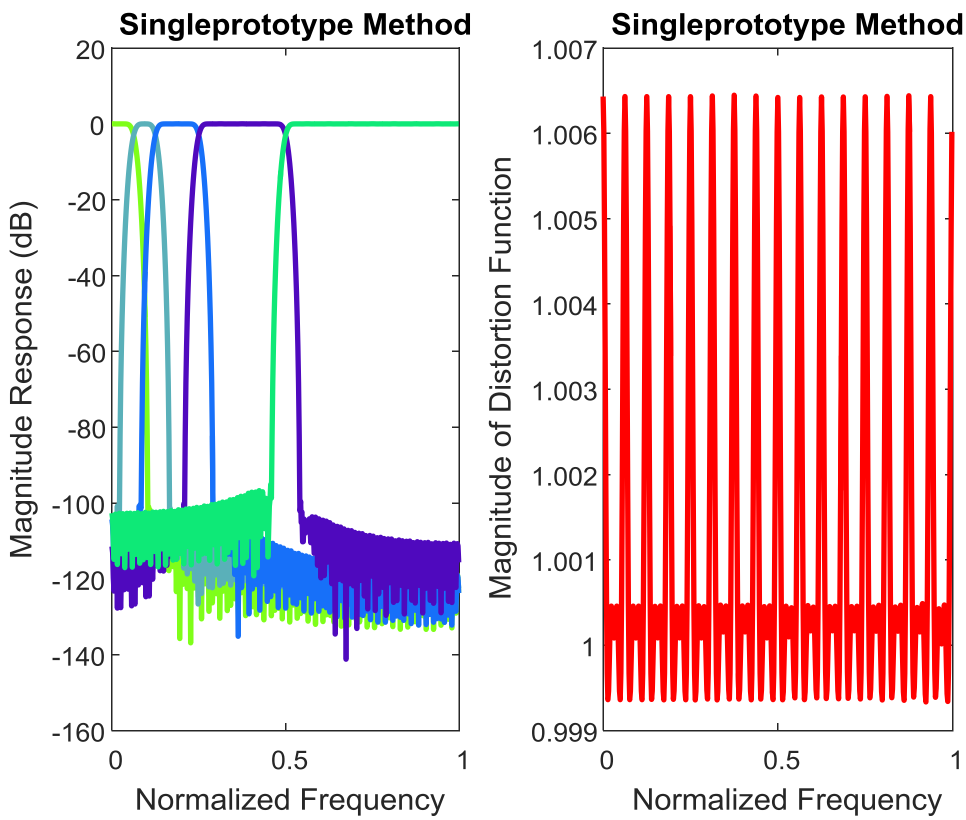
1) Design Q linear phase FIR low pass filters of length N optimized to have their cut off frequencies at $\omega_c = \frac{\pi}{2M_q}$, where, $q = 1, 2, 3, ...Q$. All the prototype filters should be of the same length and satisfying the bandlimiting and power complementary condition for near perfect reconstruction.

2) The corresponding Q uniform filter banks should be generated by cosine modulation of these prototype filters. The closed form equations as given in (1) and (2) has to be used to generate the subband filter responses.

3) Build an L- channel granularity filter bank by selecting the filters from each uniform filter bank with proper compatibility set and apply channel combination or merging in accordance with the required granularity.

Comparisons were performed between single and multiple prototype filter bank approaches. It was inferred that the distortion introduced in the multiprototype method is less when compared to single prototype approach when the combination increases. The main advantage of multiprototype technique is that the number of additions required in the channel combiner is much reduced when compared to that of single prototype approach. Hence the complexity in the system and the distortions introduced by the adders are reduced. This is illustrated in Figure 4, where we compare the distortion functions introduced by channel combiners when using single and multiple prototype method.

The aliasing error of the given design is not altered much as compared with the uniform bank case. Both have same values since the stop band attenuation is not altered during channel combinations. This is because the additions are meant for optimizing flat pass band in order to get reduced amplitude distortion which does not alter the stop band attenuation and hence aliasing error. The design examples and results are discussed in the next section.



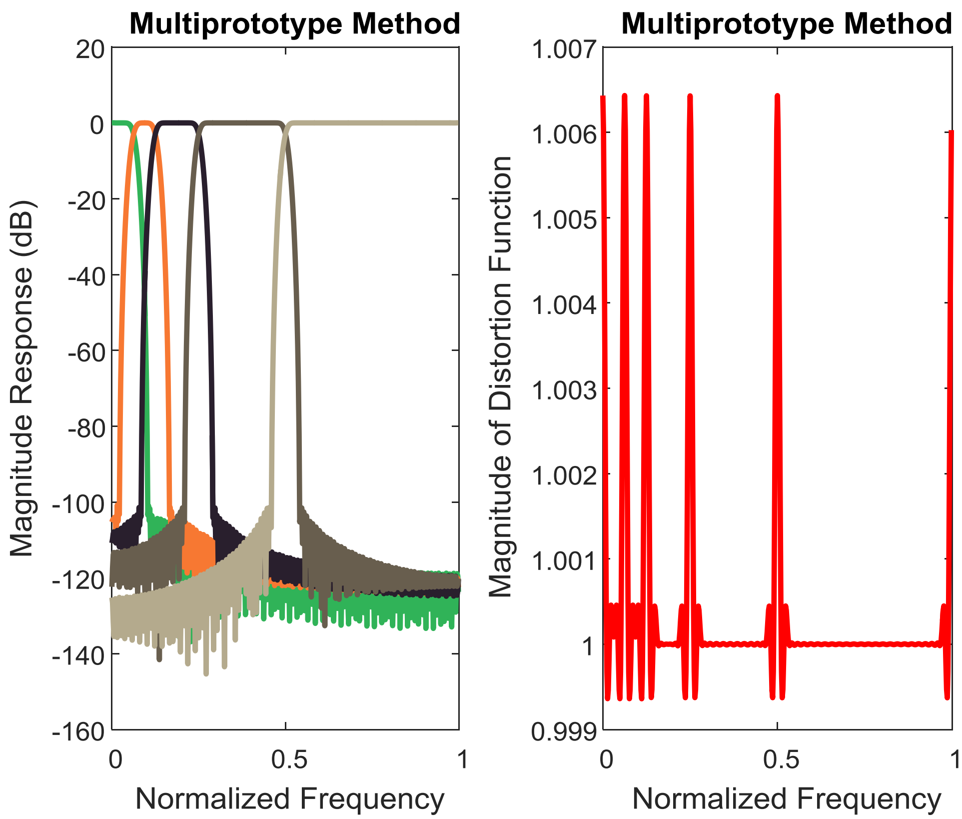


Figure 4 Non uniform Filter bank design using *single and multiple prototype methods* and the corresponding distortion functions

V. SIMULATION AND RESULT S

a. Design Examples

Example 1:

The prototype filters were designed using Kaiser window approach [22]. To highlight the simplicity and performance of this method, a design example of a 3-channel non uniform filter bank constructed from 3 different prototypes is shown. Here we have taken $M_0 = 4$, $M_1 = 8$ and $M_2 = 16$. Figure 5 show the magnitude responses of the different low pass prototype filters designed with variable granularity. The uniform filter banks generated using the above prototypes are shown in Figure 6. The smallest granularity possible is $B_Q = 2\pi/16$. Here, length of the prototype does not become an issue while combining, since the prototypes are optimized with the same filter length N. When the filter banks are generated with proper granularity set, the amplitude distortion is E_{pp} = 0.0031 with an stopband attenuation of A_s = -110dB. The implemented filter bank is shown in Figure 7 (a).

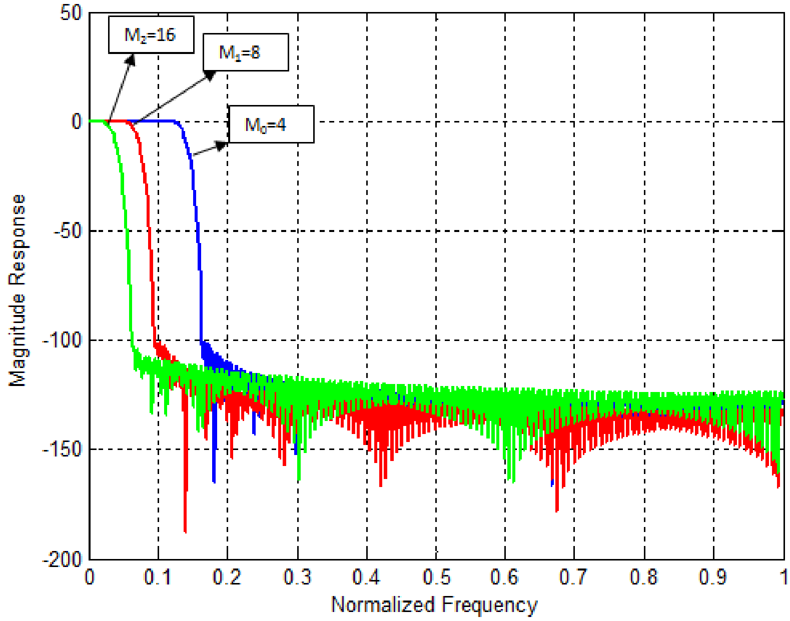
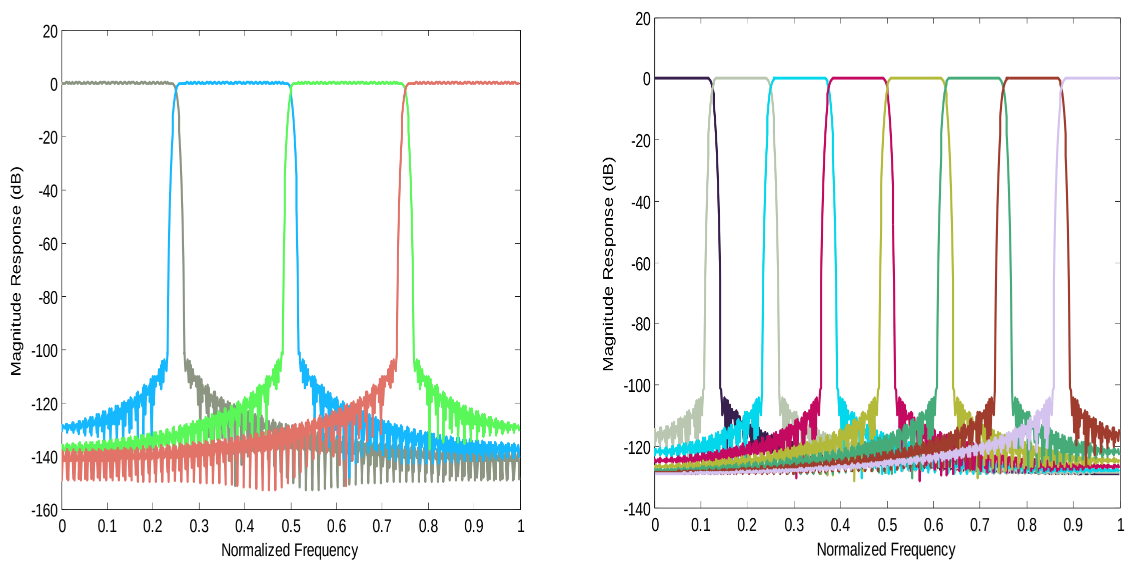


Figure 5 Different low pass prototype filters with variable granularity.



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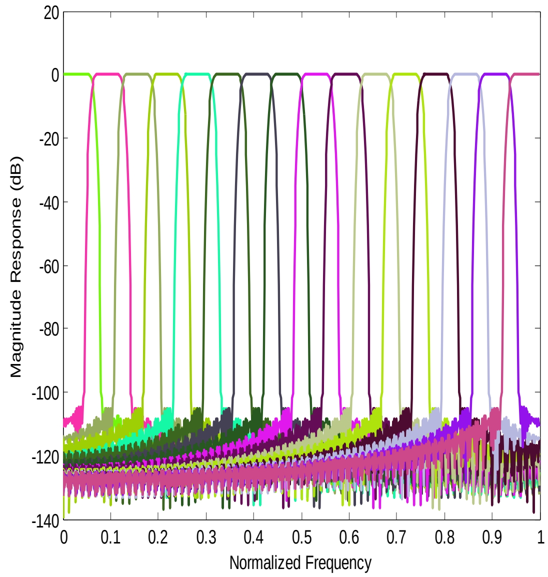
(a) (b)



(c)

Figure 6 Uniform filter banks with variable granularity bands (a) $M_0 = 4$ (b) $M_1 = 8$ (c) $M_2 = 16$

Example 2:

Here, we demonstrate a case where, significant amplitude distortions occur when combined at locations others than the integer powers of 2. The prototypes are designed with the same specification as example 1. A 3-channel non uniform filter bank has been designed and the magnitude responses of the analysis filters are shown in Figure 7 (b). The amplitude distortions in the form of bumps are clearly highlighted when combined at locations other than the integer powers of two where the additions are performed. The E_{pp} and A_s values for this example are E_{pp} = 2.0004 and A_s = -110dB.

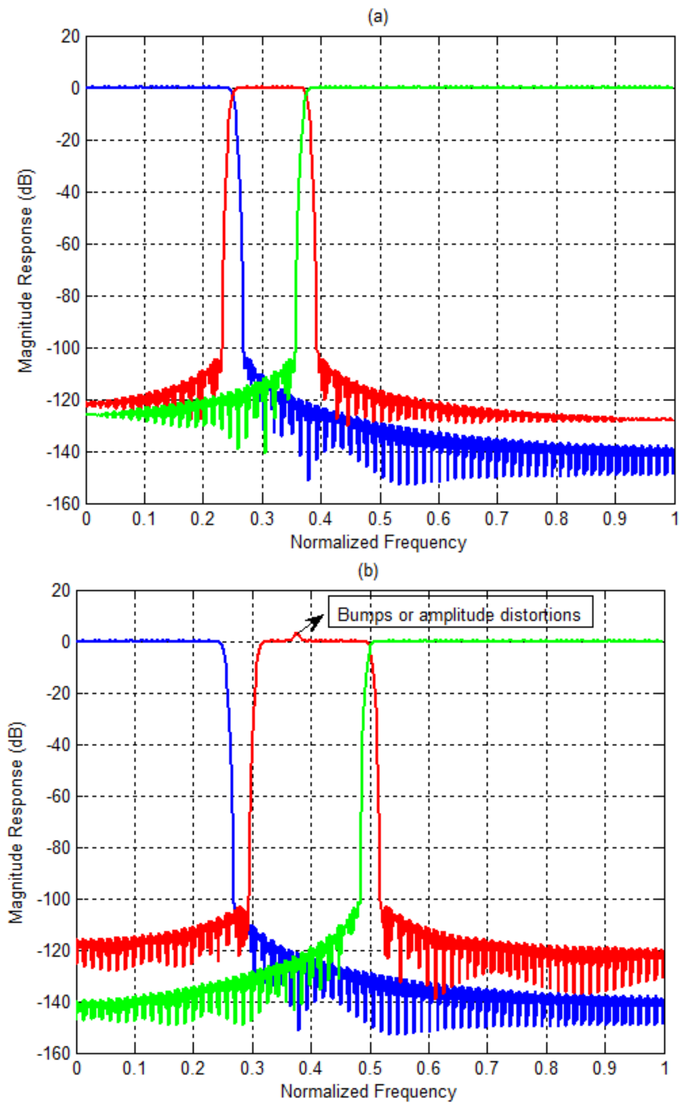


Figure 7 Variable granularity bands from multiple prototypes (a) Example 1: Proper combiners (b) Example 2 : Improper combiners with amplitude distortion

b. Signal Reconstruction and Analysis

A comparison is done between single and multiple prototype filter to implement a 5 channel NUFB with variable granularity. In single prototype approach initially a 16 channel CMFB was implemented, then with decimation factors (16,16,8,4,2) and with combinations (1,1,2,4,8), a NUFB was obtained with 5 channels. The single prototype approach required a total of $11N$ additions, with N being the prototype filter length. In the multiprototype the same NUFB was implemented using four prototype filters where, $M_1 = 2$, $M_2 = 4$, $M_3 = 8$ and $M_4 = 16$ for the same decimation factors (16, 16, 8, 4, 2). Here the finest bandwidth possible is

$B_Q = 2\pi/16$ and we require only one channel combiner. The performance comparison was done between single and multiple prototype filter bank approaches in terms of amplitude distortion (E_{pp}), number of filter taps (N) and stopband attenuation (A_s) for variable granularity bands and tabulated in Table I. From the table it can be inferred that multiprototype filter banks have reduced distortion when compared to single prototype filter approach. Table II shows the comparison of the proposed method with some methods existing in literature.

The designed NUFBs with variable granularity was tested for subband coding using ECG and speech signals. Several fidelity parameters such as mean squared error (MSE), maximum error (ME), percent root mean square difference (PRD) and SNR as given in [2] has been computed and shown in Table III. It was found that multiprototype filter bank performs better than single prototype also in terms of the fidelity measures.

The performance of the variable granularity band filter bank structure is also evaluated for speech signals in terms of the following fidelity parameters. Where $x(n)$ and $y(n)$ are the input and reconstructed signals respectively for a total of N_tot samples:

(i) Percent root mean square difference (PRD)

$$PRD = \left\{ \frac{\sum_n [x(n) - y(n)]^2}{\sum_n [y(n)]^2} \right\} X\ 100\%$$

(ii) Mean Square Error (MSE)

$$MSE = \frac{1}{N\_tot} \sum_n \left[x(n) - y(n) \right]^2$$

(iii)Maximum Error (ME)

$$\max \left| x(n) - y(n) \right|$$

(iv) Signal to Noise Ratio (SNR)

$$SNR = 10\log_{10} \left(\frac{\sum_n x(n)^2}{\sum_n \left| x(n) - y(n) \right|^2} \right)$$

Table I Performance of variable granularity bands with single and multiple prototype filters

Band	**As**	**N**	**Single Prototype**	**Multiple Prototype**
Three Band (4,4,2)	-80dB	47 65 71	2.7×10^{-3} 2.5×10^{-3} 2.6×10^{-3}	2.7×10^{-3} 2.5×10^{-3} 2.6×10^{-3}

Band	As	N	Single Prototype	Multiple Prototype
Four Band (8,8,4,2)	-80dB	65 71 79	5.4×10^{-3} 3.8×10^{-3} 5.1×10^{-3}	2.7×10^{-3} 2.6×10^{-3} 2.6×10^{-3}
Five Band (16,16,8,4,2)	-80dB	95 125	7.09×10^{-2} 8.4×10^{-3}	5.4×10^{-3} 3.2×10^{-3}

Table II Performance comparison with some methods existing in literature

Work	M	Technique	N	A_s	E_{pp}
Li.et.al (1997) [4]	(4,4,2)	Cosine Modulation	64	-60dB	7.803×10^{-3}
Xie.et.al [8] (2006)	(4,4,2)	Recombination	63	-110dB	7.803×10^{-3}
Soni.et.al [9] (2010)	(4,4,2)	Tree Structure	63	-80dB	3.85×10^{-3}
Kumar.et.al [2] (2013)	(4,4,2)	Tree Structure	48	-80dB	3.11×10^{-3}
Proposed	(4,4,2)	Cosine Modulation	45	-80dB	2.60×10^{-3}

Table III Assessment of different fidelity parameters using single and multiple prototype filters for non uniform filter bank implementation.

Signal	**PRD**		**MSE**		**ME**		**SNR**	
	SP-FB	**MP-FB**	**SP-FB**	**MP-FB**	**SP-FB**	**MP-FB**	**SP-FB**	**MP-FB**
MIT-BIH Rec.800	0.1040	0.0984	8.212 × 10-7	7.346 × 10-7	1.867 × 10-3	1.677 × 10-3	59.6602	60.1444
MIT-BIH Rec.825	0.1107	0.0942	8.130 × 10-7	5.890 × 10-7	1.912 × 10-3	1.786 × 10-3	59.1187	60.5183
MIT-BIH Rec.829	0.1119	0.0944	8.390 × 10-7	5.965 × 10-7	1.880 × 10-3	1.872 × 10-3	59.0207	60.5020
MIT-BIH Rec.855	0.1046	0.0971	8.173 × 10-7	7.039× 10-7	1.989 × 10-3	2.095 × 10-3	59.6114	60.2599
Speech, L, Eng.: M 45	0.1302	0.1285	4.722 × 10-8	4.602 × 10-8	1.667 × 10-3	1.700 × 10-3	57.7068	57.8191

VI. CONCLUSIONS

A non uniform filter bank with variable granularity is designed using multiple prototypes and cosine modulation with channel combination technique. The prototypes are designed using an iterative method where the prototypes are optimized from the same filter length. The complexity in filter additions and hence the increased distortions when using a single prototype approach is reduced in this method since we have the flexibility in choosing the required prototype. The stop band attenuation of the bank is not altered here as compared to uniform case thus ensuring a reasonable aliasing error. Thus this approach is simple for implementing non uniform filter banks with integer powers of two with reduced amplitude distortions and aliasing error.

REFERENCES

[1] P. P. Vaidyanathan, “Multirate Systems and Filter Banks,” Prentice- Hall, Englewood Cliffs, NJ, USA, 1993.

[2] A.Kumar,G.K.Singh,S.Anurag,“Design of nearly perfect reconstructed non-uniform filter bank by constrained equiripple FIR technique”, Applied Soft computing,Vol.13,Issue 13,Jan 2013, pp 353-360.

[3] Smitha, K. G., and A. P. Vinod, “A reconfigurable non-uniform filter bank architecture for military radio receivers”, Telecommunications (ICT), 2010 IEEE 17th International Conference on. IEEE, 2010.

[4] Li, Jianlin, Truong Q. Nguyen, and Sawasd Tantaratana, “A simple design method for near-perfect-reconstruction nonuniform filter banks,” IEEE Transactions on signal processing, Vol 45,.No.8 , pp. 2105-2109, 1997.

[5] Princen, John, “The design of nonuniform modulated filter banks”, IEEE Transaction on Signal Processing, 43.11, pp. 2550-2560, 1995.

[6] Wang, Ming, Jian Wan, and Yan Zhao, “Design of Linear Phase Nonuniform Filter Banks with Interpolated Prototype Filters,” Procedia Engineering vol.29 435-440, 2012.

[7] Ogale, Jyotsna, and Samrat Ashok. "Cosine Modulated Non-Uniform Filter Banks." Journal of Signal and Information Processing vol 2, No.3, pp. 178-183, 2011.

[8] Xie, X. M., S. C. Chan, and T. I. Yuk, “Design of perfect-reconstruction nonuniform recombination filter banks with flexible rational sampling factors,” IEEE Transactions on Circuits And Systems-I: Regular Papers, vol. 52, no. 9, pp. 1965–1981, 2005.

[9] Soni, Ram Kumar, Alok Jain, and Rajiv Saxena., “An Optimized Design of Non-Uniform Filterbank Using Blackman Window Family,” International Journal of Signal and Image Processing, vol. 1, no. 1, pp. 18–23, 2010.

[10] Amir Eghbali, Håkan Johansson, Per Löwenborg, “Reconfigurable Nonuniform Transmultiplexers Using Uniform Modulated Filter Banks,” IEEE Transactions On

Circuits And Systems—I: Regular Papers, Vol. 58, No. 3, pp.539-547, March 2011.

[11] R. D. Koilpillai and P. P. Vaidyanathan, "Cosine-Modulated FIR filter banks satisfying perfect reconstruction," IEEE Trans. on Signal Processing, vol. 40, no. 4, pp. 770-783, 1992.

[12] Li Chen, Xiyan Wang, Ronghua Peng, Fu Yang , "Design Of Linear-Phase Filter Banks With Multiplier-Less Lattice Structures," International Journal On Smart Sensing And Intelligent Systems Vol. 6, No. 5, December 2013.

[13] F. Cruz-Roldan and M. Blanco-Velasco, "Joint use of DFT filter banks and modulated transmultiplexers for multicarrier communications," Signal Processing, vol. 91, no. 7, pp. 1622-1635, July 2011.

[14] Amir Eghbali, Håkan Johansson, "A Multimode Transmultiplexer Structure", IEEE Transactions on Circuits And Systems-II, Express Briefs, Vol. 55, No.3, pp279-283, 2008.

[15] Håkan Johansson and Per Löwenborg, "Flexible Frequency-Band Reallocation Network Based on Variable Oversampled Complex-Modulated Filter Banks", Acoustic speech and signal processing, 2005 proceeding ICASSP'05, IEEE International conference,Mar 2005, pp 973-976.

[16] F. Cruz-Roldan, M. Elena Dominguez-Jimenez, Gabriela Sansigre Vidal, Jose Pineiro-Ave, and Manuel Blanco-Velasco, "Single-Carrier and Multicarrier Transceivers Based on Discrete Cosine Transform Type-I", IEEE Transaction Wireless Communication, vol. 12, no. 12, pp6454-6463, December 2013.

[17] R. Zakaria and D. Le Ruyet, "A novel filter-bank multicarrier scheme to mitigate the intrinsic interference: application to MIMO systems", IEEE Transaction Wireless Communication, vol. 11, no. 3, pp. 1112-1123, Mar. 2012.

[18] Y.P. Lin, S.-M. Phoong and P. P.Vaidyanathan, "Filter Bank Transceivers for OFDM and DMT Systems", Cambridge University Press, 2011.

[19] Guangyu Wang, Kai Shao and Ling Zhuang, "Time-varying Multicarrier and Single-carrier Modulation System", IET Signal Processing, Vol. 7, pp.1-12, March 2013.

[20] Argenti, F., and E. Del Re., "Non-uniform filter banks based on a multiprototype cosine modulation." IEEE International Conference on. Acoustics, Speech, and Signal Processing, ICASSP, 1996.

[21] Argenti, Fabrizio, Benedetto Brogelli, and Enrico Del Re, "Design of pseudo-QMF banks with rational sampling factors using several prototype filters," IEEE Transactions on Signal Processing, Vol 46.No.6 , pp. 1709-1715, 1998.

[22] Yuan-Pei Lin and P. P. Vaidyanathan "A Kaiser Window Approach for the design of Prototype Filters of Cosine modulated Filter Banks," IEEE Signal Processing Lett., vol. 5, , pp. 132–134, June 1998.

[23] S. W. A. Bergen, A.Antoniou, "An efficient closed form design method for cosine modulated filter banks using window functions," Signal Processing , vol.87, pp.811-823, 2007.

[24] S. W. A. Bergen, "A design for cosine modulated filter banks using weighted constrained least squares filters," Digital Signal Processing, 2008, vol.18, no.3, pp.280-290.

[25] Akkarakaran, Sony, and P. P. Vaidyanathan, "New results and open problems on nonuniform filter-banks," in the proceeding of IEEE International Conference on Acoustics, Speech, and Signal Processing, pp. 1501-1504, 1999.

[26] Maneesha K and S Chris Prema, "A Channel Combiner approach for the design of Near Perfect Reconstruction Non Uniform Filter Banks," in Proceedings of IEEE International Conference on Communications and Signal Processing (ICCSP), 2014.

[27] S.Chris Prema and Maneesha K , "Analysis of multiprototype over single prototype filter bank for non uniform filter bank,",in Proceedings of 11th IEEE India Conference INDICON 2014, Pune, India, 2014.