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A Novel Window and Its Application in NPR Type Transmultiplexer Design

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Abstract This paper proposes a new window based approach for the design of *M*-channel maximally decimated Near-Perfect Reconstruction (NPR) type transmultiplexer. Cosine modulation is used to design the synthesis and analysis sections of the transmultiplexer. The prototype filter is designed with high Side-Lobe-Fall-Off-Rate (SLFOR) combinational window functions. A gradient based optimization algorithm has been applied to minimize the interference parameters like Inter-Channel Interference (ICI) and Inter-Symbol Interference (ISI).The proposed method of design of transmultiplexers are showing the improvements in terms ICI and ISI.

Keywords QMF, Filter Bank, Variable Window, SLFOR, ICI, ISI, Combinational Window Functions

1. Introduction

Digital filter banks are used in a number of communication applications such as sub-band coders for speech signals, frequency domain speech scramblers and image coding. The theory and design of Quadrature Mirror Filter (QMF) bank was first introduced by Johnston [1]. These filter banks find wide applications in many signal processing fields such as trans-multiplexers[2], equalization of wireless communication channel [3], sub-band coding of speech and image signals[4-5], sub-band acoustic echo cancellation[6-7]. Trans-multiplexer (T-MUX) systems are traditionally used for inter conversion between the Time-Division Multiplexing (TDM) format and the Frequency-Division Multiplexing (FDM) format, and have been successfully utilized to describe several popular communication applications such as Code Division Multiple Access (CDMA), Discrete Multi-Tone (DMT) or Orthogonal Frequency-Division Multiplexing (OFDM) [2]. This study focuses on a uniform-band structure in which all the incoming data signals are interpolated at the sampling rate M and the received signal is splitted and up sampled at the same integer factor (M). Within the different families of TMUX, modulated filter bank-based systems are emphasized because all the sub-channel filters can be obtained from a single prototype filter. Cosine-modulated filter banks will be used in designing the NPR Trans-multiplexer systems.

2. Synthesis of Window Function

The impulse response of the ideal low pass filter with cut-off frequency ω_c is given as-

$$h_{id}(n) = \frac{\sin(\omega_c n)}{\pi n}, \qquad -\infty < n < \infty \tag{1}$$

$h_{id}(n)$ is doubly infinite not absolutely summable and therefore unrealizable [8]. Hence shifted impulse response of $h_{id}(n)$ will be-

$$h_{id}(n) = \frac{\sin(\omega_c (n-0.5N))}{\pi(n-0.5N)}, \qquad 0 \le n \le N-1 \tag{2}$$

where, N is the length of rectangular window function. For making a causal filter, direct truncation of infinite-duration impulse response of a filter results in large pass band and stop band ripples near transition band. These undesired effects are well known Gibbs phenomenon. However, these effects can be significantly reduced by appropriate choice of window function $w(n)$. Hence, a filter $p(n)$ of order N is of the form [8-9]-

$$p(n) = h_{id}(n)\, w(n) \tag{3}$$

where, $w(n)$ is the time domain weighting function or window function. Window functions are of limited duration in time domain, while approximates band limited function in frequency domain.

3. Proposed Window Function

Window functions are broadly categorized as fixed and variable windows. In fixed window, the window length N governs main-lobe width. On the other hand, variable window has two or more independent parameters that control the window's frequency response characteristics [10]. The data window functions used in the design of combinational window family are given in Table 1. This table clearly indicates that the data window function at last but one row of Table 1 with a_0=0.4, a_1=0.5 and a_2=0.1gives the best

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Maximum Side-Lobe Level (MSSL) and SLFOR. The proposed window family is developed by taking the combination of Papoulis (Lag-Window) [11] and three term cosine window functions (Data-Window) in the following manner-

$$w_{proposed} = \begin{cases} \delta[l(n)] + (1-\delta)[k(n)], \ for\ |n| \le N/2 \ ; 0 \le \delta \le 1.315 \\ 0, \qquad\qquad\qquad\qquad |n| > N/2 \end{cases} \quad (4)$$

where,

$$l(n) = \frac{1}{\pi}\left|\sin\left(\frac{2\pi n}{N}\right)\right| + \left(1 - 2\left|\frac{n}{N}\right|\right)\cos\left(\frac{2\pi n}{N}\right)$$

$$k(n) = 0.4 + 0.5\cos\left(\frac{n\pi}{N}\right) + 0.1\cos\left(\frac{2n\pi}{N}\right), \quad for\ |n| \le N/2$$

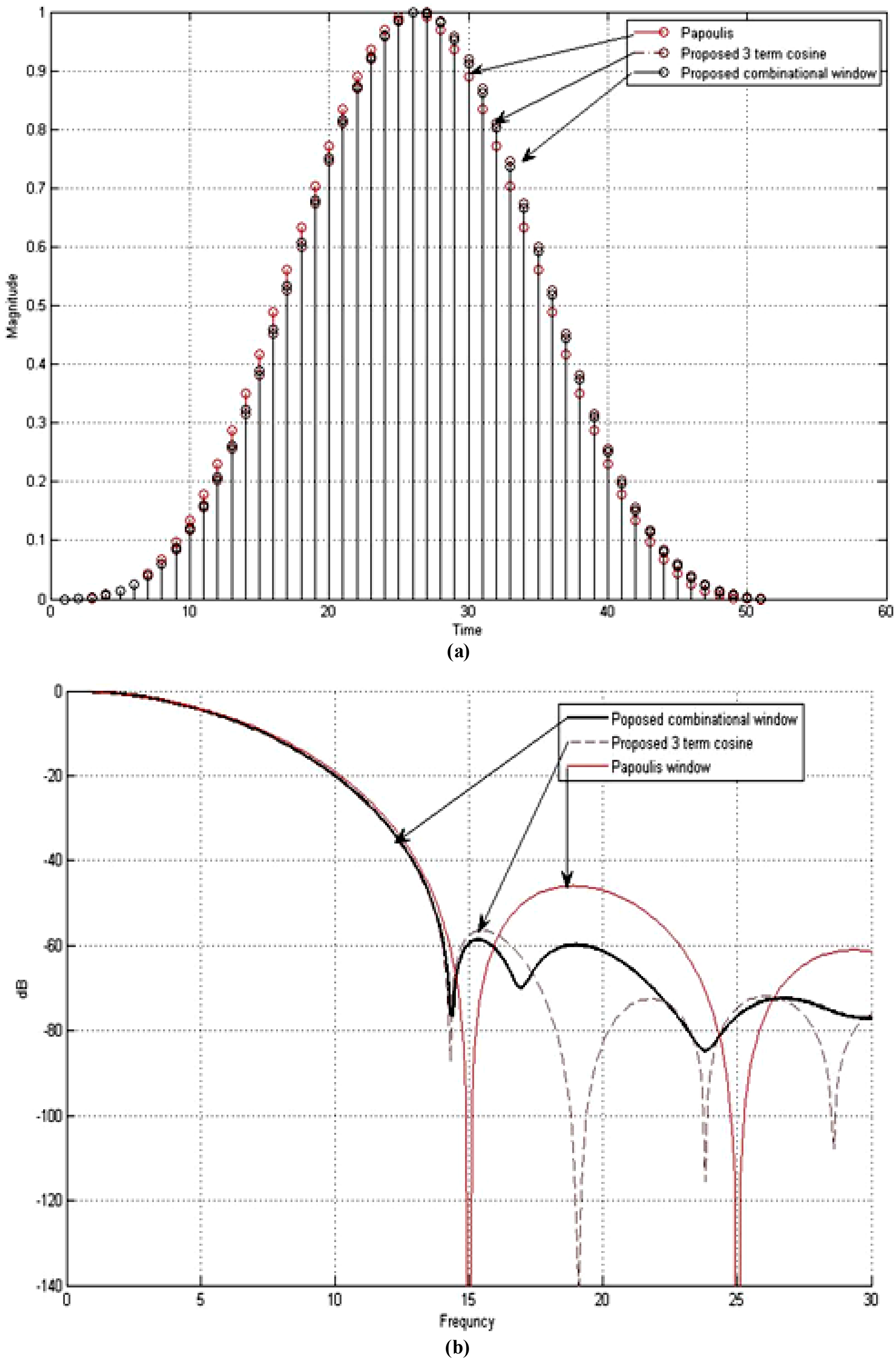


Figure 1. Time & frequency response of proposed window

Table 1. Comparative study of three term cosine window functions

$k(n)=a_0+a_1\cos\left(\frac{n\pi}{N}\right)++a_2\cos\left(\frac{2n\pi}{N}\right)$			Parameter of window functions	
a_0	a_1	a_2	MSSL (dB)	SLFOR (-dB/Octave)
0.3	0.5	0.2	-35.00	18
0.35	0.5	0.15	-41.46	24
0.37	0.5	0.13	-45.57	30
0.375	0.5	0.125	-46.8	36
0.38	0.5	0.12	-50.13	18
0.39	0.5	0.11	-51.50	18
0.4	0.5	0.1	-56.71	18
0.48	0.5	0.02	-46.57	24

The data window k(n)[12] is chosen by performing studies on different combinations of various window functions and their respective parameters. The Table 1 shows the different parametric values for different combinations. The design equations for prototype FIR low pass filter with proposed window function used in this study is given below-

(i)Relationship between window shape parameter (δ) and desired minimum stop band attenuation (ATT)

$$\delta = a + b(ATT) + c\left(ATT^2\right) + d\left(ATT^3\right) + e\left(ATT^4\right) \quad (5)$$

where, a = 47.551; b = -2.3814; c = 0.04524;
d = -0.00038411; e = 0.0000012265, for $22 \leq ATT \leq 74$

(ii)Relationship between normalized window width parameter (D) and (ATT)

$$D = c_1\left(ATT^2\right) + d_1\left(ATT^3\right) + e_1\left(ATT^4\right) + f_1\left(ATT^5\right) \quad (6)$$

where,
c_1 = -0.48548; d_1 = 0.057101; e_1 = -0.0022059;
f_1 = 0.000028274, for $22 < ATT \leq 26$

$$D = a_1(ATT^6) + b_1(ATT^7) + c_1(ATT^8) + d_1(ATT^{10}) + e_1(ATT^{12}) \quad (7)$$

a_1=-0.0000058038; b1=0.00000073426;
c_1= -10.00000003459; d_1=0.00000000073426;
e_1=0.0000000000055982, for $26 < ATT \leq 37$

$$D = a_1 + b_1(ATT) + c_1\left(ATT^2\right) + d_1\left(ATT^3\right) + e_1\left(ATT^4\right) \quad (8)$$

a_1 = 3607.3; b_1 = -335.13; c_1 = 11.662; d_1 = -0.18009;
e_1 = 0.0010417, for $37 < ATT \leq 49$

$$D = a_1 + b_1(ATT) + c_1\left(ATT^2\right) + d_1\left(ATT^3\right) \quad (9)$$

a_1 = 255.1; b1 = -13.531; c_1 = 0.23899; d_1 = -0013889, for $49 < ATT \leq 62.8$

$$D = a_1 + b_1(ATT) + c_1\left(ATT^2\right) + d_1\left(ATT^3\right) + e_1\left(ATT^4\right) + f_1\left(ATT^5\right) \quad (10)$$

a_1 = 257450; b_1 = -18972; c_1 = 558.74; d_1 = -8.2203;
e_1 = 0.060417; f_1 = -0.00017747, for $62.8 < ATT \leq 74$

The variable window functions used in designing the prototype FIR filter for the QMF banks are given. It has been observed that the resultant window function with δ = 0.207 gives the best characteristics. The filter designed using the window is specified by three parameters–cut-off frequency (w_c), filter order (N), and window shape parameter (δ). For desired stop band attenuation (ATT) and transition bandwidth, the order of the filter (N) can be estimated by

$$N = \left[\frac{D}{\Delta F_S}\right] + 1, \quad (11)$$

4. Transmultiplexer Systems

Transmultiplexers have been used as key building blocks in multicarrier transmission for several years now. A typical filter bank based transmultiplexer structure is as shown in Fig.3. The signals x_k (n) are symbol streams such as PAM or QAM signals. These are passed through the transmitter filters F_k (z) and the sum x(n) is passed through the channel C(z). At the receiver the analysis filters H_k (z) separate the signals and reduce them to their original rates by M fold decimation.

A filter bank structure consists of an analysis filter bank that provides modulation of the input signal and at the receiver the synthesis filter bank produces demodulation. Filter banks where the filters in the sub channels are modulated versions of the prototype filters are called modulated filter banks. If the M analysis filters of the M-channel filter bank are derived from the prototype filter by the process of cosine modulation then the filter bank is said to be a cosine modulated filter bank. The filter bank is said to be perfect reconstruction, if the output signals are equal to the input or a delayed version of the input. In the case of the critically sampled filter bank the number of sub bands N is equal to the up sampling/down sampling factor M. Basically, it is a TDM-FDM-TDM converter [13]. It consists of synthesis block at transmitter end and precedes the analysis block at receiver end. At the transmitter end, M-input signals are first interpolated by the factor of M and synthesized into one composite signal using synthesis filter-bank F_k (z) for k = 0, 1, . . ., M − 1. Conversely, at the receiver end, the composite signal is split out into M-output signals with the help of the analysis filter bank H_k (z) and then decimated by a factor of M. The Z-transform of the output at particular l_{th} sub channel is given by (12), in terms of Z-transform of the M-input signals [14]:

Multicarrier systems can be analyzed by using an M channel critically sampled TMUX system as shown in Fig.3.The Z-transform of the output signal of the l_{th} channel, denoted by $\hat{X}_l(z)$, is expressible in terms of the Z-transforms of the input signals, denoted by $X_k(z)$ for k = 0, 1, M−1, as

$$\hat{X}_l(z) = \sum_{k=0}^{M-1}\left[\frac{1}{M}\sum_{m=0}^{M-1} H_l\left(z^{1/M}W^m\right)C\left(z^{1/M}W^m\right)F_k\left(z^{1/M}W^m\right)\right]X(z) \quad (12)$$

where, $W^m = e^{-j2\pi m/M}$ and C (z) represents the transmission characteristics of the transmission channel. Equation (12) can also be expressed in transfer function form as:

$$\hat{X}_l(z) = \sum_{k=0}^{M-1} T_{lk}(z)X(z) \quad (13)$$

Where, $T_{lk}(z)$ is the transfer function between the output of the l_{th} sub channel and the input of the k_{th} sub channel, which is defined as

$$T_{lk}(z) = \frac{1}{M}\sum_{m=0}^{M-1} H_l\left(z^{1/M}W^m\right)C\left(z^{1/M}W^m\right)F_k\left(z^{1/M}W^m\right) \quad (14)$$

In case of PR-type transmultiplexer with the ideal channel, $T_{lk}(z)$ should be zero for $l \neq k$ and one for $l=k$, i.e., the total error and interference are vanished.

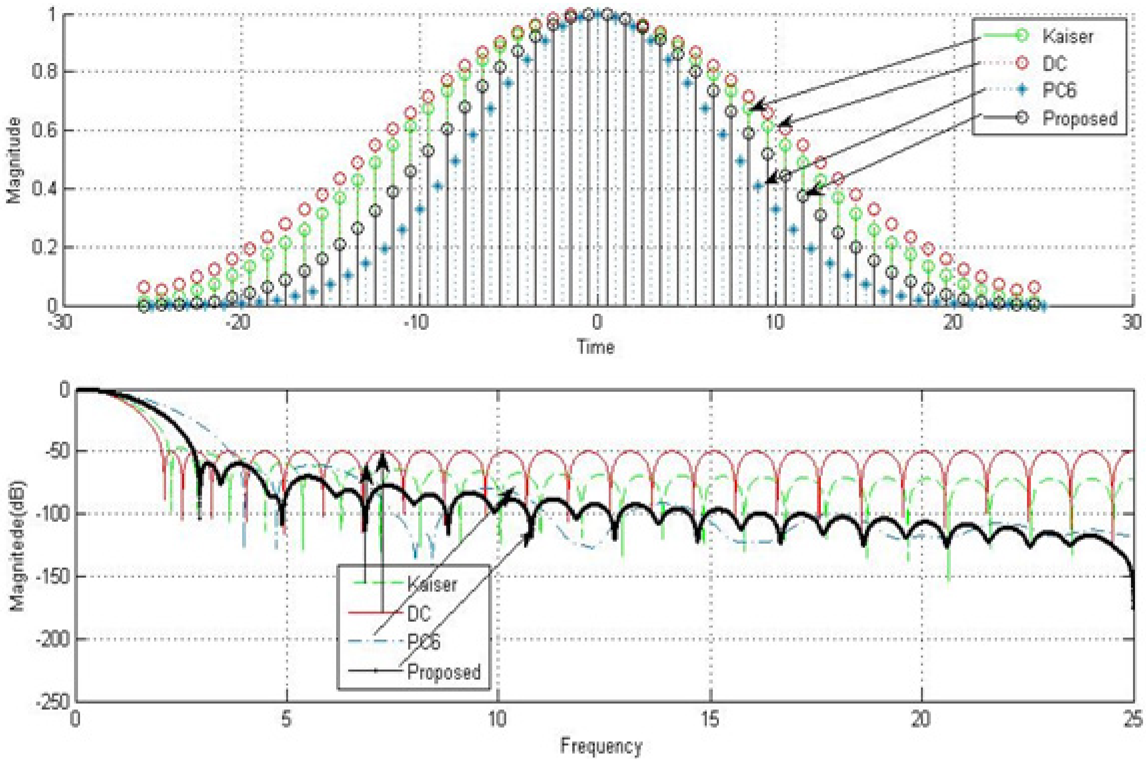


Figure 2. Time & frequency response of different window function

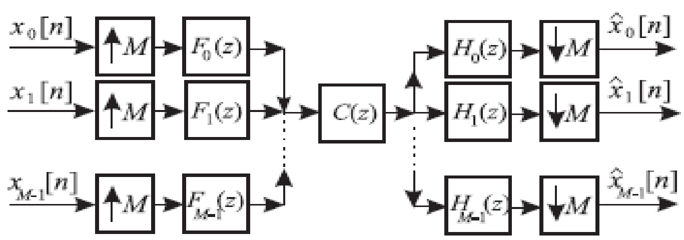
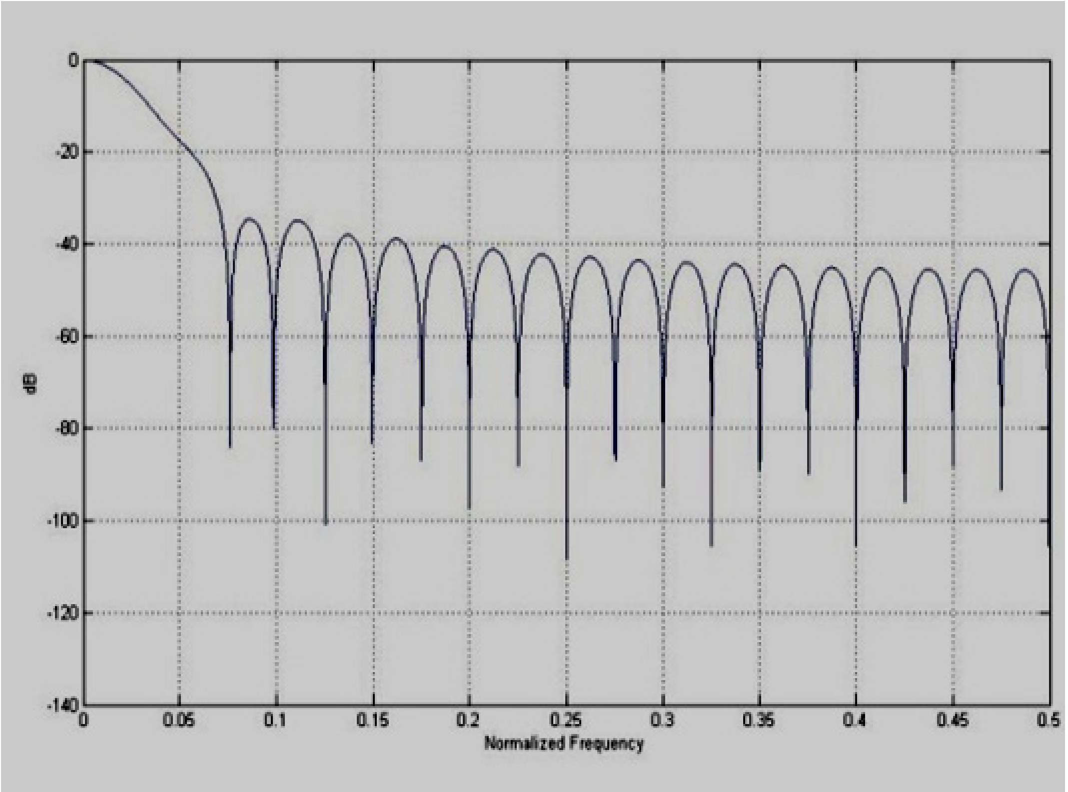
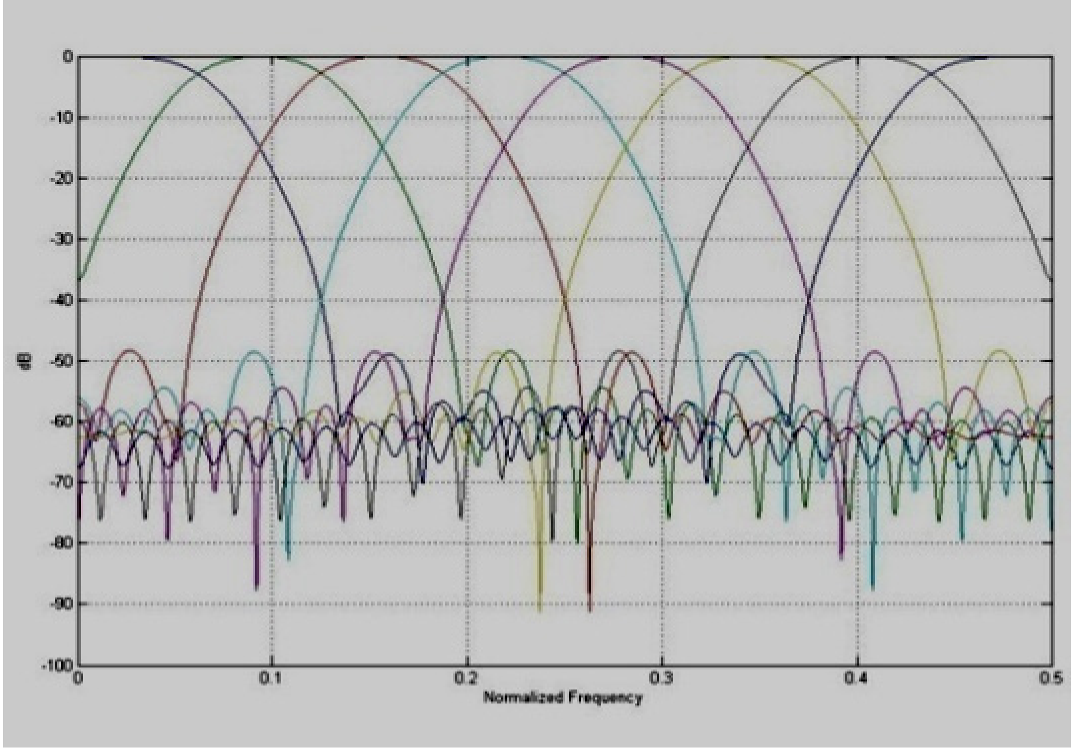


Figure 3. M-Channel maximally decimated transmultiplexer



(a)



(b)

Figure 4. Magnitude responses of 8-band CMFB using proposed window at ATT = 35.8 dB. (a) Prototype low pass filter; (b) Filter bank

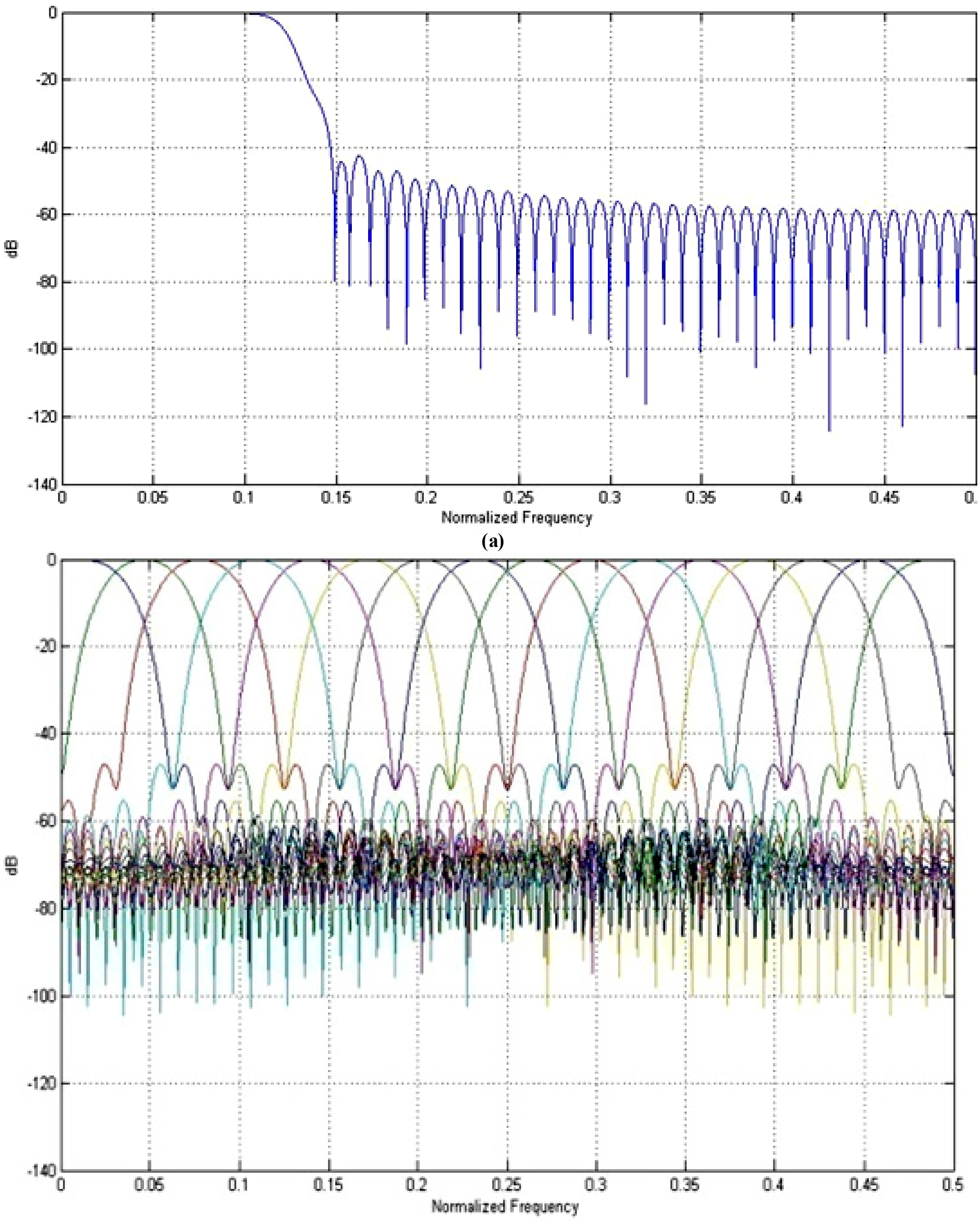


Figure 5. Magnitude responses of 16-band CMFB using proposed window at ATT = 45 dB. (a) Prototype low pass filter; (b) Filter bank

4.1. Cosine Modulation

Cosine modulation is one of the efficient techniques which provide minimum computational cost in the design of filter bank. All filters of synthesis and analysis sections are obtained by cosine modulation of a linear phase low pass prototype filter [2, 15].

$$h_k(n) = 2p(n)\cos\left[(2k+1)\frac{\pi}{2M}\left(n-\frac{N}{2}\right)+(-1)^k\frac{\pi}{4}\right]$$
$$f_k(n) = 2p(n)\cos\left[(2k+1)\frac{\pi}{2M}\left(n-\frac{N}{2}\right)-(-1)^k\frac{\pi}{4}\right]$$
$$\text{for } 0 \le k \le M-1, \text{ and } 0 \le k \le N \qquad (15)$$

where, M is the number of bands and $h_k(n)$ and $f_k(n)$ are the impulse responses of the analysis and synthesis sections, respectively.

4.2. Performance Measuring Parameters

The output at the receiver end is not a perfect replica of the input signal. These signals have distorted due to mixing of undesired interference during the processing and transmission. The amplitude of these interference signals is considered as performance measure of the designed system. The following are the performance measure parameters in the transmultiplexer system. The ICI is the leakage of signal from the remaining (M-1) sub channels to given particular sub channel. This occurs due to interference of the filters in their stop band. The ICI in the l_{th} sub channel can be conveniently measured as [14]:

$$E_{ICI}(l) = \frac{1}{\pi}\int_0^{\pi}\left(\sum_{k=0,k\neq l}^{M-1}\left|T_{lk}\left(e^{jw}\right)^2\right|\right)dw \tag{16}$$

where, T_{lk} ($e^{j\omega}$) can be obtained from (14). On the other hand, the ISI is caused by the interference of other symbols in the same sub channel. This occurs due to the non-ideal nature of the filters within their pass band and the fact that channel frequency response is not uniform for all sub channels. The ISI

$$E_{ISI}(l) = \frac{1}{\pi}\int_0^{\pi}\left(\left|T_{ll}\left(e^{jw}\right)-1\right|^2\right)dw \tag{17}$$

where, T_{ll} ($e^{j\omega}$) can be obtained from (14).

4.3. Optimization Technique

Different authors used different objective function and obtained the minimum possible value of reconstruction error in a filter bank. Since transmultiplexer is dual of filter bank[13], therefore similar optimization techniques can be applied to transmultiplexer with different objective functions [16]. In this proposed work, a single-variable optimization technique is used with ICI given in (4) as an objective function, i.e., [g(ω_c) = |E_{ICI}(l)|]. The cut-off frequency (ω_c) of the prototype filter is selected as a variable parameter. The proposed optimization technique is independent of the window function. Initially, the supplied input parameters, i.e., sampling rate, pass band and stop band frequencies, number of bands, pass band ripple and stop band attenuation are specified. Based on these inputs, the filter order and initial value of cut-off frequency will be calculated, then the window coefficients of the selected window function are determined and they remain fixed. The filter coefficients of the prototype low pass filter and filters of synthesis and analysis section are determined using cosine modulation. The ICI in a particular sub channel for current value of cut-off frequency is calculated. The absolute value of ICI is selected as an objective function. In the optimization routine cut-off frequency of the prototype filter is continuously iterates as per the search direction and calculate the corresponding value of these parameters. The algorithm terminates the loop as it attains the optimum value of the objective function. The desired steps required to be undertaken for designing the prototype filter using the proposed method are recorded chronologically:

i. Specify sampling frequency, number of bands, stop band attenuation, and pass band ripple.

ii. Initialize pass band and stop band frequency. Calculate the cut-off frequency, transition band, filter length and window coefficients of selected window function.

Initialize step size (step), search direction (dir), flag, minimum value of ISI error (k_err) and initial value of ISI (n_err).

Design of prototype filter and obtain filters for synthesis and analysis sections using Cosine modulation scheme.

Calculation of ISI and absolute value of objective function (tnt).

Check whether tnt > n_err. If yes, step=step/2, dir=-dir. If no, follow the next step.

iii. Check tnt ≤ k_err If yes, flags comes out of loop and optimized value of reconstruction error. If no, follow the next step.

iv. Check tmt = n_err If yes, flags comes out of loop and optimized value of reconstruction error. If yes, compute the new cut off frequency wc*= wc +dir*step and follow the step (iv).Program halts when n_err = tnt.

These steps are supported by a flow chart shown in Annexure (1).

Table 2. The performance comparison with earlier work

Window function	ATT	N	ICI(dB)	ISI(dB)
Modified Blackman	50	48	-49.81	-46.06
Kaiser	50	48	-108.58	-72.24
PC4	50	48	-99.97	-72.23
PC6	50	48	-100.17	-72.24
Proposed	50	48	-103.50	-77.52

5. Results and Discussion

In NPR system, the PR conditions are certainly relaxed by allowing a small amount of error and interferences. These interferences can be minimized by applying suitable optimization techniques. Much work has been done in this field [10, 17].

Initially, Johnston [1] developed a nonlinear optimization technique for the design of filter banks. Later on, many prominent authors such as Creusere et al. [8] and Lee et al.[9] and others[10, 18 and 19] have simplified it and developed single-variable linear optimization techniques. In these algorithms, a single-variable parameter is varying as per search direction and calculates the corresponding values of the objective function.

Table 3. The performance comparison for stop band attenuation

Window function	ATT	N	ICI(dB)	ISI(dB)
Kaiser	56	54	-92.59	-72.22
PC4	56	102	-97.99	-72.23
PC6	56	82	-102.05	-72.24
Proposed	56	56	-107.33	-78.16

Table 4. The performance comparison for filter order (N=92)

Window function	ATT	N	ICI(dB)	ISI(dB)
Kaiser	90	92	-98.78	-72.22
PC4	51	92	-102.67	-72.23
PC6	59	92	-98.90	-72.24
Proposed	54	92	-102.86	-78.18

The evaluation of the optimization technique is done with the help of the examples of different window functions. The first two examples compare the performance with the earlier reported work [14, 15 and 20]. The third one shows the optimal performance and the comparison with widely used Kaiser window function. In the first example, the input parameters such as stop band attenuation and filter order are taken like in reported work [6], and correspondingly, the initial value of the cutoff frequency is calculated for the chosen values of pass band and stop band frequencies. These input parameters are fixed before calling the optimization algorithm. Only one parameter, i.e., cut-off frequency, is variable during optimization and attains the minimum value of the objective function. The obtained values of different parameters are given in Table 2. The magnitude responses of 8-channel and 16-channel transmultiplexer are shown in Fig. 4a, b and 5a, b. The obtained values of ICI and ISI are given in Table 2.

In the last half decade, Martin et al. [5-11] have done excellent work in this field. They used cosine-based fixed window functions for the design of the prototype filter of transmultiplexers. A specific four-variable optimization technique is used in their design, which optimizes the weight terms of the window function. As per [6], this technique requires a good starting point for obtaining the optimum results. However, in the proposed work, a single variable generalized optimization technique is applied. Variable combinational window functions with high SLFOR are used for the design of prototype filter. These window functions provide more flexibility and better performance than fixed window functions. As it is clear from the Fig. 4a that these window functions have better far end attenuation than widely used Kaiser window function. This property provides better suppression of ICI when compared to Kaiser window function. It is evident from the results of the quoted examples that the obtained values of interferences parameters are much better than earlier reported work. It is clear from Table 3 that the proposed window provides better results as compared to other combinational window by using proposed optimization technique.

6. Conclusions

A simple and an efficient design for CMTs are presented. The proposed window provides better result as compared to other combinational window functions. It provides very small and stable interference levels against variation in the input parameters, i.e., stop-band attenuation and filter order. Also, the interference level in all sub channels is almost equal. Therefore, there is no burden of selecting a particular sub channel for a given particular application. This wide range stability makes it useful for a variety of applications of audio and video fields.

REFERENCES

[1] Johnston, J. D.,1980,A filter family designed for use in quadrature mirror filter banks., Proceedings of IEEE International Conference Acoustics, Speech and Signal Processing, Denver, 291–294.

[2] Prasad, R., and Van, N.R., 2000, OFDM for wireless multimedia communications. Artech House Publishers.

[3] Rizos, A.D., Proakis J.G., and Nguyen,T. Q.,1994, Comparison of DFT and cosine modulated filter banks in multicarrier modulation., Proceedings of 2nd Conference Global Tele-communication, San Francisco, USA, 687–691.

[4] Goudard, D. N., and Alard, M.,2001, OFDM with guard interval versus OFDM/Offset QAM for high data rate UMTS downlink transmission., Proceedings of IEEE Conference on Vehicular Technology, 2682–2686

[5] Martin-Martin, P. Cruz-Roldán, F. and Saramaki, T., 2005, Optimized transmultiplexers for multirate systems, Proceedings of 2nd International Symposium on Circuit and System, Kobe, Japan, 1106–1109.

[6] Martin-Martin, P., Cruz-Roldán, F., and Saramaki, T., 2004, A new window for the design of cosine-modulated multirate systems. Proceedings of IEEE International Symposium Circuits and System, Vancouver Canada, pp. 529–532.

[7] Jain, A., Saxena, R., and Saxena, S. C.,2006, Anti-image FIR filters for large interpolation factors., Signal Processing, 86,3240–3245.

[8] Xu, H., Lu, W.S., and Antoniou, A.,1998, An improved method for design of FIR quadrature mirror image filter banks., IEEE Trans. Signal Processing, 46(6),1275-1281.

[9] C.K., Chen and J.H. Lee," Design of quadrature mirror filters with linear phase in frequency domain", IEEE Trans Circuits System", Vol.39, No.9, 1992, pp.593-605.

[10] Jain, A., Saxena, R., and Saxena, S. C., 2006, An improved and simplified design of cosine modulated pseudo-QMF filter banks., Digit. Signal Processing, 16(3), 225–232.

[11] Sharma, S.N., Saxena, R., and Saxena, S. C., 2004, Design of FIR filters using variable window families: a comparative study., J. Indian Inst. Science, 84(5), 155–161.

[12] Nuttall, Albert H., 1981, Some windows with very good side-lobe behavior., IEEE Transactions on Acoustics, Speech and Signal processing: Analog and Digital Signal Processing. 1(29), 84-91.

[13] Soni, R.K., Jain, A., and Saxena, R., 2008, Recent patents in transmultiplexers and applications., Trans. Recent Pat. Eng.,

Bentham Science Publishers Ltd, 2(1).

[14] Soni, R.K., Jain, A., and Saxena, R., 2011, An optimized transmultiplexer using combinational window functions., Signal, Image and Video Processing, 5(3), 389-397.

[15] Cruz-Rolden F., and Monteagudo-Prim, M., 2004, Efficient implementation of nearly perfect reconstruction FIR cosine-modulated filter banks., Proc. IEEE Trans. Signal Processing, 52, 2661–2664.

[16] Soni, R.K., Jain, A., and Saxena, R., 2010, An improved and simplified design of pseudo transmultiplexer using Blackman window family., Digital Signal Processing, 20(3), 743–749.

[17] Creusere C.D., and Mitra, S. K.,1995, A simple method for designing high quality prototype filters for M band pseudo QMF banks., IEEE Trans. Signal Process,43(4),1005–1007.

[18] Lin, Y., and Vaidyanathan, P.P., 1998, A Kaiser window approach for the design of prototype filters of cosine modulated filter banks., IEEE Signal Process. Lett. 5(6), 132–134.

[19] Sandberg, S. D., and Tzannes, M.A., 1995, Overlapped discrete multitone modulation for high speed copper wire communications., IEEE J. Sel. Areas Communication, 13, 1571–1585.

[20] Soni, R.K., Jain, A., and Saxena, R., 2006, New efficient iterative optimization algorithm to design the two channel QMF bank., Trans. Eng. Comput. Technology,18, 206–210.