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ORIGINAL ARTICLES

Design of near-perfect-reconstructed transmultiplexer using different modulation techniques: A comparative study

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Inter-symbol interference (*ISI*)

Abstract In this paper, an efficient iterative method for design of near-perfect reconstructed transmultiplexer (NPR TMUX) is proposed for the prescribed roll-off factor (*RF*) and stop band attenuation (A_s). In this method, windowing technique has been used for the design of prototype filter, and different modulation techniques have been exploited for designing multi-channel transmultiplexer (TMUX). In this method, inter-channel interference (*ICI*) is iteratively minimized so that it approximately reduces to ideal value zero. Design example is given to illustrate the superiority of the proposed method over earlier reported work. A comparative study of the performance of different modulation techniques for designing TMUX is also presented.
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1. Introduction

Multirate signal processing is useful for all branches of natural and social science, which involve data acquisition and analysis (Mitra, 2001; Vaidyanathan, 1993). Multirate system such as the filter bank is a bank of low pass, high pass and band pass filters; these filters are employed to cover a complete band in the frequency range. The filter banks consist of delay elements, down samplers and up samplers, and work in two modes; first is analysis/synthesis mode and second is synthesis/analysis mode. First mode or structure corresponds to the filter bank (Zhao et al., 2013a; Zhao and Swamy, 2013; Boukabou et al., 2013; Zhang et al., 2011), which is used in source coding such as data compression, subband coding and the second mode corresponds to a transmultiplexer (TMUX) (Vetterli, 1990; Vaidyanathan and Vrcelj, 2000; Parker, 2007; Jian and Zaichen, 2009), which is used in channel equalization, channel coding etc.

TMUX refers to a system that converts time the multiplexed signal to a frequency multiplexed signal, and finally to the time multiplexed signal (TDM–FDM–TDM). Due to TMUX, higher processing rate is achieved and the system cost

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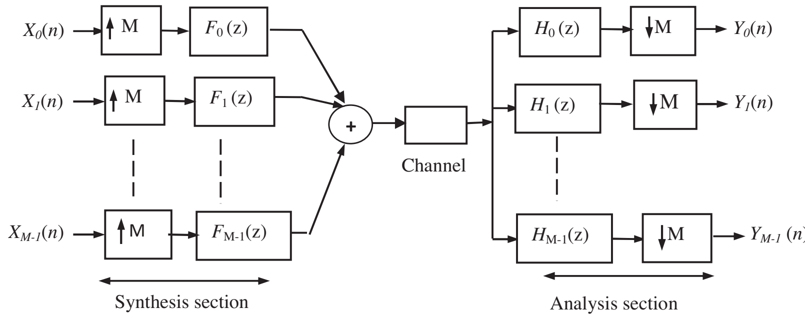

Figure 1 A block diagram of transmultiplexer system Kumar et al. (2013).

is also decreased (Vetterli, 1990; Vaidyanathan and Vrcelj, 2000; Parker, 2007; Jian and Zaichen, 2009). Therefore, a number of efficient TMUX systems have been developed to minimize the system cost, overall computational complexity needed to design a TMUX system. In the early stage of research, TMUX systems were designed using non-DFT based Freeny et al. (1971) and DFT based Cruz-Roldan et al. (2012) and Lim et al. (2005)) methods. In the non DFT based approach (Freeny et al., 1971), analog filters were employed that cause a large interference between adjacent channels of TMUX, while the DFT based technique for designing TMUX systems (Cruz-Roldan et al., 2012; Lim et al., 2005) employs Fast Fourier Transform (FFT), which results in fast implementation of TMUX and efficient channel equalization (Parker, 2007; Jian and Zaichen, 2009). DFT based filters have a main lobe and side lobes. Main lobe interferes with adjacent channels and side lobes spread all over the spectrum band. Due to that, selectivity of DFT based TMUX is limited, and it is not very suitable for narrow band applications (Umehara et al., 2006). To get high selective filters, cosine modulation technique (Vaidyanathan, 1993) is employed which reduces the design complexity of TMUX because the first prototype filter is designed and then, other analysis/synthesis filters are generated using the cosine modulation technique (Manoj and Elias, 2009a; Soni et al., 2010a,b, 2013). So, design complexity is equal to design of a prototype filter plus modulation overhead. To achieve faster implementation of the TMUX system, modulation is done by fast Discrete Cosine Transform (DCT) (Vaidyanathan, 1993). Several cosine modulation based algorithms have been proposed for designing of TMUX. A detailed discussion on cosine modulation and applications of cosine modulated filter banks have been given in Manoj and Elias (2009a) and Soni et al. (2010a,b, 2013)) and reference therein.

First iterative method for designing Pseudo QMF banks was proposed by Creusere and Mitra (1995) based on linear optimization, and it has been further modified in Zhao et al. (2013b), Lin and Vaidyanathan (1998), Martin et al. (2004), Kumar et al. (2011a,b), Kumar and Kuldeep (2012) and Berger and Antoniou (2007). Later on, this algorithm was used to design cosine modulated TMUX, while in Manoj and Elias (2009b, 2012), artificial bee colony (ABC) algorithm and genetic algorithm (GA) have been used for designing TMUX. Recently, several design methods (Soni et al., 2013; Hoc et al., 2005; Ribeiro et al., 2009) have been proposed and evaluated for the design of TMUX systems based on optimization and non-optimizations. But still, there is no such iterative technique reported in the literature that can reduce the computation time, converge in a low number of iterations, and can also reduce inter-channel interference (*ICI*), which can be used for filter banks with larger taps. Authors have proposed an optimized algorithm in Cruz-Roldan et al. (2003) and Martin et al. (2003) for designing TMUX with the windowing technique based on the algorithm given in Creusere and Mitra (1995).

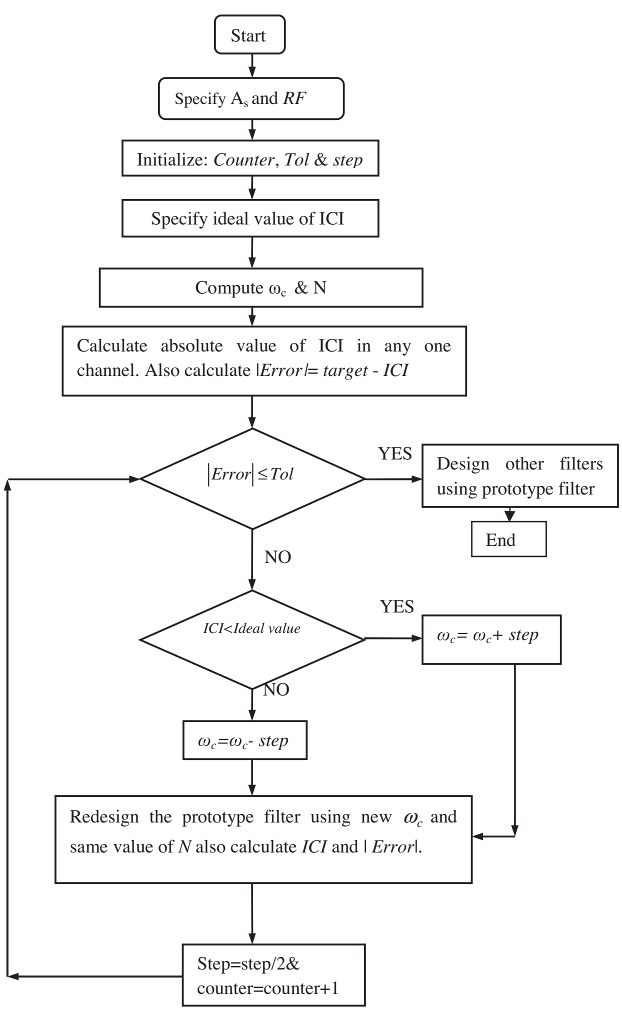

Figure 2 Flowchart of the proposed optimization algorithm.

2. Overview of transmultiplexer (TMUX) system

Fig. 1 shows the synthesis/analysis subsystem of the TMUX system. In the synthesis section, *M* input signals are first interpolated by a factor of *M*. After that, output of the

Table 1 Performance of the proposed method for designing TMUX using cosine modulation.

Window function	N	Bands (M)	A_S (dB)	RF	ICI (dB)	ISI (dB)	$SICI$ (dB)	$SISI$ (dB)	SI (dB)
Blackman	64	8	70	1.1	−235.21	−116.62	99.72	−18.85	−18.85
	124	8	75	1.1	−296.64	−116.58	159.01	−21.04	−21.04
Blackman–Harris	64	8	70	1.1	−203.71	−116.08	70.37	−16.53	−16.53
	124	8	75	1.1	−358.34	−116.29	214.6	−27.43	−27.43
Blackman–Nuttall	64	8	70	1.1	−207.76	−116.77	74.22	−16.76	−16.76
	124	8	75	1.1	−350.29	−116.29	206.37	−27.63	−27.63
Modified Blackman	64	8	70	1.1	−233.91	−116.64	98.72	−18.53	−18.53
	124	8	75	1.1	−255.17	−116.62	118.37	−20.18	−20.18
Kaiser	64	8	70	1.1	−270.96	−115.72	87.43	−67.8	−67.8
	124	8	75	1.1	−284.48	−115.95	127.26	−41.26	−41.26
Saramaki	64	8	70	1.1	−252.3	−115.7	57.32	−79.28	−79.28
	124	8	75	1.1	−372.99	−115.72	188.85	−68.49	−68.41
Ultraspherical	64	8	70	1.1	−250.92	−115.69	55.52	−79.7	−79.7
	124	8	75	1.1	−365.01	−115.72	180.49	−68.72	−68.79
Transitional	64	8	70	1.1	−252.89	−115.7	58.08	−79.11	−79.11
	124	8	75	1.1	−376.47	−115.72	192.48	−68.57	−68.25

interpolation is fed to synthesis filters ($F_1(z)$, $F_2(z)$,…, $F_M(z)$). Output of the synthesis section is combined into a wide band signal and transmitted through an ideal transmission channel having unity impulse response and zero channel noise. In the analysis section, transmitted composite signal is filtered with analysis filters ($H_1(z)$, $H_2(z)$,…, $H_M(z)$), and then M filtered signals are decimated by factor M. The output $Y_i(z)$ of the ith branch due to all inputs $X_i(z)$ is given in Cruz-Roldan et al. (2003) and Soni et al. (2010b). The transfer function between ith channel output signal $Y_i(z^M)$ and rth channel input signal $X_r(z^M)$ is defined as

$$T_{i,r}(z^M) = \sum_{k=0}^{M-1} H_i(zW_M^k) \cdot F_r(zW_M^k) \tag{1}$$

The term $T_{i,r}(z^M)$, $i \neq r$ represents the interference mainly crosstalk between the sub-channels of TMUX. *ICI* is one kind of crosstalk, which occurs in TMUX due to the response in the stop band region. *ICI* is given in Soni et al. (2010b). *ISI* occurs in TMUX due to non-ideal response of filters in their passband region but practically filters having ripples in their pass band region. *ISI* is given in Soni et al. (2010b). Signal to inter-channel interference (*SICI*) is the ratio of signal to *ICI*, which

Table 2 Performance of the proposed method for designing TMUX using sine modulation.

Window function	N	Bands (M)	A_S (dB)	RF	ICI (dB)	ISI (dB)	$SICI$ (dB)	$SISI$ (dB)	SI (dB)
Blackman	64	8	70	1.1	−235.11	−116.62	99.64	−18.85	−18.85
	124	8	75	1.1	−296.28	−116.52	158.64	−21.04	−21.04
Blackman–Harris	64	8	70	1.1	−203.75	−116.81	70.37	−16.53	−16.53
	124	8	75	1.1	−356.03	−116.29	212.29	−27.43	−27.43
Blackman–Nuttall	64	8	70	1.1	−205.42	−116.78	71.91	−16.72	−16.72
	124	8	75	1.1	−350.82	−116.29	206.89	−27.63	−27.63
Modified Blackman	64	8	70	1.1	−233.37	−116.64	98.19	−18.53	−18.53
	124	8	75	1.1	−260.21	−116.62	123.4	−20.18	−20.18
Kaiser	64	8	70	1.1	−274.32	−115.72	90.79	−67.81	−67.81
	124	8	75	1.1	−290.19	−115.95	132.97	−41.32	−41.26
Saramaki	64	8	70	1.1	−252.3	−115.7	57.32	−79.7	−79.28
	124	8	75	1.1	−372.99	−115.72	188.81	−68.43	−68.41
Ultraspherical	64	8	70	1.1	−250.93	−115.69	55.52	−79.7	−79.7
	124	8	75	1.1	−365.01	−115.72	180.22	−68.76	−68.79
Transitional	64	8	70	1.1	−252.9	−115.67	58.06	−79.11	−79.11
	124	8	75	1.1	−376.47	−115.72	192.81	−68.61	−68.25

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Table 3 Performance of the proposed method for designing TMUX using complex exponential modulation.

Window function	*N*	Bands (*M*)	A_S (dB)	*RF*	*ICI* (dB)	*ISI* (dB)	*SICI* (dB)	*SISI* (dB)	*SI* (dB)
Blackman	64	8	70	1.1	−231.78	−115.38	89.31	−27.07	−27.07
	124	8	75	1.1	−298.71	−115.37	155.27	−28.06	−28.06
Blackman–Harris	64	8	70	1.1	−199.28	−115.39	35.39	−23.61	−23.61
	124	8	75	1.1	−360.26	−115.42	210.62	−34.21	−34.21
Blackman–Nuttall	64	8	70	1.1	−200.74	−115.39	60.92	−24.47	−24.43
	124	8	75	1.1	−224.92	−115.38	83.65	−25.89	−25.89
Modified Blackman	64	8	70	1.1	−233.93	−115.38	91.81	−26.72	−26.73
	124	8	75	1.1	−262.38	−115.35	119.75	−27.28	−27.28
Kaiser	64	8	70	1.1	−280.29	−115.64	89.08	−75.56	−75.56
	124	8	75	1.1	−293.19	−115.54	130.03	−47.01	−47.63
Saramaki	64	8	70	1.1	−247.61	−115.66	46.97	−84.97	−84.97
	124	8	75	1.1	−374.78	−115.64	184.75	−74.38	−74.38
Ultraspherical	64	8	70	1.1	−246.23	−115.66	45.29	−85.28	−85.28
	124	8	75	1.1	−366.8	−115.64	176.02	−74.12	−74.76
Transitional	64	8	70	1.1	−248.2	−115.66	47.69	−84.84	−84.84
	124	8	75	1.1	−378.26	−115.64	188.01	−74.24	−74.23

should be high for optimum TMUX. Higher values of *SICI* signify lesser effect of *ICI* in signals to be transmitted. *SICI* is given in Soni et al. (2010b). Signal to inter-symbol interference (*SISI*) is a ratio of the signal to *ISI*; again it should be as high as possible. Higher values of *SICI* signify a low effect of *ICI* on signals to be transmitted. *SISI* is given in Soni et al. (2010b). Signal to total interference in the kth channel (*SI*) is basically a combined effect of *ICI* and *ISI* on signal strength. SI is given in Soni et al. (2010b).

Near perfect reconstructed (NPR) filter banks (FBs) provide better performance in the stopband as compared to perfect reconstructed (PR) FBs, because of that, authors have proposed a NPR TMUX (Cruz-Roldan et al., 2003). In the proposed technique, four types of modulation based TMUX have been designed. In this approach, first a single prototype filter is designed then using cosine modulation (Vaidyanathan, 1993), sine modulation (Liu et al., 2012), complex exponential modulation (Alhava et al., 2003) and ELT (Abdul Hameed and Elias, 2005), synthesis and analysis filters of TMUX are designed, but in non-DFT based approach, every filter of the synthesis section and analysis section is separately designed. This results in low design cost and complexity. Further, efficient implementation of modulated TMUX is done with the aid of polyphase decomposition structure (Vaidyanathan, 1993). In cosine modulation, the parameters needed for optimization are less, because there are only one or two prototype filters.

2.1. Cosine modulated transmultiplexer (TMUX)

If $p(n)$ is a prototype filter then, analysis and synthesis filters are generated with Eqs. given in Vaidyanathan (1993), Manoj and Elias (2009a) and Soni et al. (2010a,b, 2013).

Table 4 Performance of the proposed method for designing TMUX using ELT.

Window function	*N*	Bands (*M*)	A_S (dB)	*RF*	*ICI* (dB)	*ISI* (dB)	*SICI* (dB)	*SISI* (dB)	*SI* (dB)
Blackman	64	8	70	1.1	−259.69	−115.94	100.14	−43.65	−43.65
	124	8	75	1.1	−340.02	−115.89	178.31	−45.81	−45.81
Blackman–Harris	64	8	70	1.1	−227.78	−115.94	70.37	−41.47	−41.47
	124	8	75	1.1	−397.4	−115.82	229.59	−51.99	−51.99
Blackman–Nuttall	64	8	70	1.1	−229.53	−115.93	71.82	−41.76	−41.76
	124	8	75	1.1	−376.03	−115.82	208.02	−52.18	−52.18
Modified Blackman	64	8	70	1.1	−259.06	−115.92	99.84	−43.31	−43.35
	124	8	75	1.1	−287.96	−115.9	127.07	−44.98	−44.98
Kaiser	64	8	70	1.1	−300.9	−115.68	93.29	−91.93	−91.93
	124	8	75	1.1	−312.8	−115.73	131.48	−65.52	−65.56
Saramaki	64	8	70	1.1	−276.39	−115.67	57.32	−103.39	−103.39
	124	8	75	1.1	−480.13	−115.68	271.93	−92.58	−92.18
Ultraspherical	64	8	70	1.1	−275.52	−115.67	57.28	−102.55	−102.55
	124	8	75	1.1	−489.81	−115.68	281.21	−92.92	−92.22
Transitional	64	8	70	1.1	−276.9	−115.67	58.08	−103.21	−103.21
	124	8	75	1.1	−469.08	−115.68	261.99	−92.38	−92.38

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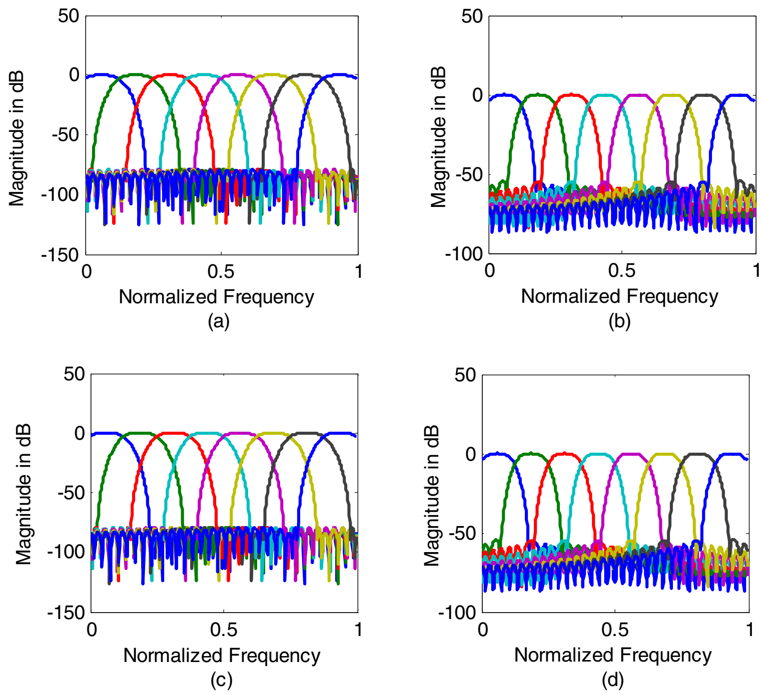

Figure 3 8-Channel NPR transmultiplexer system designed by Blackman window with $RF = 1.1$ and $N = 64$. The magnitude response of synthesis filters using (a) ELT (b) cosine modulation (c) complex exponential modulation (d) sine modulation.

2.2. Sine modulated transmultiplexer (TMUX) (Vaidyanathan, 1993; Liu et al., 2012)

Sine modulated filter banks (SMFBs) have similar properties as CMFBs. PR SMFB has similar efficient implementation complexity and design as CMFB, but in SMFB, additional 90° phase shift is added. The synthesis and analysis filters are generated using Eqs. (2) and (3), respectively.

$$h_k[n] = 2p[n]\sin\left((2k+1)\frac{\pi}{2M}\left(n-\frac{N-1}{2}\right)+(-1)^k\frac{\pi}{4}\right) \tag{2}$$

$$f_k[n] = h_k[N-1-n]. \tag{3}$$

In Eqs. (2) and (3), $K = 0, 1, \ldots, M-1$.

2.3. Complex exponential modulated transmultiplexer (TMUX) (Alhava et al., 2003)

In this, an exponential function is multiplied by the prototype filter to design sub-channel filters. In cosine modulation based TMUX, sub-channel filters suffer from the alias terms generation due to overlapping image of the negative and positive pass bands. This overlapping of negative and positive passband distortion is removed by complex exponential modulation. In complex exponential modulation, extension is done by sine modulating the prototype filter on the imaginary axis. Due to this, only a single pass band alias is removed and some alias may still be present due to non-ideal response of the prototype

Table 5 Comparison of the proposed method over earlier reported work for 8-channels or bands ($M = 8$).

Type of algorithm	Technique	N	*ICI* (dB)	*ISI* (dB)	*SICI* (dB)	*SISI* (dB)	*SI* (dB)
Algorithm [33]	Parks–McClellan	128	−126.23	−57.88			
	KWA	128	−100.32	−58.84			
	CMT	128	−97.85	−64.61			
Algorithm [34]	Kaiser window	64	−92.22	−44.03			
Algorithm [24]	Mod. Blackman	48	−49.81	−46.06			
Algorithm [19]	Mod. Blackman	48	−157.65	−72.24	−29.07	−114.48	−114.49
Algorithm [39]	Mod. Blackman	64	−164.06	−72.24	−37.41	−129.22	−129.23
	New window	48	−103.50	−77.52			
	New window	56	−107.33	−78.16			
	New window	92	−102.86	−78.18			
Proposed algorithm	Kaiser (ELT)	64	−300.9	−115.68	93.29	−91.93	−91.93
Proposed algorithm	Kaiser (ELT)	48	−194.69	−115.98	45.47	−33.24	−33.24
Proposed algorithm	Kaiser (ELT)	56	−263.72	−115.74	89.27	−58.71	−58.71
Proposed algorithm	Kaiser (ELT)	92	−276.80	−115.88	114.31	−46.61	−46.61
Proposed algorithm	Kaiser (ELT)	128	−198.29	−116.10	54.66	−27.52	−27.53

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filter. Design of synthesis/analysis filters of complex exponential modulation based TMUX is given in Eqs. (4) and (5).

$$h_k(n) = p(n) \exp\left(j\frac{\pi}{M}\left(k+\frac{1}{2}\right)\left(n-\frac{N}{2}-\frac{M}{2}\right)\right) \quad (4)$$

$$f_k(n) = p(n) \exp\left(j\frac{\pi}{M}\left(k+\frac{1}{2}\right)\left(n-\frac{N}{2}+\frac{M}{2}\right)\right) \quad (5)$$

In Eqs. (4) and (5), $K = 0, 1, \ldots, M-1$.

2.4. Extended Lapped Transform transmultiplexer (ELT TMUX) (Abdul Hameed and Elias, 2005)

ELT is a modified form of Modulated Lapped Transform (MLT) with larger length of basis functions compared to cosine, sine and complex exponential modulation techniques. Due to that, filters obtained from ELT modulation have comparatively better pass band, stop band and transition band response. For real time speech coding, performance of ELT is good as compared to block transform such as DCT. ELT based filter banks significantly improve response of the filters because ELT generates more coefficients in impulse response of the filter. More information on ELT is given in Abdul Hameed and Elias (2005). The synthesis/analysis filters of ELT TMUX are derived using Eqs. (6) and (7), respectively.

$$f_k[n] = p[n] \times \cos\left[\left(k+\frac{1}{2}\right)\left(\left(n-\frac{N-1}{2}\right)\frac{\pi}{M}+(2k+1)\frac{\pi}{2}\right)\right] \quad (6)$$

$$h_k[n] = f_k[N-1-n] \quad (7)$$

where, N is the length of filter and K = 0, 1, 2,...,M−1.

3. Design of prototype filter using windowing technique

Windowing (Kumar et al., 2011b) is a simple method for designing finite impulse response (FIR) linear phase filter. In the window technique, a window function $w(n)$ is multiplied by a function $h(n)$ to get a finite length filter. Values of pass band, stop band and cutoff frequency have been given in Kumar et al. (2011b). In this paper, for designing of the prototype filters of TMUX, different window functions such as Blackman window family (Soni et al., 2010b; Martin et al., 2004), Kaiser window (Soni et al., 2010a; Datar et al., 2013), Saramaki window (Datar et al., 2013), Ultraspherical window (Datar et al., 2013), Transitional window (Datar et al., 2013), are used as window function possesses a closed form expression, which reduces the computation complexity.

4. Proposed methodology

From the literature review, it has been found that several methods have been developed for designing NPR TMUX systems using cosine modulation; in which initially, NPR cosine modulated filter bank is designed (Umehara et al., 2006; Manoj and Elias, 2009a; Soni et al., 2010a,b, 2013; Singh and Saxena, 2012), and then NPR TMUX is derived. From the analysis of TMUX systems (Soni et al., 2010a,b, 2013; Singh and Saxena, 2012), PR is achieved as

$$|H_0(e^{j\omega})|^2 + |H_0(e^{j(\omega-\pi/M)})|^2 = 1, \quad \text{for } 0 < \omega < \pi/M \quad (8)$$

In the proposed method, inter-channel interference (*ICI*) is taken as an objective function similar to the algorithm given in Soni et al. (2010a,b, 2013) and it is minimized by optimizing the prototype filter coefficients in each iteration by adjusting the cut-off frequency (ω_c). Here, the following steps in the matlab program have been undertaken for designing the optimized prototype filter and are shown in Fig. 2 (Vishwakarma et al., 2014; Kumar et al., 2013).

5. Results and discussion

Design example: NPR TMUX, with different value of roll-off factor (*RF*), stop band attenuations (A_s), filter lengths (N), tolerance (*Tol*) = 0.000000001, ideal value of inter-channel interference (*ICI*) = 0.0000001, step = 0.05, have been designed with the proposed method using different modulations such as cosine modulation, sine modulation, complex exponential modulation and ELT. Different window functions mentioned in Section 3 have been used for estimating the prototype filter coefficients. For the given stop band attenuation and *RF*, cutoff frequency is calculated. The prototype filter was designed with the given specifications, and the performance measures obtained in each design are listed in Tables 1–4 using cosine modulation, sine modulation, complex exponential modulation and ELT, respectively. The simulation results obtained from Blackman window are shown in Fig. 3 which shows the analysis/synthesis filter response for 8-channels. In Fig. 3(a) and (c), the overlapping of analysis/synthesis filters responses obtained from ELT modulation and complex exponential modulation, respectively is higher compared to cosine and sine modulation shown in Fig. 3(b) and (d). As it can be seen from the simulation results presented in Tables 1–4, the proposed method gives satisfactory values of *ICI* and *ISI*. In cosine, sine and complex exponential modulated TMUX, Blackman window gives a lower value of *ICI*. However, in ELT based TMUX, Ultraspherical window gives a better performance as compared to all modulation techniques. ELT based TMUX gives minimum values of *ICI*.

In Table 5, a comparative study of performance of the proposed method with earlier reported work (Soni et al., 2010b; Martin et al., 2003, 2004; Cruz-Roldan et al., 2003; Singh and Saxena, 2012) is made. It was found that the proposed method provides much lower values of *ICI* and *ISI* with different values of roll-off factor and filter order. It was also observed that for the same filter order, the proposed method yields better values of *ICI*, *ISI*, *SICI*, *SISI* and *SI*.

6. Conclusion

In this paper, an improved method for designing NPR TMUX based on optimized *ICI* is presented using different modulation techniques. The simulation results presented in this paper clearly show that the adjustable window functions with ELT modulation yield good performance as compared to other modulation techniques.

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