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Adjustable window based design of multiplier-less cosine modulated filter bank using swarm optimization algorithms

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ABSTRACT

In this paper, an adjustable window based approach is presented for the design of multiplier-less near perfect reconstruction cosine modulated filter bank (CMFB) for specified stopband attenuation (A_s) and channel overlapping. Kaiser window function is employed for designing the computationally efficient prototype filter with filter coefficients in canonic signed digit (CSD) space. Optimized performance of the designed filter is achieved using swarm based algorithm such as cuckoo search (CS) optimization, so that the filter coefficients of a multiplier-less prototype filter are optimized to achieve the magnitude response of 0.707 at frequency $\omega = \pi/2M$. In this method, instead of using two optimization techniques: one for designing continuous coefficients and other for optimizing quantized prototype filter coefficients, single swarm based technique is used, while a comparative study using proposed scheme based on the performance of different window functions as well as different swarm based techniques such particle swarm optimization (PSO) and artificial bee colony (ABC) algorithm is made. Design examples presented, using this technique, illustrates the improved performance of proposed technique as compared to other published algorithms.

1. Introduction

During the past few years, design of multirate filter banks has become an important field of research due to continuously increasing numerous applications of signal processing such as power harmonic analysis [1], EEG signal analysis [2], and image analysis and classifications [3]. The research effort was originally motivated by the subband coder for audio signal, image and video signals for transmission and storage purpose. Subsequently, this was extended to various fields such as beam forming antenna, and communication systems [4]. Filter banks are classified into two types: first is two-channel filter bank, also known as quadrature mirror filter (QMF) bank and second is multi-channel filter bank (FB) based on separation of input signal into number of sub-bands [4]. Cosine modulated based multichannel filter bank is widely used in different applications due to its simple and efficient design; in which only one prototype filter is needed to design, and rest of other composing filters are derived from it using cosine modulation [4]. Efficiency of all the subband coders used in various applications mentioned above is significantly dependent on optimal design of cosine modulated filter banks. Therefore, several algorithms have been proposed for optimal design of cosine modulated filter bank (CMFB) using linear search optimization [5–11] and evolutionary techniques [12,13]. In linear search optimization based algorithms [5–11], either pass-band edge frequency (ω_p) or 3 dB cutoff frequency (ω_c) was optimized to get optimal reconstruction error. In [12,13], evolutionary techniques such as PSO, and Memetic optimization were used to compute the optimal value of cutoff frequency. In [14], authors have proposed a closed form method for optimal designing of CMFB, and were further modified in [15].

In several applications, digital filters and filter banks are required to be designed such that they can satisfy some sophisticated design specifications such as high stopband attenuation, fast switching resolution and small channel overlapping that is important for high quality reconstruction of audio signal [3,5,14–16], fast switching resolution and adjustable stopband attenuation is more essential for biomedical signal processing [3,14,15]. For hearing aids, a filter bank with adjustable gain characteristics in the required band of frequency is required [17,18]. In software defined radio (SDR) application, a flexible technology is required that provides multi-band, multi-standard and multi-service, for which several important features of the channel filters such as low complexity, low power consumption and reconfigurable are required

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[19,20]. When digital filters are realized in hardware, adders and multipliers are needed. Multipliers are the expensive components than adder rising implementation complexity, and consume more power and space [21,22]. If coefficients of filter are represented in sign power of two terms (SPT), then multipliers can be realized as a simple circuit, consisting of adder and shifter; and hence, the circuit becomes multiplier-less that reduces the implementation complexity, area requirement and power consumption [21–23].

Signed digit number system provides diversity in representation, while canonic signed digit representation is a unique case of signed digit number system, which possesses special qualities with minimum number of SPTs, providing efficient implementation of multiplier into adders and shifters [21–23]. Thus, the resulting filter becomes multiplier less; and this leads to realization of filter with less implementation complexity with low power and low silicon area. Therefore, during the past few years, several researchers have developed the new design of digital filters which were computationally efficient and with low hardware requirement [22–25].

When continuous filter coefficients are rounded in terms of quantized CSD valued coefficients, performance of the filter is deteriorated and given specifications are no longer satisfied. Therefore, to overcome these problems, authors in [26] have used genetic algorithm (GA) for designing digital filter with optimal performances. Since then, several designs for digital filter and filter banks have been proposed based on GA [27–30]. Recently, evolutionary algorithms (EA) such artificial bee colony (ABC), differential evolution (DE), harmony search algorithm (HSA), gravitational search algorithm (GSA), CS algorithm and PSO have been developed and have become more promising optimization techniques in problem solving due to their multi dimension and multivariable steps for achieving a global solution [38–41]. Therefore, researchers have exploited these techniques for designing optimal digital filter banks [30,31]. Multiplier-less reconfigurable non-uniform channel filters using meta-heuristic algorithms have been proposed, where DE, HAS, gravitational search algorithm and artificial bee colony algorithm were used to design the multiplier-less reconfigurable non-uniform channel filters [32,33]. Then, modified meta-heuristic algorithms such as modified ABC algorithm, GA, and GSA have been employed to design frequency response masking (FRM) based multiplier-less uniform and non-uniform filter bank [34,35], while authors in [36,37] have used linear search technique for designing filter bank and represented the filter coefficients in CSD form and DE for digital filter, respectively. In all the methods discussed above for designing multiplier-less filter banks, two optimization techniques have been used. Initially, continuous filter coefficients of a prototype filter are derived to satisfy perfect reconstruction, and then CSD coefficients are optimized using evolutionary techniques. There is no technique available for designing digital filter bank that can satisfy sophisticated design specifications, give perfect reconstruction and also optimize the CSD coefficients using single optimization.

Therefore in above context, in this paper, an adjustable window based simplified design of multiplier-less CMFB is proposed, using evolutionary technique. This technique is more efficient than other existing techniques as instead of using complex objective function, multiplier-less prototype filter coefficients are computed at $\omega = \pi/2M$ in each iteration using evolutionary techniques such CS algorithm, ABC and PSO algorithm. In other words, optimization is done in single step, i.e. filter coefficients are generated and converted into quantized CSD value each time inside the respective swarm based algorithm used for optimization. There is no need of generating filter coefficients separately, and then again optimizing the CSD rounded coefficients.

Organization of this paper is as follows: Section 2 gives a brief review and analysis of CMFB bank. Section 3 presents the general overview of CS algorithm. In Section 4, an overview of CSD is provided. Section 5 comprises of a detailed description of the proposed methodology for CMFB. Finally, the simulation results obtained with the proposed method are discussed in Section 6, followed by the conclusion in Section 7.

2. Overview of cosine modulated filter bank

Multichannel filter bank consists of a bank of band pass filters, arranged in parallel form along with down-samplers and up samplers as shown in Fig. 1 [4,8]. It can be seen that $H_l(z)$ and $F_l(z)$ represents the analysis filter bank and synthesis filter bank, respectively. Relation between input and output of CMFB shown in Fig. 1 is defined in z-domain as [4,8]:

$$Y(z) = T_0(z)X(z) + \sum_{s=0}^{M-1} T_s(z)X(ze^{-j2\pi s/M}), \tag{1}$$

where

$$T_0(z) = \frac{1}{M}\sum_{l}^{M-1} F_l(z)H_l(z), \tag{2}$$

and

$$T_s(z) = \frac{1}{M}\sum_{l}^{M-1} F_l(z)H_l(ze^{-j2\pi s/M}) \quad \text{for} \quad s = 1, 2, \ldots, M-1; \tag{3}$$

Here, $T_0(z)$ denotes the distortion transfer function responsible for distortion occurred due to overall system and $T_s(z)$ denotes the alias transfer function, which determines how worst the input signal is attenuated [3,4,8].

When these conditions are fulfilled, the reconstructed output signal becomes mirror image of the input signal with some delay associated with it, and can be represented as: $y(n) = x(n-k)$. This kind of multirate system is known as perfect reconstructed (PR) M-channel filter banks [4,9]. When these conditions are fulfilled partially, then filter banks are called as nearly perfect reconstructed (NPR) M-channel filter bank. It suffers from both aliasing and amplitude distortions [4,8–10]. In design of M-channel filter banks, modulation based filter banks are usually preferred due to ease of implementation and low computational complexity [4,8–10]. In modulation based filter bank, a prototype filter is designed to satisfy the perfect reconstruction, and the rest of filters are generated by modulating the response of prototype filter. For this, cosine modulation has become the preferred choice, and the designed filter bank is known as cosine modulated filter bank (CMFB) [4,8–10].

If $h(n)$ is the impulse response of a prototype filter [4,8–10],

$$H(z) = \sum_{n=0}^{N} h(n)z^{-n} \tag{4}$$

then impulse response of analysis and synthesis filters are given as $h_l(n)$ and $f_l(n)$ respectively, both in PR and NPR-CM filter CMFB [13,14,19].

$$h_l(n) = 2h(n)\cos\left[\omega_l\left(n - \frac{N-1}{2}\right) + \theta_l\right], \tag{5}$$

$$f_l(n) = h_l(N-1-n); \tag{6}$$

with $l = 0, 1, \ldots, N$ and $\theta_l = (-1)^l\pi/4$

In nearly perfect reconstruction CM filter banks, phase distortion can be eliminated by the help of linear-phase filters. Thus, the error in amplitude response is given as [13,14]:

$$e_{am} = \max\left(1 - |T_0(e^{j\omega})|\right), \tag{7}$$