

Advances in Multirate Filter Banks: A Research Survey

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1 General Overview

Multirate filter banks (FBs) play a substantial role in numerous signal processing applications such as data compression, detection of harmonics, de-noising, subband decomposition, recognition of one and two dimensional (2-D) signals, adaptive filtering, design of wavelet bases, and wireless communication [1–12]. The specific idea of developing multirate systems is their ability to split original input signal into multiple signals or to combine multiple signals into a single composite signal in the frequency domain. Division of a signal into number of subband is also known as subband coding. Originally, the concept of subband coding was introduced to minimize the effect of quantization noise in speech coding. Later on, with the advancement in multirate signal processing, subband coding concept has been extensively used in several applications. Performance of a subband coding system or a multirate system in different applications relies on the optimal design methodologies that have used for a multirate system. Therefore, there is always a strong motivation to develop an efficient technique for designing a multirate system that can improve the performance for given specific applications. Basically, the

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multirate system consists of a linear time-invariant (LTI) system and subsampling operations such as down-sampling or up-sampling. In general, multirate systems are classified in two types on the basis of their mode of operations. The first type corresponds to a filter bank structure in which original input signal is subdivided into different bands or channels, depending upon the requirement of given application, while the second type corresponds to a transmultiplexer (TMUX) structure, where several signals are combined and transferred through same channel in communication system. A generalized block diagram of these structures is graphically shown in Fig. 1. In Fig. 1a, the input signal is decomposed into different subbands using a bank of filters; here an input signal is analyzed, so these filters are also known as analysis filters, and at the receiver side, these subbands are synthesized into a reconstructed signal, so they are known as synthesis filters. Due to this operation, this structure is also known as analysis/synthesis multirate system. In Fig. 1b, several input signals are filtered by a set of filters, also termed as synthesis filters and combined into a composite signal, which is again filtered into several signals at receiver side by a bank of filters, also called as analysis filters.

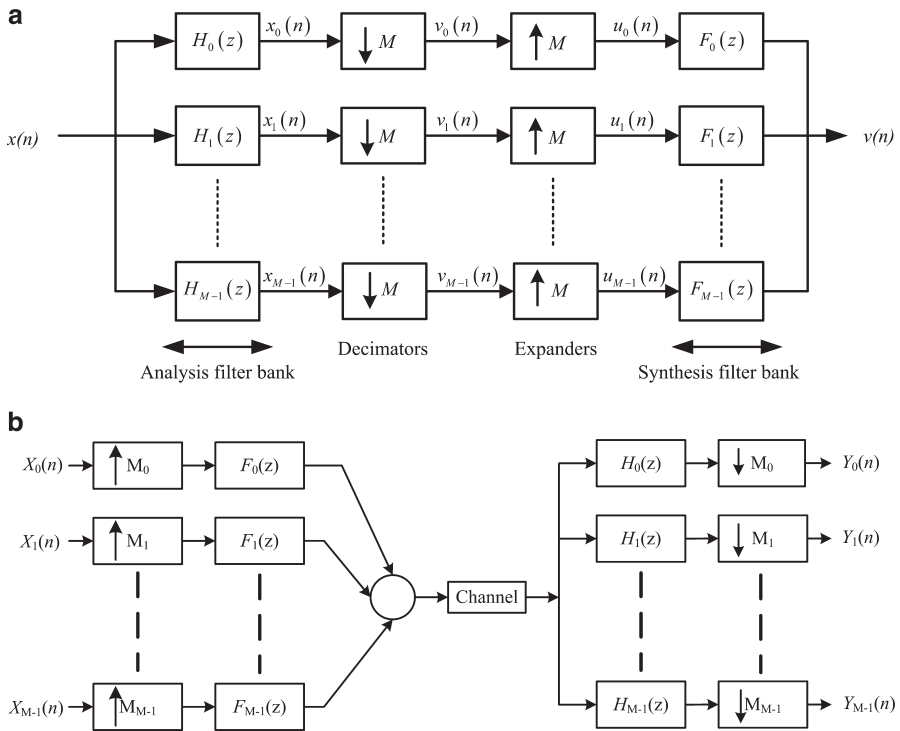


Fig. 1 (a) A block diagram of a filter bank [14, 15]. (b) A generalized block diagram of a transmultiplexer system [1, 2]

Therefore, this structure is also known as synthesis/analysis or transmultiplexer system. In absence of channel coding, a multirate system should be a pure delay system, it should not introduce any distortion to original input signal, and this type of a system is known as perfectly reconstructed (PR) multirate system [13–16]. However, due to subsampling operations and non-ideal nature of LTI systems, multirate systems suffer from three different types of distortions during reconstruction of a signal. The first is aliasing distortion, which occurs due to sub-sampling operation; the next two distortions are amplitude and phase distortion, which occurs due to imperfect frequency response of the composing filters. A multirate system that suffers from these distortions is called nearly perfect reconstructed (NPR) filter bank. Therefore many researchers and scientists have proposed numerous methods to reduce or eliminate these distortions in multirate systems [14, 15].

Initially, the subband coding systems, introduced by Crochiere et al. [13, 17], were influenced by all three types of distortions, and cancellation of aliasing distortion in this multirate system was not completely achieved. Therefore, to remove aliasing distortion in a multirate system, a concept of quadrature mirror filter (QMF) bank was introduced by Croisier et al. [18]. In this context, firstly Esteban and Galand [19] have employed a two-channel filter bank structure in the voice-coding application and the aliasing distortion was reduced with the use of QMF [18, 19]. The phase distortion was eliminated by using linear-phase finite impulse response (FIR) filters. However, the amplitude distortion cannot be eliminated except for trivial case [14–16, 20]. It can be abated by using computer-aided techniques or proper optimization techniques. The amplitude distortion can be thoroughly removed by employing infinite impulse response (IIR) [14–16, 20–24]. But in that case, the amplitude distortion is eliminated at the cost of introducing phase distortion. Later on, Smith and Barnwell [25] and Mintzer [26] were able to design PR FB. Since then numerous techniques have been proposed and described for the design of PR multirate systems [14–16, 27–31], but for achieving the PR property, some important properties of analysis/synthesis filters have to be relinquished such as low stopband attenuation, narrow transition bands, and linear phase.

It is revealed from above discussion that the QMF banks are extensively used in a number of applications. However, in certain applications such as videos, communication systems, etc., the linear-phase QMF banks are strictly needed to avoid signal distortion and subband coding expansion problem [6, 11, 32]. Initially, the effort was concentrated on the efficient design of two-channel FBs, and later on, it was prolonged to multichannel FBs [14, 15, 20]. Among all multichannel FBs, cosine-modulated filter banks (CMFBs) are one of the most often used filter bank due to their simpler and more realizable design structure. As similar to QMF banks, several competent techniques have also been projected to design CMFBs efficiently [14, 15, 33–37], as the filter and FBs have become the most fundamental systems used in various applications among multirate systems.

2 Digital Filter Bank

The digital filter can be defined as a frequency selective network that picks and adjusts certain interlude of frequencies comparative to other frequencies, or it attenuates all the frequency content outside the anticipated interval [38, 39]. - Fundamentally, filtering operation is accomplished to enhance the quality of a signal. The characteristic of filtering is determined by the frequency response of filter. The frequency response of filter is computed by the system parameters or coefficients. Thus, by suitable assortment of system coefficients, appropriate frequency-selective network can be designed according to given applications [38]. Two classical types of digital filters used are finite impulse response (FIR) and infinite impulse response (IIR) filters, between which FIR digital filters are widely used as component of digital signal processing systems due to their ease of execution, stability, and linear design [16].

The digital FB is amalgamation of different band pass filters with a shared input and a summed output, which are mostly employed for synthesis and examination of different spectrums of signal. Therefore, FBs are grouping of analysis FBs and synthesis FBs as depicted in [14–16].

Analysis FB consists of sub-filters, which are known as analysis filters. Analysis filters are used to divide the input signal into dissimilar set of subband in frequency domain. Each subband comprises some frequency share of original signal. Similarly, the synthesis FB comprehends sub-filters called synthesis filters, which combine the subband signals and generate signal or reconstruct signal [38]. These FBs can be classified in two types; two-channel and M -channel FBs, based on the number of channels used for the signal separation.

2.1 Two-Channel Filter Bank

The two-channel FB or QMF bank consists of an analysis filters followed by down-samplers at transmission end, and up-samplers followed by synthesis filters at the receiving end. The block diagram of QMF bank is depicted in Fig. 2. This arrangement is termed as critically sampled FB, where decimation factor and interpolation factor are equal to the number of subbands. On the performance basis of reconstructed output, two-channel FBs can be further classified into nearly perfect reconstruction (NPR) and perfect reconstruction (PR) filter banks. The NPR two-channel FB is called conventional QMF banks, where the reconstructed output and input signal is not exact replica to each other. Usually, in NPR two-channel FB, the analysis and synthesis filters are in linear phase. In PR FBs, all the three types of distortions can be eliminated. These FBs have some delay, but the signal is an exact replica of original signal [38].

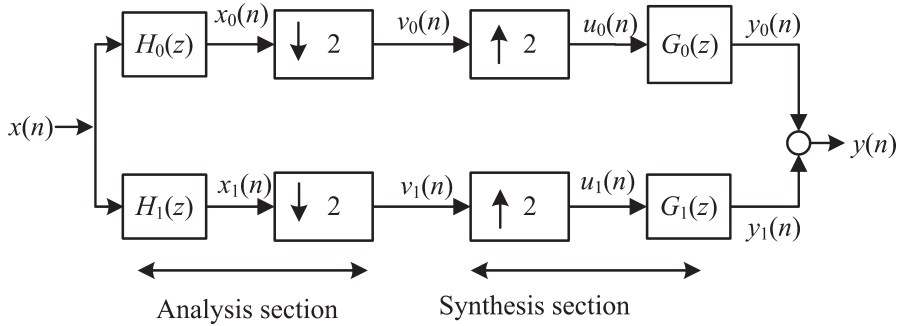


Fig. 2 A generalized block diagram of a two-channel filter bank [14, 15]

2.1.1 Analysis of Two-Channel Filter Bank

In general, the two-channel FB splits an input signal into two subbands and is made up of an analysis and synthesis filter as well as a processing unit in between the FBs. Hence, the elementary process of a two-channel FB involves two sequential steps in the absence of processing unit: operation of the analysis banks and synthesis banks. A general block diagram of two-channel FB is shown in Fig. 2. [14, 15, 38].

From the analysis of input and output relation, the output of two-channel FB is written as [14–16]

$$Y(z) = T(z)X(z) + A(z)X(-z), \quad (1)$$

where $T(z)$ is the overall distortion transfer function of FB, expressed as

$$T(z) = \frac{1}{2}[H_0(z)G_0(z) + H_1(z)G_1(z)], \quad (2)$$

and $A(z)$ is the aliasing transfer function, defined as [14, 15]

$$A(z) = \frac{1}{2}[H_0(-z)G_0(z) + H_1(-z)G_1(z)]. \quad (3)$$

To cancel aliasing distortion, the second term of Eq. (1) must be cancelled, that is, $A(z) = 0$. Thus, the following choice cancels the aliasing error [14–16, 20]:

$$G_0(z) = H_1(-z) \text{ and } G_1(z) = -H_0(-z). \quad (4)$$

It is thus possible to completely cancel the aliasing distortion by this choice of synthesis filters. Therefore, using above relations, the input–output relation of the FB expressed by Eq. (1) can be further simplified as

$$Y(z) = T(z)X(z). \quad (5)$$

If $H_0(z)$ is a casual real coefficient FIR filter and $H_1(z) = H_0(-z)$ [14, 15], it conforms that $H_1(z)$ is a noble high-pass filter if $H_0(z)$ is a good low-pass filter and vice versa. By carefully examining these responses, it is perceived that one filter is the complementary or mirror of other filter at $\omega = \pi/2$, which is the cutoff frequency of both high-pass and low-pass responses and justifying the name Quadrature mirror filter (QMF) bank. Thus, by using $H_1(z) = H_0(-z)$ condition, the aliasing-cancellation condition given by Eq. (4) can be modified as

$$G_0(z) = H_0(z) \text{ and } G_0(z) = -H_0(-z). \quad (6)$$

Consequently, the above equations suggest that the analysis and synthesis filters of QMF bank can be generated by proper design of $H_0(z)$ called prototype FB. By using Eq. (6) and mirror-image condition $H_1(z) = H_0(-z)$, the distortion function given by Eq. (2) can be further rewritten as

$$T(z) = \frac{1}{2} [H_0^2(z) - H_1^2(z)] = \frac{1}{2} [H_0^2(z) - H_0^2(-z)]. \quad (7)$$

Consider a casual FIR filter $H_0(z)$ defined as

$$H_0(z) = \sum_{n=0}^{N-1} h_0(n) z^{-n}, \quad (8)$$

where, N is the order of filter. Given that $h_0(n) \neq 0$ and $h_0(N) \neq 0$, $H_0(z)$ has linear-phase characteristics if

$$h_0(n) = h_0(N - 1 - n). \quad (9)$$

For a linear-phase FIR filter, the frequency response $H_0(e^{j\omega})$ can be written as

$$H_0(e^{j\omega}) = |H_0(e^{j\omega})| e^{-j\frac{N-1}{2}\omega}, \quad (10)$$

where $|H_0(e^{j\omega})| = H_0(\omega)$. Substituting (10) into (7) and using the fact that $|H_0(e^{j\omega})|$ is an even function, the FB transfer function reduces to

$$T(e^{j\omega}) = \frac{e^{-j(N-1)\omega}}{2} \left(|H_0(e^{j\omega})|^2 - (-1)^{(N-1)} |H_0(e^{j(\pi-\omega)})|^2 \right). \quad (11)$$

If $N - 1$ is even, then above expression reduces to zero at $\omega/2$, resulting in severe amplitude distortion. Hence, even order filters cannot be used, since they allow the existence of nulls in overall system response. If the N is to be taken as odd, then, FB transfer function is reduced to

$$T(e^{j\omega}) = \frac{e^{-j(N-1)\omega}}{2} \left(|H_0(e^{j\omega})|^2 + |H_0(e^{j(\pi-\omega)})|^2 \right). \quad (12)$$

For perfect reconstruction, a FB must have

$$|H_0(e^{j\omega})|^2 + |H_0(e^{j(\pi-\omega)})|^2 = 1. \quad (13)$$

But, this is not exactly possible because of amplitude distortion, which is defined as

$$e(\omega) = 1 - |H_0(e^{j\omega})|^2 + |H_0(e^{j(\pi-\omega)})|^2 \quad (14)$$

In linear-phase QMF bank design, the minimization of amplitude distortion will be a major consideration. Regarding this issue, several techniques for designing a linear-phase QMF bank have been reported in literature [14, 15, 20].

2.2 *M*-Channel Filter Bank

M-channel FB divides the signal into *M* number of subbands. On the basis of nature of channel bandwidth, *M*-channel FBs are categorized into two ways: uniform and nonuniform *M*-channel FBs [14, 15, 20, 38]. Uniform *M*-channel FBs are subgrouped into three different types: tree structure, independent *M*-channel (parallel FB), and modulation FBs [14, 15, 20, 38]. As compared to two-channel FB, the conditions for alias-cancellation and perfect reconstruction are much more complicated. The general theory of *M*-channel FB was developed by a number of researchers [14, 15, 20]. The *M*-channel filter banks are further classified as uniform and nonuniform filter bank on the basis of channel bandwidth, and so as the subsampling factors. When these sub-sampling factors are kept same throughout the design procedure, the *M*-channel filter bank is known as uniform as shown in Fig. 1a, and when these sub-sampling factors are changed, the *M*-channel filter bank is known as nonuniform filter bank as shown in Fig. 3. [14, 15, 20, 38]. It can be observed that from Fig. 3, a two-channel filter bank has been used as a basic building block for designing NUFB. With meticulous governance of two-channel filter banks, they are designed to be alias free, so as to eventually make NUFB alias free.

This section concentrates mainly on cosine modulation technique of *M*-channel FB design, because cosine modulated (CM) filter banks have become very popular in many applications of signal processing due to use of easy prototype filter design and fast discrete cosines transform (DCT).

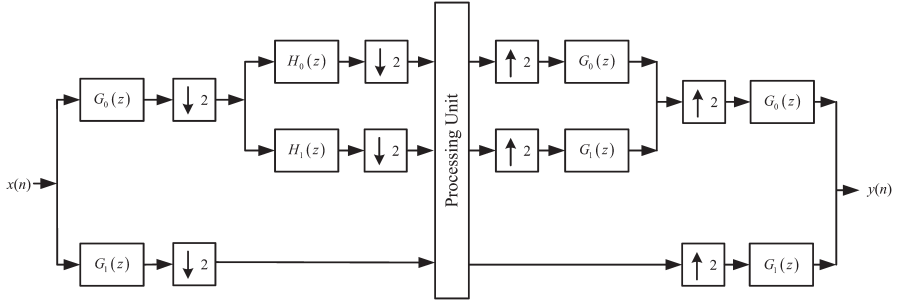


Fig. 3 Block diagram of tree structural NUFB [15–17]

2.2.1 Analysis of M-Channel CM Filter Bank

During the past, theory of multirate systems has been well developed and available in several research books [14, 15]. The generalized system structure of M -channel CMFB [14, 15, 20, 38], is graphically shown in Fig. 1a. In this architecture, $(h_k(n)$ and $H_k(z))$ and synthesis filters $(f_k(n)$ and $F_k(z))$ are derived from cosine modulation. Here, $h_k(n)$ and $H_k(z)$ are the impulse responses, and z -transforms of the analysis filters, while $f_k(n)$ and $F_k(z)$ represent the impulse responses, and z -transforms of the synthesis filters. In Fig. 1, M represents the number of channels in a multirate filter bank. In general, the basic components of a multirate system are either it is a filter bank (FB) or transmultiplexer (TMUX) are decimators, expander, and filters. Based on input/output relations of a decimator and expander, the reconstructed output of a considered structure in Fig. 1 [14, 15, 20, 38]:

$$Y(z) = T_0(z)X(z) + \sum_{l=1}^{M-1} T_l(z)X\left(ze^{-j2\pi l/M}\right), \quad (15)$$

where, $X(z)$ and $Y(z)$ is the input and output signals, respectively,

$$T_0(z) = \frac{1}{M} \sum_k^{M-1} F_k(z)H_k(z), \quad (16)$$

and

$$T_l(z) = \frac{1}{M} \sum_k^{M-1} F_k(z)H_k\left(ze^{-j2\pi l/M}\right) \text{ for } l = 1, 2, \dots, M-1. \quad (17)$$

In Eq. (15), $T_0(z)$ stands for distortion transfer function, which decides the distortion, resulted from overall filter bank structure for un-aliased component of input signal $(X(z))$. Second term $T_l(z)$ decides aliasing error [14, 15, 20]. For perfect reconstruction, $T_0(z)$ is to be a delay function (z^{-K}) , where K is an integer and

aliasing error should be zero. If a filter bank structure satisfies these conditions, then it is known as perfect reconstructed (PR) cosine-modulated filter banks (CMFBs), in which the reconstructed output signal is an exact replica of original input signal. This structure is highly suitable for data compression application in lossless coding. If these conditions are partially satisfied, then it is known as nearly perfect reconstructed (NPR) CMFB with amplitude distortion and aliasing error [14, 15, 20]. In a CMFB, impulse responses of the analysis filters ($h_k(n)$) and synthesis filters ($f_k(n)$) are cosine-modulated version of a prototype filter $h_0(n)$ with following transfer function given by Eq. (18). The remaining analysis and synthesis filters are determined by

$$h_k(n) = 2h_0(n) \cos \left[\omega_k \left(n - \frac{N-1}{2} \right) + \theta_k \right], \quad (18)$$

$$f_k(n) = h_k(N-1-n) \quad (19)$$

with $k=0, 1, \dots, M-1$, and

$$\omega_k = \frac{(2k+1)\pi}{2M}, \quad (20)$$

where

$$\theta_k = (-1)^k \pi/4. \quad (21)$$

As discussed above, in a multirate filter bank, three types of distortions known as phase distortion, amplitude distortion, and aliasing distortion are encountered. Generally, the phase distortion is completely eliminated by using a finite impulse response (FIR) filter due to their exact linear-phase response characteristic. In NPR CMFB, distortion in amplitude response is computed as [14, 15, 20]

$$e_{\text{am}} = \max_{\omega} (1 - |T_0(e^{j\omega})|), \quad (22)$$

and aliasing distortion (e_a) is computed as

$$e_a = \max_{l, \omega} (T_l(e^{j\omega})) \text{ for } \omega \in [0, \pi], 1 \leq l \leq M-1. \quad (23)$$

3 Literature Review

In this section, a comprehensive review on multirate filter banks, M -channel filter banks, and two-channel filter banks, is presented.

3.1 Review on Multirate Filter Bank

In past few decades, an extensive research has been carried out in the area of multirate FB design, because of its significant importance in the field of signal processing. On the basis of number of channels employed for subband decomposing of a signal in frequency domain, the research and development of multirate FB belongs to two-channel and M -channel FB [40–105]. On the basis of reconstruction of signal, the investigation of multirate FB is further divided into NPR and PR FB design. Moreover, research in NPR FB is classified as linear and nonlinear phase FB on the basis of phase of compound filters. In linear-phase two-channel multirate FB or QMF banks, aliasing and phase distortions are removed by deploying appropriate design of the composite filters and linear-phase FIR filter, respectively, whereas an amplitude distortion can be minimized using computer-aided techniques or optimization techniques [14–16, 20, 40–42]. The exact reconstruction of signal with good frequency resolution is pretty difficult due to various distortions occurring in multirate FB.

In QMF bank, due to quadrature relationship between the analysis and synthesis filters, the design problem merely reduces to solitary prototype filter design [14–16, 20, 40–42]. In this context, there are numerous methods have been reported for designating prototype filter of two-channel multirate FB [43–50]. These design methods can be further categorized into optimization and non-optimization based methods. The design problem using optimization techniques is framed as nonlinear single or multi-objective functions, which is solved by numerous optimization techniques such as classical iterative, non-iterative [38, 47, 51–82] methods, and nature-inspired optimization techniques [99–105].

In 1980, the first symmetric iterative method for the design of two-channel FB was introduced by Johnston [47]. In this method, the objective function, which is framed as weighted sum of the prototype filter with stopband error energy and ripple energy, is optimized through Hooke and Jeeves optimization algorithm [47]. This method does not give optimum solution and needs manual initialization. Further, Jain and Crochiere [51] proposed a novel design approach with same objective function. In [51], manual initialization has been eliminated and solution becomes more optimal than that in [47], but it is well-suited to higher-order filter bank due to high degree of nonlinearity. However, in both these algorithms, reconstruction error is not Equiripple. Therefore, Chen and Lee [52] have introduced an iterative technique for the optimization of objective function in frequency domain that affects the Equiripple reconstruction error. Further, there are numerous algorithms introduced by the researchers based on [53–56]. These are superior from the algorithm given in [52] in term of peak reconstruction error and computational time, but all these algorithms are not acceptable for higher-order FB design. After that, Bregovic and Saramaki [57, 58] have developed a two-step method for designing two-channel FBs for those applications where Equiripple reconstruction error and less stopband energy are required.

It was found that the design problem, which is constructed in minimax logic, needs more efficient optimization techniques. Thus, the weighted least squares optimization technique is more appropriate than other conventional techniques, because of its smaller code and delivery of solution analytically. Therefore, several researchers used weighted least squares method in the field of FB design [47, 50–56, 59–64]. Fundamentally, the weighted minimax design is a nonlinear constrained optimization problem, which is complex to solve. In [54], weighted minimax problem is resolved by means of unconstrained weighted least squares (WLS) approach using two iterative methods. This method has been later on modified [53, 55–57, 59–61] in terms of computation time and reconstruction error. After that, WLS techniques have been successfully used by various researches with the modification in objective function, different parameters and constraints, or use of different modeling [62–65].

In this context, many classical iterative and WLS techniques have been introduced for the efficient design of QMF bank using constraints or unconstrained formulation. In [66], the researchers have used Lagrange multipliers method to optimize the nonlinear constrained problem. In [67–70], the unconstrained optimization methods have been used to optimize the objective functions, which have been framed as linear or nonlinear combination of reconstruction error, stopband residual energy or passband energy. Unfortunately, all the above discussed techniques were not much well organized in terms of peak reconstruction error (*PRE*) and computational complexity.

Recently, several efficient classical techniques have been explored for efficient NPR filter bank design. In the early stage of research, several gradient-based techniques such as Levenberg–Marquardt (LM) algorithm and quasi-Newton method [71–74] were developed to enhance the *PRE* and computational efficiency. A new methodology for the design of a two-channel FB by deploying Marquardt optimization technique is given in [71]. These design methodology was further enhanced by using quasi-Newton (QN) [75] and Levenberg–Marquardt (LM) method [76] and again modified as a hybrid technique based on LM and QN optimization techniques in [77]. As similar to linear-phase NPR QMF design, there are numerous classical techniques also reported in the stream of nonlinear phase and PR QMF bank [66, 75–81]. It is clear that the PR condition can be attained by surrendering the linear phase or some other properties of FB. Since this chapter quintessence on linear-phase NPR QMF design, therefore, here no detail on PR QMF bank is included. The detail on nonlinear and PR QMF bank is explained in [14–16, 20, 38, 82].

In this regard, primarily, the research effort was focused on two-channel FB, and thereafter, it was extended to multichannel FBs, particularly modulation-based multichannel FB, because of easy design and less complexity. Numerous modulation techniques are reported in literature such as modulated lapped transform, cosine modulation, a modified discrete Fourier transform (MDFT) technique, etc. [14, 15, 20, 83]. Cosine modulation technique is more popular in various requirements among different class of modulation techniques. Cosine-modulated FB is also categorized into PR and NPR cosine-modulated (CM) filter bank [14, 15,

20]. Initially, the concept of modulated FBs was presented by Nussbaumer [84–107]. The first NPR M -channel critically sampled FB employing cosine modulation on prototype filter was produced by Rottweiler [85]. In NPR CMFBs, PR state is relaxed to reduce the design complexity. After that, FBs with such property have been studied in detailed, and various approaches have been developed [86–105]. Several efficient methods have also been advanced, so that it can facilitate the efficient design of prototype filters for NPR CMFBs. In conventional design approaches [33, 34, 83], in overall, a relationship has to be made amongst the $2M$ th band filter, and a group of quadratic constraints in impulse response coefficients of the prototype filter. These constraints and stopband attenuation of the prototype filter have to be reduced as much as possible using either constrained or unconstrained optimization techniques, which is quite time consuming. As a consequence of continued development in this field, several new procedures that have simpler minimizing cost functions have been established. To decrease the computational complexity in conservative designs [33, 34, 83], Creusere and Mitra [86] have presented the first systematic linear search optimization method for designing a prototype filter for CMFB, by varying passband frequency (ω_p) in each of iteration. This method yields improved performance of filter bank in terms of reconstruction. However, it also suffers from slow convergence. Therefore, these algorithms are not suitable for filter with larger taps. Thus, in search of efficiency and simplicity, a new efficient technique has been introduced by Lim and Vaidyanathan [87], in which Kaiser window function has been deployed for designing the prototype filters. This technique was further modified to include other windows [88, 89]. Furthermore, other efficient methods using different window techniques have been introduced [90–96] with improvement in [86–89]. In general, the FBs designed with windowing result in reduced stopband error, while passband ripple should be kept approximately equal to stopband ripple [97]. Therefore, a new method based on the weighted constraint least square (CLS) technique is devised for designing CMFB for given channel overlapping, and it was further improved in [98, 99]. Similarly, many other researchers [100–105] have also developed various methods for cosine-modulated FBs with NPR design. Similarly, various methods have also been proposed for M -channel PR FB design [14, 15, 36, 106]. These FBs are used in various applications such as lossless coding. Here, the detailed discussion on PR FB design is not given, because this chapter emphasizes on NPR M -channel CMFB design. The details of PR FB design can be found in [14, 15, 36, 106]. It is reflected from the above review that there are numerous conventional techniques have been proposed for two-channel and M -channel FB design. The general disadvantage of all these conventional techniques is that they may get stuck in local minima. To overcome this problem, recently various global optimization techniques are employed [107–113] in the field of FB design. Most of the global optimization techniques are driven by the natural phenomena's such as social behavior: flock of birds, schooling of fish, intelligence of swarm of bee; and biological process: reproduction, mutation, and interaction. Therefore, these algorithms are also termed as nature-inspired (NIO) or swarm optimization techniques (SOTs). Thus, many global optimization techniques are employed to design highly optimized FB such as

GA [113, 114], PSO and its different variants [115–118], ABC algorithm [116], and ADE algorithm [119]. In this context, a CORDIC genetic algorithm was used for a two-channel filter bank design in [107], which is based on coordinate rotation. A new design technique using nonlinear unconstraint optimization was presented for QMF banks based on PSO optimization and was further modified in [110]. Here, a new hybrid technique based on PSO and ABC algorithms was presented for a two-channel QMF bank design. This design was further improved by using ADE algorithm in [113]. Similarly, for M -channel FB design; a new technique based on genetic algorithm (GA) was devised by formulating a new cost function in [108], which is based on the weighed sum of aliasing error and amplitude distortion. Whereas, a novel design method was also presented for CMFB [111]. This design is based on Lagrange polynomial approximation and PSO, by considering stopband attenuation as a cost function, which was further modified using new variant of PSO [112], where quantum mechanics involved on particles of PSO is exploited and the reconstruction condition was formulated as a new cost function or objective function for optimization.

In recent years, several researchers have proposed the new design methodologies for optimal designs of digital filters and filter bank which are computationally efficient and require least hardware resources [115–119]. Here the continuous filter coefficients are quantized and converted into binary form (two's complement, maximal signed digit, canonical signed digit (CSD), etc.). These filter bank are also known as multiplierless multirate filter bank as all of the multipliers are realized in terms of adders and shifter. As the multipliers are the most resource-consuming component in hardwired realization, the removal of multipliers from the circuits reduces its overall resources cost. However, when these continuous filter coefficients are rounded in terms of binary or quantized CSD valued coefficients form, the performance of the filter is deteriorated due to quantization and conversion process, and, thus, the given specifications are no longer satisfied. Therefore, to overcome these problems, many global optimization techniques have been exploited to optimize the performance. In this context, authors in [120] 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 [121–123]. Recently, evolutionary algorithms (EA) such as artificial bee colony (ABC), differential evolution (DE), harmony search algorithm (HSA), gravitational search algorithm (GSA), CSA 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 [124, 125]. Therefore, researchers have exploited these techniques for designing optimal digital filter banks [123, 126, 127]. Multiplierless reconfigurable multichannel filters using metaheuristic algorithms have been proposed, where DE, HAS, gravitational search algorithm, and artificial bee colony algorithm were used to design the multiplierless reconfigurable nonuniform channel filters [93, 94, 128, 129]. Then, modified metaheuristic algorithms such as modified ABC algorithm, GA, and GSA have been employed to design frequency response masking (FRM)-based multiplierless uniform and non-uniform filter bank [132, 133], while

authors in [130, 131] have used linear search technique for designing filter bank and represented the filter coefficients in CSD form and DE for digital filter, respectively.

From the literature review, it is quite evident that marked progress has been made in the field of FB design, and various conventional, nature-inspired, constraint optimization is incorporated in the field of FB design. Some methods are not good in computational time, and some do not give less distortion. Moreover, the new research trend in the field of multiplierless multirate filter banks has attracted many researchers to develop an efficient and resource-optimized designs for designing optimal multirate system. Therefore, there is still need to develop an efficient method, which can minimize the computational time, reconstruction error, and aliasing distortion and utilize least resources simultaneously.

4 Research Gap and Future Direction

The above discussion reveals that there are various literatures available in for efficient design of multirate filter bank. For the recent advancement in multirate system, some latest research aspects are discussed in this section, which are based on simultaneous utilization of nature inspire optimization techniques, fractional derivative, polyphase components, minor component analysis, multiplierless realization of filter, and filter bank. Recently, conventional integer derivative constraints have been used to design various FIR filters to improve design accuracy at the prescribed frequency point. However, a fractional calculus has shown improved performance in many engineering applications such as electrical networks, electromagnetic theory, biomedical applications, signal and image processing. The fractional derivative increases the possibility of improving control performance by reducing the convergence time in mentioned control problems. Therefore, a new technique for designing linear-phase FIR filters, based on fractional derivative constraints (FDCs), was devised in 2012. It gives smoother passband and stopband region than conventional least square and conventional derivative methods. But, it was not so efficient. The literature, available so far on fractional derivative, reveal that there is still need for an efficient technique, which shall use FDCs and evolutionary optimization technique for designing different types of linear-phase FIR filters and multirate FBs for higher order. Literature review also reveals that there is no method available for optimizing all the FDCs simultaneously. Fractional derivative has also been not employed in the field of multirate filter bank design.

The important advancement in signal processing is the polyphase representation of digital filter which reduces the computational complexity and data storage. But according to current literature, there is no method presented that has been used for optimized design of FIR filter and multirate filter bank, where polyphase components (PCs), FDCs, and swarm intelligent optimization algorithms are employed simultaneously.

As seen from the literature, nowadays, neural network plays a major role in several signal processing applications such as antenna, constraint beam forming, and biomedical processing [24, 56, 112, 113], due to fast convergence rate as compared to other reported techniques. In addition, it has parallel architecture, more suitable for higher order design, and real-time applications. Minor component analysis (MCA)-based neural learning technique is more preferred for digital filter design as compared to conventional Eigen filter design, in which an eigenvector corresponding to smallest eigenvalue of the associated matrix is computed. Recently, authors have applied MCA technique for the design of FIR and IIR FBs in [56, 113]. In literature, no method is given for optimized design of FIR filter and multirate filter bank, where PCs, MCA neural learning optimization, FDCs, and swarm intelligent optimization algorithms are employed simultaneously.

The literature available so far reveals that there is still need for an efficient technique, which shall enhance the filter response for quantized filter coefficient using different swarm-based techniques in design of different types of multiplierless FIR filters and multirate filter banks. Literature review also reveals that no such technique is available in the literature which can simultaneously design digital multiplierless FIR filter that can optimize the CSD coefficients and, at the same time, minimize the requirement of adders for MCM problems using single optimization. With these developments, there are strong motivations to undertake a thorough and systematic investigation toward the design and analysis of low complex multiplierless digital filter and filter bank using evolutionary algorithms with major focus on minimization resources.

Additionally, in several applications, it is needed to design digital filters and filter banks (FBs) with sophisticated design specifications. For example, high stopband attenuation (A_s), fast switching resolution and small channel, and overlapping are required for high-quality reconstruction of an audio signal, while for biomedical signal processing, fast switching resolution and adjustable A_s are highly desired. For software-defined radio (SDR) application, a flexible technology is required for multi-band, multi-standard, and multi-service, for that several important features of the channel filters such as low complexity, low power consumption, and reconfigurable are required. Thus, the sufficient and precise control of various frequencies such as passband cutoff frequency, stopband cutoff frequency, and transition width is required which is not possible with windowing technique.

In view of the above research gap recently, Kuldeep et al. [105–112] have presented the design of digital FIR filter and multirate filter bank using fractional derivative constraints, polyphase decomposition and nature-inspired optimization. Moreover, for efficient realization of multiplierless multirate system, Sharma et al. [134–136] have presented the design of multiplierless CMFB multirate filter bank, two-channel filter bank, etc. using evolutionary technique and sub-expression elimination algorithm in CSD space [137–139]. For further advancement in FIR filter and filter bank design, authors of this book proposed the design of digital FIR filter and M -channel multirate filter bank using MCA algorithm, fractional derivative constraints, polyphase decomposition, and nature-inspired optimization simultaneously (coming chapters in this book).

For further advancement in the field of optimal multirate filter bank design, following directions are suggested:

1. The optimal design of multirate filter can be achieved by improving the optimization algorithm. The hybrid combination of two conventional techniques such as gradient-based or swarm optimization methods can be employed to improve the optimization algorithm for filter bank.
2. Other form of fractional derivative like Riemann–Liouville, M. Caputo, can also be employed to achieve more optimal multirate filter bank.
3. The improved problem formulation like hybrid combination of L_2 , L_1 , and L_∞ error function can also improve the response of multirate filter bank.
4. The concept for sub-expression elimination technique (CSE) with CSD or other adder minimization techniques can be explored for designing digital multiplierless FIR filter and multiplierless multirate filter bank have not been introduced and analyzed since now.
5. The efficient design of multiplierless filter and filter bank having flexibility to satisfy the variety of sophisticated design specification has not been accomplished yet, which can be explored with the advancement of mathematical-based algorithms.
6. An efficient design of multirate system can be used as optimal trans-receiver system for 5G communication and other communication technology.
7. The concept of optimal filter bank structure can be utilized as filter bank-based sensing tool or may provide great aid in spectrum sharing and allocation for cognitive radio, smart antennas, and wireless sensor networks.

5 Conclusion

This chapter has presented a research survey on multirate filter banks design. A generalized theory of a multirate filter bank has been carried out. Research gap is also presented with various important aspects discussed between the reported methods and methods presented in this book in the field of digital FIR filter and multirate filter bank design. A future direction is also suggested for further advancements in the field of multirate filter bank design

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