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Full Length Article

Design of multiplier-less sharp non-uniform cosine modulated filter banks for efficient channelizers in software defined radio

Shaeen Kalathil *, Elizabeth Elias

Department of Electronics and Communication, National Institute of Technology Calicut, Kerala, India

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Forthcoming software defined radios require filter banks which satisfy stringent specifications efficiently with low implementation complexity. Cosine modulated filter banks (CMFB) have simple and efficient design procedure. The different wireless standards have different channel spacing or bandwidths and hence demand non-uniform decomposition of subbands. The non-uniform CMFB can be obtained from a uniform CMFB in a simple and efficient approach by merging the adjacent channels of the uniform CMFB. Very narrow transition width filters with low complexity can be achieved using frequency response masking (FRM) filter as prototype filter. The complexity is further reduced by the multiplier-less realization of filter banks in which the least number of signed power of two (SPT) terms is achieved by representing the filter coefficients using canonic signed digit (CSD) representation and then optimizing using suitable modified meta-heuristic algorithms. Hybrid meta-heuristic algorithms are used in this paper. A hybrid algorithm combines the qualities of two meta-heuristic algorithms and results in improved performances with low implementation complexity. Highly frequency selective filter banks characterized by small passband ripple, narrow transition width and high stopband attenuation with non-uniform decomposition of subbands can be designed with least the implementation complexity, using this approach. A digital channelizer can be designed for SDR implementations, using the proposed approach. In this paper, the non-uniform CMFB is designed for various existing wireless standards.

1. Introduction

Digital filter banks are largely used in different applications such as compression of speech, image, video and audio data, transmultiplexers, multi carrier modulators, adaptive and bio-signal processing [1]. Filter banks decompose the spectrum of a given signal into different subbands and each subband is associated with a specific frequency interval. Most of the applications of filter banks demand good frequency response characteristics with reduced implementation complexity. The frequency selectivity of individual filters is due to small passband ripple, high stopband attenuation and narrow transition width. If the specifications are very stringent or a good frequency selective filter is required, then the complexity of the conventional FIR filter will be very high, since the order of the FIR filter is inversely proportional to the transition width. Frequency response masking (FRM) is a cost efficient way for the design of FIR filters with narrow transition width [2]. The upcoming software defined radios (SDR) require efficient digital channelizers, which will select individual channels from the digitized wideband signal. Extremely frequency selective filter banks with excellent design flexibility and low implementation complexity are highly appreciated in SDR Channelizers. Hence the filter bank proposed in this paper is an outstanding choice for digital channelizer.

The digital channelizers in SDRs select individual channels from the digitized wideband signal. In order to extract equal bandwidth signals, polyphase DFT filter banks are efficiently used [3]. But when the individual subbands are from different communication standards, uniform filter banks will not be a feasible option. Different non-uniform filter banks are proposed, using tree structured filter banks, multi-stage filter banks, variable bandwidth filter banks and using FIR prototype in non-uniform CMFB [4–7]. The stringent specifications of wireless communication standards require filter banks with narrow transition widths and the least implementation complexity.

In perfect reconstruction (PR) filter banks, the output will be a weighted delayed replica of the input. In case of near perfect reconstruction (NPR) filter banks, a tolerable amount of aliasing and amplitude distortion errors are permitted. Cosine modulated filter banks are one popular class among the different M-Channel

* Corresponding author. Tel.: +91 9447100244, fax: +91 4952287250.
E-mail address: shaeen_k@yahoo.com (S. Kalathil).
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maximally decimated filter banks [1]. Design of NPR CMFB is easier and less time consuming compared to the corresponding PR CMFB. Even though small amounts of aliasing and amplitude distortion errors exist, these filter banks are widely used in different applications due to the design ease [1]. Also, it is difficult to attain high stopband attenuation with PR CMFB. Hence, as a compromise, NPR structures can be preferred in those applications, where some amount of aliasing can be tolerated. NPR CMFBs with narrow transition widths and good stopband attenuation and small passband ripple give very small amplitude distortion and aliasing distortion errors, which are comparable to that of PR CMFB.

In uniform filter banks, the spectrum is decomposed into equal bands. In many applications a non-uniform decomposition of subbands is preferred. The input signal is decomposed into signals having different bandwidths. A simple and efficient design of non-uniform filter bank is by the cosine modulation of the prototype filter and then merging appropriate filters of the resulting uniform filter bank [8]. The non-uniform CMFB design is derived from a uniform CMFB. Hence the attractive properties of a uniform CMFB are retained in the non-uniform CMFB. This is an easy and efficient design method. The prototype filter alone is required to be designed and optimized. All the other analysis and synthesis filters with unequal bandwidths are obtained from this filter, by merging the appropriate filters of the uniform filter bank. The prototype filter is designed using non-linear optimization in Reference 8. A modified approach, in which the prototype filter is designed using linear search technique is given in Reference 9. Multiplier-less design of non-uniform CMFB using different prototype filter design techniques for FIR filter such as Window method, weighted Chebyshev approach and weighted constrained least square is given in Reference 10.

NPR uniform CMFB design using FRM prototype filter has been proposed by Furtado et al. in References 11 and 12. The design involved non-linear optimization and their main aim was to reduce the number of optimization variables. This was achieved since the FRM prototype filter contains less number of distinct coefficients compared to the conventional FIR filter. NPR CMFB using a different class of prototype filter was proposed by Rosenbaum et al. [13], where the prototype filter is a non-linear phase filter with increased overall delay. Their main aim was to reduce the arithmetic complexity by replacing two cosine modulation blocks with a single sine modulation block. This design also involves non-linear optimization. A multiplier-less design of NPR uniform CMFB with sharp transition band using modified meta-heuristic algorithms is proposed in Reference 14.

Multipliers are the most expensive components for implementing a digital filter in hardware. The multipliers in filters can be implemented using shifters and adders, if the coefficients are represented by signed power of two (SPT) terms. Canonic signed digit (CSD) representation is a particular subset of SPT representation [15]. It contains minimum number of SPT terms and the adjacent digits will never be both non-zeros. As a result, efficient implementation of the multipliers using shifters/adders is possible [15]. But CSD representation of the coefficients may lead to deterioration of the filter performances. Hence suitable optimization techniques have to be deployed to improve the performances.

In this paper an approach for the design of multiplier-less NPR non-uniform CMFB is given, in which the prototype filter is designed using FRM approach. The continuous coefficient design of the FRM prototype filter does not require any non-linear optimization. The edge frequencies are iteratively adjusted to satisfy the 3-dB condition as given in Reference 16. The sub-filters in the FRM prototype filter are designed using weighted Chebyshev approximation. A highly frequency selective filter bank having non-uniform decomposition with less implementation complexity is designed. The coefficients are quantized using canonic signed digit (CSD) representation. The finite precision performances of the filter bank in the minimal SPT space can be made at par with those with continuous coefficients. To improve the frequency response characteristics of the filters, optimization in the discrete domain is required. Conventional gradient based approaches cannot be deployed here, as the search space is discrete. Meta-heuristic algorithm is a proper choice for such problems and it is reported [17] to result in global solutions by properly tuning the parameters. Hybrid meta-heuristic algorithm, which combines the best qualities of two algorithms, further improves the performance with less number of adders. Multiplier-less design of NPR non-uniform CMFB with FRM filter as the prototype filter and the coefficients synthesized in the CSD form using modified meta-heuristic algorithms are hitherto not reported in the literature. The filter bank proposed in this paper is a suitable choice for digital channelizers in SDRs.

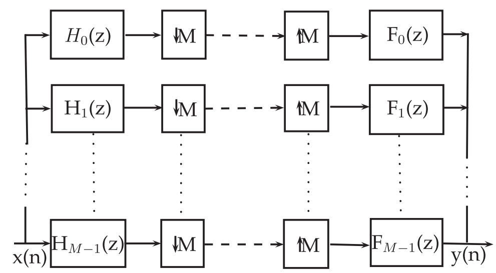

Fig. 1. M channel maximally decimated filter bank.

The remaining part of the paper is organized as follows: Section 2 gives an introduction of NPR CMFB. Section 3 briefly illustrates the design of non-uniform NPR CMFB. Section 4 gives a brief description of the frequency response masking approach. Section 5 explains the design of the proposed continuous coefficient CMFB. Different design examples and comparison with conventional FIR filter are also given. Section 6 outlines the design and optimization of the CSD coefficient filter bank using various modified meta-heuristic algorithms. Section 7 explores the applicability of the proposed filter banks as efficient channelizers in SDRs and also gives a brief review of existing digital channelizers. Result analysis is given in section 8 and the conclusion in section 9.

2. Cosine modulated uniform filter banks

The structure of an M-channel maximally decimated uniform CMFB is shown in Fig. 1. The input signal is decomposed into subband signals having equal bandwidths. A set of M analysis filters $H_k(z)$, $0 \le k \le M-1$ decomposes the input signal into M subbands, which are in turn decimated by M fold down-samplers. A set of synthesis filters $F_k(z)$, $0 \le k \le M-1$ combines the M subband signals after interpolation by a factor of M on each channel.

The reconstructed output, $Y(z)$ is given by Equation (1) [1].

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

where $T_0(z)$ is the distortion transfer function and $T_l(z)$ is the aliasing transfer function.

$$T_0(z) = \frac{1}{M}\sum_{k=0}^{M-1} F_k(z)H_k(z) \tag{2}$$

$$T_l(z) = \frac{1}{M}\sum_{k=0}^{M-1} F_k(z)H_k\left(ze^{-j2\pi l/M}\right) \tag{3}$$

$$l = 1, 2 \ldots\ldots\ldots M-1$$