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Meta-heuristic evolutionary algorithms for the design of optimal multiplier-less recombination filter banks

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ABSTRACT

This paper proposes a design for multiplier-less recombination non-uniform filter banks (RNUFBs) optimized using meta-heuristic algorithms. The structure consists of an *M*-channel uniform filter bank, with some channels combined by the synthesis filters of a transmultiplexer (TMUX), yielding non-uniform sub-bands. When any structure is realized in hardware, it is necessary to have low power consumption and a small chip area. These can be achieved by replacing the multipliers with shifters and adders. Once the continuous coefficient recombination non-uniform filter bank is designed, the coefficients are converted to the canonic-signed-digit (CSD) space to make the design multiplier-less, so as to reduce the complexity of the hardware implementation. To reduce the number of adders and shifters in the multiplier-less implementation, the filter coefficients are rounded with a restricted number of signed power-of-two (SPT) terms, which may cause degradation in the performance of the RNUFBs. To improve the performance of the CSD rounded filters and filter bank, meta-heuristic algorithms such as the artificial bee colony (ABC) algorithm, harmony search algorithm (HSA) and gravitational search algorithm (GSA) are deployed. Of these meta-heuristic algorithms, GSA is found to give the best performance. The method proposed in this paper results in non-uniform filter banks with rational sampling factors which are multiplier-less and have linear-phase and near-perfect-reconstruction.

1. Introduction

In many applications such as image coding, non-uniform filter banks (NUFBs) are required, which divide the frequency spectrum of the input signal into non-uniform sub-bands [61]. For example, in the design of filter banks that approximate the time-frequency resolution of human ears, non-uniform spacing that matches the critical bands is preferred [57]. The constraints of uniform filter banks, such as integer and uniform decimation in each sub-band and limited time frequency resolution, increase the importance of NUFBs. Many design methods are proposed in the literature to implement NUFBs [13,17,18,22,31,33,36,39,46,48,54,61,66–68,73].

Hoang and Vaidyanathan [22] have proposed a new structure for non-uniform quadrature mirror filter (QMF) banks with conditions for perfect-reconstruction (PR) NUFBs. Another method, known as the indirect or recombination method, where certain channels in an *M*-channel uniform filter bank are combined using the synthesis filters of another filter bank with a smaller number of channels, is proposed in [13]. In [31], the problem of designing NUFBs with rational decimation factors is converted into the design of an NUFB with integer decimators. The approach to designing near-perfect reconstruction

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(NPR) critically sampled NUFBs proposed by Princen [48] is based on modulated filter banks and the adjacent band alias cancellation principle. Of these various methods for designing NUFBs, only a few have linear-phase. The tree-structured method proposed in [61] is the simplest method which can be used to design NPR alias-free linear-phase (LP) non-uniform filter banks. An iterative algorithm is proposed in [33] by Kumar et al. for the design of the NPR tree-structured non-uniform filter bank. However, the unequal sampling factors that can be implemented using this method are limited to powers of two and there is a significant delay because of their cascaded structure. Nagai et al. proposed a new approach to the design of linear-phase PR NUFBs based on frequency domain constraints to eliminate the amplitude and the aliasing distortions [46]. The PR condition and a design procedure for LP finite impulse response (FIR) filter banks using pseudo-QMF are derived in [64]. In this method, however, FIR filters are required to have complex coefficients to reduce the aliasing distortion in the resulting NUFBs. A method for designing LP NUFBs with rational decimators is proposed in [36,66,67] based on the recombination structure given by Cox [13]. Another direct design method for LP NPR NUFBs with integer sampling factors is proposed by Xie et al. [68]. This method is extended to the rational case in [12]. The recombination non-uniform filter bank (RNUFB) is a good choice for realizing NUFBs with rational sampling factors, in which some channels of an *M*-channel uniform filter bank (UFB) are merged by the synthesis filters of uniform transmultiplexers (TMUXs) [30] with a smaller number of channels in order to generate sub-bands with different sampling factors [36,66–68]. The advantage of the recombination NUFB is that the PR property is structurally imposed if the original UFB and the TMUX have PR property. This paper is based on the recombination filter banks proposed in [36], in which the constituent PR uniform filter banks are designed using the direct method proposed in [52].

FIR filters and filter banks require considerably more arithmetic operations and hardware components than their infinite impulse response (IIR) counterparts. This makes their implementation very expensive. Multipliers, being relatively complex units, are the deciding factors in the overall speed, area and power consumption of digital signal processing systems. With the current advancements in VLSI technologies, fast multipliers, operating at speeds exceeding 100 MHz, are available. They employ parallel processing, which requires a large chip area and high power. If the filter banks are employed in high-speed applications such as real-time image compression systems, a separate fast multiplier is required for each filter coefficient, which will result in high hardware complexity [23]. Hence, the need to eliminate the multipliers using equivalent blocks is essential for hardware-efficient signal processing systems. One such popular approach is to replace the multipliers by means of simple shifters and adders/subtractors, which can result in reduced area and power consumption [37]. The implementation approach in which the digital filters are designed with no multipliers is referred to as a multiplier-less or multiplier-free approach. This is achieved by representing the filter coefficients in the signed power-of-two (SPT) space [38]. Canonic signed digit representation [21] is a special case of the SPT space, which uses a minimum number of non-zero bits (SPT terms) to represent a decimal number. The number of shifters and adders required for the implementation of the multiplier-less filter depends on the total number of SPT terms in the filter coefficient representation. Hence, the CSD-represented filter offers minimum complexity, area and power consumption compared to other representations.

In order to realize multiplier-less filter banks, the continuous coefficient filter banks are designed first by designing the continuous coefficient analysis and synthesis filters. The next phase is to convert them into the CSD space to obtain multiplier-less filters and multiplier-less filter banks. To bring the complexity down further, the number of adders in the CSD-represented multiplier-less implementation is reduced. To achieve this, the coefficients of the constituent filters in the filter bank are rounded to the discrete values in the CSD space with a restricted number of SPT terms. This rounding of the coefficients may cause a deterioration of the frequency responses of the filters and the filter bank and calls for the use of suitable optimization techniques to improve the response. The higher the number of non-zero bits used to represent the filter coefficients, the closer the rounded filter coefficients are to the unrounded coefficients and the closer the rounded performance is to the unrounded performance. However, a higher number of non-zero bits means greater hardware complexity and a higher cost. Thus, there should be a trade-off between the hardware cost and performance characteristics. Because the coefficient space is discrete, the optimization methods developed for the continuous variables are not applicable here. Meta-heuristic algorithms are good alternatives for these types of optimization problems because it is reported that these can finally reach a global solution if the parameters are properly selected with respect to a particular design problem [70]. They are especially useful in finding near-optimal solutions in multi-modal, multi-objective, and multidimensional problems. Various nature-inspired meta-heuristic algorithms are employed in various optimization applications in the literature [1,5–9,11,16,24,25,40–43,53,58,62,63,65].

The design of multiplier-less reconfigurable channel filters using a ternary-coded genetic algorithm (GA) is reported in [8]. Integer-coded GA and integer-coded artificial bee colony (ABC) algorithms, in which the integer indices of look-up-table entries are used to arrive at the solution, are used for the optimization of the multiplier-less transmultiplexer in [40] and [41], respectively. A design for a multiplier-less frequency response masking (FRM) filter using an integer-coded ABC algorithm and differential evolution (DE) algorithm is presented in [42]. In [4–7], an integer-coded ABC algorithm, DE algorithm, harmony search algorithm (HSA) and gravitational search algorithm (GSA) are proposed for the optimization of reconfigurable channel filters and tree-structured non-uniform filter banks. No design for a multiplier-less recombination filter bank using meta-heuristic algorithms has been reported in the literature so far. In this paper, various meta-heuristic algorithms are proposed for the design of multiplier-less non-uniform RNUFBs.

This paper is organized as follows: Section 2 gives an overview of the recombination non-uniform filter banks. In Section 3, the proposed methodology, for designing multiplier-less RNUFBs using meta-heuristic algorithms is discussed. This section also discusses the various meta-heuristic algorithms such as DE, ABC, HSA and GSA. Section 4 gives an example