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Design of Optimal IIR Band pass and Band stop Filters using TSA Technique and Their FPGA Implementation

V. Karthik, K. Susmitha, S. K. Saha, R. Kar

***Abstract*—A new optimizing technique, named Tree Seed Algorithm (TSA) is utilized for optimizing the coefficients of impulse infinite response (IIR) type bandpass filter (BPF) and bandstop filter (BSF) of order 8. The employed optimizing technique uses the error fitness (EF) function to enhance the performance capabilities of the filter in terms of stopband attenuation, passband ripples (PBR), stopband ripples (SBR) and transition width. The employed algorithm converges rapidly to the optimal solution in fair number of iterations. An analysis of optimally designed IIR filter is carried out by Verilog hardware description language on field programmable gate array (FPGA) platform.**

***Keywords*—Tree Seed Algorithm; Convergence; IIR Filter; BPF; BSF.**

I. INTRODUCTION

Information is carried out by the signals. However, due to the presence of noise, signals are getting contaminated. Hence, at receiver-end to extract the information from the noise corrupted signal, a method called signal processing is employed. Signal processing may be digital, analog or both. It varies upon the nature and the point of application of the signal. Digital signal processing (DSP) is confined with addition, multiplication and recall of previous information; hence its application has increased in various fields. Digital filter utilizes less discrete components. So, its performance does not get effected by thermal drift.

Finite impulse response (FIR) and infinite impulse response (IIR) are two varieties of filter [1-2]. FIR filter is termed as non-recursive filter because the yield of this filter relies on the present and past values of input. Hence, less memory is required. While the IIR filter is termed as recursive filter, as the output of the filter relies on both previous and present inputs and previous outputs. So, a considerable memory is needed for storing of past outputs of the IIR filter.

As the design complexity and memory requirement are less, the FIR filter realisation is easier compared to IIR filter. In addition to these, stability and linear phase response over a wide frequency range are also the benefits of the FIR filter. On the other hand, IIR filter ensures to meet the specifications such as sharp transition width, lower PBR, SBR and higher stopband attenuation at lower order in comparison with FIR filter. Due to these, an adequately designed IIR filter can produce the frequency response (FR), which is close to ideal magnitude response and better in comparison with FIR filter response [3]. Various gradient based algorithms namely, steepest descent and quasi newton algorithms are employed for the design of optimal filters [4-5].

These algorithms provide the best solution only when a very simple search space is provided. But the search space is multimodal, multidimensional, discontinuous and highly complex. So, only global optimization techniques give the optimal solution. Several metaheuristic algorithms such as genetic algorithm [6], simulated annealing [7], variants of particle swarm optimization [8], artificial immune system [9], ant colony optimization [10] and bacteria foraging algorithm [11] are successfully applied for filter design problem. These optimized filters are applied in the fields of biomedicine for design of electrocardiogram [12].

a. Contribution

In this paper, to obtain the optimal coefficients an algorithm called TSA [13] which is inspired by the relation between trees and seeds is utilized for optimizing the coefficients of filter.

b. Organization of paper

The rest of the paper is structured as follows. Section 2 briefly illustrates the problem definition for the filter design. Section 3 discusses the TSA algorithm for optimizing the filter coefficients. Section 4 discusses the FPGA implementation of IIR filter, and section 5 presents the simulation results and discussions. Finally, section 6 concludes the work.

II. PROBLEM DEFINITION OF FILTER

In this paper, IIR type BPF and BSF are designed by TSA technique. The difference equation of IIR filter [14] is presented in (1):

$$y(p) + \sum_{k=1}^{n} a_k y(p-k) = \sum_{k=0}^{m} b_k x(p-k) \tag{1}$$

where $x(p)$ and $y(p)$ are the input and output, respectively; $n(\geq m)$ represents order of the filter; a_k represents the denominator coefficient, and b_k represents the numerator coefficient.

Transfer function (TF) of the IIR filter is stated by following equation:

$$H(z) = \frac{\sum_{k=0}^{m} b_k z^{-k}}{1+\sum_{k=1}^{n} a_k z^{-k}} \tag{2}$$

The FR of the IIR filter is given (2) assuming $z = e^{j\omega}$:

$$H(e^{j\omega}) = \frac{\sum_{k=0}^{n} b_i e^{-kj\omega}}{1+\sum_{k=1}^{m} a_i e^{-kj\omega}} \tag{3}$$

where $\omega \in (0, \pi)$ in radians.

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In this optimization problem, the fitness function, *J(ω)* is defined in (4). The error fitness value of each search agent is calculated on the basis of magnitude response deviation from its practical response which includes the PBR (δ_p), SBR (δ_s), and transition width of the designed filter, $|H_d(\omega)|$.

$$J(\omega) = \sum_{\omega} \mathrm{abs}[(|H_d(\omega)|)-\delta_s] + \sum_{\omega} \mathrm{abs}\big[\mathrm{abs}(|H_d(\omega)|-1)-\delta_p\big] \quad (4)$$

EF function which is mentioned in (4) is the generalized EF function that is to be optimized by TSA optimization technique. The first part and second part of (4) give the error contribution in *J(ω)* for stopband and passband regions, respectively.

III. TREE SEED ALGORITHM

TSA is a natural phenomenon-based optimization technique that mimics the relation between the trees and the seeds [14]. Seeds that are spread over the surface become new trees which again spread seeds over the surface and this phenomenon continues. The surface area is considered as the search space of the optimization problem. For exploration the search starts randomly form multiple points on problem space by location of trees. The seed location which is produced by a tree plays a key role for solving optimization problem as this procedure contributes for the exploitation. This process can be done in two ways, first one gives the seed location by the tree location which produces this seed, and the better location in the tree population. Second one deals with the producing of a new seed from two different locations [15]. The equations for these phenomena are given by:

$$S_{i,j} = T_{i,j} + \alpha_{i,j} * (B_j - T_{r,j}) \quad (5)$$

$$S_{i,j} = T_{i,j} + \alpha_{i,j} * (T_{i,j} - T_{r,j}) \quad (6)$$

where, $S_{i,j}$ represents the j^{th} vector of seed produced by i^{th} tree; $T_{i,j}$ represents j^{th} vector of i^{th} tree; B_j represents the best tree location in the j^{th} vector; $T_{r,j}$ represents the randomly selected r^{th} tree in j^{th} vector; α is randomly generated scaling factor in range [-1,1] for *i* and *r* indices.

In TSA the exploration and exploitation rely on search tendency (ST), a controlling parameter in range [0,1]. The larger the value of ST, faster the convergence and provides the better exploitation. The smaller the value of ST, slower the convergence, and better the exploration. The initialization of location of trees is given by (7).

$$T_{i,j} = L_{j,min} + r_{i,j} * (H_{j,max} - L_{j,min}) \quad (7)$$

where, $L_{j,min}$ and $H_{j,max}$ are lower and upper boundaries of search space; $r_{i,j}$ is a randomly generated number in range [0,1]. The efficiency of exploitation also depends on the number of seeds. The range for number of seeds produced is 10% to 25% of number of trees. The termination criterion relies on the maximum number of iterations.

The flowchart of TSA for producing the optimal set of coefficients is given in Fig. 1.

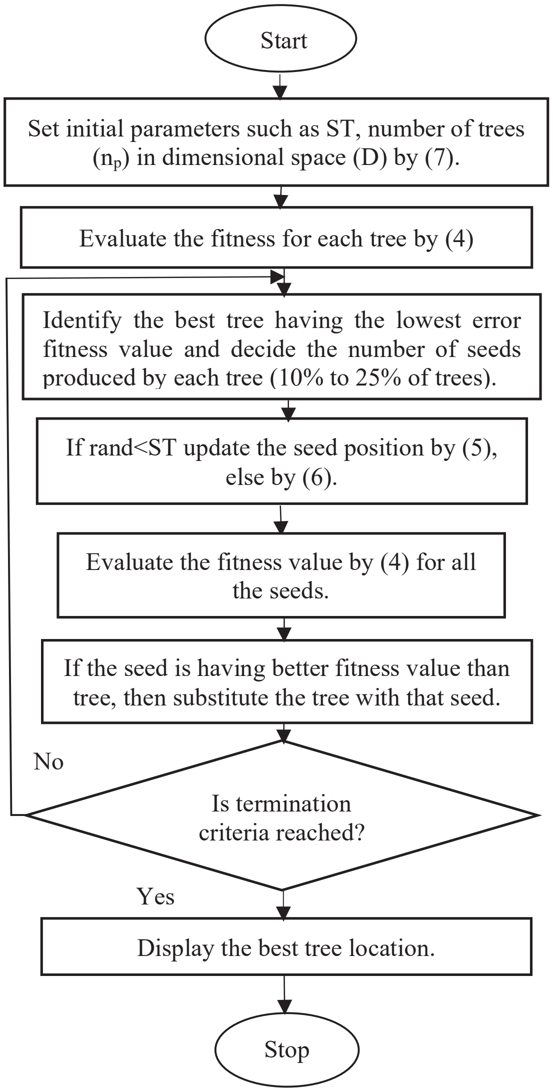


Fig. 1. Flowchart representing TSA for IIR filter design.

IV. IIR FILTER IMPLEMENTATION

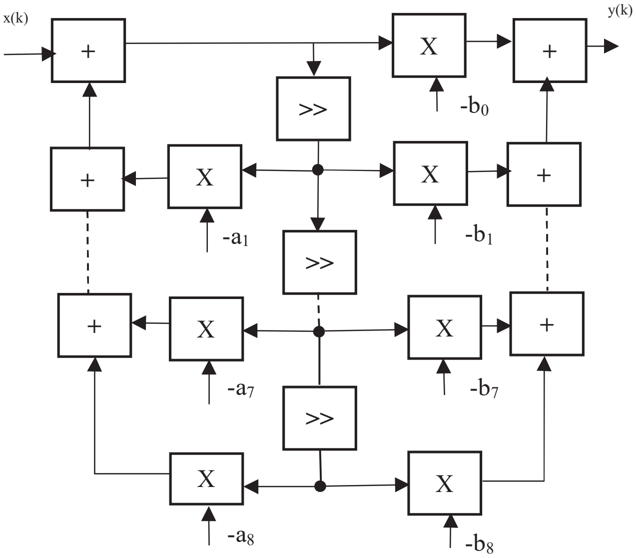


Fig. 2. Architecture of IIR filter.

The architecture of IIR filter implemented is shown in the Fig. 2. The filter is designed for order 8, with equal number of numerator and denominator coefficients.

V. SIMULATION RESULTS

a. Optimization of IIR BPF and BSF coefficients by TSA.

The TSA based optimally designed filter coefficients are obtained after 500 iterations. All the design parameters connected with algorithm and filter specifications are presented in Table I. This algorithm is executed on MATLAB 2017a version platform on Intel core i3 processor, 2.30GHz with 8GB RAM.

TABLE I. DESIGN PARAMETERS

Design parameters	**Values**
Number of trees (n)	25
Iteration cycle ($iter_{max}$)	500
Search tendency (ST)	0.1
Dimensionality (D)	18
Upper limit of coefficients (d_{max})	+2
Lower limit of coefficients (d_{min})	-2
Stopband ripples (δ_s)	0.001
Passband ripple (δ_p)	0.01

In Table II and Table III, optimized coefficients approximated upto 5 decimal points of IIR BPF and BSF, respectively of order 8 are presented, with the optimal set of coefficients presented in Table II, for BPF is used to draw the magnitude response in dB and normalized magnitude response plots as shown in Figs. (3) – (4), respectively.

TABLE II. OPTIMALLY OBTAINED COEFFICIENTS BY TSA FOR BPF

Numerator coefficients (b_k)	**Denominator coefficients (a_k)**
b_0 = 0.00986	a_0 = 1.11071
b_1 = -0.07363	a_1 = 0.09074
b_2 = -0.07270	a_2 = 1.60576
b_3 = 0.11380	a_3 = -0.05861
b_4 = 0.15451	a_4 = 1.77204
b_5 = -0.10515	a_5 = 0.01578
b_6 = -0.15467	a_6 = 1.01974
b_7 = 0.02576	a_7 = 0.00229
b_8 = 0.08283	a_8 = 0.30200

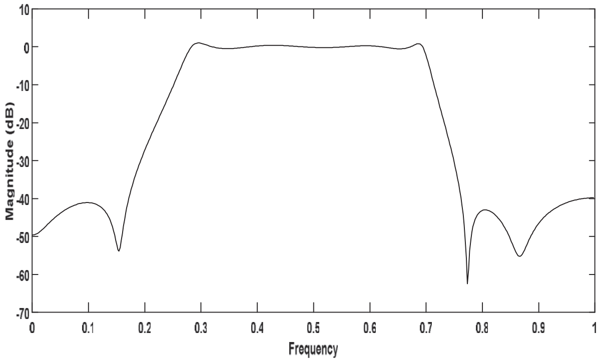


Fig. 3. Magnitude response (dB) plot of IIR BPF of order 8 designed by TSA.

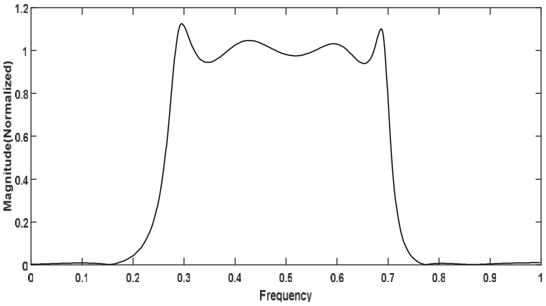


Fig. 4. Normalized magnitude response plot of IIR BPF of order 8 designed by TSA.

TABLE III. OPTIMALLY OBTAINED COEFFICIENTS BY TSA FOR BSF

Numerator coefficients (b_k)	**Denominator coefficients (a_k)**
b_0 = -0.23495	a_0 = -0.21851
b_1 = -0.00852	a_1 = -0.71535
b_2 = -0.87565	a_2 = 1.89002
b_3 = 0.11280	a_3 = 1.20077
b_4 = -1.3791	a_4 = 0.49315
b_5 = 0.19104	a_5 = -1.58091
b_6 = -1.15111	a_6 = 1.50957
b_7 = 0.09613	a_7 = 0.72490
b_8 = -0.45958	a_8 = 0.32883

Also, with the optimized coefficients presented in Table III, magnitude response plot in dB and normalized magnitude response plot are shown in Figs. (5) – (6) for BSF, respectively. From figures different performance metrics are calculated and presented in Table IV. Algorithm convergence plot for both the design problems are shown in Figs. (7) – (8) and the optimal solutions are obtained, those are ensured by these convergence plots.

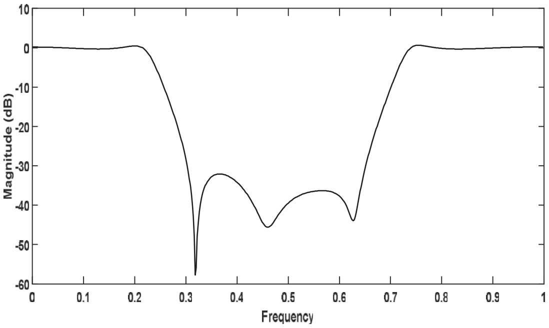


Fig. 5. Magnitude response (dB) plot of IIR BSF of order 8 designed by TSA.

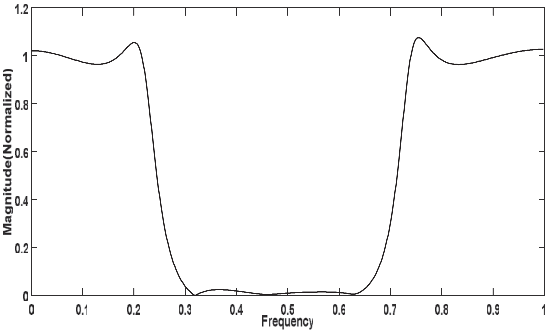


Fig. 6. Normalized magnitude response plot of IIR BSF of order 8 designed by TSA.

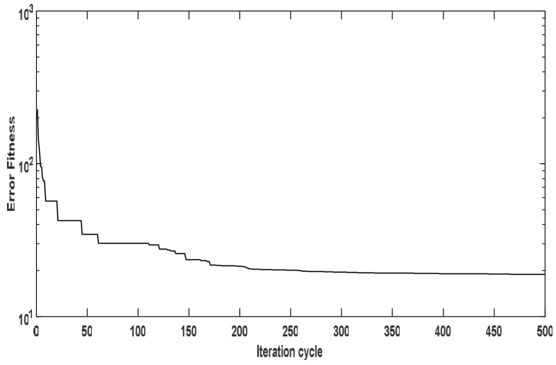


Fig. 7. Converging profile of TSA technique for 8th order IIR BPF design technique.

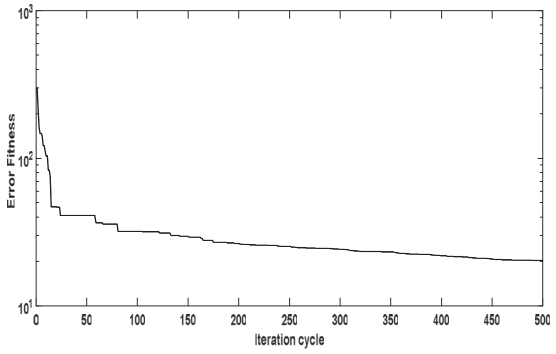


Fig. 8. Converging profile of TSA technique for 8th order IIR BSF design technique.

TABLE IV. ANALYSED DATA OF DESIGNED IIR BPF AND BSF.

Parameters	BPF	BSF
Maximum stop band attenuation (dB)	-42.99	-32.06
Maximum δ_p	0.124	0.076
Maximum δ_s	0.01025	0.02494
Average of δ_s	0.00550215	0.0131145
Transition width	0.1289	0.1113

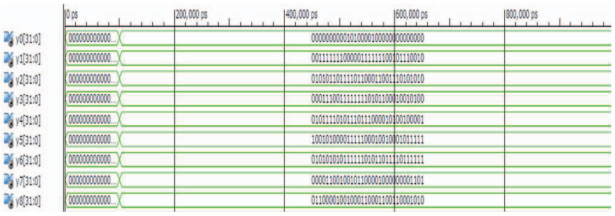
b. *FPGA implementation of IIR BPF and BSF*

IIR filter is realized in FPGA with the device name Vertex 7 with device name xc7vx330t-3ffg1157. The device utilization for the FPGA implementation of the IIR filter of order 8 are tabulated below.

TABLE V. DEVICE UTILIZATION FOR IIR BPF AND BSF.

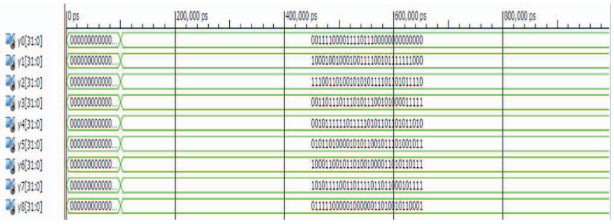
Logic utilization	Used	Available	Utilization (%)
Look up tables (LUTs)	47	204000	0
Input output blocks (IOBs)	576	600	96
DSP48E1	106	1120	09

The optimal coefficients obtained are converted into the binary form, and the simulation response is done for the verilog HDL with the optimal coefficients. It has been observed that responses obtained from verilog HDL simulation study shown in Figs. (9) – (10) for BPF and BSF, respectively and the difference equation of the IIR filter are same.



```
y0[31:0]  000000000000...  00000000001010000100000000000000
y1[31:0]  000000000000...  00111111100000111111100101110010
y2[31:0]  000000000000...  01010110111101100011001110101010
y3[31:0]  000000000000...  00011100111111101011000010010100
y4[31:0]  000000000000...  01011110101110111000010100100001
y5[31:0]  000000000000...  10010100001111100010010001011111
y6[31:0]  000000000000...  01010101011111101011011110111111
y7[31:0]  000000000000...  00001100100101100001000000001101
y8[31:0]  000000000000...  01100001001000110001100110001010
```

Fig. 9. Simulation response of the optimized coefficients for BPF IIR.



```
y0[31:0]  000000000000...  00111100001111011100000000000000
y1[31:0]  000000000000...  10001001000100111100101111111000
y2[31:0]  000000000000...  11100110100101010111101101011110
y3[31:0]  000000000000...  00110111011101011100101000011111
y4[31:0]  000000000000...  00101111110111110101101101011010
y5[31:0]  000000000000...  01011010000101011001011101001011
y6[31:0]  000000000000...  10001100101101001000011010110111
y7[31:0]  000000000000...  10101110011011110110110000101111
y8[31:0]  000000000000...  01111100000100000011010010110001
```

Fig. 10. Simulation response of the optimized coefficients for BSF IIR.

VI. CONCLUSION

IIR BPF and BSF are designed by the optimization of coefficients using the TSA technique. This optimization technique attains the optimal solution in acceptable number of iterations and ensures the quality performance of the designed filter in terms of PBR, SBR, stop band attenuation and transition width. IIR filter is realized in the FPGA by Verilog HDL with the optimized coefficients.

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