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Design of low power multiplierless FIR filter with enhanced adder efficiency using flower pollination optimization

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ABSTRACT

This paper presents an improved design of minimal power multiplierless finite impulse response (FIR) by using flower pollination algorithm (FPA) and newly proposed hybrid common sub-expression elimination (CSE) algorithm. The novel extract of this paper is three fold: first, enhancement of the power performance by reducing the switching activity; second, raising adder efficiency using newly proposed hybrid CSE algorithm; and third, optimizing the frequency response characteristics of filter by controlling ripples in passband and stopband region using FPA in one step. For this purpose, the minima of an objective function is achieved, constructed as sum of integral mean squared error with allowable tolerable limits to control ripples in passband and stopband region, and the dynamic power that has computed through hamming distance (HD) between two successive filter coefficients. In addition to this, the application of recently proposed CSE reduces the amount of adders, and lowers the value of HD. The significance of proposed algorithm is measured on the basis of different performance evaluation parameter such as; stopband attenuation (A_s), stopband ripple (δ_s), passband ripple (δ_p), hamming distance (HD), power and amount of adders respectively.

1. Introduction

In the recent trends, several applications in engineering domain such as electrocardiogram (ECG) signals in cloud computing [1], embedded system for real time application [2], software defined radio (SDR) and massive MIMO in communication [3], etc. require an optimal design of digital signal processing (DSP) system that efficiently fulfil their essential requirements. Filters are the most common component required in DSP system for filtering and smoothing of signals. In this context, the finite impulse response (FIR) filters are mostly used due to its greatest advantage of absolute stability and linear-phase property. Generally, FIR filter used in these systems requires high speed of operations with less consumption of power. These objectives are achieved through developing low power design of FIR filters. The low power design of FIR filter are accomplished either by reducing the hardware complexity of filters or by reducing the switching activities of filter coefficients. In the first approach, the hardware complexity of filter is reduced by reducing the amount of primary design components i.e. multipliers and adders, between which, the multipliers are remarked as most resource consuming component than adders. Therefore, to realize a filter as resource efficient, multipliers are needed to be eliminated from the circuit. For this purpose, multipliers are transformed into adders, (multiplier adders) by applying shift and add operation, and in this way, multipliers are completely removed from the circuit. These adders are further minimized by different adder minimization approaches such as graph based methods [4–6], sub-optimal optimization [7–9], and common subexpression elimination (CSE) [10–13]. Recently, different CSE approaches are promptly opted due to their efficiency in design, less execution time, and least computational complexity [10–13]. In the second approach, low power in FIR filter is achieved by reducing the dynamic power of filter. The dynamic power is mainly induced through the switching activity of filter coefficients. Many literature have reported that switching activity raises the change in filter coefficients, and power can be reduced by reducing this activity [14]. In literature, the hamming distance (HD) computation is preferred for minimizing of the switching activity due to their better accuracy and least complexity. In HD, the successive bit differentiation among coefficients is performed [15–19,22,23]. The HD is calculated between the conjugate binary represented filter coefficients, and to minimize switching activities, this HD is

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minimized. In this context, many techniques has been developed to reduce the HD for efficient minimization of power such as coefficient scaling, reordering and optimization [15], iterative optimization based on steepest descent [16], swarm based optimization algorithms such as genetic algorithm (GA) [17], metaheuristic algorithm [18].

In both of these approaches, either hardware complexity minimization or switching activity minimization, the continuous filter coefficients are quantized and converted into binary form in each of the time. However, the performance of filter is debilitated due to this conversion and quality of filter is diminished. In literature, this issue have been addressed by many authors, and resolved through proper use of optimization algorithm, where an objective function is constructed to achieve a desired characteristic of filter [19,20]. In these techniques, separate optimization algorithms have been used for optimizing the performance of filter that improves the frequency response characteristics. Recently, authors in [19,22–23] have introduced a single objective function based optimization approach, where power consumption and desired filter characteristics were combinly optimized. In this technique, an improved artificial bee colony (ABC) algorithm has been used for optimization, while power consumption is minimized by reducing HD that is compounded by the Lagrange multiplier [19,22–23]. In a similar fashion, authors in [24,25] have developed a new methodology, where, optimization algorithm has been used for achieving hardware efficient multiplierless FIR filter by reducing adders through CSE. In these papers, multiplierless realization of FIR filter is succeeded with comparatively analysing the performance of different evolutionary algorithms, while amount of adders are significantly minimized by using different CSE techniques. In all of above techniques, for designing low power multiplierless FIR filter, two different issues are resolved. Firstly, in [19,22–23], power is minimized by minimizing the switching sensitivity (by minimizing the HD), and secondly in [24,25], hardware complexity is minimized by minimizing multiplies and adders (using CSE). In both of these approaches, evolutionary and heuristic based algorithms are used for optimization, which improve frequency response characteristics of hardwired filter. However, there is no technique available in literature for designing efficient low power multiplierless FIR filter that combine optimizes hardware resources (adders and multipliers), switching activity (hamming distance), and desired frequency response characteristics of filter, all-together. Additional to this, recently introduced optimization method flower pollination algorithm (FPA) can also be incorporated in proposed design.

Therefore in above context, in this paper, an optimal approach for a low power multiplierless FIR filter with efficiency in adders is presented, where the three major issues encountered separately in design of low power realization of FIR filter have been resolved through single optimization algorithm FPA. the minima of an objective function is achieved, constructed as sum of integral mean squared error to control ripples in passband and stopband region with allowable tolerable limits and the dynamic power due to switching activity. A newly proposed hybrid CSE technique has also been incorporated to reduce the adders. In this context, comparative analysis of different optimization techniques such as cuckoo search optimization algorithm (CSOA), particle swarm optimization (PSO), artificial bee colony algorithm (ABC), hybrid algorithm, and flower pollination algorithm (FPA) have also been examined for optimizing the overall performance of filter. The organization of this paper is as follows: Section 2 states a short review of power consumption in filter. Section 3 presents the overview FPA. The problem formulation is explained in Section 4. Simulation results obtained with the proposed method followed by comparison with other methodologies are discussed in Section 5. Finally, in Section 6, the concluding remarks are described.

2. Power dissipation in FIR filter

In FIR filter, the dissipation of power is occurred mainly due to signal switching activity, which can be seen in the address and data buses of memory and multipliers during filtering. In the data buses, the power is dissipated during switching activity. Therefore, the frequency of switching and capacity of loading plays an important role in dissipation of power, while the inter-signal capacitance is also a reason for power dissipation [15–19,22–28]. This power dissipation in FIR filters are broadly minimized by two ways. Firstly, by minimizing hardware complexity, and secondly by minimizing switching activity through minimizing hamming distance calculated between contiguous coefficients. The brief discussion on minimization of power is illustrated as below:

2.1. Hardware complexity minimization

In practical implementation of digital filters, two major components, named as multipliers and adders are realized, among which multipliers have been founded as most area, power and resources consuming component. The designed filter structure can be realized with fixed filter coefficients, dedicatedly utilizing these hardware components [24]. In this technique, the multipliers are transformed in terms of adders, known as multiplier adders by using shift and add mechanism, and in this way, multipliers are completely removed from the circuit. Recently, the canonical signed digit number systems are mostly preferred due to their unique number representation. It is a ternary digit number representation, where given number are coded in the form of 1,-1, and 0. In CSD, if x bit number is converted into CSD, then maximum $x/2$ number of non-zero digits will be presented in converted number, and hence, least numbers of nonzero digits are acquired. Mathematically, If T represents any fractional number, then in CSD space, it can be represented as [24]:

$$T = \sum_{i=1}^{Nt} S_i 2^{-P_i}, \tag{1}$$

In above Eq. (1), S_i is {1, 0, and −1} and P_i = 0, 1… Nt, WL. While, WL is a word length, and Nt represents maximum number of nonzero digits occurred [24]. In this context, another method for complexity minimization is coefficient reusability or coefficient sharing. CSE is one of the mostly used coefficients sharing technique, where the redundant bit patterns, which have repeatedly appeared in coefficient set are eliminated/ shared. In CSE, sub-expressions or bit patterns, which are commonly present, are searched and eliminated [25–28]. The concept of CSE was initially aided to increase the speed of comparators and other devices [25–28]. Later on, many researchers have utilized it for an efficient design of filters and filterbanks so as to minimize the numbers of adders [25–28]. CSE can be classified as horizontal CSE (HCSE) and vertical CSE (VCSE) based on their behaviour of searching and elimination of sub-expressions. Several approaches have been developed on theses HCSE and VCSE, in which 2-bit, 3-bit, and 4-bit patterns are searched and shared or eliminated for reducing the resultant adders [25–28].

2.2. Hamming distance minimization

In literature, the power dissipation (PD) in FIR filter can be minimized through minimizing the switching activity. In this context, it has found that the hamming distance (HD) calculated between the filter coefficients can be used to evaluate the switching activity. In general, the transition of the binary bits presented in filter coefficients (due to signalling), and the transition of adjoined signal values are main cause of the PD in filter. Further in the multipliers, the power dissipation is because of switching at the internal nodes. This activity depends on the transitions stated as transaction per unit time and can be measured by measuring the HD between the input signal values. Therefore, it has concluded that hamming distance plays crucial role in power consumption. Hence, to minimize power dissipation, many researchers have used several mechanisms to minimize HD, which is calculated between the contiguous coefficients [16–19,22,23,27–29].

In general, HD is calculated as the difference of the input signal values represented as a binary strings, thus, the HD between two binary strings can be calculated as follows:

The two input data streams represented in binary form are given as [22,23]:

$$S_1 = \{a_{11}, a_{12}, a_{13}, \ldots, \; a_{1n}\} \text{ and } S_2 = \{a_{21}, a_{22}, a_{23}, \ldots\ldots\ldots, a_{2n}\}, \quad (2)$$

In Eq. (2), $\{a_{11}, a_{12}, \ldots, a_{1n}\}$ and $\{a_{21}, a_{22}, \ldots, a_{2n}\}$ represents number of bits, and the HD is calculated as [22,23]:

$$H(B_1, B_2) = \sum_{i=1}^{n} |a_1^i - a_2^i|, \quad (3)$$

This HD is minimized through several techniques and the detailed discussion can be found in Refs. [16–19,21–23,27–29]. This paper resolves to obtain the filter coefficients that use less power during the switching activity and the FPA is used to search the coefficients that ensure low switching activity, which gives low power consumption. Hence, the coefficients ($h(1)$, $h(2)$,. . ., $h(n)$) of FIR filter is written in the binary form, and the HD is used to calculate the total power consumption of the FIR filter which is deduced as follows [22,23]:

$$J_M = \sum_{i=0}^{n} H(h(i), h(i+1)). \quad (4)$$

3. Flower pollination algorithm

FPA is based on the flower pollination process of plants. The main mechanism involved in FPA is their reproduction process for pollination, associated with the transfer of pollen linked with other different animals such as birds, flies, bats etc. Pollination is classified into two different forms; biotic and abiotic. In biotic pollination, pollen is transferred by a pollinator (birds, flies, bats etc.), while in abiotic pollen is transferred through nature aid (wind and diffusion in water) [32]. Basically, there are two types of pollination occurred in flower i.e. self-pollination and cross pollination. In self-pollination, fertilization of flower is occurred in oneself i.e. from pollen of the same flower to the same plant, whereas in cross pollination, fertilization is occurred from pollen of a flower of a different plant [32]. Thus in FPA, pollination mechanism of flowers is transformed in terms of mathematical algorithm for global optimization. The cross pollination occurs at far distance through pollinators following Lévy flight mechanism. Generally, the four basic rules are followed in FPA given as [32]:

Rule 1: The global pollination process (GPP) considered to biotic and cross-pollination with those pollinators that performs Lévy flights.

Rule 2: The local pollination process (LPP) considered to abiotic and self-pollination.

Rule 3: The reproduction probability represents the flower constancy.

Rule 4: The switch probability (p) in range [0, 1] controls the GPP and LPP.

Mathematically, the two key steps are followed in FPA; global pollination and local pollination. In first step, pollens are assumed to be carried out by different species and pollinator that takes large distance and range such as flies, insects, birds etc. [32].

$$x_i^{t+1} = x_i^t + L(x_i^t - g_*), \quad (5)$$

In this Eq. (5), x_i^t is termed as pollen also known as solution vector x_i at iteration t, and g_* represents current best solution, L represents step size that is responsible for the strength of the pollination. The Lévy flight mechanism is used by pollinator given as [32]:

$$L \sim \frac{\lambda \cdot \Gamma(\lambda)\sin(\pi \cdot \lambda/2)}{\pi} \frac{1}{s^{1+\lambda}}, \text{for } (s > 0). \quad (6)$$

In Eq. (6), $\Gamma(\lambda)$ is the standard gamma function used for large distance pollens and this distribution is valid for large steps $s > 0$. While $\in$ is a constant value given from a uniform distribution in [0, 1]. Whereas, the local pollination constancy of flower are given as [32]:

$$x_i^{t+1} = x_i^t + \in \left(x_j^t - x_k^t\right). \quad (7)$$

In this paper, each flower (plant (x_i)) has been encoded as different FIR response to design FPA based optimized FIR filter, while the parameters are taken after regress statistical analysis [32]. The pseudo code of FPA is given in Table 1.

Table 1
Flower Pollination Algorithm [32] (Pseudo code).

```
Initialize a population of n flowers/pollen gametes with random solutions.
---
Initialize Objective function min f(x),
Opt out the best solution (g * ) from population.
Set the switching probability p ∈ [0, 1].
WHILE (t < MaxGeneration)
for i = 1:n (Population)
if rand < p,
Define a step vector L following a Lévy distribution in d-dimension.
Global pollination using Eq. (5).
else
Construct ∈ from a uniform distribution in [0, 1].
Select j and k among all the randomly generated solutions.
Check for local pollination using Eq. (7).
end if
Compute new solutions.
If new solutions are better than previous one, update them as best value in the population set.
end
Find the current best solution
end
```

4. Problem formulation

In this section, the problem formulation of proposed low power multiplierless FIR filter with adder efficiency is explained. The three major issues encountered in design of low power realization of FIR filter have been resolved through single optimization algorithm FPA. A comparative analysis on the performance of different optimization techniques such as PSO, ABC, CSA, and hybrid method is also performed. To achieve these objectives, one objective function that is comprised of mean squared error between desired and designed filter has been constructed along with involvement of HD, compounded by the Lagrange multipliers. To begin with algorithm, consider a LPF having frequency response $H(\omega_m)$ given as [33]:

$$H(e^{j\omega}) = \sum_{n=0}^{N} h(n) \cdot e^{-j\omega n}, \tag{8}$$

In Eq. (8), $h(n)$ is impulse response of FIR filter and N is order. The desired magnitude response is given as [33]:

$$H_d(e^{j\omega}) = \left\{ \begin{matrix} 1 \pm \delta_p \; for \; 0 \leqslant \omega \leqslant \omega_p \\ \delta_s \text{ otherwise} \end{matrix} \right\} [0, 1], \tag{9}$$

In Eq. (9) $\delta_P$is a passband ripple andδ_s is stopband ripple. In this paper, Type-I FIR filter is designed that has odd length and symmetric impulse response. Due to symmetry,$h(n) = h(N - n)$, thus the filter transfer function becomes [33,43]:

$$H(e^{j\omega}) = e^{\frac{-jN\omega}{2}} \cdot G(e^{j\omega}), \tag{10}$$

and,

$$G(e^{j\omega}) = h\left(\frac{N}{2}\right) + 2\sum_{k=1}^{\frac{N}{2}} h\left(\frac{N}{2} - k\right) \cdot \cos(\omega k). \tag{11}$$

Now, rearranging the above equation in vector form [32,33]:

$$G(e^{j\omega}) = \boldsymbol{a}^T \cdot \boldsymbol{c}(\omega). \tag{12}$$

In above Eq. (12), $\boldsymbol{a}$is given as:

$$\boldsymbol{a} = [\,h(N/2) \quad h(N/2-1) \quad h(N/2-2) \quad \cdots \quad h(0)\,], \tag{13}$$

and,

$$\boldsymbol{c}(\omega) = \left[\cos(0\omega) \quad 2\cdot\cos(\omega) \quad \cdots \quad 2\cdot\cos(\tfrac{N}{2}\omega)\right]. \tag{14}$$

Now, the main objective is to find optimal values of this vector $\boldsymbol{a}$, so as to achieve desired magnitude response given as in Eq. (7). For this purpose, an objective function is constructed using FPA. In this context, a controlled error function formulated that achieves a desired magnitude response within the limits of $1 \pm \delta_P$ and δ_S, in passband and stopband region respectively. Thus, the governed error function in PB is given as [34]:

$$e_{PB}(\omega) = \begin{cases} \left(\left|H(e^{j\omega})\right| - (1+\delta_p)\right)^2, \text{ if } \left|H(e^{j\omega})\right| > 1+\delta_p \\ \left(\left|H(e^{j\omega})\right| - (1-\delta_p)\right)^2, \text{ if } \left|H(e^{j\omega})\right| < 1-\delta_p \,, \omega \in PB, \\ 0, \text{ if } 1 \text{ - } \delta_p \leqslant \left|H(e^{j\omega})\right| \leqslant 1+\delta_p \end{cases} \tag{15}$$

while, the resulted error in SB is computed as:

$$e_{SB}(\omega) = \begin{cases} \left(\left|H(e^{j\omega})\right| - \delta_s\right)^2, \text{ if } \left|H(e^{j\omega})\right| > \delta_s \,, \omega \in SB. \\ 0 \end{cases} \tag{16}$$

Now, the mean squared error is computed as:

$$J_N = \frac{1}{NS_{pb}} \sum_{\omega \in PB} e_{pb}(\omega) + \frac{1}{NS_{sb}} \sum_{\omega \in SB} e_{sb}(\omega), \tag{17}$$

In Eq. (17), NS_{PB} and NS_{SB} are frequency samples in passband and stopband region respectively. FPA is employed to obtain the desired frequency response filter. Now, the objective function ($F(J)$) is constructed on the basis of the design specifications of the FIR filter such that a controlled ripples are allowed in given band. The power is minimized by subsuming the component, which is integrated by using the Lagrange's multiplier (λ), given as [22,23]:

$$F(J) = J_N + \lambda \times J_M, \tag{18}$$

In Eq. (18), J_M represents J^{th} power as given in Eq. (4), and the Lagrange's multiplier computed for current iteration (T) is defined as:

$$\lambda^T = \frac{J_N^{T-1}}{J_M^{T-1}}. \tag{19}$$

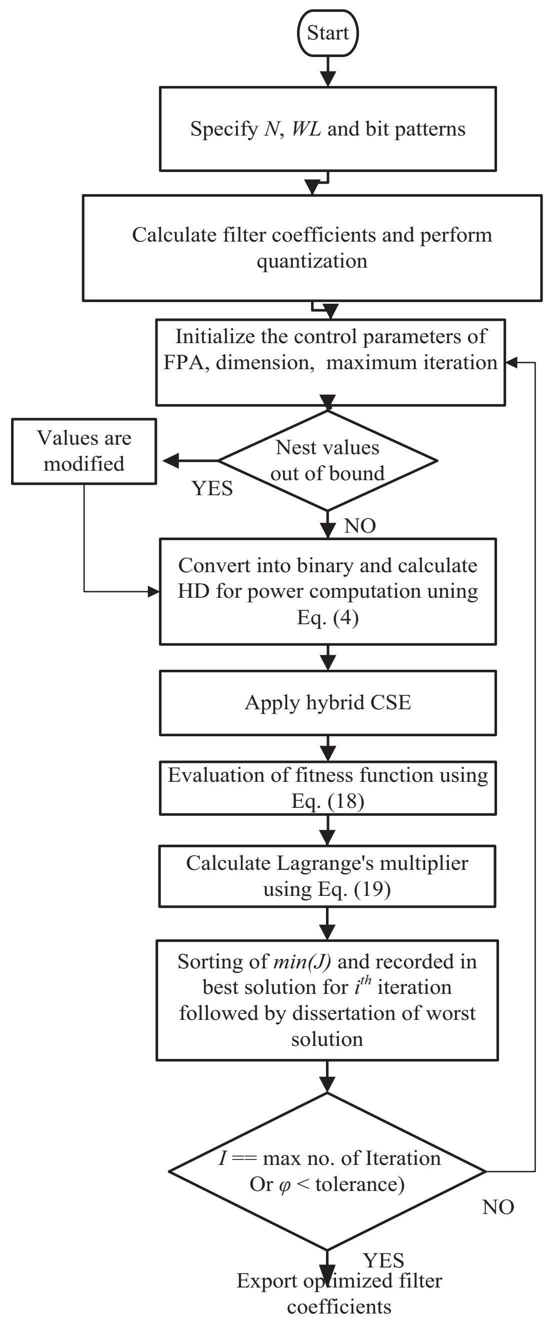
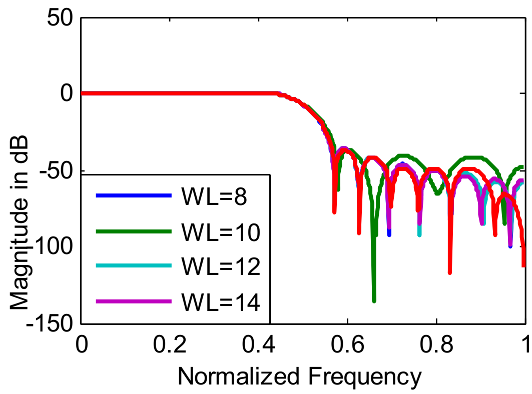
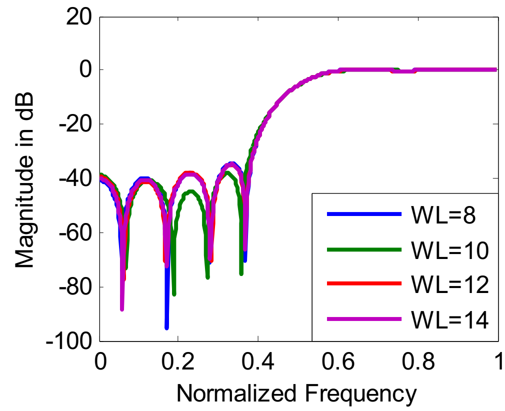


Fig. 1. A generalized flowchart of proposed methodology.



(a)



(b)

Fig. 2. Magnitude response of proposed filter designed using FPA for order 20 (a) LP-filter, (b) HP-filter.

Table 2
Performance of Low Pass filter designed using CSOA with different order and wordlength.

N	WL	A_S (in dB)	PBE (in dB)	SBE (in dB)	Power
	8	26.89	−51.87	−47.7864	5.1
20	10	27.72	−52.9	−48.7864	5.75
	12	27.03	−55.64	−48.3834	6.05
	14	27.41	−76.07	−47.2541	7.51
	8	17.96	−32.87	−33.05	3.7
30	10	18.55	−33.09	−33.18	3.8
	12	26.21	−52.62	−41.05	4.6
	14	26.91	−47.28	−42.61	6.5
	8	26.76	−54.81	−48.16	3.5
40	10	27.68	−54.05	−48.90	3.72
	12	41.35	−55.15	−49.85	4.40
	14	27.41	−55.23	−48.05	6.30

Table 3
Performance of Low Pass filter designed using PSO with different order and wordlength.

N	WL	A_S (in dB)	PBE (in dB)	SBE (in dB)	Power
	8	22.77	−20. 7	−27.74	6.1
20	10	22.91	−20.9	−28.4	6.5
	12	23.08	−31.4	−28.34	6.15
	14	24.01	−40.7	−27.21	6.72
	8	18.34	−22.7	−33.5	6.87
30	10	18.92	−23.9	−33.78	6.68
	12	22.14	−42.2	−41.24	6.46
	14	22.84	−47.8	−42.37	6.15
	8	26.47	−34.1	−48.2	7.1
40	10	27.23	−34.5	−48.8	6.32
	12	41.73	−35.5	−49.7	6.7
	14	27.75	−35.3	−48.1	7.20

Table 4
Performance of Low Pass filter designed using ABC with different order and wordlength.

N	WL	A_S (in dB)	PBE (in dB)	SBE (in dB)	Power
	8	22.1	−25.2	−30.24	7.8
20	10	23.2	-32.4	-32.5	7.1
	12	22.3	-33.54	-33.6	7.3
	14	22.48	−41.8	−39.4	7.7
	8	18.9	−31.15	−33.1	7.7
30	10	19.5	-32.26	-33.7	7.8
	12	21.1	−50.17	−41.5	7.2
	14	21.27	−49.25	−42.06	8.5
	8	23.14	−52.5	−48.5	7.5
40	10	23.47	−53.1	−48.33	7.2
	12	23.54	−54.6	−49.41	8.1
	14	29.27	−55.4	−48.12	8.51

Table 5
Performance of Low Pass filter designed using hybrid optimization with different order and wordlength.

N	*WL*	A_S (in dB)	PBE (in dB)	SBE (in dB)	Power
	8	26.41	−52.7	−46.17	5.1
20	10	26.612	−53.9	−45.36	5.75
	12	27.53	−54.4	−47.39	6.05
	14	28.421	−75.03	−48.24	7.51
	8	16.16	-33.7	-32.71	3.9
30	10	19.75	−34.9	−33.75	4.2
	12	27.09	−51.2	−42.05	4.7
	14	29.33	−48.8	−42.61	6.3
	8	27.18	−55.1	−48.16	4.5
40	10	29.34	−55.5	−48.90	4.72
	12	43.71	−57.14	−49.85	4.40
	14	37.09	−58.3	−48.05	5.30

Table 6
Performance of Low Pass filter designed using FPA with different order and wordlength.

N	WL	A_S (in dB)	PBE (in dB)	SBE (in dB)	Power
	8	29.6	−49.7	−50.78	5.1
20	10	29.85	−52.4	−49.8	5.05
	12	20.2	−55.13	−50.83	5.75
	14	30.34	−66.65	−51.54	7.84
	8	30.4	−51.2	−51.23	6.23
30	10	31.3	−51.64	−51.45	5.79
	12	31.57	−51.7	−52.74	5.6
	14	32.1	−52.1	−53.2	5.2
	8	31.5	−52.24	−52.4	5.66
40	10	32.41	−52.94	−53.1	5.09
	12	32.72	−53.35	−53.5	5.6
	14	32.9	−53.77	−57.9	5.8

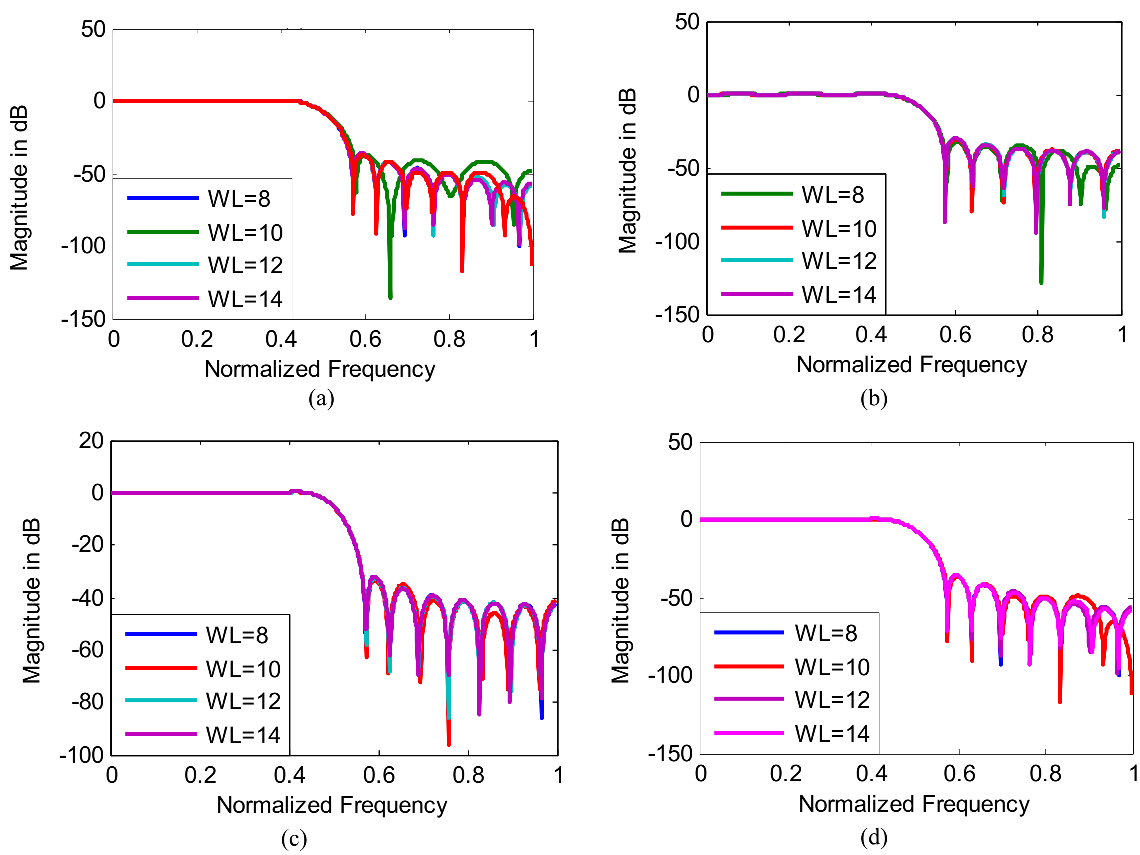


Fig. 3. Magnitude response of LP-FIR filter designed using proposed method for order 20 (a) using CSOA, (b) using PSO, (c) using ABC, and (d) using hybrid method.

Table 7
Performance of High Pass filter designed using CSOA with different order and wordlength.

N	WL	A_S (in dB)	PBE (in dB)	SBE (in dB)	Power
	8	25.9	−50.87	−47.64	5.2
20	10	26.1	−51.9	−48.64	5.8
	12	27.5	−54.64	−48.34	6.1
	14	27.54	−72.07	−47.41	7.21
	8	18.62	−32.7	−33.51	3.9
30	10	18.27	−33.1	−33.84	4.1
	12	25.45	−53.5	−42.55	4.6
	14	26.52	−48.4	−42.62	5.5
	8	26.47	−54.7	−48.15	4.51
40	10	28.25	−55.1	−48.92	4.2
	12	40.14	−55.3	−49.85	4.4
	14	29.75	−56.5	−49.04	6.5

Table 8
Performance of High Pass filter designed using PSO with different order and wordlength.

N	WL	A_S (in dB)	PBE (in dB)	SBE (in dB)	Power
	8	23.1	−22. 4	−26.7	6.41
20	10	23.6	−22.9	−27.14	6.51
	12	22.5	−31.4	−27.3	6.3
	14	23.3	−42.5	−28.1	6.4
	8	18.3	−22.7	−33.4	6.7
30	10	18.2	−23.8	−33.7	6.6
	12	22.74	−42.21	−41.4	6.6
	14	22.8	−47.4	−42.7	6.5
	8	26.77	−34.2	−48.1	7.2
40	10	27.23	−34.4	−48.5	6.2
	12	41.13	−35.6	−49.6	6.5
	14	27.74	−35.04	−48.2	7.2

Table 9
Performance of High Pass filter designed using ABC with different order and wordlength.

N	WL	A_S (in dB)	PBE (in dB)	SBE (in dB)	Power
	8	23.89	−34.2	−32.4	7.182
20	10	23.72	−33.7	−33.7	7.217
	12	23.03	−34.04	−34.34	7.35
	14	23.41	−41.1	−35.41	7.47
	8	17.49	−32.1	−33.1	7.27
30	10	18.25	−33.3	−33.7	7.81
	12	22.19	−52.2	−41.5	7.62
	14	22.7	−47.18	−42.06	8.35
	8	22.04	−54.45	−48.5	7.55
40	10	22.7	−54.71	−48.33	7.32
	12	28.4	−55.36	−49.41	8.102
	14	27.7	−55.4	−48.12	8.521

Table 10
Performance of Low Pass filter designed using hybrid optimization with different order and wordlength.

N	WL	A_S (in dB)	PBE (in dB)	SBE (in dB)	Power
	8	26.2	−51.2	−48.22	5.3
20	10	27.2	−52.13	−46.3	5.7
	12	27.5	−52.44	−47.2	6.5
	14	28.21	−75.2	−49.5	7.1
	8	17.5	−34.17	−32.71	3.8
30	10	19.8	−35.59	−33.75	4.1
	12	27.9	−50.62	−42.05	5
	14	29.4	−49.48	−42.61	6.2
	8	27.43	−55.21	−48.16	4.58
40	10	29.4	−55.65	−48.90	4.79
	12	44.5	−57.3	−49.85	4.8
	14	40.1	−58.74	−48.05	5.2

Table 11
Performance of Low Pass filter designed using FPA with different order and wordlength.

N	WL	A_S (in dB)	PBE (in dB)	SBE (in dB)	Power
	8	30.7	−51.7	−50.8	4.1
20	10	31.7	−55.4	−50.4	4.5
	12	30.9	−59.13	−51.3	5.72
	14	31.54	−66.67	−52.54	7.84
	8	30.4	−51.6	−51.6	5.6
30	10	30.87	−51.71	−52.49	5.69
	12	31.5	−51.9	−53.06	6.1
	14	31.71	−52.14	−53.14	6.2
	8	32.14	−52.5	−52.5	6.2
40	10	32.47	−53.1	−53.33	6.3
	12	32.49	−55.36	−53.41	6.32
	14	32.5	−55.4	−55.12	6.51

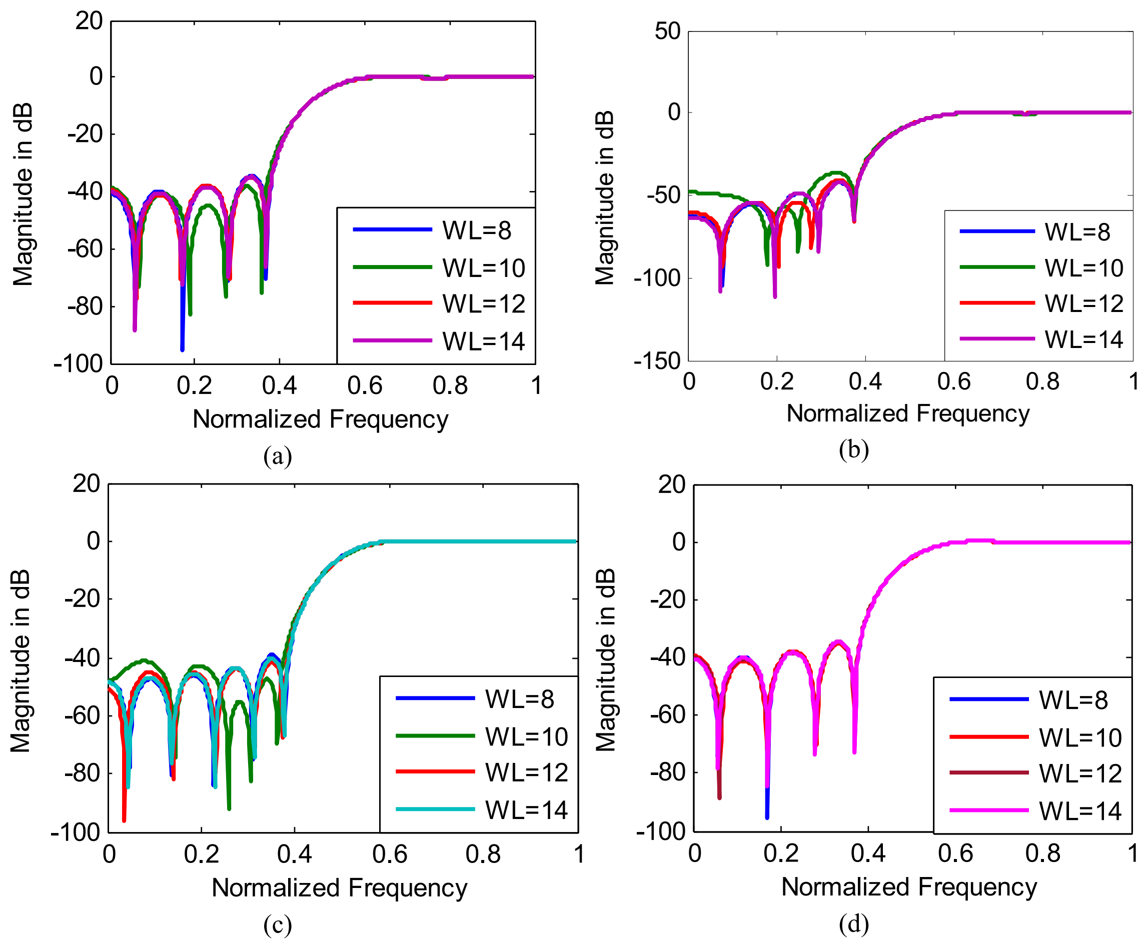


Fig. 4. Magnitude response of HP-FIR filter designed using proposed method for order 20 (a) using CSOA, (b) using PSO, (c) using ABC, and (d) using hybrid method.

Table 12
Impact of CSE on proposed filter designed by CSOA with different order and wordlength.

N	CSE	WL = 8	WL = 10	WL = 12	WL = 14
20	Vertical	21	28	26	30
	Horizontal	19	25	24	23
	Hybrid	18	25	21	22
30	Vertical	26	30	31	32
	Horizontal	25	26	29	29
	Hybrid	23	25	27	27
40	Vertical	28	30	32	33
	Horizontal	27	28	31	32
	Hybrid	28	28	29	31

Table 13
Impact of CSE on proposed filter designed by PSO with different order and wordlength.

N	CSE	*WL* = 8	*WL* = 10	*WL* = 12	*WL* = 14
20	Vertical	22	28	29	32
	Horizontal	20	26	28	29
	Hybrid	19	25	26	28
30	Vertical	25	30	31	33
	Horizontal	24	28	29	31
	Hybrid	25	26	27	30
40	Vertical	29	31	32	35
	Horizontal	27	29	30	34
	Hybrid	25	28	29	32

Table 14
Impact of CSE on proposed filter designed by ABC with different order and wordlength.

N	CSE	*WL* = 8	*WL* = 10	*WL* = 12	*WL* = 14
20	Vertical	22	26	28	30
	Horizontal	20	24	25	28
	Hybrid	19	23	26	22
30	Vertical	26	30	31	32
	Horizontal	26	28	29	30
	Hybrid	25	26	28	29
40	Vertical	29	32	33	34
	Horizontal	27	29	32	33
	Hybrid	26	30	30	31

Table 15
Impact of CSE on proposed filter designed by FPA with different order and wordlength.

N	CSE	*WL* = 8	*WL* = 10	*WL* = 12	*WL* = 14
20	Vertical	22	26	28	29
	Horizontal	19	25	26	27
	Hybrid	18	24	25	26
30	Vertical	26	31	32	33
	Horizontal	25	29	30	30
	Hybrid	23	28	29	30
40	Vertical	29	32	33	34
	Horizontal	28	30	31	30
	Hybrid	23	29	29	31

Table 16
Impact of CSE on proposed filter designed by hybrid method with different order and wordlength.

N	CSE	*WL* = 8	*WL* = 10	*WL* = 12	*WL* = 14
20	Vertical	20	26	27	30
	Horizontal	19	24	25	26
	Hybrid	18	25	26	27
30	Vertical	25	29	30	31
	Horizontal	24	27	28	29
	Hybrid	24	26	26	26
40	Vertical	27	30	31	32
	Horizontal	26	28	29	30
	Hybrid	25	27	28	29

Then hybrid CSE is employed for further reduction of adders counted on the occupancy of unpaired ones and shared sub-expressions. The flow chart of proposed methodology is given in Fig. 1.

5. Simulation results and discussion

In this section, results and discussion aroused using several design examples are discussed. LPF and HPF have been designed using proposed methodology using FPA, PSO, ABCE, CSOA and hybrid method.

A regress analysis is done using different *WL*, *N*, optimization techniques and CSE. The statically stability of the proposed method using FPA for designing LP and HP filter is also studied and shown in Fig. 2 (a) and (b), respectively. Each design example designed using proposed method for 30 times. The efficiency of the designed filter is tested on the basis of following fidelity parameters:

Stopband attenuation:

$$A_s = 20 \cdot \log_{10}\left(\left|H\left(e^{j\omega}\right)\right|\right)\Big|_{\omega=\omega_s}, \tag{20}$$

Passband error (PBE):

$$Er_{pb} = \frac{1}{N_{pb}} \sum_{\omega \in pb} e_{pb}(\omega), \tag{21}$$

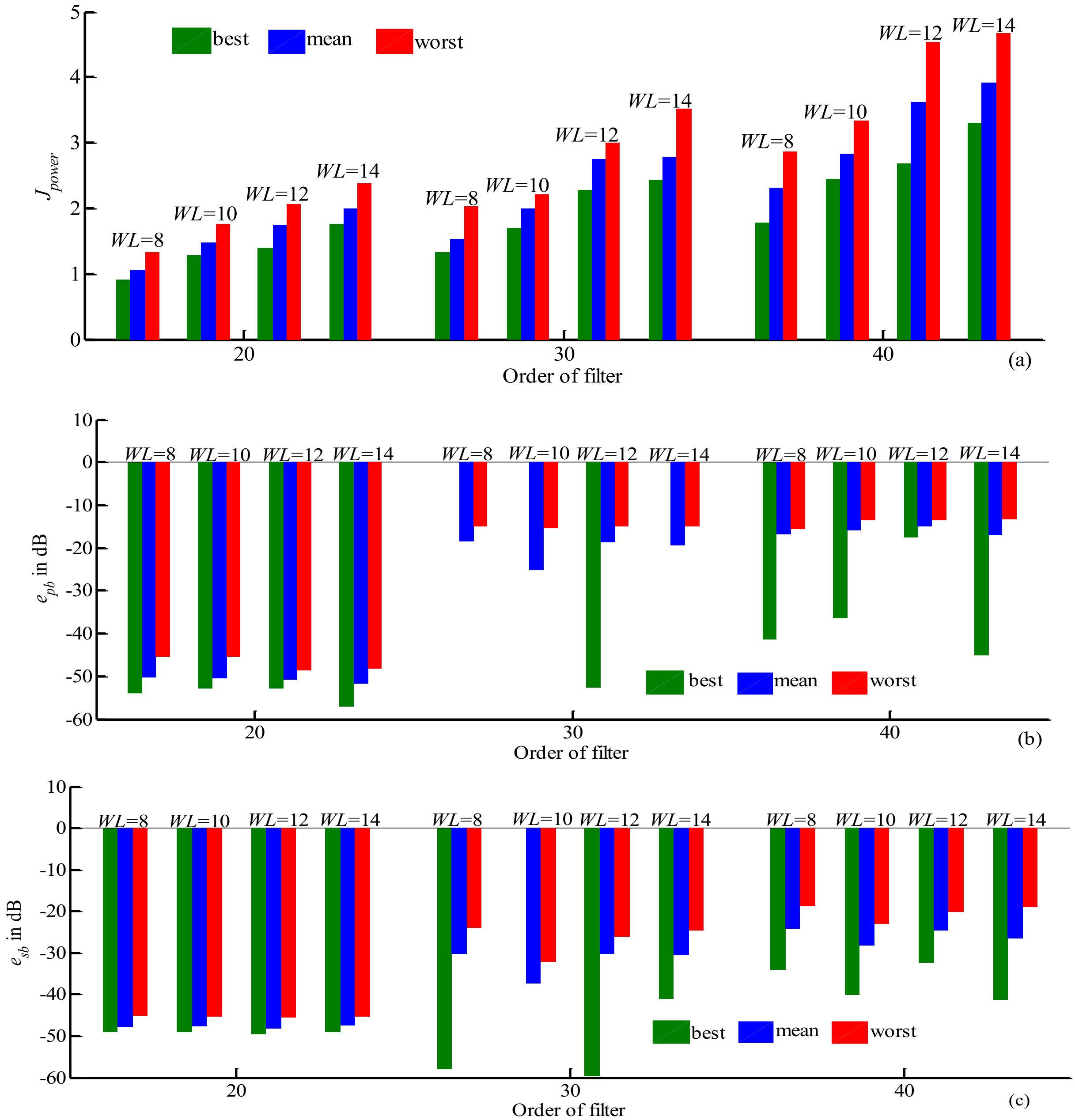


Fig. 5. Statistical performance evaluation of proposed methods for search space size of 30 on the basis of best, mean and worst values of (a) J_{power}, (b) e_{pb}, and (c) e_{sb}.

Stopband error (SBE):

$$Er_{sb} = \frac{1}{N_{sb}} \sum_{\omega \in sb} e_{sb}(\omega). \tag{22}$$

Example I:

FIR low pass filter (LPF) is designed using specifications given as pass band frequency 0.45π, stopband frequency = 0.55π, PBR = 0.1, SBR = 0.01, N = 20.

Analysis:

The resultant performance is summarized in Tables 2, 3, 4, 5, and 6, respectively, where different design examples of low pass FIR with different *WL* and *N* are tabularized, each for executing CSOA, PSO, ABC, and hybrid method, respectively as shown in Fig. 3.

Example II:

FIR high pass filter (HPF) is designed using the specifications given as passband frequency 0.55π, stopband frequency = 0.45π, PBR = 0.1, SBR = 0.01, N = 20.

Analysis:

The resultant performance is summarized in Tables 7–11, respectively, where different design examples of high pass FIR with different *WL* and *N* are tabularized each for executing CSOA, PSO, ABC, and, hybrid method, respectively as shown in Fig. 4.

It has observed that performance of proposed FPA based filter shows improved results in terms of PBE and SBE. Although, comparable performance is achieved between CSOA and FPA in terms of power and SBE. The overall performance can be summarized as FPA > CSOA > hybrid > ABC > PSO.

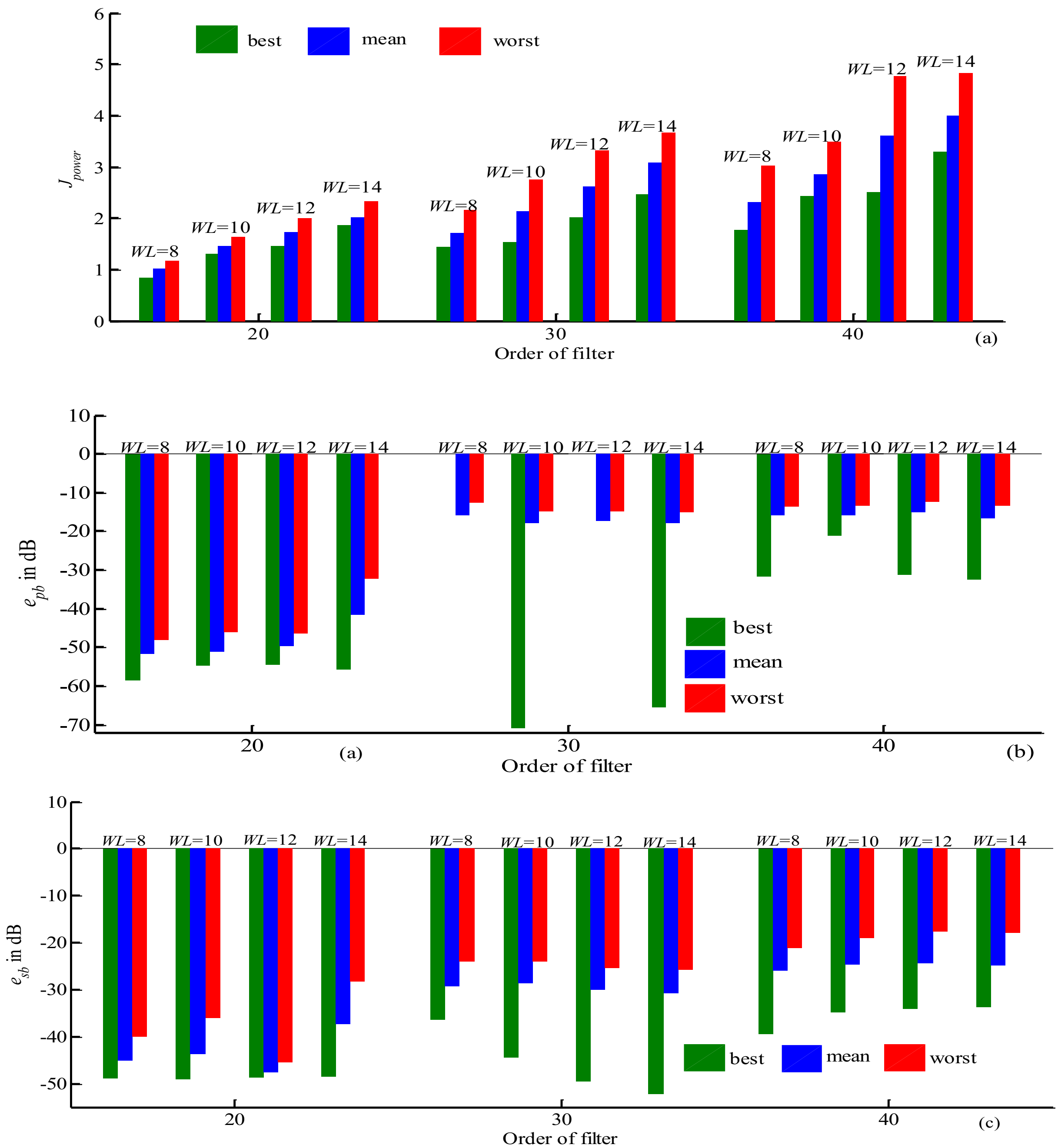


Fig. 6. Statistical performance evaluation of proposed methods for search space size of 40 on the basis of best, mean and worst values of (a) J_{power}, (b) e_{pb}, and (c) e_{sb}.

In Tables 12–16, performance of proposed filter using various CSE approaches is summarized. It has observed that for given *WL* and *N*, hybrid method yields grater saving of adders.

A regress statistical analysis on proposed methodology using FPA is also performed. For this purpose, firstly, search space of 30 is considered with different values of order and *WL*. Then resultant performance of power, passband error and stopband error is examined as shown in Fig. 5. It has observed that for each of orders given as 30, 40 and 50, the resultant power is varied, when size of *WL* is varied from *WL* = 8, to *WL* = 14.

In continuation to this, the performance of passband and stopband errors showed steady behaviour, as difference between best and worst value is very minute. Similar statistical analysis is performed on swarm size of 40 and 50 as shown in Figs. 6 and 7, respectively. It has observed that, excellent power and passband response is achieved using the swarm size of 50, and minimum passband error can be acquired with different *WL*. The statistical analysis also revealed that the proposed method is stable as consistent mean values of fidelity

6. Comparison with other methodologies

In this section, the proposed prototype is compared with other existing technique. A regress analysis has been done on FPA with other optimization technique given as CSOA, PSO, ABC and hybrid method, and the impact of sub-expression elimination algorithm is also deduced with different specifications. The comparison of obtained results using proposed methodology is also performed with other published

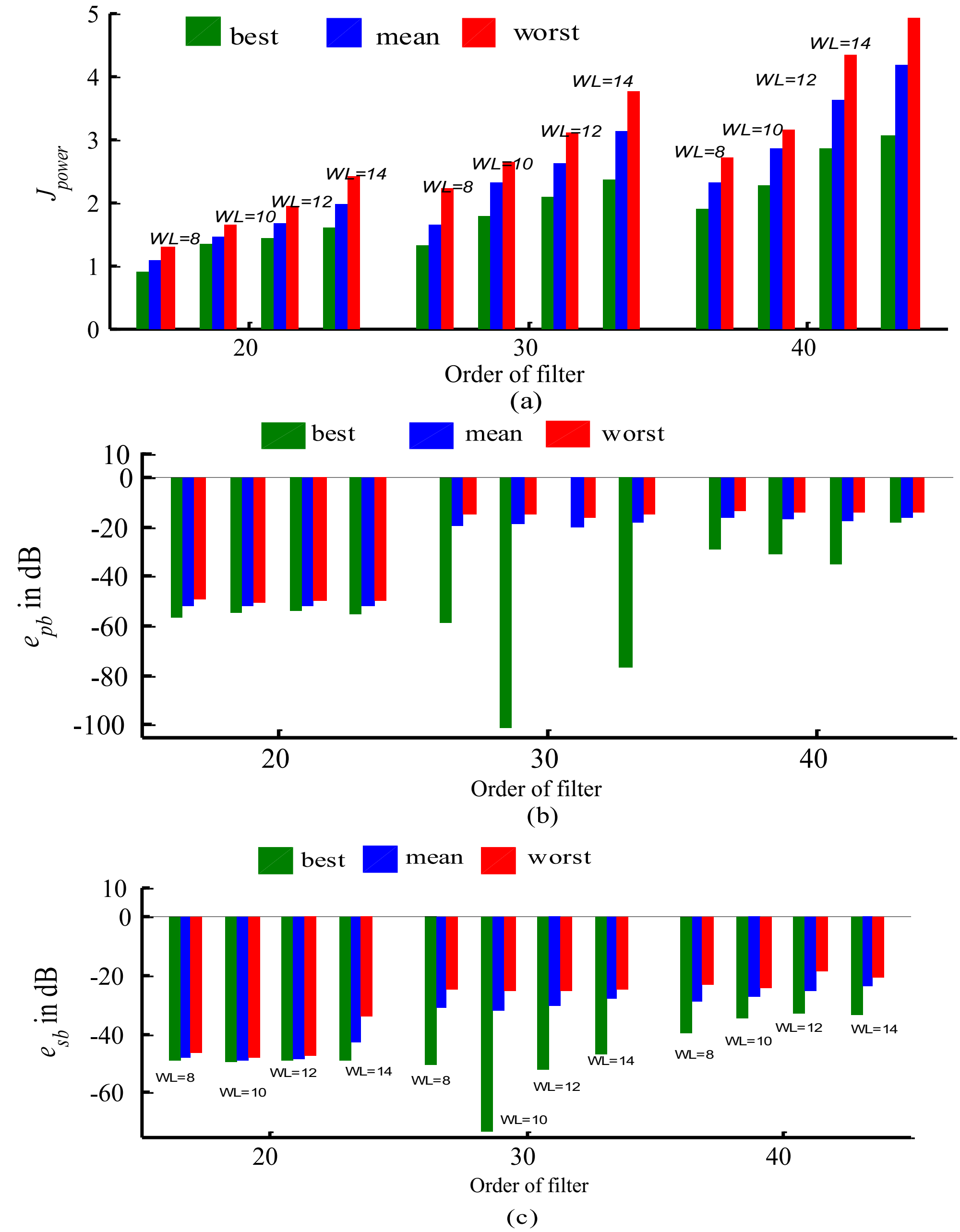


Fig. 7. Statistical performance evaluation of proposed methods for search space size of 50 on the basis of best, mean and worst values of (a) Jpower, (b) epb, and (c) es.

Table 17
Comparison of proposed filter in terms of adders.

Filter	N	WL	Total adder
Algorithm in [35]	33	13	79
Algorithm in [36]	29	12	57
Algorithm in [37]	28	8	56
Algorithm in [38]	28	11	54
Algorithm in [30]	28	11	54
Proposed	30	12	28
Proposed	30	14	29

algorithm and summarized in Tables 17 and 18, respectively. In Table 17, Formula for calculating adders has been taken from ref [31].

Firstly in Table 17, the performance is compared in terms of number of adders. Then secondly, in Table 18, the proposed prototype is compared in terms of power and other parameters. It can be observed that the designed filter shows good filter characteristics with significant improvement in utilization of resources. Thus, it can be concluded that the proposed prototype achieves better reduction of overall resource i.e. power and adders.

Table 18
Comparison of proposed filter in terms of performance parameter.

Filter	N	PBR	SBR	A_S	HD
Algo in [20]	21	1.037	0.071	0.071	
Algo in [22]	21	0.1400	0.0174	35.1623	8.2813
Algo in [38]	21	0.0664	0.0665	23.5400	8.7188
Algo in [39]	21	0.1640	0.0198	28.8603	8.9375
Algo in [38,39]	21	0.1142	0.0495	26.1100	9.0313
Algo in [40]	21	0.075	0.071	0.071	
Algo in [41]	21	0.04	−0.063	–	–
Algo in [42]	21	0.0577	0.0156	28.8603	–
Proposed	21	0.1620	0.0010	27. 7726	3.8000
Proposed	21	0.0207	0.0139	28.5562	3.7237

7. Conclusion

In this paper, an optimal design of low power FIR filter with improved adder efficiency is presented. The novelty of proposed algorithm is its single optimization approach to resolve three different issues of power minimization, namely given as, multiplierless realization and adder minimization, switching activity minimization through hamming distance minimization and finally, achieving desired filtering performance by optimizing quantized and converted filter coefficients. FPA is exploited with improved fitness functions constructed in frequency domain as mean squared error of designed and desired filter response. The minima of an objective function is achieved, constructed as sum of integral mean squared error to control ripples in passband and stopband region with allowable tolerable limits and the dynamic power due to switching activity. A comparative analysis of different optimization technique such as PSO, ABC, CSA, hybrid method along with FPA is also illustrated and summarized as. FPA > CSOA > hybrid > ABC > PSO. Finally, the newly proposed hybrid CSE has been demonstrated as a most significant one to minimize the resulted quantity of adders among others CSE.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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