Optimization of Control Parameters of Differential Evolution Technique for the Design of FIR Pulse-shaping Filter in QPSK Modulated System

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***Abstract*—Signal Processing in modern era, involves rigorous applications of various evolutionary algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Differential Evolution (DE) for the optimized design of aerodynamic shape, automated mirror, digital filter, computational intelligence etc. DE has been judged to be quite effective in designing different types of digital filter with good convergence behavior. The performance of the DE optimization technique could be improved to a further extent if the values of the two control parameters namely "Weighting Factor" and "Crossover Probability", be chosen properly. In this paper, the effect of these two control parameters on the design of low pass FIR digital filter has extensively been studied. The impact of these control parameters on the convergence behavior of the DE technique has also been presented. The performance of the DE optimized filter has been adjudicated in terms of its magnitude and impulse responses. In addition, the DE optimized filter has been utilized as a pulse-shaping filter in a Quadrature Phase Shift Keying (QPSK) modulated system and its performance has further been studied in terms of Bit Error Rate (BER). Finally, the optimized values of the ''Weighting Factor'' and "Crossover Probability" for this specific modulated system design problem has been recommended. Experimentally measured Eye diagrams have also confirmed the optimized values.**

***Index Terms*—Cost Function, Crossover Probability, DE, Eye diagram, Finite-Duration Impulse Response (FIR) filter, Pulse-Shaping Filter, Weighting Factor.**

I. Introduction

Digital Filters are frequency selective systems, which are used to pass a certain range of frequency and to stop another range of frequency. They are actually characterized by their impulse responses. Depending upon the duration of the impulse response, digital filters are classified as Finite-Duration Impulse Response (FIR) and Infinite-Duration Impulse Response (IIR) filters. Stable and linear phase FIR filter can be implemented quite easily under certain constraints [1]-[3]. These properties of FIR filter make it very much attractive for use in various digital communication systems. In mobile communication system, different types of FIR filters are being used as a transmitting pulse-shaping filter [4].

Different techniques have been used for the design of FIR filter, which includes window-based method, frequency sampling method and Parks-McClellan equiripple algorithm [1]. Of late, various evolutionary algorithms are also being used for this purpose.

An FIR filter design process using Genetic Algorithm (GA) has been presented in [5]. It requires a minimum number of GA parameter adjustments and the main part has been developed using the Gallops GA tool [6]. The frequency response of the designed FIR filter shows that for short transition band, it can be an alternative to the Parks-McClellan method [7]. It has also been mentioned in [5] that the design tool works well for symmetric, anti-symmetric, odd and even order FIR filters.

The design of low-pass and band-pass FIR digital filters using Particle Swarm Optimization (PSO) has been presented in [8]. In this paper, the utility of various error norms namely Least Mean Square (LMS) and Minimax along with their impact on the convergence behavior of the optimization technique has been focused. Finally, it has been established that PSO using Minimax strategy offers faster convergence speed than LMS strategy [8].

Shing-Tai Pan et.al. [9] have emphasized on the application of Differential Evolution (DE) algorithm for the design of robust and stable digital filter. It has been established that the performance of DE is much superior to that of GA in terms of the convergence behavior in the context of filter design problem with due consideration of robust stability.

Manuscript received January 31, 2011; revised April 25, 2011; accepted June 5, 2011.

doi:10.4304/jcm.6.7.558-570

The design of a linear-phase low-pass FIR filter using DE algorithm has also been described in [10]. The designed low-pass filter has further been extended as a pulse-shaping filter in a Quadrature Phase Shift Keying (QPSK) modulated system and the resulting system performance has been studied by means of various performance parameters such as Error Vector Magnitude (EVM), Signal to Noise Ratio (SNR) and Waveform Quality Factor. It has also been established that the proposed filter outperforms the standard Raised Cosine (RC) and Root Raised Cosine (RRC) filters in terms of the above mentioned parameters.

An efficient technique for adapting control parameter settings, associated with DE has been described in [11]. The algorithm presented in this paper shows good performance on numerical benchmark problems. It has been established that the self-adaptive control parameter setting algorithm performs better than or at least comparable to standard DE and other evolutionary algorithms found in the literature, as far as the quality of the solution is concerned.

The impact of the Weighting Factor on the convergence behavior of the DE algorithm for the design of low-pass filter has been critically studied in [12]. The performance of the designed filter has properly been analyzed and also been measured practically. From the experimental results, it has been established that the FIR filter designed with a Weighting Factor value of 0.7 gives the best performance in terms of convergence speed, magnitude response, impulse response and other performance parameters.

In this paper, we have critically studied the impact of two very important control parameters associated with DE, i.e., “Weighting Factor” and “Crossover Probability” on the convergence behavior of the algorithm for efficient design of low-pass FIR filter. The effect of these parameters on the performance of FIR pulse-shaping filter has also been evaluated in QPSK modulated system. The magnitude response, the impulse response and the Bit Error rate (BER) have mainly been measured with different combinations of “Weighting Factor” (F) and “Crossover Probability” (CR).

II. Theoretical Background

A. Differential Evolution

A new floating-point encoded DE algorithm for global optimization has been proposed by Storn and Price [13]. The effectiveness, efficiency and robustness of the DE algorithms are greatly dependent on the settings of the few control parameters [14]. The fundamental characteristics of evolutionary algorithm dictate that each population member should undergo initialization, mutation, recombination and selection processes, during each iteration [15].

The process of mutation expands the search space, where a mutant vector is generated in accordance with the following equation [15]:

$$v_{i,G+1} = x_{r_1,G} + F(x_{r_2,G} - x_{r_3,G}); i = 1,2,\ldots..,P \quad (1)$$

where $x_{r_i,G}$ are the parameter vectors of the previous generation, $v_{i,G+1}$ is the mutant vector of the current generation and P is the total number of populations.

During the process of recombination, the elements of the donor vector enter the trial vector with a certain probability, named crossover probability. Thus the trial vector $u_{i,G+1}$ is of the form [15]:

$$u_{j,i,G+1} = \begin{cases} v_{j,i,G+1} & iff \;\; rand_{j,i} \le CR \vee j = I_{rand} \\ x_{j,i,G} & iff \;\; rand_{j,i} > CR \wedge j \ne I_{rand} \end{cases} \quad (2)$$

with $i = 1,2,\ldots,P$, $j = 1,2,\ldots,D$ and $rand_{j,i}$ is a random number within the set [0, 1] that has to be generated in each iteration of the algorithm for each population member and for each of the parameters that we want to optimize.

In the final step of DE, the trial vector is compared with the target vector of previous generation and the one with lower cost function is permitted to make an entry to the next generation. This has been summarized mathematically as follows [15]:

$$x_{i,G+1} = \begin{cases} u_{i,G+1} & iff \quad f(u_{i,G+1}) \le f(x_{i,G}) \\ x_{i,G} & iff \quad f(u_{i,G+1}) > f(x_{i,G}) \end{cases} \quad (3)$$

There are only two control parameters associated with the traditional DE algorithm. The choice of these two parameters, namely mutation control parameter and recombination control parameter, is very important in any design problem incorporating DE. It has been found in the literature that the value of mutation control parameter is more sensitive than the other.

Various methods of adapting two important control parameters of DE algorithm have been reported in [16]-[20]. A Self Adaptive Differential Evolution (SADE) has been proposed in [16] where an appropriate learning strategy and suitable control parameters have been self-adapted in accordance with some learning experience. Another new version of DE called Fuzzy Adaptive Differential Evolution (FADE) has been reported in [17] to control the DE parameters dynamically in a more efficient manner than traditional DE. Different versions of adaptive and self-adaptive DE algorithm have been compared in [18]. The comparison results show that the jDE algorithm performs better than FADE and DESAP algorithms and self-adaptive jDE-2 algorithm gives comparable result on benchmark functions as SADE algorithm. Different opinions regarding the choice of control parameters associated with DE technique have been discussed in [19]-[20] where it has been mentioned that DE algorithm is much more sensitive to the choice of weighting factor than the others. Determination of the suitable values for the control parameters of DE algorithm, for a particular design problem is still a vast area of research.

The work carried out in [15] has not considered the variation of the control parameters to judge the performance of the application. Thus, from application point of view it is incomplete. In our work, we have further extended the ideas described in [15] to find out the optimized values of the two useful control parameters of DE algorithm applied to filter design problem, namely "Weighting Factor" and "Crossover Probability" in a particular fashion, which is widely different from those described in [16]-[20]. In order to accommodate the practical aspect of this design problem, it has been successfully used as a pulse-shaping filter in a QPSK modulated system and its performance has been studied. From this study, it has been established that the filter designed with the optimized values of the control parameters of DE algorithm also performs quite satisfactorily as a pulse-shaping filter in a QPSK modulated system.

B. Role of Pulse-shaping filter in communication system

In digital communication system, the symbols are transmitted in the form of different pulses over a band limited channel. However, due to practical channel impairment there is considerable spreading of these pulses in the time domain resulting in interference amongst the transmitted symbols. This phenomenon, well known as Inter Symbol Interference (ISI) is mainly responsible for making the overall system performance to deteriorate. Elimination of this interference as far as practicable, is of primary concern to the digital communication system designer [21]-[22]. The pulse-shaping technique has been used extensively in reducing system ISI to a great extent and thereby resulting in lower BER values.

Pulse shaping is usually done at the transmitter end prior to the digital modulation by means of a pulse-shaping filter [21]-[22]. In order to make a digital filter to act as a proper pulse-shaping filter, it has to satisfy the Nyquist minimum bandwidth criterion to ensure near zero ISI under the worst-case condition. Thus the transfer function of the Nyquist minimum bandwidth filter can be represented mathematically as follows [21]-[22]:

$$H_{Nyquist}(e^{j\omega}) = \begin{cases} 1, & 0 \le \omega \le \omega_{Nyquist} \\ 0, & \omega_{Nyquist} \le \omega \le \pi \end{cases} \tag{4}$$

where $\omega_{Nyquist} = 2\pi . f_{Nyquist}$ is the cut-off frequency in rad/pi and $f_{Nyquist} = f_s / 2$ is the cut-off frequency in Hz of the Nyquist filter and f_s is the symbol rate of the input data in Hz. The minimum bandwidth Nyquist filter is actually an ideal, brick-wall low pass filter that requires an infinite number of filter sections to synthesize the sharp attenuation slope in the stop band. This concept is very difficult to realize in practice. The practically realizable pulse shaping filters used in various digital communication systems include Raised Cosine (RC) and Root Raised Cosine (RRC) pulse shaping filters [21]-[22]. These filters can be realized with a finite number of filter sections and hence are widely accepted as a pulse-shaping filter in practice [23].

III. Problem Formulation

The main objective of this work has been to utilize DE technique to find out the optimum solution vector $\vec{h}_{opt}$ of dimension D over the search space S^D that can well represent the impulse response of a linear-phase low-pass FIR filter. The optimization procedure has been carried out in such a way that it takes care of the impact of various control parameters of DE. Mathematically, the choice of $\vec{h}_{opt}$ has been outlined as:

$$\Im(\overrightarrow{\mathrm{h}_{\mathrm{opt,F_{opt}},CR_{opt}}}) < \Im(\overrightarrow{\mathrm{h}_{\mathrm{F_{opt}},CR_{opt}}})$$

$$\forall\ \vec{h}, \overrightarrow{h_{opt}} \in \{S^D\} \tag{5}$$

where $\Im()$ signifies the associated cost function. Equation (5) has been implemented by considering the effect of two control parameters of DE, i.e. "Weighting Factor" (F) and "Crossover Probability" (CR). Since DE is more sensitive to the choice of Weighting Factor, it has been optimized first prior to the optimization of "Crossover Probability". The optimum value of "Weighting Factor" F_{opt}, from a vector of sample Weighting Factors $F_S = [F_1, F_2, \ldots.., F_{m_1}]$ has been located according to:

$$\Im(\overrightarrow{\mathrm{h}_{\mathrm{opt,F,CR_{nom}}}})\Big\|_{\mathrm{F_{opt}}} < \Im(\overrightarrow{\mathrm{h}_{\mathrm{F,CR_{nom}}}})\Big\|_{\hat{\mathrm{F}}}$$

$$\exists\ F_{opt} \ne \hat{F}\ \& F_{opt}, \hat{F} \in F_S \tag{6}$$

In the above equation, the value of the Crossover Probability has been kept at its nominal value CR_{nom}. Thereafter, the value of F_{opt} has been employed in place of Weighting Factor in order to find out the most favorable value of Crossover Probability for this specific filter design problem. Selection of the most suitable Crossover Probability has been made from a vector of sample Crossover Probabilities $CR_S = [CR_1, CR_2, \ldots.., CR_{m_2}]$. The necessary scheme has been illustrated as:

$$\Im(\overrightarrow{\mathrm{h}_{\mathrm{opt,F_{opt}},CR}})\Big\|_{\mathrm{CR_{opt}}} < \Im(\overrightarrow{\mathrm{h}_{\mathrm{F_{opt}},CR}})\Big\|_{\hat{\mathrm{CR}}}$$

$$\exists\, CR_{opt} \neq \hat{CR} \;\&\, CR_{opt}, \hat{CR} \in CR_S \quad (7)$$

The values of F_{opt} and CR_{opt}, as obtained from Equations (6) and (7) respectively, represent the optimum values of the two control parameters for this specific filter design problem.

The termination of any optimization process is largely determined by the choice of the cost function, associated with it. This paper attempts to observe the impact of control parameters on the effective design of low-pass FIR filter. Hence, the deviation of the magnitude response of the designed filter from that of the ideal one has been considered as a metric to realize the cost function of the design methodology.

The ideal frequency response of a low pass digital filter is given by the following equation [1], [21]:

$$H_{ideal}(e^{j\omega}) = \begin{cases} 1; & 0 \le \omega \le \omega_c \\ 0; & \omega_c \le \omega \le \pi \end{cases} \quad (8)$$

If the impulse response of the digital filter is of finite duration, then the transfer function of such a filter is related to its impulse response as shown [1], [21]:

$$H_{ideal}(e^{j\omega}) = \sum_{n=0}^{L} h_{ideal}[n] e^{-j\omega n} \quad (9)$$

where $h_{ideal}[n]$ is the impulse response of the ideal FIR filter of length L+1.

When the ideal frequency response is sampled in the frequency domain at an equal interval, the resultant sampled frequency response is of the following form :

$$H_{ideal}(k) = \left| H_{ideal}(e^{j\omega_k}) \right|, \omega_k = k\pi / N, \quad k = 1,2,\ldots..,N \quad (10)$$

where N is the number of frequency samples.

DE technique can be used to find the impulse response of the low pass FIR digital filter. Let h (n) denotes the impulse response of the FIR filter obtained using the optimization technique. Then the resulting frequency response of the designed filter can be characterized mathematically as follows [1]:

$$H(e^{j\omega}) = \sum_{n=0}^{L} h[n] e^{-j\omega n} \quad (11)$$

The frequency-sampled version of the designed filter is defined by:

$$H(k) = \left| H(e^{j\omega_k}) \right|, \omega_k = k\pi / N \;\; k = 1,2,\ldots..,N \quad (12)$$

The value of the sampled error function between the desired magnitude response and the DE obtained magnitude response at any frequency is given by:

$$E(k) = \left| H_{ideal}(k) - H(k) \right|, \; k = 1,2,\ldots..,N \quad (13)$$

If the error value is lower, the actual magnitude response is closer to the ideal one. This can be achieved by using DE algorithm wisely. In our design problem, we have used the minimax error as the averaged cost function for the DE optimization technique. Here our goal is first to find out the maximum value of the sampled error function for all the members of the population and then to identify that particular member which yields the minimum of these maximum error values. So, the minimax error can now be written mathematically

$$Error = \max\{E(k)\}, \; k = 1,2,\ldots..,N \quad (14)$$

$$Minimax Error = \min\{Error(i)\}, \; i = 1,2,\ldots..,P \quad (15)$$

Using (11), (13) and (14), equation (15) can be rewritten as:

$$Error = \max\{\sum_{j=1}^{N} \left| H_{ideal}(e^{jw_j}) - H(e^{jw_j}) \right|\} \quad (16)$$

where P is the number of populations and N is the total number of frequency samples. The primary objective behind this work is to reduce the error under the worst-case condition.

Based on the above mathematical model, the developed algorithm has been presented below:

Step 1: Choose the length of the FIR filter and the value of the cut-off frequency.
Step 2: Initialize the size of population, maximum iteration number, mutation strategy, crossover scheme, value of the weighting factor & crossover probability, threshold value of the cost function and initial value of each element of the population vector.
Step 3: Allow the process of mutation, crossover and selection to occur subsequently between the members of the population.
Step 4: Go to step 3 until and unless the value of the averaged cost function is less than the threshold specified during the initialization phase.
Step 5: Identify the member of the population yielding the minimum cost function and accept it as the impulse response of the designed FIR filter.

Various parameters of the above mentioned algorithm have been selected as follows:

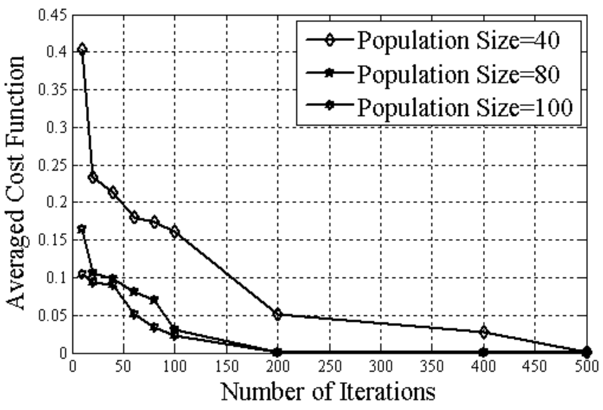
Length of the FIR filter: 8
Value of the cut-off frequency: 0.5 rad /pi
Size of population: Three different population sizes, namely 40, 80 and 100.
Maximum iteration number: Nine different iteration numbers, namely 10, 20, 40, 60, 80, 100, 200, 400 and 500.
Mutation strategy: DE/rand/1
Crossover scheme: Binary
Sample value of the Weighting Factor: Four different

sample values, namely 0.3, 0.5, 0.7 and 1.0.
Sample value of the Crossover Probability: Four different sample values, namely 0.3, 0.5, 0.7 and 0.9.
Threshold value of the cost function: 0.0001
Initial value of each element of population vector: From the set [-1, 1].

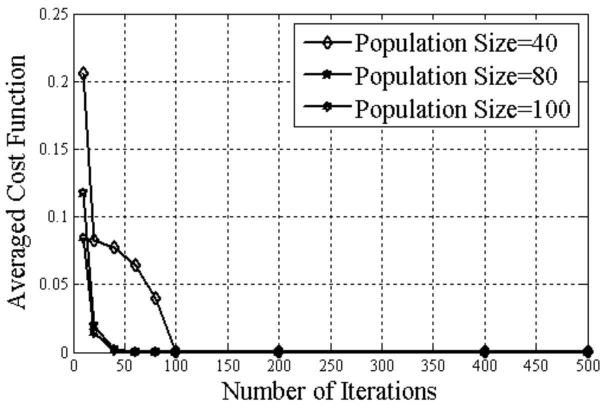
IV. Simulation Results

Fig. 1 represents the convergence behavior of the DE optimization technique for four different values of Weighting Factors (F), namely 0.3, 0.5, 0.7 and 1.0 for a specific Crossover Probability of 0.5, using minimax error as the averaged cost function.

The comparison of the figures below shows that for F=0.3, the curves for the averaged cost function need a large number of iterations to converge for all the specified population sizes. When the value of the F is increased to 0.5, the algorithm needs only one fifth of its iterations to converge. This is a great achievement in respect of convergence speed of the DE algorithm. Further improvement in the convergence speed is observed when the value of the Weighting Factor (F) is increased from 0.5 to 0.7. However, if the value of F is increased further to 1.0, there is hardly any improvement in the convergence speed of the algorithm. Accordingly for the FIR pulse-shaping filter design problem, the optimized value of Weighting Factor (F) can now be recommended as 0.7 irrespective of Population sizes.



(a)



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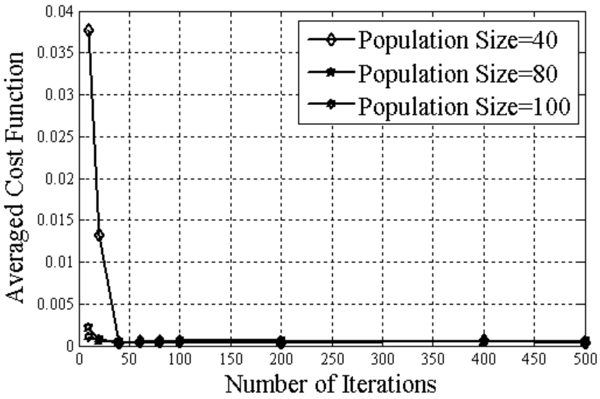

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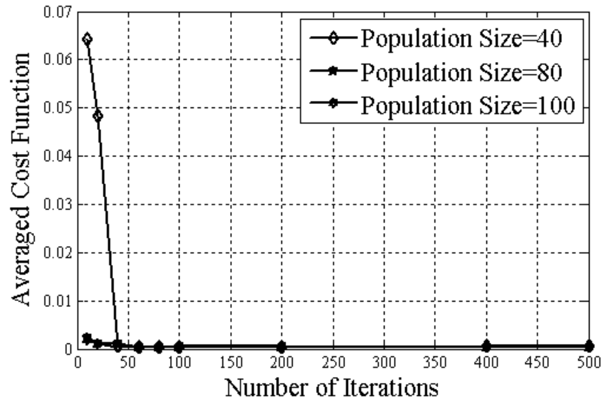


(d)

Figure 1. Convergence behavior of DE in design of low-pass FIR filter with CR=0.5 (a) F = 0.3 (b) F=0.5, (c) F=0.7 and (d) F=1.0

The above results can conveniently be summarized in a much compact form by plotting the variation of averaged cost function with Weighting Factor F as shown in Fig. 2. Fig. 2 confirms the fact that the lowest value of the averaged cost function i.e. error value is obtained for F=0.7, after which there is hardly any variation in the averaged cost function value.

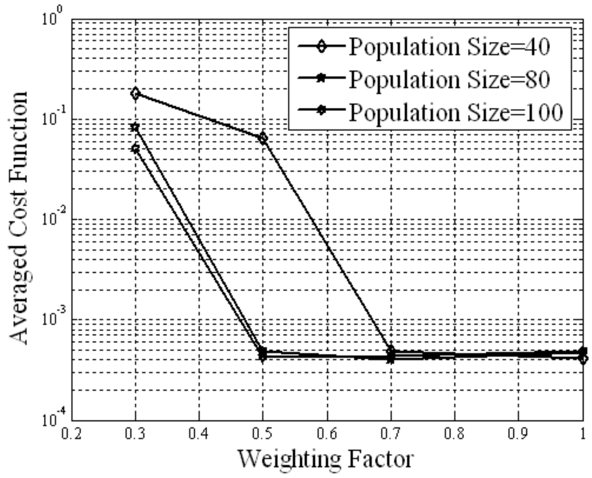
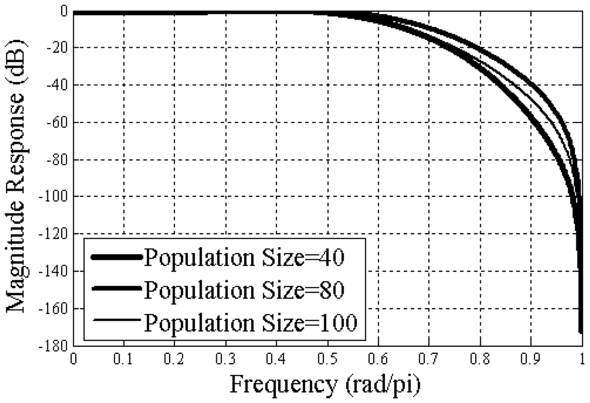
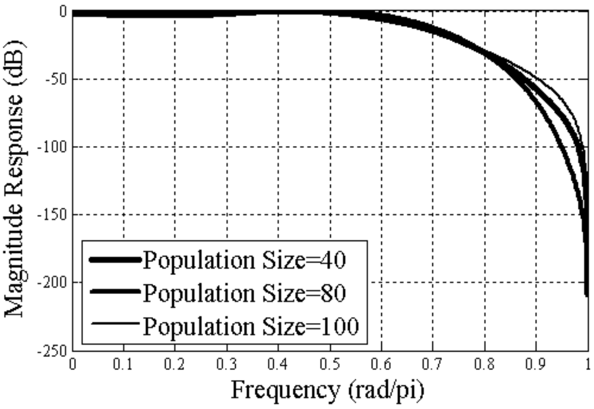


Figure 2. Variation of averaged cost function with Weighting Factor (F)

The performance of the FIR filter with the variation of F has been analyzed by plotting the magnitude response of the filter as shown in Fig. 3 with number of iterations being 100.



(a)



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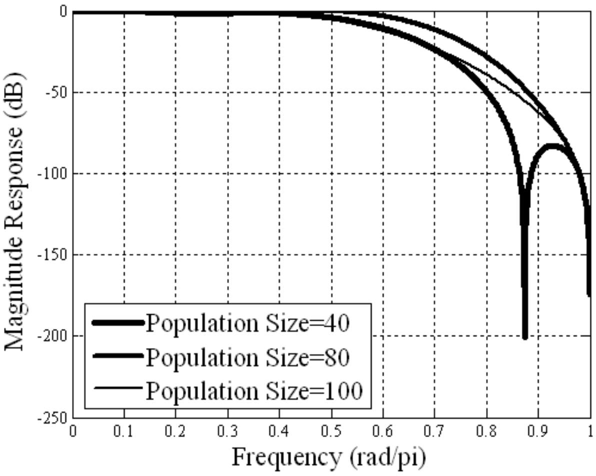

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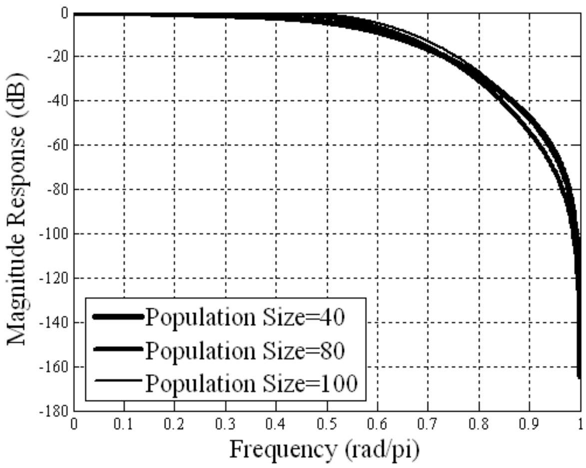


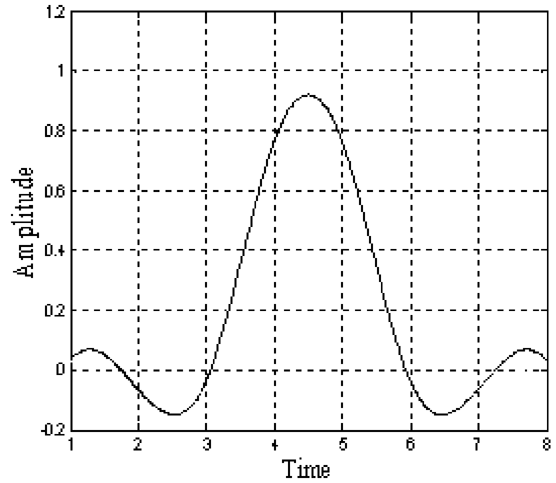
(d)

Figure 3. Magnitude response of designed low-pass FIR filter with CR=0.5 (a) F=0.3 (b) F=0.5 (c) F=0.7 (d) F=1.0

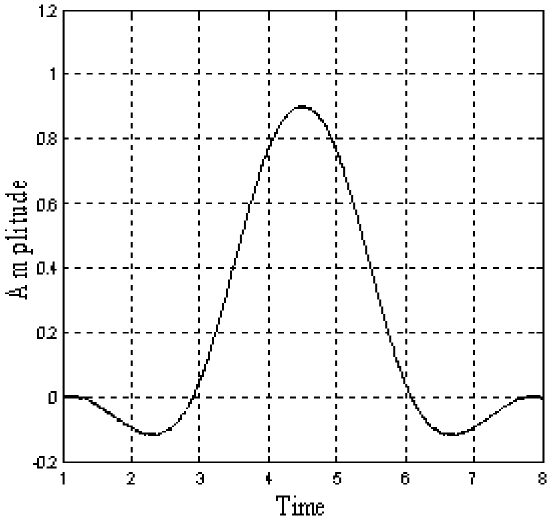
From the above figures, it can be clearly seen that the designed low-pass FIR filter shows better performance in terms of attenuation in the stop band, when the value of F is set to 0.7. More explicitly, when F is equal to 0.5 or 1.0, the maximum attenuation at a frequency of 0.8 rad/pi is almost equal to 30 dB. Whereas, for F = 0.7, the maximum attenuation at the same frequency is approximately found to be 50 dB. However, in terms of the performance in the pass band, FIR filter designed with the maximum population size exhibits a response, which is very close to the ideal one irrespective of the values of the Weighting Factor. Thus from these magnitude response plots we can infer that when the Weighting Factor (F) is set to a value of 0.7, the low-pass FIR filter shows the best result. Hence from the performance point of view, the optimized value of F is to be considered as 0.7 for the efficient design of low-pass FIR filter.

The performance of the FIR filter has also been evaluated in terms of its impulse response. The nature of the impulse response of the designed low-pass FIR filter for three different values of the Weighting Factor (F) has been depicted in Fig. 4 each for population size (P) = 100 and number of iterations (I) of 100.

From the figures below it is quite evident that the impulse response of the FIR filter with F = 0.7 gives the best result as it shows less amount of side lobe variation compared to others. Less number of side lobes with smaller amplitude will result in a lower value of ISI if the DE optimized FIR filter with F=0.7 is used as a pulse-shaping filter in a QPSK modulated system.



(a)



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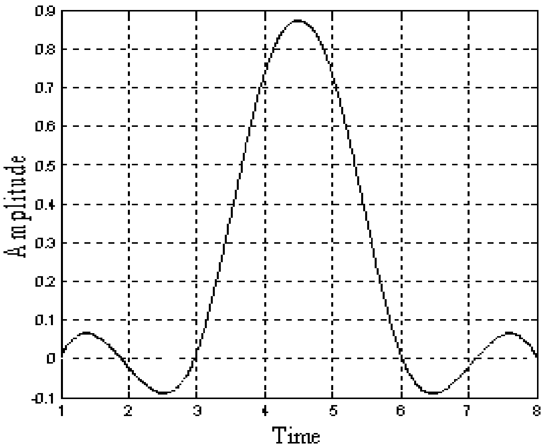

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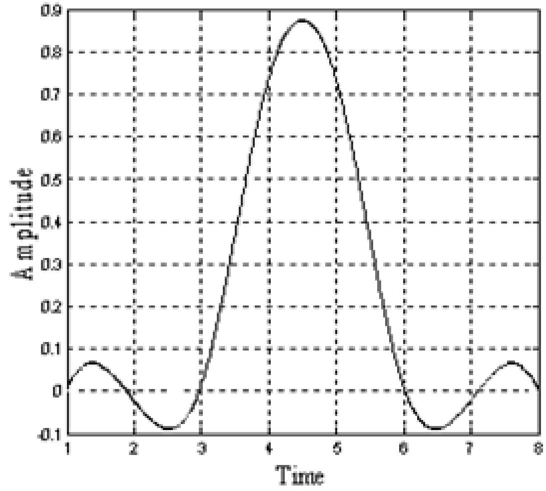
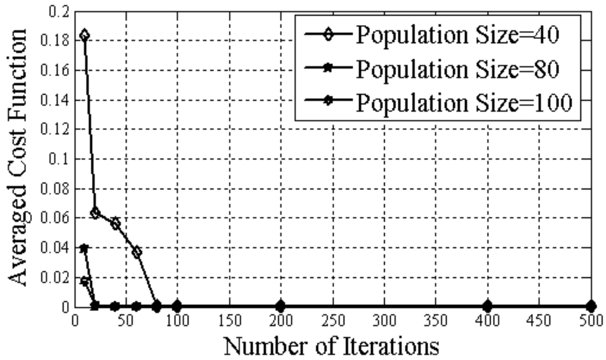


(d)

Figure 4. Impulse response of the designed low-pass filter with CR=0.5 (a) F = 0.3 (b) F=0.5, (c) F=0.7 and (d) F=1.0

Keeping the control parameter F at its optimized value of 0.7, the impact of another control parameter, namely Crossover Probability (CR) on the convergence behavior of the DE algorithm has next been studied, as presented in Fig. 5.



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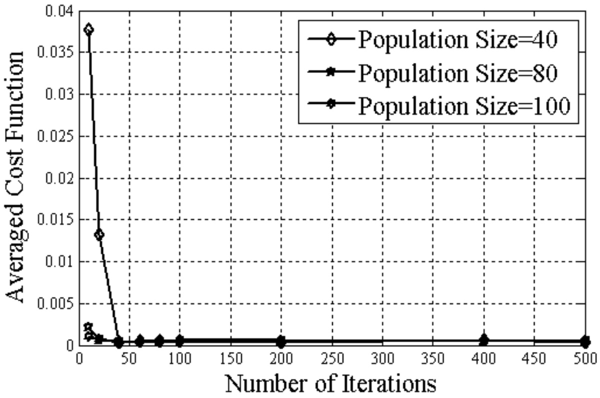

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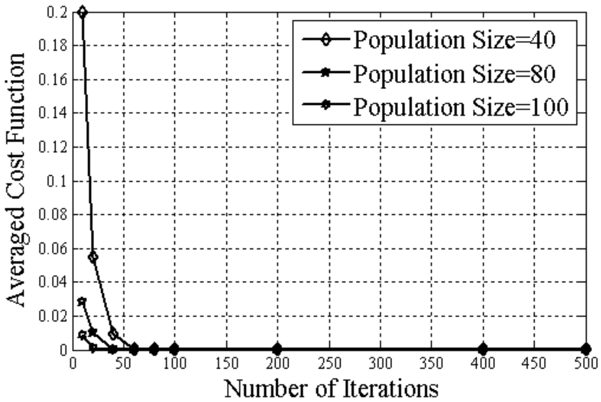

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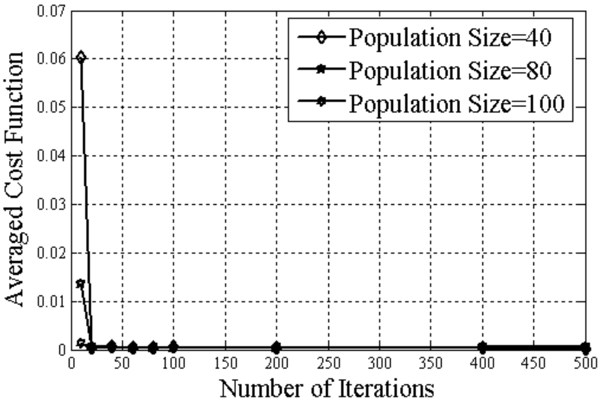


(d)

Figure 5. Convergence behavior of DE in design of low-pass FIR filter with F=0.7 (a) CR = 0.3 (b) CR=0.5, (c) CR=0.7 and (d) CR=0.9

It can be observed from Fig. 5 that the convergence behavior of DE is less sensitive to the control parameter "Crossover Probability" for population sizes of 80 and 100. But corresponding to population size of 40, it shows a considerable improvement in the convergence speed when the value of "Crossover Probability" is varied from 0.3 to 0.5. However, further higher values of "Crossover Probability" hardly show any considerable improvement in the convergence speed. Hence considering the above facts, the optimum value of "Crossover Probability" can be considered as 0.5 when F = 0.7.

The above facts have also been presented in a concise manner in Fig. 6, which clearly indicates that the optimum value of "Crossover Probability" could be considered as 0.5.

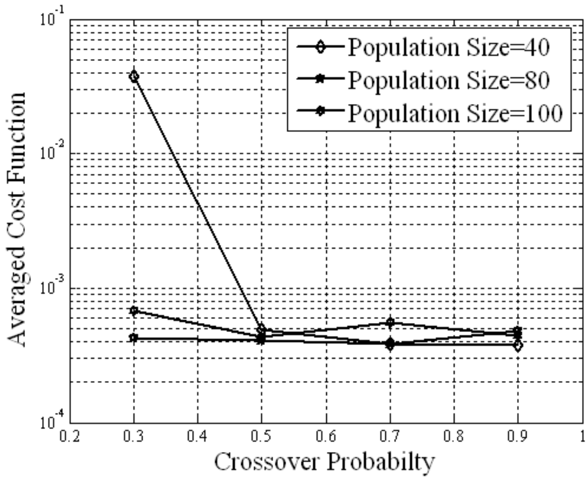
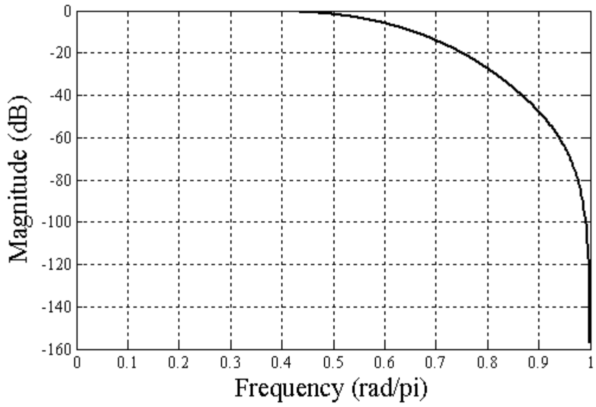
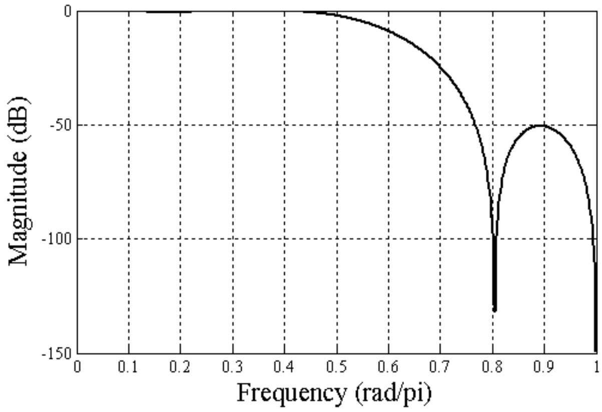


Figure 6. Variation of averaged cost function with Crossover Probability (CR)

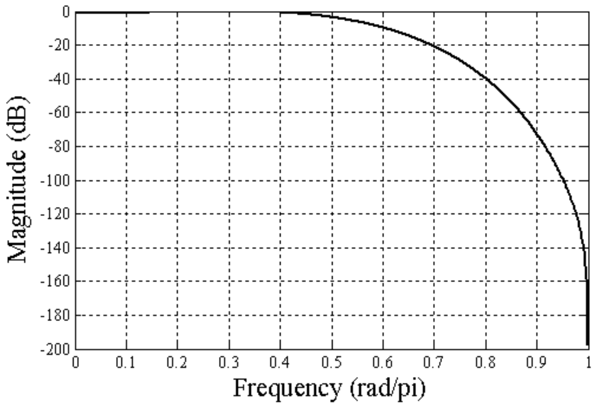
The magnitude response of the FIR filter for different values of "Crossover Probability" has been presented in Fig. 7, with the optimized value of the "Weighting Factor" as 0.7. The curves corresponding to Fig. 7 have been plotted with the values of population size and number of iterations, both to be 100.



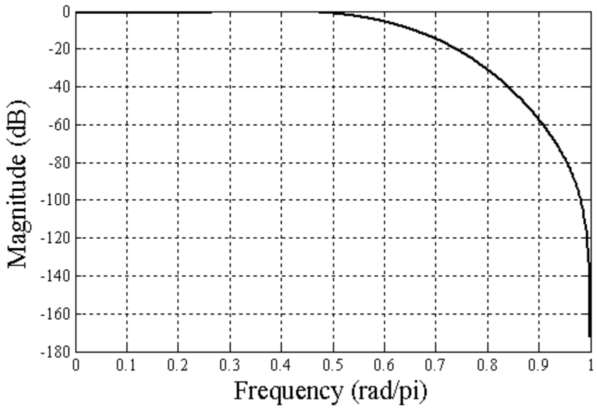
(a)



(b)



(c)



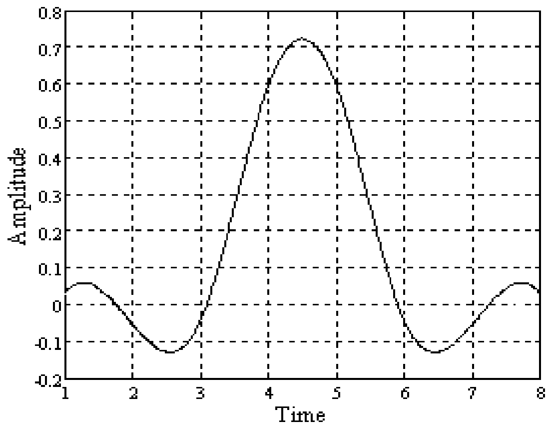
(d)

Figure 7. Magnitude response of designed low-pass FIR filter with F=0.7 (a) CR=0.3 (b) CR=0.5 (c) CR=0.7 (d) CR=0.9

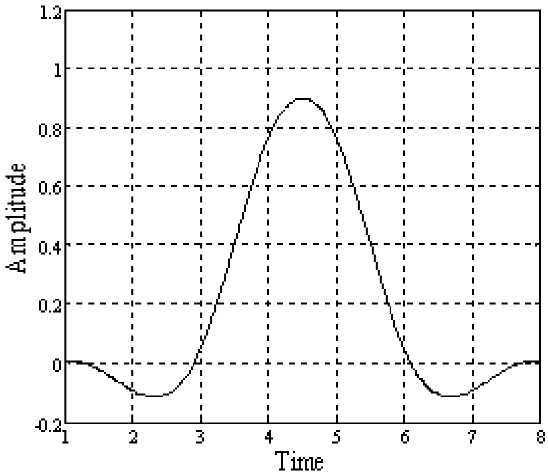
A close inspection of the above curves shows that the pass band behavior of the designed filter for different values of "Crossover Probability" is almost similar. Where as the stop band behavior shows supremacy for CR = 0.5. This can be clearly explained by considering a particular frequency of 0.8 rad/pi. At this frequency, the stop band attenuation is around 120 dB for CR = 0.5, where as, for other values of CR, the stop band attenuation varies between 20 to 40 dB.

The nature of the impulse responses of the FIR filter, designed with the optimized value of F and four different sample values of CR, has been depicted in Fig. 8. Each of the impulse responses has been obtained with a population size (P) of 100 and number of iterations (I) also of 100.

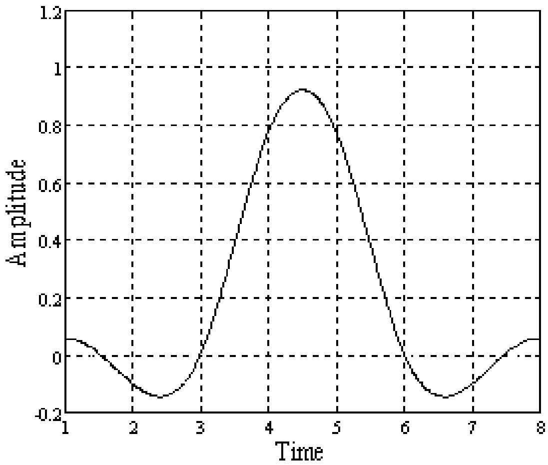
Fig. 8 illustrates that impulse response obtained with a CR value of 0.5 yields the best response amongst the four as it includes less number of side lobes with quite insignificant amplitudes of them. Consequently, it will result in less interference amongst the succeeding and preceding pulses in a band limited digital communication system.



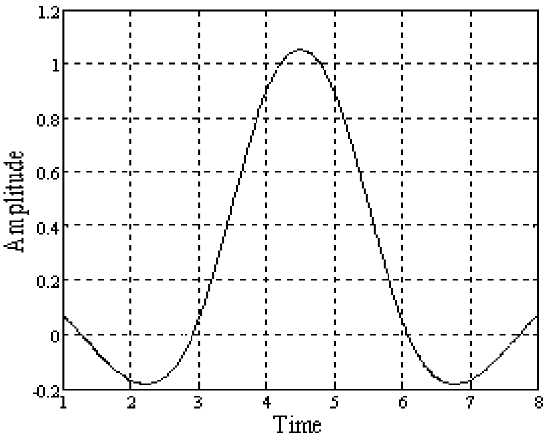
(a)



(b)



(c)



(d)

Figure 8. Impulse response of the designed low-pass filter with F=0.7 (a) CR = 0.3 (b) CR=0.5, (c) CR=0.7 and (d) CR=0.9

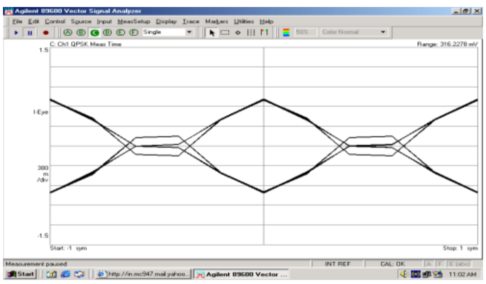
The above fact has also been substantiated by recording the In-phase Eye diagrams of the QPSK modulated system based on the DE designed FIR filter using Agilent E4438C 250 KHz–3 GHz ESG vector signal Generator (VSG), E4405B 9 KHz– 13.2 GHz ESA-E Series Spectrum Analyzer together with 89600 Vector Signal Analyzer (VSA) version 5.30 software, for F = 0.5, 0.7 and 1.0 as shown in Fig. 9, each for Population Size (P) = 100 and number of Iterations of 100.

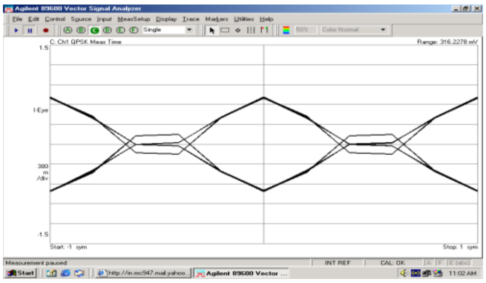
During measurement, the VSG has been characterized in the following ways:

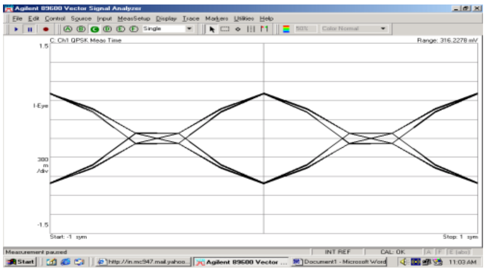
Baseband data	: pn-sequence of length 63
Symbol rate	: 25 Ksps
Pulse-shaping filter	: User defined FIR
Modulation type	: QPSK
Carrier amplitude	: 0dBm
Carrier frequency	: 10 MHz

Following options have been set in VSA software:

Reference filter	: user defined
Measurement filter	: off
Symbol rate	: 25 KHz
Modulation format	: QPSK
Result length	: 256 symbols
Points/symbol	: 5


(a)


(b)


(c)

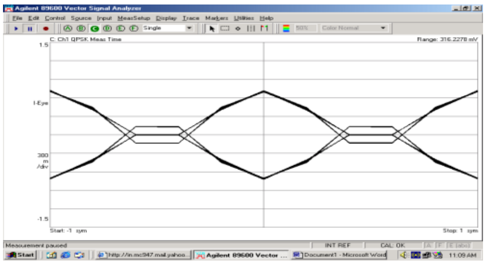
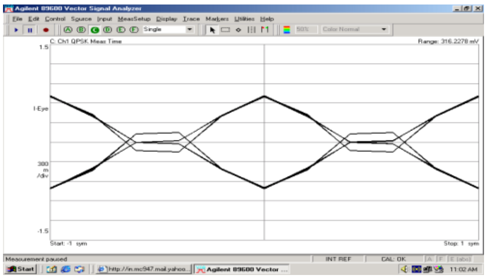

(d)

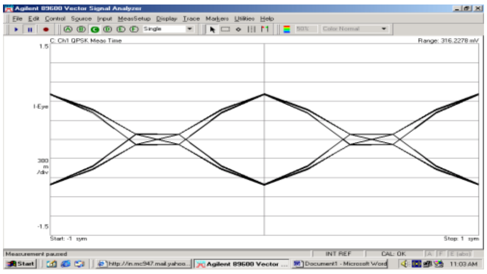
Figure 9. Eye diagram of the designed low-pass filter with CR=0.5 (a) F = 0.3 (b) F=0.5, (c) F=0.7 and (d) F=1.0

Comparison of the above figures shows that the Eye width and hence the Eye opening for the FIR filter with F=0.7 is slightly more than those with F=0.5 and F=1.0. Since the open part of the Eye represents the time over which the signal can be sampled with fidelity, larger the Eye opening, less the effect of ISI. It is also prominent that the effective crossover region of the Eye diagram and hence the amount of jitter present in the signal is less for F=0.7 as compared to others. Hence from the system ISI point of view, the FIR filters with F=0.7 provides the optimized performance.

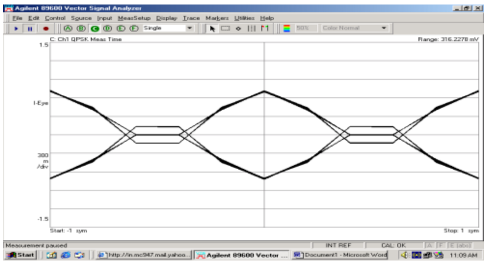
The effect of “Crossover Probability” (CR) on the In-phase Eye diagrams of the QPSK modulated system has also been demonstrated in Fig. 10. Fig. 10 reflects the fact that the best Eye diagram is obtained with CR = 0.5, which again supports the other measured results.



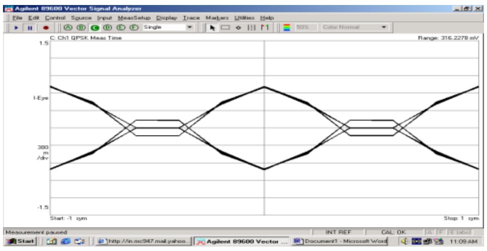
(a)



(b)



(c)



(d)

Figure 10. Eye diagram of the designed low-pass filter with F=0.7 (a) CR = 0.3 (b) CR=0.5, (c) CR=0.7 and (d) CR=0.9

To study the effect of the "Weighting Factor" (F) on the BER performance of the QPSK modulated system, the DE optimized filter has been used as a pulse-shaping filter. Table I depicts the variation of the BER with Weighting Factor (F) when the parameter "Crossover Probability" (CR) has been maintained at a value of 0.5.

TABLE I
VARIATION OF BER WITH WEIGHTING FACTOR (F)
(CR=0.5)

Population Size	F=0.3	F=0.5	F=0.7	F=1.0
40	0.4762	0.4921	0.5079	0.4603
80	0.4762	0.4921	0.4286	0.4556
100	0.4687	0.4603	0.3651	0.3810

Table I clearly indicates that the resulting BER value largely depends on the choice of the Weighting Factor. It is quite apparent that for the larger population size, the BER of QPSK modulated system attains its minimum value when the Weighting Factor is chosen to be 0.7.

The effect of another control parameter "Crossover Probability" (CR) on the BER performance of QPSK modulated system has been presented in Table II when the value of "F" has been maintained at its optimized value i.e. 0.7.

TABLE II
VARIATION OF BER WITH CROSSOVER PROBABILITY (CR)
(F=0.7)

Population Size	CR=0.3	CR=0.5	CR=0.7	CR=0.9
40	0.4762	0.4921	0.4762	0.4921
80	0.4762	0.4286	0.4603	0.4603
100	0.4762	0.3651	0.4762	0.4603

From the numerical data presented in Table II, it is clear that once the control parameter "F" is maintained at its optimized value of 0.7, the corresponding optimized value of "CR" is found to be 0.5.

From the detailed discussion of the above measurement results, the final outcome of this work i.e. the optimized values of the control parameters "F" and "CR" have been presented in Table III.

TABLE III
OPTIMIZED VALUES OF "F' & "CR"

Different values of "F" used	Optimized value of "F"	Different values of "CR" used	Optimized value of "CR"
0.3	0.7	0.3	0.5
0.5		0.5	
0.7		0.7	
1.0		0.9	

Finally it is now recommended that the FIR filter designed with a "Weighting Factor" of 0.7 and "Crossover Probability" of 0.5 provides the best performance in terms of convergence speed, magnitude response, impulse response and BER performance, supported with practically measured Eye diagrams when used as a pulse-shaping filter in a QPSK modulated digital communication system.

V. CONCLUSION

DE is a very useful optimization technique that exhibits a very good convergence property using less number of control parameters. The values assigned to those parameters have a great impact on the convergence speed of the algorithm since the averaged cost function depends significantly on those parameter values. Accordingly, the right choice of these parameters is of paramount importance in any particular application utilizing this evolutionary algorithm. In this paper, we have investigated the effect of two control parameters of DE, namely "Weighting Factor" (F) and "Crossover

Probability" (CR) on the convergence behavior of the algorithm, applied in FIR filter design problem. Analyzing our simulation results, we have recommended the optimized value for the Weighting Factor (F) and the Crossover Probability (CR) for this specific design problem when used as a pulse-shaping filter in a QPSK modulated system. The optimized value of the control parameters have also been equally supported by experimentally measured Eye diagrams.

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