Simulation and Performance Analysis of Chaotic Sequences using Enhanced Cuckoo Search Optimization Method

K. Renu and P. Rajesh Kumar

Abstract: The most desirable property required for pulse compression is that the output should have low peak sidelobes that prevent weaker targets from being masked off in the nearby strong targets. Pulse compression can be obtained with matched filter. Matched filter is an optimal linear filter used in radar signal processing and various communication fields to increase the signal to noise ratio. The output of matched filter consists of unavoidable sidelobes which causes false alarm for multiple target detection in many radar system design. For this purpose, mismatched filter is used after matched filter. In this paper a new method of design of mismatched filter is discussed which reduces these sidelobes in the compressed waveform. Here new version of cuckoo search algorithm is used along with differential evolution technique for complete design of proposed filter to compare the performance of chaotic sequence. The performance of pulse compression is measured in terms of peak sidelobe ratio. The simulation results show that the performance of chaotic sequence is obtained at the output of cascaded filter. And further improved performance is achieved with adaptive filters.

Keywords: Pulse compression, Auto-correlation, Peak sidelobe ratio (PSLR), Matched filter (MF), Mismatched Filter (MMF), Cross-correlation, Enhanced Cuckoo search algorithm.

I. INTRODUCTION

With the view of increase in applications of modern radars, navigation and ultrasonic systems there is a continuous requirement of better accuracy and high range resolution with limited peak power. These requirements have been met with pulse compression technique that is widely used in radar and navigation systems. This is mainly used to solve the problems of extending the range of radar by keeping the desired range resolution. Short pulses having high peak power helps to detect the targets at long distance. The detection capability is improved with the transmission of long coded pulse whereas narrow pulse retains its resolution capability. When a matched filter at the receiver is fed with anecho signal from target along with additive noise that results in large value of signal power with respect to noise power [1],[2]. The peak sidelobe is defined as the highest sidelobe in the output pattern. A major drawback of pulse compression techniques is relatively weak sidelobe suppression which can overcome by using mismatched filter in the receiver. But in some cases removing sidelobes comes out with some important information. Lots of research work has been carried out to reduce these unwanted sidelobes. Binary sequence with large PSLR is suitable for many applications.

Rohling and Plagge proposed a method of eliminating range sidelobes in periodic binary sequences with the help of mismatched filtering. The peak sidelobe ratio and the integrated sidelobe ratio are two important parameters to measure radar performance. Since drawbacks appear with longer length binary sequences, the analysis is carried out with multi-level sequences. The theory of chaos is applicable in radar and various chaotic systems that depends on initial conditions [3], [4]. The application of chaos with different algorithms is also studied [5]-[7]. Therefore, in this paper the performance of chaotic sequences is tested with enhanced version of cuckoo search method. The role of matched filter and mismatched filter makes it convenient to use in various areas of applications. The design of mismatched filter has been studied from years together by many scientists and engineers [8], [9]. It was studied that the optimization has to be done for the signal whose ACF contains lower peak sidelobes. The design of longer mismatched filter is proposed earlier [10]. The cross-correlated output of mismatched filter with input as binary and ternary chaotic code is discussed here which is not symmetric about zero delay. Generally, the performance of mismatched filter depends on filter elements or coefficients. In this paper cascaded mismatched filter weights are designed where differential evolution is integrated with enhanced version of cuckoo search method and its performance is studied. The generation of chaotic sequence using chaotic maps was discussed in [11], [12] and their performance with adaptive filters is compared [13].

II. METHODOLOGY

This paper begins with the generation of random population which are considered as elements of mismatched filter. The design of mismatched filter using differential evolution is studied. The differential evolution algorithm (DE) is a direct search optimization technique. The applications of this technique is quite easy, fast and gives robust performance. It can be used in linear and non-linear optimization problems due to its high reliability and consistent nature. The DE algorithm is achieved with perturbation of individuals, mutation and their crossover operation which is suggested by Price and Storn [14]. Here random population uses one difference vector for DE. The recombination of elements is controlled by the binomial decisionas in [15]. The optimized weights obtained in DE is again processed through new cuckoo search method for optimization. In general, mathematical modeling is used in several areas where optimization plays vital role [16]. Basically, the optimization is broadly divided into two types. One is deterministic method of optimization which provides only theoretical way of finding local minimum of the objective function. It requires some

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theoretical assumptions and analytical properties for problem formulation. Second one is stochastic method which is faster in locating global minima[17]. Evolutionary algorithms are the members of stochastic group which is a combination of several natural phenomena. Some of the methods depends on the behaviour of animal like Ant Colony optimization (ACO) algorithm which is proposed by Dorigo et al. [18]. Ant bee colony by Karaboga & Basturk, 2007 [19], bat algorithm by Yang, 2010 [20], bat flower pollinator by Salgörta & Singh, 2016 [21], and Particle Swarm optimization (PSO) algorithm by Kennedy and Eberhart [22]. In EA, global optimum value is obtained by properly selecting a parameter value which is quite expensive and also limit their use in real world application. Therefore, it is required to search for many local optima along with the global optima as in multimodal optimization [23]. Hence the quality of acceptable performance with a local minimum is achieved with moderate cost. Recently a nature inspired meta-heuristic optimization algorithm known as Cuckoo Search (CS) algorithm that is used to solve various complex problems in optimization suggested by Yang and Deb in 2009 [24]. This is finding popularity not only in engineering optimization problems, but also it finds in areas such as business management, stock market and finding optimal path in travelling. Here the candidate solutions are updated continuously by applying small changes which enhances the searching capabilities[25]. The wide application of CS in recent years is due to its simple structure, adaptability and is most efficient as compared to other optimization techniques. Exploration of population and exploitation are the two important factors in the search process that decides the performance of optimization. These two properties are satisfied by cuckoo search method which helps in enhancing the searching capability. Cuckoos are very fascinating birds. They have the characteristics of not only making interesting sound but also have the tendency of aggressive reproduction strategy. Brood parasitism says that some cuckoos put down their eggs gently in the nests of others. As long as the eggs are not identified by host birds they will get the chance to grow up in new nest and can get more feed from the host birds. Here each cuckoo egg corresponds to a new candidate solution. Also, cuckoo eggs hatch earlier than host eggs and propels the host eggs out of the nest. But if the host bird recognizes the eggs which are not its own then it may throw the eggs or vacate the nest. In this algorithm the search process is divided into two parts which are called as local phase and global phase. New nests are generated in global phase and a fraction of worst nests are removed in local phase. That means global phase indicates the exploration while local phase refers to exploitation. It is enhanced by Lévy flight to generate step size that improves the search space effectively. Therefore, new candidate solutions are generated with Lévy distribution as in (1) and (2) in global and local phases that replaces worse solutions in the population or nest. 

\[ x_{i+1} = x_i + \alpha \times \text{Lévy}(\lambda) (x_{\text{best}} - x_i) \]  

(1) 

Where \( x_i \) represents the previous solution and \( x_{\text{best}} \) is the current best solution. Similarly \( x_i^+ \) and \( x_i^- \) are random solutions from the population. \( \alpha \) is the step size that depends on the problem. \( \text{H} \) stands for heavy-side function, \( \epsilon \) is the random number and \( p_a \) represents switching probability. This is the basic background of CS algorithm. The evolution process of CS is defined by three different operators: (i) the distribution function such as Lévy flight, Cauchy distribution, (ii) generation of new solutions by replacing some nests and (iii) elitist selection strategy. The first step is to generate new solution with the help of distribution function. The next step is the selection of a uniform random number in the range [0,1]. If this random number is less than the switching probability \( p_a \in [0,1] \) that particular solution or sequence is selected and used for further computation. The third step is to choose high quality eggs or solutions \( x_i^{+1} \) whose fitness value is better than \( x_i^- \). 

\[ x_{i+1}^+ = \begin{cases} x_i^{+1}, & \text{if } f(x_i^{+1}) < f(x_i^-) \\ x_i^- & \text{otherwise} \end{cases} \]  

(2) 

In this way the best solutions are derived which will exist in the next generation.

A. Proposed variants

The necessity of switching over to enhanced version of cuckoo search method from Lévy flight method is discussed here. The detailed analysis of modifications in search process and their implementation are presented. The Lévy flight behaviour of CS helps to increase the search space. So it is better than simple random walk. The probability switch determines the global explorative and the local exploitative random search. Hence the above method is more efficient for achieving the convergence. But as days going on the complexity in optimization problems increases. Hence it is required to design a new algorithm that is based on particular problem.

This paper deals with two new concepts which are based on division of generations and population. These two concepts are clearly explained with the help of proposed method. Using this method, better position of cuckoo is obtained with some modifications in local and global search phase. The modification is included for second half of the generation in which enhanced global search is followed by two divisions in local phase. But for the first half of the generation, Cauchy operator is used to obtain new solution in global search and original CS concept is used for local search.

B. Division of generations:

The explorative tendency of CS makes the algorithm in ignoring local minima the exploitative tendency decides its convergence properties. The division of population and generation has been implemented to keep the balance between the exploitation and exploration. To achieve this balance, a standard equation is used for one half of the generation to obtain best exploitative tendency and the remaining half should have more intensive exploitation.

C. Division of Population

In division of population, the population is split into smaller groups and each group is computed with separate search equation that will add up the balance. The extensive global walkways follows intensive local walkTwo different search equations are adapted for each half of the population to complete the search process.
III. ENHANCED VERSION OF CUCKOO SEARCH METHOD

In the enhanced version of CS, the first half of the generation uses Cauchy distributed random number 'δ' in global search to obtain the new solutions.

The probability density function is defined in (3)

\[ f(\delta) = \frac{1}{\pi} \left( \frac{g}{\delta^2 + g^2} \right) \quad (3) \]

where the scale parameter 'g' is considered as 1. Similarly, the Cauchy distribution function can be written in (4)

\[ y = 0.5 + \frac{1}{\pi \alpha} \arctan \left( \frac{\delta}{\alpha} \right) \quad (4) \]

Where \( y \in [0,1] \). From the above equation the Cauchy random number 'δ' is as in (5)

\[ \delta = \tan(\pi(y - 0.5)) \quad (5) \]

whose range is between 0 and 1. The Cauchy distribution helps in escaping local minima by examining the search space. In one half of generations, the new solution in global search is obtained by using (6)

\[ x_i^{t+1} = x_i^t + \alpha \odot \text{Cauchy}(\delta)(x_i^t - x_j^t) \quad (6) \]

Which is similar to (1) of original CS algorithm, but instead of Lévy distribution, Cauchy distribution is used in (6) due to its flatter tail and larger step size.

In second half of iterations, the improvement in global search phase is obtained by using (10) where the average of the three solutions is considered which are defined in (7), (8) & (9)

\[ x_1 = x_i - S_1(V_1 * x_{best} - x_i^t) \quad (7) \]
\[ x_2 = x_i - S_2(V_2 * x_{best} - x_i^t) \quad (8) \]
\[ x_3 = x_i - S_3(V_3 * x_{best} - x_i^t) \quad (9) \]

and

\[ x_{\text{new}} = \frac{x_1 + x_2 + x_3}{3} \quad (10) \]

Where \( S_1, S_2 \) and \( S_3 \) are obtained by using (11) for different random values.

\[ S = 2rd_1 - r \quad \text{and} \quad V = 2d_2 \quad (11) \]

\( d_1 \) and \( d_2 \) are uniformly distributed random number that helps in obtaining new location in the search space which improves the explorative tendency. 'r' is the linearly decreasing random number between 0 to 2. This concept has been taken from Grey Wolf Optimization where the new solutions are achieved by adjusting the parameters of best search agent. Therefore, the new solution will become (12).

\[ x_i^{t+1} = x_{\text{new}} + \alpha \odot \text{Cauchy}(\delta)(x_{\text{best}}^t - x_{\text{new}}) \quad (12) \]

The performance of original CS can be improved with some enhanced search in local phase. Here the population is divided into two halves. The first half is computed with (2) of standard CS to obtain new solution. However, the second half of the population is (13).

\[ x_i^t = x_i^t + D \cdot (x_i^t - x_l^t) + (x_l^t - x_r^t) \quad (13) \]

The parameter \( D \) is in the range 0 to 1. The new solution is updated with the four random solutions \( x_i^t, x_l^t, x_r^t \) and \( x_n^t \).

Finally, the Cauchy global search and dual division local search maintains balance between the exploration and the exploitation.

IV. PROBLEM IDENTIFICATION

The computation for the coefficients of mismatched filter using different optimization techniques has been reported earlier [26], [27]. In this paper mismatched filter elements are designed as per differential evolution and then same procedure is adapted to optimize the mismatched filter coefficients using cuckoo search algorithm to obtain optimized coefficients. The sidelobe levels are reduced in the output of mismatched filter. Here random chaotic sequences are given as input to matched filter which results in aperiodic autocorrelation function in phase coded pulse compression. The ternary chaotic sequences of length \( N \) represented by +1,0,-1 are taken as input given by

\[ S = \{s_0, s_1, s_2, \ldots, s_N\} \]

whose autocorrelation without doppler shift for positive delays is represented in (14)

\[ RR(k) = \sum_{j=0}^{N-1-k} y_j s_j + k \quad \text{for } k \text{ range from } 0 \text{ to } 1 \quad (14) \]

The coefficients or weights of mismatched filter are real with filter length considered as 'M' but greater than 'N'. \( M \geq N \). The output of mismatched filter is defined in (15)

\[ CC_k = \sum_{j=0}^{M-1} y_j s_j + k \quad \text{for } (N - 1) \leq k \leq (M - 1) \quad (15) \]

where \( Y \) is the filter elements \( Y = \{y_0, y_1, \ldots, y_{M-1}\} \) and \( x_i \) existing between 0 to N-1. Depending on whether \( N \) is even or odd, \( M \) will be even or odd respectively. The value of 'x' will become zero for \( i < 0 \text{ and } i > N - 1 \). The objective function of mismatched filter is defined in (16)

\[ PSLR = 20 \times \log \frac{\text{abs(sidelobemaximum)}}{\text{abs(max(CC_k))}} \quad (16) \]

where \( F = \text{max}(H_k) \) is the main lobe peak that is to be maximized. Each solution or individual is considered as impulse response coefficients of mismatched filter. The initial random population is chosen as per differential evolution algorithm. The mismatched filter length is taken as three times longer than that of the input sequence.

V. SIMULATION RESULTS

This paper deals with the detailed analysis of proposed method which is clearly shown in Fig. (1). The performance of chaotic sequence is measured in terms of peak sidelobe ratio. The sequence is undergone mismatched filter 1 whose elements are designed by using differential evolution method followed by mismatched filter 2 that is designed with new cuckoo search algorithm. The simulation is being carried out using Matlab and the performance of mismatched filters is discussed for Barker code, binary and ternary chaotic code for different lengths. The optimized results of DE mismatched filter and cascaded MMF are tabulated in I and II. It is evident that the proposed method achieved better results than the MMF which is implemented only with DE. The parameter 'a' is taken as 0.01 and the probability switch 'P_{cr}' as 0.5 for simulation. The output is obtained by cross-correlating the chaotic sequence and the coefficients of mismatched filter which is taken as random population initially. The cascaded mismatched filter output for chaotic sequence of length 20 is shown in Fig. (2). Further improvement of PSLR is obtained with adaptive filter that is connected after cascaded MMF.
The coefficients of the adaptive filter are updated with least mean square and binary step size least mean square algorithm.

Fig. 2 Mismatched filter response of ternary sequence

Fig. 1 Block diagram representation of proposed method

Fig. 3 Performance of Binary code

Fig. 4 Performance of Ternary code

Table. I PSLR comparison of Binary Sequence using cascaded MMF along with adaptive filter

| Sequence Length | PSLR of MF (dB) | MF ASP | PSLR of DE MMF (dB) | PSLR of Cascaded MMF using DE & Basic CS (dB) | PSLR of Cascaded MMF using DE & New CS (dB) | PSLR of Adaptive Filter with LMS (dB) | PSLR of Adaptive Filter with BSSLMS (dB) |
|-----------------|----------------|--------|--------------------|-----------------------------------------------|----------------------------------------------|--------------------------------------|------------------------------------------|
| 20              | -16.4782       | 0.15   | -20.6710           | -22.6344                                      | -25.2326                                     | -32.0434                             | -38.0054                                |
| 25              | -18.4164       | 0.12   | -23.8117           | -26.9161                                      | -27.7399                                     | -39.2191                             | -42.2132                                |
| 30              | -17.5012       | 0.1333 | -22.4618           | -25.6010                                      | -27.6253                                     | -31.3052                             | -32.3310                                |
| 35              | -16.9020       | 0.1429 | -21.9650           | -25.4385                                      | -24.5308                                     | -26.7982                             | -29.7076                                |
| 40              | -18.0618       | 0.1250 | -21.2167           | -24.5438                                      | -25.7902                                     | -28.0029                             | -29.3102                                |
| 45              | -17.5012       | 0.1333 | -19.4290           | -22.0227                                      | -22.9612                                     | -26.0669                             | -26.5547                                |
| 50              | -18.4164       | 0.1200 | -20.8651           | -23.6070                                      | -24.3869                                     | -27.8803                             | -26.6319                                |
| 60              | -17.5012       | 0.1333 | -19.9053           | -21.8712                                      | -22.7521                                     | -24.0994                             | -24.3901                                |
| 70              | -17.8171       | 0.1286 | -20.0811           | -22.4277                                      | -23.0139                                     | -25.8099                             | -25.6433                                |
| 80              | -18.9769       | 0.1125 | -19.8070           | -21.9654                                      | -22.0461                                     | -25.0719                             | -25.5612                                |
Table II PSLR comparison of Binary Sequence using cascaded MMF along with adaptive filter

| Sequence Length | PSLR of MF (dB) | MF ASP | PSLR of DE MMF (dB) | PSLR of Cascaded MMF using DE & Basic CS (dB) | PSLR of Cascaded MMF using DE & New CS (dB) | PSLR of Adaptive Filter with LMS (dB) | PSLR of Adaptive Filter with BSSLMS (dB) |
|-----------------|----------------|--------|--------------------|--------------------------------------------|------------------------------------------|--------------------------------------|--------------------------------------|
| 20              | -17.5012       | 0.1333 | -23.2601           | -25.9866                                   | -28.3662                                 | -52.4615                             | -43.5033                             |
| 25              | -16.4782       | 0.1500 | -20.9613           | -23.7410                                   | -24.9498                                 | -27.1811                             | -33.2651                             |
| 30              | -17.6921       | 0.1304 | -21.9220           | -24.8412                                   | -27.0602                                 | -28.3593                             | -31.4696                             |
| 35              | -18.4164       | 0.1200 | -21.9297           | -25.9506                                   | -27.4511                                 | -28.7865                             | -31.6038                             |
| 40              | -17.7860       | 0.1290 | -19.9577           | -22.3354                                   | -23.9838                                 | -25.6898                             | -27.2516                             |
| 45              | -16.6502       | 0.1471 | -20.4160           | -23.8290                                   | -24.4505                                 | -26.1543                             | -26.5626                             |
| 50              | -18.8402       | 0.1143 | -21.2207           | -25.2694                                   | -27.1736                                 | -31.0194                             | -29.3834                             |
| 60              | -17.6921       | 0.1304 | -19.6591           | -22.3488                                   | -23.1368                                 | -24.7326                             | -25.8957                             |
| 70              | -18.5884       | 0.1176 | -19.4310           | -21.9170                                   | -22.8083                                 | -24.9556                             | -25.2526                             |
| 80              | -18.2155       | 0.1228 | -19.5246           | -22.2077                                   | -22.8863                                 | -26.3259                             | -27.1024                             |
| 90              | -18.4597       | 0.1194 | -19.5052           | -22.4003                                   | -22.7833                                 | -24.8042                             | -25.3924                             |
| 100             | -18.5114       | 0.1184 | -19.6528           | -21.8209                                   | -22.7707                                 | -24.7692                             | -25.0977                             |
| 150             | -19.2442       | 0.1091 | -19.9653           | -22.1384                                   | -22.9513                                 | -24.4375                             | -25.1544                             |
| 200             | -20.2848       | 0.0968 | -21.0265           | -23.2507                                   | -24.1258                                 | -26.0649                             | -24.3536                             |
| 250             | -19.8618       | 0.1016 | -20.8839           | -23.0938                                   | -23.7159                                 | -25.3729                             | -26.0707                             |
| 300             | -20.5993       | 0.0933 | -21.1811           | -23.3418                                   | -24.0003                                 | -26.7309                             | -26.6204                             |

Fig. 5 Comparison of output for sequence length of 100 in each stage of block diagram
Table. III Improvement in PSLR of Ternary Sequence with Number of Iterations

| Sequence Length | PSLR of MF (dB) | MF ASP | No. of Iterations | PSLR of DE MMF (dB) | PSLR of Cascaded MMF using DE & Basic CS (dB) | PSLR of Cascaded MMF using DE & New CS (dB) | PSLR of Adaptive Filter with LMS (dB) | PSLR of Adaptive Filter with BSSLMS (dB) |
|-----------------|-----------------|--------|-------------------|---------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| 20              | -17.5012        | 0.1333 | 50                | -18.9502            | -23.0076                          | -23.6411                          | -32.3949                          | -38.3997                          |
| 20              | -17.5012        | 0.1333 | 100               | -21.2409            | -24.8603                          | -26.2322                          | -46.6002                          | -39.1501                          |
| 20              | -17.5012        | 0.1333 | 200               | -23.2601            | -25.9866                          | -28.3662                          | -52.4615                          | -43.5033                          |
| 20              | -17.5012        | 0.1333 | 300               | -24.5978            | -27.3246                          | -29.7682                          | -63.1376                          | -47.2109                          |
| 20              | -17.5012        | 0.1333 | 400               | -25.3689            | -28.4107                          | -29.1387                          | -57.9792                          | -46.8573                          |
| 20              | -17.5012        | 0.1333 | 500               | -26.3723            | -28.1916                          | -29.2455                          | -60.7179                          | -46.1775                          |

VI. CONCLUSION

In this work, the performance of chaotic sequence is optimized by using enhanced version cuckoo for the design of mismatched filter along with DE. The length of the mismatched filter should increase proportionally with input sequence. Due to this, implementation of the filter will be difficult for practical applications for larger length codes. The PSLR of Barker code with cascaded filter is increased to -41.8877 dB whose value with matched filter is -22.2789. Better improvement in performance of sequences is observed for lower length than compared to larger length. The values in I and II will change every time when the matlab program is being executed. This is because of random population that is taken as the coefficients of MMF. DE finds wide application due to its interesting characteristics such as better convergence, robustness and versatility. With this advantages of DE when it is integrated with new cuckoo search for designing of mismatched filter results in significant improvement in the performance of sequence compared to Lévy flight standard cuckoo search. These values will increase with increase in number of iterations.

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