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Optimization Algorithms for Generating Golomb Ruler Sequences – A Comparison

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ABSTRACT: An undesirable nonlinear effect which degrades system performance significantly is acknowledged as Four Wave Mixing (FWM). In the optical communication systems, the FWM crosstalk is reduced by using unequally spaced channel allocation method. This channel allotment method is constructed on optimal Golomb ruler (OGR) which not only maintains the bandwidth efficiency but also decreases the FWM effect. To generate and optimize Golomb ruler sequence, classic approaches as well as nature- inspired algorithms have been used by various researchers. In this paper, some of the algorithms are reviewed and compared.

KEYWORDS: Channel allocation algorithm, Optimal Golomb ruler, Soft Computing, Firefly algorithm, Ant Colony Optimization, Cuckoo Search, Genetic algorithm.

I. INTRODUCTION

A method of multiplexing various signals on laser beams at different Infrared (IR) wavelengths for transmission along optical fiber media is known as wavelength-division multiplexing (WDM). In standard WDM systems, center frequencies which are equally spaced from each other determine the allocation of channels. Due to this, the noise (like FWM) has large possibility that they may enter into the equally spaced channels which results in severe crosstalk [1].
The definition of Four-Wave Mixing states it as an intermodulation phenomenon in non-linear optics, in which two extra wavelengths are produced by interactions between two wavelengths in the signal.
The fourth wavelength (f4) is generated when the fourth photon is produced by the scattering of the incident photons.
For input frequencies f1, f2 and f3, the non-linear system will generate

$\pm f1 \pm f2 \pm f3$

Due to this, the three co-propagating waves produce nine new optical waves [2].And the most deteriorating signals to the working of system are calculated as:

$f_{ijk} = f_i + f_j - f_k$, where $i,j \neq k$, because these frequencies will be in close proximity to the input frequencies.

To improve the performance, the FWM generation is avoided at the channel frequencies.
FWM can be alleviated by employing uneven channel spacing or a fiber that increases dispersion [3], [4].
It can be seen that FWM is suppressed if any two channels use different frequency spacing than other two channels in a WDM system [5]-[8].
However, using unequal channel spacing increases the required bandwidth in contrast to equal spaced channel allocation.
This can be taken care of by employing the idea of optimal Golomb ruler (OGR) and a bandwidth allocation algorithm which reduces the FWM effect resulting in the improvement of the performance of the WDM system without incorporating extra cost in terms of bandwidth. The various algorithms proposed by researchers from time to time have been studied and a critical analysis has been carried out and the same have been compared upon some significant parameters such as Run time, success rate, algorithm basis and classification.

II. RELATED WORK

Vrizlynn L. L. Thing et. al. [5], proposed a channel allocation method which was based on fractional optimal Golomb ruler that allows suppression of FWM crosstalk in WDM systems while maintaining the bandwidth efficiency. Through this scheme an average bit–error rate improvement factor of 1.336 for an 8–channel WDM system was achievable.
Shobhika [32], proposed that how Genetic Algorithm can be used to solve the problem of OGR sequences and compare the results obtained from GA in terms of ruler length and bandwidth with the two classical approaches i.e. EQC and SA proposed in [11] and [12]. From simulation results she concluded that the results obtained from Genetic Algorithm, approaches to optimal after a number of iterations.
N. Ayariet. al. [22], presented that by using exact methods, many months on thousands computers are necessary to prove the optimality of a large rulers. To deal with this, they proposed a hybrid Genetic Algorithm combined with a local search to find optimal and near–optimal Golomb rulers to reduce the search space exploration. The hybrid GA algorithm incorporates a Tabu Search as a mutation operator. The advantage of this approach was to diversify solutions with the crossover operator in GA and improve these solutions with the TS. In fact, this hybrid algorithm allowed increasing the performance in terms of effectiveness of approximate methods.
S. Sugumaran et al. [12], implemented a DWDM system using opt–sim software to evaluate bit error rate (BER) and Q–factor in the presence of FWM under the impact of equal and unequal channel spacing. They also implemented a channel allocation method based ontwo classical computing algorithms i.e. Exhaust algorithm and Search algorithm to construct the Golomb ruler sequences in order to suppress the FWM crosstalk in MATLAB.
S. Bansalet. al.in [13] applies two soft computing based approaches i.e. GA and BBO to generate OGR sequences for various marks. From the simulation results they concluded that BBO/GA outperforms the two existing classical algorithms i.e. EQC and SA.

III. OPTIMAL GOLOMB RULER

The concept of Golomb Rulers' was proposed by W.C. Babcook [9] in 1952 and developed by Professor Solomon W. Golomb [10] in 1977.
The phrase "Golomb ruler" [25] denotes a set of positive integer values, where any two numbers from the set consisting of different pairs do not have the same difference. An illustration of the Golomb ruler is shown in Figure 1 [2]. An Optimal Golomb Ruler depends on given number of marks and is the shortest ruler possible[6].

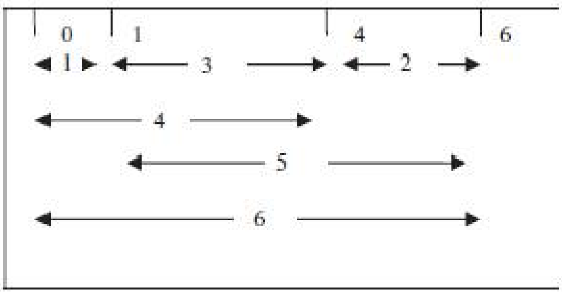

Fig.1 Perfect Golomb Ruler

Fig. 1 shows a Perfect Golomb ruler which measures the distances {1, 2, 3, 4, 5, 6}. A Golomb ruler with n marks measures exactly $\frac{1}{2}n(n-1)$ distances. When these distances are exactly the first $\frac{1}{2}n(n-1)$positive integers, we have a perfect Golomb ruler.
For allocating channels in WDM system, it is feasible to attain the least distinct number by applying Optimal Golomb Ruler to the channel allocation problem. The new FWM frequencies produced will not lie in the one previously allocated for the channels since the difference between any two numbers is distinct.

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A g-mark Golomb ruler is a collection of g discrete non negative integers (p1, p2, .., pg) defined as marks, where the positive differences |pi-pj|, calculated on the whole possible pairs of distinct i, j = 1,… g with i≠j are dissimilar. Assume pg be the biggest integer in a g-mark Golomb ruler. Then g-mark Golomb ruler exists if

1. Another g-mark Golomb ruler with smaller largest mark pg is nonexistent.

2. The ruler should be smaller of the comparable rulers (0, p2,….,pg) and(0,...., pg–p2,pg), when written in canonical form where the first conflicting entry is smaller than the equivalent entry in the other ruler.

IV. ALGORITHMS TO GENERATE GOLOMB RULER

Various algorithms used to create Golomb ruler sequences are discussed in this section. The two basic approaches are classical and soft computing. The classical approach is used to create exact sequences whereas the soft computing approach is used to create optimal sequences in a feasible time. Due to this reason various metaheuristic algorithms are employed to resolve optimization problems proficiently. Of all the algorithms, those inspired by nature give better results.

A. Exhaust Algorithm (EA)

Exhaust algorithm requires two parameters for the generation procedure. Firstly, the number of marks contained in the desired Golomb ruler and the second parameter confines the length of the Golomb ruler. This procedure is recursive in nature. An existing N-mark Golomb ruler is chosen and a new mark, to the right side of the ruler, is added resulting in N+1 mark ruler [12]. This procedure does not keep track of the mark position but the spaces between the adjacent marks stored in arrays are traced and are called spaces. These values make the first row of the difference triangle for the ruler. The algorithm starts by initializing the first elements in the spaces to the distance. Then it progresses to the next distance and starting at a value of 1, increments this value until the distances measured by the first two entries are unique. Then the process is repeated for the next element and so on. If the total distance, at any point, measured by these elements exceeds the maximum ruler length then the algorithm will back up one element and increment that element and add new distances from there. When the last mark is placed and a ruler of desired length is found, it prints this information and continues the search.

B. Search Algorithm (SA)

The search algorithm is used to generate optimal sequences for a given Prime number P and minimum pulse separation m.

N = P + 1 and S = (m + (P – 1) / 2) P, where N denotes the number of terms in the sequence and S is the maximum length of the slot vector [11].

1. If a prime number is denoted by P and minimum pulse separation m, the initial delay vector n1 = [n0, n1,.., nP_1] = [m, m+1, y, m+P-1] is built.
2. The jth delay vector nj =[l0, l1 ,…., lk,.., lP-1] for j ={1, 2,3,..., P-1} are generated with lk = nj⊗k, where ⊗ denotes modulo-P-multiplication.
3. The jth code word sj=[s0, s1, s2,..., sq,…, sP] with weight P+1 are created from nj, according to the rule sq = lq-1+sq-1 where q = {1,2, 3,..., P} and s0 = 0.
4. At last, the code words sj's with aperiodic correlation constraint one are found.

C. Genetic Algorithm (GA)

John Holland invented Genetic Algorithms (GA's) in 1960s and developed them with help from his collaborations at the University of Michigan [24] in 1960s and 1970s. GA's based on the technicalities of natural selection and natural genetics are used in automated global search and optimization algorithms [23]. GAs works on a population of possible answers employing the law of survival of the fittest to yield better estimations to a solution. From every generation, individuals are selected according to their fitness level and bred using operators derived from natural

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genetics for creating a new set of approximations. This procedure directs to the advancements of populations of entities which befits to their surroundings than the entities that were originate from, just as in natural adaptation [25], [22], [24].

D. Biogeography based optimization (BBO)

Biogeography Based Optimization is a population based evolutionary algorithm (EA) developed for global optimization. To unravel the optimization problem, algorithm apes the migration strategy of species [26]-[31]. Biogeography concept suggests that immigration and emigration mainly determines the number of species located on habitat. In BBO, islands correspond to problem solutions and emigration and immigration symbolize the distribution of attributes. The term island represents a habitat which is secluded from other habitats geographically [21]. Biogeography corresponds to nature's way of problem solving. An island with high Habitat Suitability Index (HSI) is similar to a good solution and a poor solution denotes an island with a low HSI [13].

E. Firefly Algorithm (FA)

Firefly Algorithm is a metaheuristic algorithm inspired by nature which is based on the movement and activities of fireflies [15]. It is described using three ideal rules:

1. All fireflies will be attracted to other fireflies as they are thought to be unisex.
2. Attraction is determined by their brightness. Therefore, the brighter one with attract the less bright one. Attraction decreases as the distance between the fireflies decreases. If there is no brighter firefly in the surrounding area, then that individual firefly will move randomly.
3. The brightness of a firefly is correlated with an objective function. For a maximization problem, the brightness is basically relational to value of objective function [15]-[16].

F. Ant Colony Optimization (ACO)

Ant colony Optimization uses positive feedback principle of pheromone to find optimal path. At the preliminary stage, pheromone concentration is not there in any paths. So, an ant will select a random path and places some quantity of pheromone all over the path they have traced [14]. Therefore, each path has disproportionate amount of pheromone and an ant can select the path based on the amount. Generally the path with highest concentration is chosen and after selecting the ant will intensify the pheromone concentration in that path during its course.
As the amount if pheromone increases in a path, more the possibility of ants to select that path, thus strengthens the concentration. Finally, all ants will join the selected path and it finds the optimal path [17]

G. Bat Algorithm (BA)

Bat algorithm as the name defines is inspired from bats based on the echolocation behaviour of bats with loudness and varying pulse emission [16]. Bats sense the distance using echolocation which also allows them to distinguish between prey and object. Bats produce pulses with maximum loudness for searching food. Once the bat finds the prey, it minimizes (usually zero) the loudness in order to avoid the loss of prey. Also, the pulse emission rate increases as the bat gets closer to prey and when the prey is found, the pulse emission rate becomes maximum [18].

H. Cuckoo Search Algorithm (CSA)

The Cuckoo Search Algorithm (CSA) is a Swarm Intelligence based metaheuristic population-based nature inspired optimization algorithm in which a nest denotes the pattern and each specific feature of the pattern relates to the bird egg [16]. Cuckoo bird uses other birds' nest to lay their eggs. This algorithm is able to remove noise from the network efficiently by training the network [19]. The cuckoo's egg is regarded as the solution for preferred object function. For simplicity, only one egg is there in a nest.The three ideal rules are given below:

1. Only one egg is laid by each cuckoo at a time and it puts it in a nest that is chosen randomly.

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2. The best nest, which has high quality eggs (solution) are carried over to the next generations.
3. If the host bird finds the alien egg, it can either discard the egg or simply vacate the nest to make an entirely new nest in a new location [18].

V. ALGORITHM COMPARISON

The algorithms are classified on the basis of approaches i.e. Exhaust and search algorithms are based on classical approach whereas Genetic and Biogeography Based Optimization algorithms are based on Soft Computing approach. The rest four algorithms – Firefly, ACO, Bat and Cuckoo search algorithm are nature inspired which have various features matching with the natural species. The Search Algorithm is better than the Exhaust Algorithm as it requires less computational time and bandwidth. Soft computing approaches show a significant improvement with respect to bandwidth and ruler length than classical approaches. Firefly algorithm is very dominant and it has a high rate of concurrence. It has very low running time and its success rate is high.

Comparison is done by using different parameters such as Running time, Success rate, Algorithm basis and classification. The comparison is given in TABLE I. Graphical comparison of Run time and success rate is shown in Fig. 2 and 3 respectively. Exhaust algorithm depends on the existing Golomb ruler to generate exact golomb ruler and Search algorithm depends on the Exhaust algorithm. Genetic Algorithm measures the survival of the fittest technique for generation of optimal Golomb ruler and Biogeography Based Optimization uses mathematics of Biogeography for generating OGR. Rest of the algorithms uses natural species behaviour to construct the Golomb ruler.

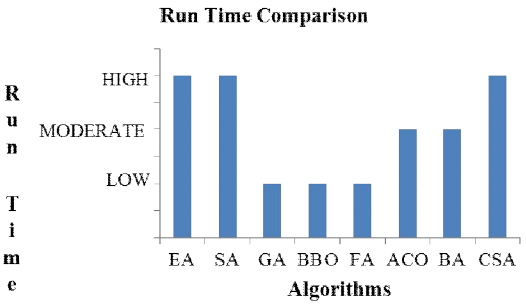

Fig.2 Run Time Comparison

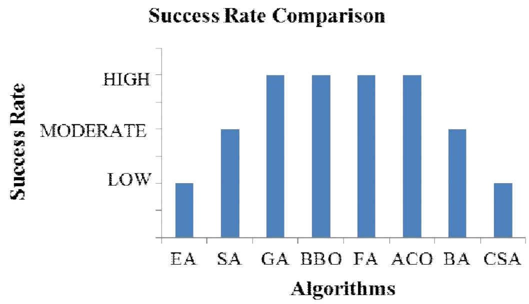

Fig. 3 Success Rate Comparison

Fig. 2 shows the Run time comparison between the different algorithms. It has been found that GA, BBO and FA have least run time as compared with other algorithms.
Fig. 3 shows the success rate comparison between the different algorithms. It has been shown that GA, BBO, FA and ACO have highest success rates as compared with other algorithms.

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TABLE IComparison of Algorithms

Algorithm Name	Run Time	Rate of Success	Algorithm Classification	Basis of Algorithm
Exhaust Algorithm (EA)	High	Low	Recursive Nature Based	Existing Golomb Ruler
Search Algorithm (SA)	High	Moderate	Given Prime Number	Exhaust Algorithm
Genetic Algorithm (GA)	Low	High	Natural Genetics And Natural Selection	Survival Of The Fittest
Biogeography Based Optimization (BBO)	Low	High	Based on Population Evolutionary Algorithm	Mathematics Of Biogeography
Firefly Algorithm (FA)	Low	High	Population Based Attraction Based Algorithm	Motion And Flashing Of Fireflies
Ant Colony Optimization (ACO)	Moderate	High	Population Based	Pheromone Concentration And Interaction Of Ants
Bat Algorithm (BA)	Moderate	Moderate	Population Based	Echolocation Behaviour Of Bats
Cuckoo Search Algorithm (CSA)	High	Low	Equation Based	Brooding Characteristics Of Cuckoo Bird

Table 1 shows the comparison of algorithms on the basis of run time, rate of success, classification and basis of algorithm.

VI. CONCLUSION

From the comparisons of the algorithms, it is clear that based on application the algorithm is chosen to give the best performance. To Find OGR sequences using classical approaches is a complicated method which sprouts in size as the size of mark increases. To solve this problem, the soft computing methods are designed which gives near optimal results under the limitations of given cost and time. Using these algorithms, it is seen that there is noteworthy improvement in Bandwidth requirement and ruler length.

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