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Generation of Golomb Ruler Sequences and Optimization Using Biogeography Based Optimization

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***Abstract*— The crosstalk due to Four Wave Mixing (FWM) with equally space channels from each other is the dominant nonlinear effect in long haul, repeaterless, wavelength division multiplexing lightwave fiber optical communication systems. To reduce FWM crosstalk in optical communication systems, the use of unequally spaced channels has been proposed. One of the unequal bandwidth channel allocation technique is designed by using the concept of Golomb Ruler that allows the gradual computation of a channel allocation set to result in an optimal point where degradation caused by inter-channel interference (ICI) and FWM is minimal. In this paper we applied Biogeography Based Optimization (BBO) method for the generation of Golomb Ruler sequences. We have observed that BBO performs better than the two other methods i.e. Extended Quadratic Congruence (EQC) and Search Algorithm (SA).**

***Keywords*— Four wave mixing, Optimal Golomb Ruler, Biogeography, Biogeography Based Optimization.**

I. INTRODUCTION

In conventional wavelength division multiplexing (WDM) systems, channels are usually assigned with center frequencies (or wavelength) equally spaced from each other. Due to equal spacing in channels there is very high probability that noise signals (FWM signals) may fall into the WDM channels, resulting in severe FWM crosstalk [1].

FWM crosstalk is the main source of performance degradation in all WDM systems. Performance can be substantially improved if FWM generation at the channel frequencies is avoided. It is therefore important to develop algorithms to allocate the channel frequencies in order to minimize the effect of FWM. Therefore the efficiency of FWM depends on the channel spacing [2].If the frequency separation of any two channels of a WDM system is different from that of any other pair of channels, no FWM waves will be generated at any of the channel frequencies. This suppresses FWM crosstalk [3], [4]. A design methodology of channel spacing is presented to satisfy the above requirement. The use of proper unequal channel spacing keeps FWM waves from coherently interfering with the desired signals [5], [6].

In an attempt to reduce the crosstalk due to FWM effect in WDM systems, several unequally spaced channel allocation (USCA) techniques have been studied [1], [7]-[14]. An optimum USCA (O-USCA) technique ensures that no FWM signals will ever be generated at any of the channel frequencies if the frequency separation of any two channels is different from any other pair of channels in a minimum operating bandwidth [10].

Forghieri et al. [8] treated the “channel-allocation” design as an integer linear programming (ILP) problem by dividing the available optical bandwidth into equal frequency slots. But the ILP problem was NP-complete and no general or efficient method was known to solve the problem. So optimum solutions (i.e., channel locations) were obtained only with an exhaustive computer search [1].

However, these techniques [7]-[14] resulted in increase of bandwidth requirement compared to equally spaced channel allocation. This is due to the constraint of the minimum channel spacing between each channel and that the difference in the channel spacing between any two channels is assigned to be distinct. As the number of channel increases, the bandwidth for the unequally spaced channel allocation methods increases in proportion [3].

In this paper, a fractional bandwidth channel allocation algorithm is designed taking into consideration the concept of Optimal Golomb Ruler (OGR) [6], [15 - 17]. This is a novel method for channel allocation to achieve reduction in FWM effect with the WDM systems without inducing additional cost in terms of bandwidth. This proposed technique allows the gradual computation of a channel allocation set to result in an optimal point where degradation caused by inter-channel interference (ICI) and FWM is minimal [3], [16].

Much effort has been made to compute short or dense Golomb rulers and to prove them optimal. Golomb rulers represent a class of problems known as NP-complete [18]. Unlike the traveling salesman problem, which may be classified as a ‘complete ordered set’, the Golomb ruler may be classified as an ‘incomplete ordered set’. The exhaustive search of such problems is impossible for higher order models. As another mark is added to the

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ruler, the time required to search the permutations and to test the ruler becomes exponentially greater. The success of Biogeography Based Optimization approach in finding relatively good solutions to NP-complete problems such as the travelling salesman problem and job-shop scheduling problem provided a good starting point for a machine intelligent method of finding Optimal Golomb Ruler sequences.

This paper proposes a method for finding the solutions to channel allocation problem by using the concept of Optimal Golomb Rulers. Section II introduces the concept of Golomb Rulers. Section III presents a brief about Biogeography Based Optimization (BBO). Section IV presents the problem formulation and steps to generate the Golomb Ruler sequences by using BBO. Section V provides some simulation results comparing with conventional classical approaches of generating unequal channel spacing i.e. Extended Quadratic Congruence (EQC) and Search Algorithm (SA). Section VI presents some concluding remarks.

II. GOLOMB RULERS

The concept of 'Golomb rulers' was first introduced by W.C. Babcock in 1952 [6], and further described by Professor Solomon W. Golomb [15], a professor of Mathematics and Electrical Engineering at the University of Southern California. According to Colannino [19] and Dimitromanolakis [20], W. C. Babcock [6] first discovered Golomb rulers up to 8- marks, while analyzing positioning of radio channels in the frequency spectrum. He investigated inter-modulation distortion appearing in consecutive radio bands and observed that when positioning each pair of channels at a distinct distance, then third order distortion was eliminated and fifth order distortion was lessened greatly.

The term 'Golomb Ruler' refers to a set/sequence of non-negative integers such that no distinct pairs of numbers from the set have the same difference [21]. Normally the first mark of the ruler [16] is set on position 0 and the position of the right most mark is called the length of the ruler. Since the difference between any two numbers is distinct, the new FWM frequencies generated would not fall into the one already assigned for the carrier channels. A normal ruler is used to measure distances. It has marks at equidistant points and the distances are measured from one point to another. We consider rulers with marks at integer locations.

Golomb Rulers are numerical sequences or a class of undirected graphs that, unlike usual rulers, measure more discrete lengths than the number of marks they carry. The particularity of Golomb rulers is that all differences between pairs of marks are unique [22], [23]. Although the definition of a Golomb ruler does not place any restriction on the length of the ruler, we are usually interested in rulers with minimum length.

Let us assume that the ruler has 'm' marks and the length of the ruler is 'n'. For a normal ruler, n = m-1. Such a ruler is shown in Figure 1. The ruler in the Figure 1 has four marks at 0, 1, 2 and 3. Thus, it can measure distances up to three units in length. The distances are marked on the ruler [24].

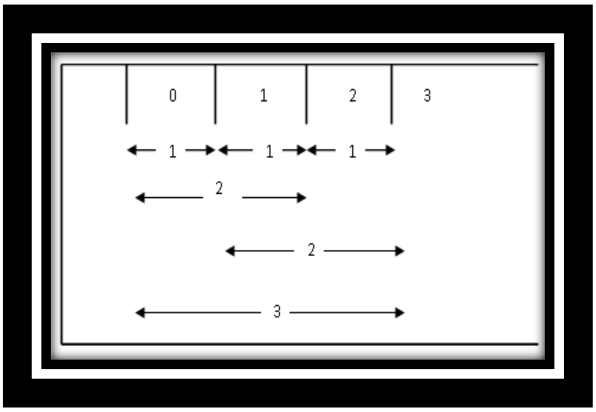

Figure 1. A Normal Ruler

Consider a ruler in which one distance can be measured only in one way. In other words, the distance between any two points on the ruler is unique. Such a ruler with four marks is shown in Figure 2. The distance between each pair of marks is also shown in the figure. As can be seen, they are all distinct. It is necessary to define some basic used to describe the characteristics of Golomb Rulers [24].

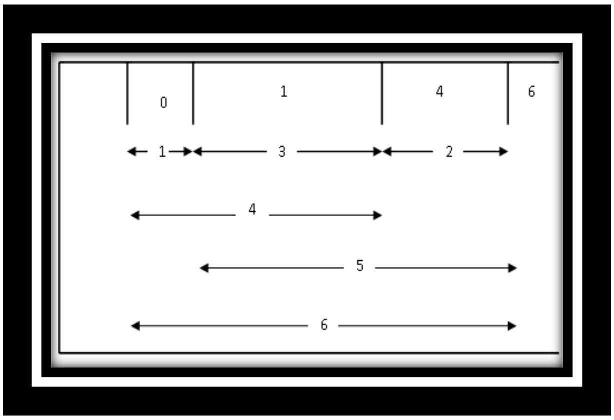

Figure 2. A Golomb Ruler

A. *MARKS AND LENGTH*

A Golomb Ruler consists of ordered series of integer numbers. These numbers are referred to as *marks*, and correspond to positions on a linear scale. The difference between the values of any two marks is called the distance between those marks. The difference between the largest and smallest number is referred to as the *length* of the ruler, and corresponds to the largest distance for that ruler. The first mark of the series is by convention at position zero. The number of marks on a ruler is sometimes referred to as the *size* of the ruler [15], [24].

B. PERFECT GOLOMB RULER

A perfect Golomb Ruler measures all the integer distances from 0 to L where L is the length of the ruler [18], [24]. In other words, the difference triangle of a perfect Golomb Ruler contains all numbers between one and the length of the ruler. The length of an N mark perfect Golomb ruler is N (N – 1) /2.

For example, as shown in Figure 3 the set (0, 1, 3, 7) is a non optimal 4-mark Golomb ruler since its differences are (1 = 1 – 0, 2 = 3 – 1, 3 = 3 – 0, 4 = 7 – 3, 6 = 7 – 1, 7 =7 – 0), all of which are distinct.

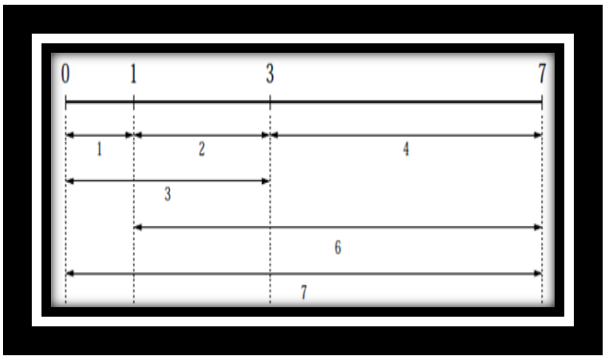

Figure 3. A Non Optimal 4-Marks Golomb ruler

For a ruler to be perfect Golomb Ruler it must meet the following criteria [25]:

1. It must be constructed of segment of unique integral length. In other words, the length of a segment must be some integer number of units and no two segments in a given ruler have the same length.
2. The ruler must be able to measure discrete spans. That means the distance between two given marks must be a unique length for that ruler, with no two spans equalling the same length.

However, the unique optimal Golomb 4-mark ruler is (0, 1, 4, 6), which measures the distances (1, 2, 3, 4, 5, 6) (and is therefore also a perfect ruler) as shown in Figure 4 [26].

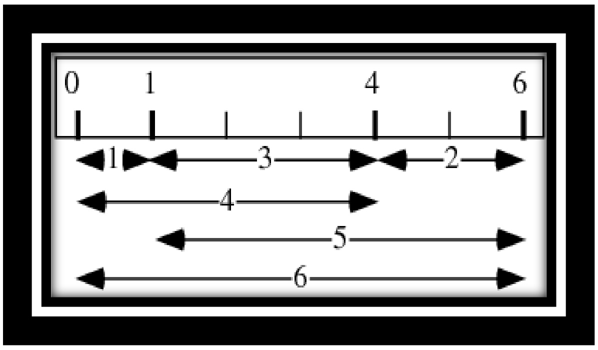

Figure 4. A Perfect Golomb Ruler of order 4 and length 6

C. OPTIMUM GOLOMB RULER

Since perfect rulers beyond four marks cannot exist, longer rulers are described in terms of whether or not they are optimum. An Optimal Golomb Ruler is defined as the shortest length ruler for a given number of marks [24], [27]. There may exist multiple different OGRs for a specific number of marks.

An n - mark Golomb ruler is a set of n distinct nonnegative integers (a_1, a_2, …, a_n), called "marks," such that the positive differences $|a_i - a_j|$, computed over all possible pairs of different integers i, j = 1, 2, …, n with $i \neq j$ are distinct [28]. Let a_n be the largest integer in an n - mark Golomb ruler [29]. Then an n - mark Golomb ruler (0, …, a_n) is *optimal* if

1. There exists no other n -mark Golomb rulers having smaller largest mark a_n, and
2. The ruler is written in canonical form as the "smaller" of the equivalent rulers (0, a_2, …, a_n) and (0, …, $a_n – a_2$, a_n), where "smaller" means the first differing entry is less than the corresponding entry in the other ruler.

In such a case, a_n is the called the "length" of the optimal n - mark ruler.

Various classical methods are proposed in [1], [7 – 14] to generate the OGRs. The soft computing methods that employ genetic algorithm (GA) based methods [23 - 25] could be found in literature. This paper proposes another technique based on the mathematics of biogeography, i.e., biogeography based optimization algorithm.

The OGRs are used in a variety of real-world applications such as Communications and Radio Astronomy, X-Ray Crystallography, Coding Theory, Linear Arrays, Computer Communication Network, PPM Communications, circuit layout, geographical mapping and Self-Orthogonal Codes [6], [15], [24], [25], [30].

III. BIOGEOGRAPHY BASED OPTIMIZATION

Biogeography Based Optimization is a population-based evolutionary algorithm (EA) developed for global optimization. It is based on the mathematics of biogeography. It is a new kind of optimization algorithm which is inspired by the science of Biogeography. It mimics the migration strategy of animals to solve the problem of optimization [31], [32]. Biogeography is the study of the geographical distribution of biological organisms. The science of biogeography can be traced to the work of nineteenth century naturalists such as Alfred Wallace [33] and Charles Darwin [34].

In BBO, problem solutions are represented as islands and the sharing of features between solutions is represented as emigration and immigration. An island is any habitat that is geographically isolated from other habitats [35].

The idea of BBO was first presented by Dan Simon in December 2008 and is an example of how a natural process can be modelled to solve general optimization problems [36]. This is similar to what has occurred in the past few decades with Genetic Algorithms (GAs), Artificial Neural Networks (ANNs), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and other areas of computer intelligence. Biogeography is nature's way of distributing species, and is analogous to general problem solving. Suppose that there are some problems and that a certain number of candidate solutions are there. A good solution is analogous to an island with a high HSI (Habitat suitability index), and a poor solution is like an island with a low HSI. Features that correlate with HSI include factors such as rainfall, diversity of vegetation, diversity of topographic features, land area, and temperature. The variables that characterize habitability are called suitability index variables (SIVs). High HSI solutions are more likely to share their features with other solutions, and HSI solutions are more likely to accept shared features from other solutions [36 -38]. As with every other evolutionary algorithm, each solution might also have some probability of mutation, although mutation is not an essential feature of BBO.

IV. Problem Formulation

If the channel spacing between any pair of channels is denoted as CS and the total number of channels is N, then the objective is to minimize the length of the ruler denoted as RL, which is given by the equation (1):

$$RL = \sum_{i=1}^{N} (CS)_i \tag{1}$$

subject to $(CS)_i \neq (CS)_j$

If each individual element is a Golomb Ruler, the sum of all elements of an individual forms the bandwidth of the channels. Thus, if an individual element is denoted as IE and the total number of elements is M, then the second objective is to minimize the bandwidth (BW), which is given by the equation (2):

$$BW = \sum_{i=1}^{M} (IE)_i \tag{2}$$

subject to $(IE)_i \neq (IE)_j$

A. *BBO Algorithm to Generate Optimal Golomb Ruler Sequences*

The basic structure of BBO algorithm [37], [39 - 41] to generate OGR sequences is as follows:

1. Initialize the BBO parameters: maximum species count i.e. population size S_{max}, the maximum migration rates E and I, the maximum mutation rate m_{max}, an elitism parameter and number of iterations.
2. Initialize the number of channels (or marks) 'N' and the upper bound on the length of the ruler.
3. Initialize a random set of habitats (integer population), each habitat corresponding to a potential solution to the given problem. The number of integers in each habitat being equal to the number of channels or mark input by the user.
4. Check the golombness of each habitat. If it satisfies the conditions for Golomb Ruler sequence, retain that habitat; if it does not, delete that particular habitat from the population generated from the step 3.
5. For each habitat, map the HSI (Bandwidth) to the number of species S, the immigration rate λ, and the emigration rate μ.
6. Probabilistically use immigration and emigration to modify each non-elite habitat, then recompute each HSI.
7. For each habitat, update the probability of its species count given by equation (3). Then, mutate each non-elite habitat based on its probability, check golombness of each habitat again and then recompute each HSI.

$$\dot{P}_s = \begin{cases} -(\lambda_s + \mu_s) P_s + \mu_{s+1} P_{s+1}, & S = 0 \\ -(\lambda_s + \mu_s) P_s + \lambda_{s-1} P_{s-1} + \mu_{s+1} P_{s+1}, & 1 \le S \le S_{\max} - 1 \\ -(\lambda_s + \mu_s) P_s + \lambda_{s-1} P_{s-1}, & S = S_{\max} \end{cases} \tag{3}$$

where λs and μs are the immigration and emigration rates, when there are S species in the habitat.

8. Is acceptable solution found? If yes then go to Step 10.
9. Number of iterations over? If no then go to Step 3 for the next iteration.
10. Stop

V. Simulation Results And Discussion

In this section, we look at the performance of BBO and its comparison with the conventional classical methods of generating unequal channel spacing i.e. Extended Quadratic Congruence and Search Algorithm [1], [24]. To get optimal solution using BBO after a number of careful experimentation, following optimum values of BBO parameters have finally been settled as shown in Table I.

TABLE I. PARAMETERS USED FOR BBO ALGORITHM SIMULATION

Parameter	**Value**
Habitat modification probability (P_{modify})	1
Lower bounds of immigration probability per gene (λ_{Lower})	0
Upper bounds of immigration probability per gene (λ_{Upper})	1
Step size (dt) for numerical integration of probabilities	1
Maximum immigration (I) rates for each island	1
Maximum emigration (E) rates for each island	1
Mutation probability (P_{mutate})	0
Elitsm (keep)	2

A. Effect of increasing generations on total bandwidth

As the number of generations increase, the total bandwidth of the sequence tends to decrease, it means that the rulers reach their optimum values after a certain number of generations. This is the point where the results are optimum and no further improvement is seen, that is, we are approaching towards the optimal solution. This can be seen in tabular form in Table II for N=4 and N=5 and graphically in Figure 5.

TABLE II. EFFECT OF INCREASE IN GENERATIONS ON BANDWIDTH FOR N=4 AND N=5

Generations	Bandwidth	
	N=4	N=5
2	28	39
5	27	39
10	21	35
20	16	34
40	16	30
60	15	30
80	15	28
100	15	28

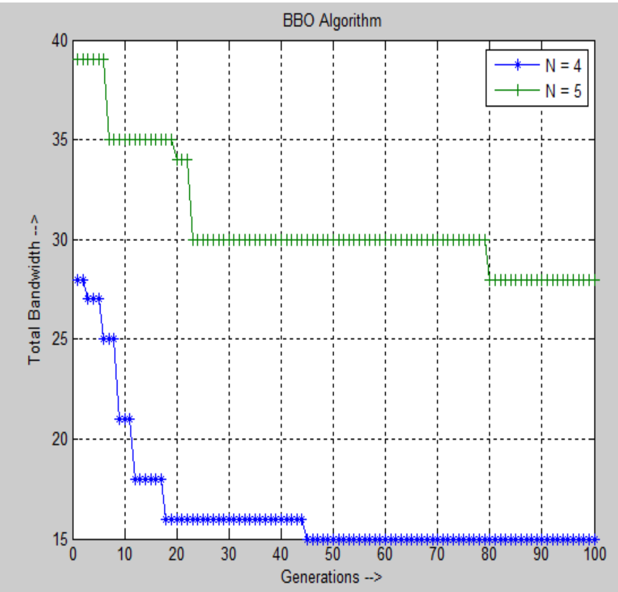

Figure 5. Bandwidth Versus Generations for N=4 and N=5

B. Comparison of BBO with EQC and SA in terms of Ruler Length

The length of optimum Golomb Ruler sequences generated by Biogeography Base Optimization algorithm upto 8-marks are shown in Table III for different values of marks (N) and are compared with known OGR length [1], EQC and SA [24]. It is observed that the ruler length generated by BBO approaches to their optimum values that is, we have got the best results. Figure 6 shows the comparison of BBO with EQC and SA with respect to the ruler length.

TABLE III. COMPARISON OF THE RESULTS OBTAINED BY BBO WITH KNOWN OGR LENGTH, EQC AND SA IN TERMS OF RULER LENGTH

N	Optimal Length	EQC	SA	BBO
3	3	6	5	3
4	6	15	15	6
5	11	28	22	12
6	17	45	25	19
8	34	91	49	44

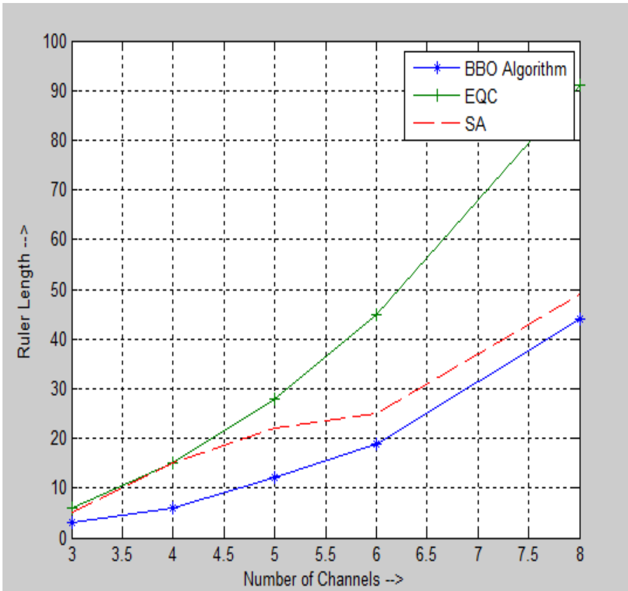

Figure 6. Comparison of BBO with EQC and SA With Respect to the Length of the Ruler

C. Comparison of BBO with EQC and SA in terms of Bandwidth

The aim to use BBO here was to optimize the length of the ruler so as to conserve the bandwidth. Comparing the simulation results of BBO with EQC and SA; we observed that there is a significant improvement with respect to the length of the ruler (see Figure 6) and thus the total bandwidth occupied (see Table IV) by the use of BBO. Figure 7 illustrate the comparison of the three algorithms with respect to bandwidth.

TABLE IV. COMPARISON OF THE RESULTS OBTAINED BY BBO WITH EQC AND SA IN TERMS OF BANDWIDTH

N	EQC	SA	BBO
3	10	10	5
4	32	28	15
5	76	68	28
6	140	95	54
8	378	196	162

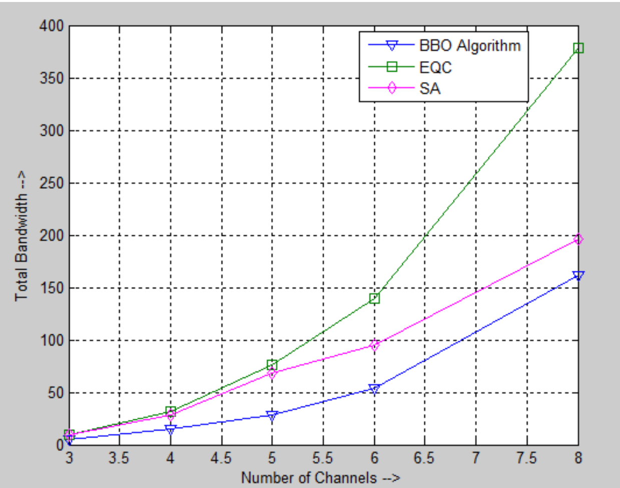

Figure 7. Comparison of BBO with EQC and SA With Respect to the Bandwidth of the Ruler

VI. CONCLUSION

Generation of Optimal Golomb Ruler sequences from classical approach is a high computational complexity problem. The purpose of BBO is not necessarily to produce perfect results, but to produce the best results under the constraints of time and cost. We have shown how biogeography, the study of the geographical distribution of biological species, can be used to derive algorithms for optimization. In this paper we applied BBO to solve Optimal Golomb Ruler problem. We have observed that BBO produces Golomb Ruler sequences very efficiently. Its performance is being compared with the classical approach i.e. Extended Quadratic Congruence (EQC) and Search Algorithm (SA). The preliminary results indicate that BBO appears to be most efficient approach to such NP-complete problems.

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