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A Review on: Suppression of FWM Crosstalk on WDM Systems Using Unequally Spaced Channel Algorithms

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Abstract—Inthis paper four–wave mixing (FWM) is one of the interference(crosstalk) which is one of the dominating demotion nonlinear optical effects in wave division multiplexing system(WDM). Generally, Optimal Golomb ruler (OGR) sequences by using unequally spaced channel allocation methods to achieved FWM crosstalk. To reduce thecrosstalk due to FWM, various algorithm based unequally spaced channel allocation technique is study in this paper .FWM effect reduce while maintaining the bandwidth efficiency, thereby optimizing the system performance.

Keywords—Channel spacing, Four wave mixing, Optimal Golomb ruler, WDM systems.

I. INTRODUCTION

Wavelength division multiplexing(WDM) systems has many application due to a very large capacity, repeaterless and light wavesystem. In WDM system FWM (four wave mixing) crosstalk occur. In optical WDM system channels are assign with central frequencies or wavelength due to equal spacing frequency may fall into the other channel which result in side band (ghost channel). The side band intractwith other frequencies and resulting as crosstalk (distortion) or FWM in WDM system. So to minimize FWM crosstalk unequal channel spacing used in WDM channel allocation.Various non–linear effects suppression methods have been developed by researchers. Generally, the suppression can be achieved by using chirped fiber Bragg gratings as a dispersion compensation method [8], laser oscillations [9], using different modulation format other than the conventional return-to-zero (RZ) modulation format [13] and unequally spaced channel allocation by using various types of algorithms [10], [11]. In literature [2], [5], [7], [12] it is stated that among the fiber nonlinearities in WDM systems, the FWM crosstalk is the most serious one because it involves a lower optical input power than other nonlinearities.

II. UNEQUALLY SPACED CHANNEL ALLOCATION

FWM interference (crosstalk) is most important source perform demotion of WDM channel system. In an attempt to reduce the FWM crosstalk in WDM system unequally spaced channel allocation (USCA) techniques have been studied in [1], [3], [4]–[6], [10], [14]–[18]. In unequal channel spacing allocation techniques to make certain that no FWM signal will generated at any channel frequencies. If frequencies between any two channel is different from any other channel in minimum operating bandwidth.

Overview of unequal channel spacing researches carried out by different authors.

- *M. D. Atkinson et. al.* [18], proposed some sets of integers with distinct sums and differences so as to avoid the third and fifth–order nonlinear inter–modulation effects for upto 100–channels.
- *N. MohamadSaaid*[10], presented a review on different methods that had been proposed by many researchers for the suppression of nonlinear optical effects in WDM systems. The nonlinear optical suppression methods can be achieved by using chirped fiber Bragg gratings, laser oscillations,unconventionalmodulation formats (such as polarisation shift–keying (PolSK)) and unequally spaced channel allocation by using various types of algorithms.
- *W. C. Kwonget. al.* [1], proposed three methods namely Extended Quadratic Congruence sequences; Search Algorithm; and disjoint difference sets to obtain the channel allocation based on algebraic approach. To show optimal results, the bounds on the total occupied optical bandwidth of the unequal spaced channels had been provided. These three methods were able to achieve optimal unequal spaced channel allocation in that no FWM signals will fall onto the channel signals. However, the application of the algorithms was limited to prime powers, and the bandwidth to be assigned to the system was much larger than that for the bandwidth for equally spaced channel allocations.
- *Bohyeon Hwang et. al.* [4], [5], proposed a simple suboptimum USCA (S–USCA) algorithm by using frequency difference triangle sets to obtain close–to–minimum operating bandwidth and to result in a close–to–minimum number of FWM signals in the carrier channels. The objective was to redistribute the FWM signals in such a way that the numbers of FWM signals falling onto a specific carrier channel get reduced substantially. Compared with the above mentioned three methods proposed by *W. C. Kwong*, the bandwidth used was reduced.

- *H.P. Sardesai*[17], presented a simple channel plan scheme which was based on selective removal of certain channels in an equally spaced channel plan (ESCP) grid to reduce nonlinear effects in WDM systems. But this scheme has a low bandwidth expansion factor (BEF) of 1.4.
- *R. Randhawa et. al.* [10], implemented in MATLAB an unequal channel allocation method by using two classical computing algorithms i.e. EQC and Search Algorithm. This channel allocation method is based on Optimal Golomb rulers that will suppress the FWM crosstalk while maintaining the bandwidth efficiency. OGR was based on two following constraints, which were minimum channel spacing between adjacent channels and the total number of slots occupied by these channels. From the simulation results, they concluded that both algorithms show better bandwidth efficiency while suppressing FWM crosstalk in WDM systems. However, search algorithm was better compared to EQC because it took lesser number of slots and much lesser computation time.
- *ShonakBansal* ,proposed One of the unequal bandwidth channel allocation technique 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. Biogeography Based Optimization (BBO) method for the generation of Golomb Ruler sequences.BBO performs better than the two other methods i.e. Extended Quadratic Congruence (EQC) and Search Algorithm (SA) to reduce FWM crosstalk in optical communication systems.

III. GOLOMB RULER BASED CHANNEL ALLOCATION

W.C. Babcockwas first introduced the concept of Golomb ruler. Golomb ruler refer to a class of undirected graphs that unlike rulers, measure more discrete lengths that's the numbers of marks carry. In Golomb ruler set of marks in such that the two pairs of marks not contain same difference.

The value difference between the two pairs of marks refers as distance of those marks. The difference between the smallest and largest marks refer to as length of ruler. Sometimes numbers of marks refers as the ruler length and size of the ruler. Figure 1 shows an example of Golomb ruler with the distance between each pair of marks .An Optimal Golomb ruler is defined as the shortest length ruler for a given number of marks [25]. There can be multiple different OGRs for a specific number of marks. However, the unique optimal Golomb 4–mark ruler is (0, 1, 4, 6), which measures the distances (1, 2, 3, 4, 5, 6) as shown in Figure 1. The particularity of Golomb rulers is that all differences between pairs of marks are unique [24], [26]. Although the definition of a Golomb ruler does not place any restriction on the length of the ruler, researchers are usually interested in rulers with minimum length. A perfect Golomb ruler measures all the integer distances from 0 to L, where L is the length of the ruler [27], [29]. 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 [30]–[32].For example, Figure 2 shows that the set (0, 1, 4, 10, 12, 17) is a non–optimal 6–mark Golomb ruler since its differences are (1 = 1 – 0, 3 = 4 – 1, 4 = 4 – 0, 6 = 10 – 4, 2= 12 – 10, 5 =17 – 12), all of which are distinct. As from the differences it is clear that the number 14, 15 is missing so it is not a perfect Golomb ruler sequence.

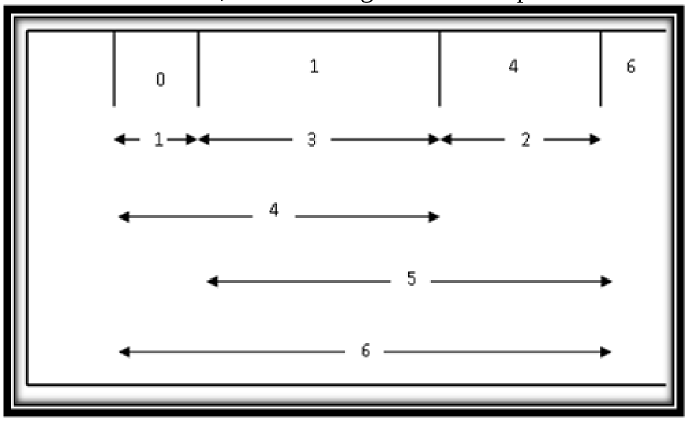

Figure: 1 AGolomb Ruler with 4–Marks and Length 6

According to [29] Golomb rulers represent a class of NP–complete problems. The exhaustive search [31], [33] of such problems is impossible for higher order marks. As another mark is added to the ruler, the time required to search the permutations and to test the ruler becomes exponentially greater. In literature, there are many different approaches to tackle the Golomb ruler problem such as exact methods [31], [33],constraint programming [24], local searches [34] and exhaustive parallel search [30].

The success of soft computing approaches such as Genetic Algorithms (GAs) [27], [35], [36], Biogeography Based Optimization (BBO) [22], [23], [37], [38] and Big Bang–Big Crunch (BB–BC) evolution theory [39], [40] in finding relatively good solutions to such NP–complete problems provides a good starting point for methods of finding Optimal Golomb ruler sequences. Hence, soft computing approaches seem to be very effective solutions for such NP–complete problems. So in this subsection, the evolution of Golombrulers' sequences and its role in WDM systems by the different researches using various classical and soft computing algorithms is being studied. As stated earlier, Golomb rulers are credited as being discovered by W. C. Babcock in 1953 [15].

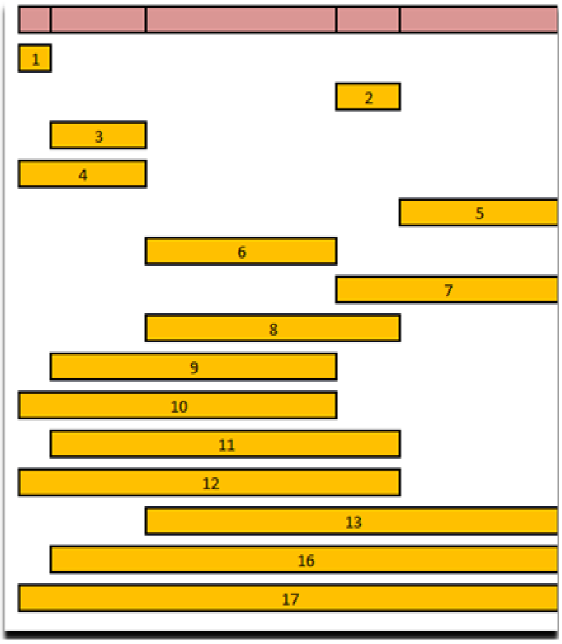

Figure: 2 A Non Optimal Golomb Ruler of 6–Marks and Length 17

IV. IMPORTANCE OF GOLOMB RULERS IN WDM SYSTEMS

To suppress FWM crosstalk in WDM systems the use of OGR has been proposed. As stated above that the performance of WDM systems can be improved by the use of proper unequal channel spacing. The one of the best method for finding unequal channel allocation is the use of OGR sequences [15], [19]–[20]. Golomb ruler is the shortest possible ruler for a given number of marks. Therefore applying OGR to the channel allocation problem, it is possible to achieve the smallest distinct number to be used for WDM channel allocation. 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. For *n*–channels, the Golomb ruler for *n*–marks is used. Golomb rulers are not redundant as they do not measure the same distance twice [24].

V. RELATED WORK

- According to by *William Mixon*by using exhaustive computer search procedurethe rulers with 8 to 11 marks have been proved.
- According to *Colannino*[40] *W. C. Babcock* first discovered Golomb rulers up to 10–marks, while analyzing positioning of radio channels in the frequency spectrum. According to *William T. Rankin* [39], all of rulers‘ up to 8 are optimum, 9 and 10–mark rulers that *W. C. Babcock* presents are near to optimum.
- Further, *J. P. Robinson* [33], published the optimal rulers with 10 to 13 marks. The search was continued by *J. B. Shearer*, who published the rulers for 14, 15, and 16 marks. Both researchers use exhaustive computer search to find optimal rulers. *Sibert*discovered rulers of 17 and 18 marks in 1993.
- *ApostolosDollaset. al.* [28], provided a parallel distributed algorithm for Golomb ruler namely shift algorithm. Using this algorithm, the optimality for 17 to 19 mark rulers was proven computationally.
- *J. P. Robinson et. al.* [16], provide the rulers with 5 to 7 marks. They presented a systematic synthesis procedure for generating a class of self–orthogonal convolutional codes by means of perfect difference sets. These codes are capable of correcting independent errors, and have the property that the decoder will recover from a decoding error if a sufficiently long error–free period occurs. The length of this period is several times the constraint length.
- *Vrizlynn L. L. Thing et. al.* [19], [13], 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.
- *William T. Rankin* [30], has developed various exhaustive parallel search algorithms for 19–mark Golomb ruler implementation using about 36,200 CPU hours. The algorithms include Scientific American Search, Token Passing Algorithm, Shift Algorithm, Tree Algorithm and Search Space Reduction. Further *J. P. Robinson*, translated Golomb rulers to rectangles.
- The search for OGRs be exhaustive search was in run and all Golomb rulers up to 24–marks were proved optimal by the Golomb ruler search project between 1998 and 2004. In 1967, *J. P. Robinson et. al.* found the 24–mark ruler, which was verified to be optimal on Nov. 1, 2004 by a 4–year computation on distributed.net [21] that performed as exhaustive parallel search. In 1984, *M. D. Atkinson* and *A. Hassenklover*found the 25–mark. A follow–up eight year distributed.net [21] project for the 25–mark ruler, announced on October 25, 2008

that the 25–mark ruler was optimal. According to [29], distributed.net has completed distributed massively parallel searches for optimal Golomb rulers of mark–26. Distributed.net also has plans to find optimal Golomb rulers of marks 27 and 28. Distributed.net is actively searching for the optimal 27–mark ruler; the expected time to discover it is about seven years.

- *Stephen W. Solidayet. al.* [27], proposed that Golomb rulers represents a class of NP–complete problems. The exhaustive search of such problems is impossible for higher order models. So they applied a population based evolutionary approach called as Genetic Algorithm, to generate OGRs from 5 to 16 marks. The Genetic Algorithm was written in C++ using object oriented programming. In addition, they use two evaluation criteria such as the overall length of the ruler and the number of repeated measurements. The Genetic Algorithm seems to be more efficient approach in producing short rulers for each of the orders. Further the research was continued by *J. P. Robinson* [35] to search Golomb arrays upto 24–mark using Genetic search and conclude the Genetic search was significantly more efficient than prior methods.
- *Shobhika* 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 [1] and [10]. From simulation results she concluded that the results obtained from Genetic Algorithm, approaches to optimal after a number of iterations.
- *Sugumaran* 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. Bansal et. al.*in [22], [23], [37], [38] apply two soft computing based approaches i.e. GA and BBO to generate OGR sequences for various marks. Later *S. Bansal et. al.*in [39], [40], again proposed a novel soft computing approach based on BB–BC evolution theory to generate the OGRs sequences for various marks. From the simulation results they concluded that BBO/GA and BB–BC outperforms the two existing classical algorithms i.e. EQC and SA. In [39], [40] they also concluded that BB–BC also outperforms the one of the existing soft computing.

VI. CONCLUSIONS

FWM crosstalk is a major source of distortion in optical WDM systems. FWM crosstalk is the interaction of two or more frequencies which results in sidebands or ghost channels. These sidebands can overlap with other channels resulting in distortion.. Hence, it has received considerable attention over the other non–linear optical effects in recent past. In this paper we have made an attempt to survey all the several unequal channel spacing. But all these results have the drawback of increased bandwidth requirement. Golomb ruler is one of the important techniques for channel spacing allocation. Here we have attempted to collect various classical and soft computing approaches to tackle the problem of OGRs. To date, the work done by [1], [3], [4]–[6], [10], [14]–[18] does not show the implementation of their algorithm in real WDM system in order to see the complexity of realising the unequal channel spacing. In the course of our study we noticed that although various techniques have been suggested for OGR, yet there is no uniformly accepted formulation. More extensive empirical investigation is needed in this area before a general conclusion can be made.

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