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Suppression of FWM Crosstalk on WDM Systems Using Unequally Spaced Channel Algorithms–A Survey

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Abstract—***The phenomenon of an undesirable nonlinear optical effects degrade the system performance. In optical wave–length division multiplexing (WDM) systems employing dispersion shifted fibers, the crosstalk due to four–wave mixing (FWM) is one of the dominating degradation nonlinear optical effects. Generally, FWM crosstalk suppression can be achieved by using unequally spaced channel allocation methods such as integer linear programming (ILP), extended quadratic congruence (EQC) algorithm, search algorithm (SA), disjoint difference sets (DDS), and optimal Golomb ruler (OGR) sequences. The main contribution of this paper is to presents a brief survey on the ILP, EQC, SA and DDS and detailed survey on OGR sequences proposed in literature for FWM crosstalk suppression in WDM systems.***

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

I. INTRODUCTION

Wavelength division multiplexing, erbium–doped fiber amplifiers (EDFA's) and dispersion–shifted fiber (DSF) can be used to design a very large capacity, long–haul, repeaterless, fiber optics communication systems. WDM systems enhance the capability of fiber optics communication system by enabling various channels to be transmitted in different wavelengths, fully exploits the vast bandwidth [1].The EDFA systems improve the performance of WDM system in which no repeater is needed to overcome the problem of attenuation and distortion of signals. But EDFA systems introduce some problems like the accumulation of amplified spontaneous emission, stimulated Raman scattering and four–wave mixing. At bit rate higher than 2.5 Gbit/s, fiber nonlinearities start to degrade the WDM system performance. Linear effects such as attenuation and dispersion can be compensated, but nonlinear effects can't be compensated [2].

The nonlinear effects in fibers can be broadly classified into two categories [3]:

- *Stimulated scattering effects:* The scattering effects are due to the interaction of light waves with molecular or sound waves in fiber. The scattering effects include *stimulated Raman scattering* (SRS) and *stimulated Brillouin scattering* (SBS).
- *Kerr effect*: The Kerr effect arises from intensity–dependent variations in the refractive index in a silica fiber. These effects include *self–phase modulation* (SPM), *cross–phase modulation* (XPM) and *four–wave mixing*, in which the latter is the most dominant noise effect [4]. In the literature [3]–[5], FWM sometimes is referred to as *four–photon mixing* (FPW).

Dispersion–shifted fiber (DSF) can effectively suppress the effects of chromatic dispersion [1], [6]–[9]. This allows very high–data–rate transmission over long distances. However, DSF increases the efficiency of the FWM signals.

FWM crosstalk is analogous to third–order inter–modulation distortion in silica fiber whereby two or more optical waves at different frequencies (or wavelengths) mix to produce new optical waves at other frequencies [3], [5].Thus, FWM crosstalk is the interaction of two or more wavelengths (channels) which results in sidebands (or ghost channels). The sidebands can coincide with other channels resulting in distortion. The effect on WDM channels can be similar to crosstalk if only few channels are used and similar to noise if a number of channels are used [10]. 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 [11], laser oscillations [12], 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 [14], [15]. In literature [3], [7], [10], [16] 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.

In optical WDM systems, channels are usually assigned with center frequencies (or wavelength) equally spaced from each other. Due to equal spacing among the channels there is very high probability that FWM signals may fall into the WDM channels, resulting in severe crosstalk [1]. Performance can be substantially improved if FWM crosstalk generation at the channel frequencies is avoided. It is therefore important to develop algorithms to allocate the channel frequencies in order to minimize the FWM crosstalk. Therefore the efficiency of FWM depends on the channel spacing and fiber dispersion [5], [10].If the frequency separation of any two channels of a WDM system is different from that of any other pair of channels, no FWM signals will be generated at any of the channel frequencies. The use of proper unequal channel spacing keeps FWM signals from coherently interfering with the desired signals [9], [17]–[19].

This paper mainly focuses on the survey on unequal channel spacing algorithms provided by different researchers. With this aim the paper is organized as follows. Section II overviews the history on unequal channel spacing and Golomb ruler based bandwidth efficient channel allocation scheme. Finally overall survey is concluded in section III.

II. Historical Perspective

A. Unequally Spaced Channel Allocation

The crosstalk due to FWM is the major source of performance degradation in all WDM systems. In an attempt to reduce the FWM crosstalk in WDM systems, several unequally spaced channel allocation (USCA) techniques have been studied in [1], [4], [6]–[9], [14], [18]–[24]. An optimumUSCA (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 [7]. This subsection is devoted to the researches carried out by different authors on unequal channel spacing has been overviewed.

- *W. C. Babcock* [19], proposed that the third and fifth order inter–modulation products at the carrier channels are due to the nonlinear characteristics of a common amplifier. So he presented the channel assignment integer sequences so as to avoid the third–order and fifth–order inter–modulation products at the carrier channels for up to 10–channel systems. He concluded that by placing each pair of channels inside the frequency spectrum at a distinct distance the third–order distortion was eliminated and the fifth–order distortion was lessened greatly.
- *J. P. Robinson et. al.* [20], provided, frequency difference triangle sets in conjunction with coding theory, a third-order intermodulation products-free USCA technique for up to 24–carrier channels.
- *R. J. F. Fanget. al.* [18], formulated the problem of channel assignment as a distinct difference problem and applied some results from graph theory and coding theory. The results are used to provide optimal frequency plans upto 23–channels.
- Further *M. D. Atkinson et. al.* [24], proposed some integer sets with distinct sums and differences so as to avoid the third and fifth–order nonlinear inter–modulation effects for upto 100–channels.
- *Marl W. Maeda et. al.* [23], presented that the optical nonlinearity in a single–mode fiber imposes a fundamental limitation on the capacity of optical frequency–division multiplexed (OFDM) systems. They proposed that the FWM crosstalk may severely degrade the system performance when the channel spacing is too small. Their theoretical results demonstrate the dependence of FWM on various systems parameters. The receiver sensitivity degradation from FWM crosstalk was measured in a 16–channel coherent system.
- *Fabrizio Forghieri et al.* [8], [9], treated the channel–allocation design as an integer linear programming (ILP) problem by dividing the available optical bandwidth into equal slots of bandwidth large enough to avoid appreciable overlap between spectra in adjacent slots. But the ILP problem was NP–complete and no general or efficient method was known to solve the problem. So they concluded that the channel allocations were obtained only with an exhaustive computer search.
- *W. C. Kwong et. 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.* [6], [7], 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 et al.* [63], the bandwidth used was reduced.
- *H.P. Sardesai* [22], 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.* [14], 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.
- *N. Mohamad Saaid* [14], 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, unconventional modulation formats (such as polarisation shift–keying (PolSK)) and unequally spaced channel allocation by using various types of algorithms.

Drawback: However, the literature [17] reviewed that the above mentioned techniques have the drawback of increased bandwidth requirement as compared to equally spaced channel allocation. This is due to the constraint that the minimum channel spacing between each channel and that the difference in the channel spacing among any two channels is assigned to be distinct. As the number of channels increases, the bandwidth for the USCA methods increases in proportion.

Lemma: One of a method for finding the solutions to channel allocation problem is by using the concept of OGR sequences [19], [25]–[27]. This method for unequal channel allocation achieves reduction in FWM crosstalk in WDM systems without inducing additional cost in terms of bandwidth. This 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 [17], [25].

B. Golomb Ruler Based channel allocation

The concept of 'Golomb rulers' was first introduced by *W.C. Babcock* [19], and further derived by *Professor Solomon W. Golomb* [27], a professor of mathematics and electrical engineering at the University of Southern California and since then his name is associated with these constructions.

Golomb ruler refers to a set of marks at non–negative integers such that no two pairs of marks from the set have the same difference [28], [29]. These numbers are referred to as marks [27], [30]–[32]. 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. The number of marks on a ruler is sometimes referred to as the size of the ruler. Normally the first mark of the ruler is set on position 0 [25], [27], [33]. Figure 1 shows an example of Golomb ruler with the distance between each pair of marks [24].

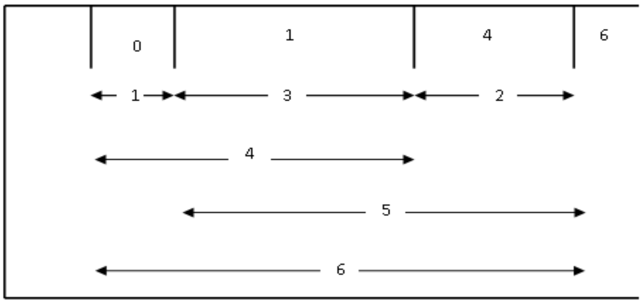

Figure 1 A Golomb Ruler with 4–Marks and Length 6

An Optimal Golomb ruler is defined as the shortest length ruler for a given number of marks [30], [34]. 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 [33], [35]. 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. The OGRs are used in a variety of real–world applications including Communications and Radio Astronomy, X–Ray Crystallography, Coding Theory, Linear Arrays, Computer Communication Network, PPM Communications, circuit layout, geographical mapping and Self–Orthogonal Codes [19], [27], [30], [36], [37].

A perfect Golomb ruler measures all the integer distances from 0 to L, where L is the length of the ruler [30], [36], [38]. 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 $\frac{1}{2}n(n-1)$ [39]–[41].For example, Figure 2 shows that 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. As from the differences it is clear that the number 5 is missing so it is not a perfect Golomb ruler sequence.

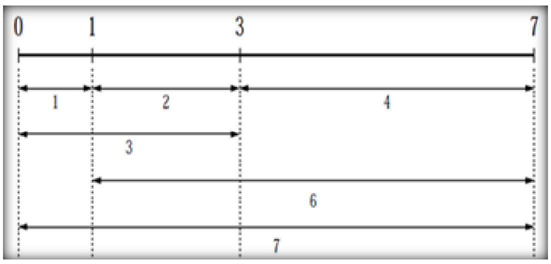

Figure 2 A Non Optimal Golomb Ruler of 4–Marks and Length 7

According to [38] Golomb rulers represent a class of NP–complete problems. The exhaustive search [40], [42] 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 [40], [42],constraint programming [33], local searches [43] and exhaustive parallel search [39]. The success of soft computing approaches such as Genetic Algorithms (GAs) [30], [36], [44], [45], Biogeography Based Optimization (BBO) [31], [32], [46], [47] and Big Bang–Big Crunch (BB–BC) evolution theory [48], [49] 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 Golomb rulers' 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 [19].

Role 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 [19], [25]–[27]. 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 [33]. In this subsection, a survey on unequal channel spacing is being overviewed.

- According to *Colannino* [50] and *Dimitromanolakis* [51], *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.
- *J. P. Robinson et. al.* [20], 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.
- According to [51], [52], the rulers with 8 to 11 marks have been proved by *William Mixon* by using exhaustive computer search procedure.
- Further, *J. P. Robinson* [42], [53], published the optimal rulers with 10 to 13 marks. The search was continued by *J. B. Shearer* [54], who published the rulers for 14, 15, and 16 marks. Both researchers use exhaustive computer search to find optimal rulers. According to [30], [51] *Sibert* discovered rulers of 17 and 18 marks in 1993.
- *William T. Rankin* [39], 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* [55], translated Golomb rulers to rectangles.
- *Apostolos Dollas et. al.* [37], 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.
- 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 [28] 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 [28] 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.
- *Vrizlynn L. L. Thing et. al.* [25], [17], 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
- *Stephen W. Soliday et. al.* [36], 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* [44] to search Golomb arrays upto 24–mark using Genetic search and conclude the Genetic search was significantly more efficient than prior methods.
- *Francisco B. Pereira et. al.* [56], presented a new Evolutionary Computation (EC) algorithm used to search for good rulers for different OGR instances and showed that the evolutionary approach is effective since it was able to quickly discover good solutions. Furthermore, they consider it as a realistic option to massive parallel approaches that need several months or years and a large computing power to discover high-quality Golomb rulers. The proposed algorithm relies on Random Key to represent individuals from the population. The research based on

Random Keys was again continued by *Tiago Leitao* [43] to represent 10 to 17 marks OGRs sequences with a population size and iterations of 100 and 5000 respectively.

- *Shobhika* [30], 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 [14]. From simulation results she concluded that the results obtained from Genetic Algorithm, approaches to optimal after a number of iterations.
- *Carlos Cotta et. al.* [35], published the Local Search–Based Hybrid algorithms for finding Golomb rulers by using various Soft Computing approaches up to 16 marks. These algorithms are based on both stochastic methods and systematic techniques. More specifically, the algorithms combine ideas from greedy randomized adaptive search procedures (GRASP), scatter search (SS), Tabu Search (TS), clustering techniques, and constraint programming (CP). Each new algorithm is, in essence, born from the conclusions extracted after the observation of the previous one. With these algorithms large rulers with a reasonable efficiency were solved.
- *N. Ayari et. al.* [45], 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.* [57], 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 [31], [32], [46], [47] apply two soft computing based approaches i.e. GA and BBO to generate OGR sequences for various marks. Later *S. Bansal et. al.*in [48], [49], 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 [48], [49] they also concluded that BB–BC also outperforms the one of the existing soft computing approaches i.e. GA.

III. CONCLUSIONS

FWM crosstalk is the interaction of two or more frequencies which results in sidebands or ghost channels. These sidebands can coincide with other channels resulting in distortion. FWM crosstalk is a major source of distortion in optical WDM systems. 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 algorithms. 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], [4], [6]–[9], [14], [18]–[24] 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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