Channel allocation algorithm for WDM systems

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Abstract: An algorithm for WDM channel allocation, based on the concept of Optimal Golomb Ruler (OGR), is proposed. This algorithm enhances system performance by locating an allocation set, where the degradation caused by the effects of interchannel interference and Four-Wave Mixing (FWM) is minimal. Two sets of simulation were performed on an 8x10Gbps-channel system (channel spacing of 50GHz for equally spaced allocation), with 50% pre-allocated bandwidth using non-zero dispersion-shifted fibers with dispersion of 3 and 6ps/nm.km at 1550nm. Results showed BER improvement of 1.75 and 0.97 for the 3 and 6ps/nm.km simulations respectively. This improvement is significant, considering the fact that no additional cost (bandwidth) was incurred, unlike existing unequally spaced channel allocation methods.

OCIS codes: (060.4510) Optical communications; (190.4380) Nonlinear optics, four-wave mixing

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1. Introduction

For any three co-propagating optical signals with frequencies f_i, f_j, and f_k, the new frequencies f_{ijk} generated by FWM [1,2] are represented by

$$f_{ijk} = f_i + f_j - f_k \text{ for } i, j, k \in [1, N] \text{ and } k \neq \{i, j\} \tag{1}$$

Considering all the possible permutations, N co-propagating optical signals will give rise to $N^2(N-1)/2$ new optical signals. Some of these new frequencies fall onto the N original channels, while others are found in other new frequency locations. Those FWM signals, which overlap with the original ones, are considered as crosstalk and will interfere with the normal operation of the WDM channels.

Channel allocation methods [3-8] had been proposed, attempting to reduce FWM effect in WDM systems. However, they 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 must be assigned to be distinct. As the number of channels increases, the bandwidth for the unequally spaced channel allocation methods increases in proportion.

In this paper, a novel method for channel allocation is proposed to reduce the FWM effect so as to improve WDM system performance without inducing additional cost, in terms of bandwidth. A fractional bandwidth allocation algorithm is designed taking into consideration the concept of OGR [9-11]. This proposed technique allows the computation of a channel allocation set to result in an optimal point where degradation caused by interchannel interference and FWM is minimal. The method is simulated and the results are analyzed to prove its effectiveness, such that the system performance has improved while maintaining bandwidth efficiency.

2. Fractional OGR based WDM channel allocation algorithm

In mathematics, the term "Golomb Ruler" [12,13] refers to a set of non-negative integers such that no two distinct pairs of numbers from the set have the same difference. An OGR is the shortest Golomb Ruler possible for a given number of marks. Therefore, applying OGR to the channel allocation problem, it was possible to achieve the smallest distinct number to be used for the 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. However, using OGR was not sufficient as the operating bandwidth would be increased significantly as the existing methods. Therefore, an efficient algorithm is designed to allocate the channels so as to restrict the expansion of the bandwidth.

In WDM systems, the slot width must be large enough to avoid appreciable overlap of channel and the FWM spectra, even with some instability in the channel frequencies. Since the rms frequency jitter for a FWM wave is three times that of a channel, the superimposition of the spectra is negligible when the channel frequency stability is of the order of slot-width/10. This is provided that the slot width is greater than or equal to 2 x bitrate. In order to provide an adequate amount of rejection without distorting the desired channel, a minimum channel separation of greater than or equal to 10 x bitrate should be provided [6].

In actual fact, the ultimate factor, which degrades the system performance is the FWM power rather than the number of FWM signals on each channel. However, the number of FWM signals could be a useful measure. In the equally spaced channel allocation, it is generally assumed that the FWM crosstalk is maximal for the center channel, as the number of FWM signals at the center channel is maximum. The assumption that the FWM power is proportional to the number of FWM signals is used here.

In this method, we aim to achieve reduction in FWM effect with the WDM system using the same operating bandwidth as for equally spaced channel allocation. This could be achieved by allocating some channels nearer to other channels. However, with the reduction of frequency spacing between some channels, the interchannel interference (ICI) would be

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increased. Therefore, this method will attempt to find an optimal point where the distortion caused by both the ICI and FWM will be minimal. Incorporating this algorithm with OGR, a systematic approach to the channel allocation could be achieved whereby no FWM signals fall exactly on the carrier channel and the operating bandwidth would not need to be expanded.

For N channels, the OGR for N marks is used. The first element of all OGRs is 0 and in this scheme, only the rest of the elements are utilized in the algorithm. The operating bandwidth is split into “Pre-allocate” and “Post-allocate” section. The “Pre-allocate” bandwidth section is divided by the total number of channels, so as to obtain the initial channel spacing. The “Post-allocate” bandwidth section is then divided into parts determined by the modified OGR. The OGR vector is formed by removing the first element of 0. The initial modified OGR vector is then formed by rearranging the elements so that the channel spacing of channels nearer to the center frequency will be wider. Subsequent modified OGR vectors are formed by incrementing each element with an Incrementation Factor. The notion here is that since the difference for any two elements in the OGR is distinct, incrementing each element of the OGR by a same value would still result in distinct difference. The Incrementation Factor will also have an impact on the allocation in that it will be in increasing order of significance from the outer to the inner elements. After which, a near equally spaced channel allocation situation would be reached following multiple iterations of the algorithm. The performance of the WDM system is then observed for each iteration to locate the allocation where the performance is optimal. This channel allocation set will be used for the WDM system design eventually. An example is described below.

For an eight-channel 10Gbps WDM system, the OGR for 8 marks is used. For an equally spaced channel allocation, the slot width is 20Hz and the channel spacing is 100GHz. Therefore, the total operating bandwidth is 700GHz. This bandwidth is then split into “Pre-allocate” and “Post-allocate” sections. In this case, we choose the “Pre-allocate” to be 75% and leave the 25% for post allocation purpose. The initial channel spacing will be (75% x 700GHz)/7 = 75GHz. The “Post-allocate” section will be left with 175GHz. The OGR for 8 marks is 0, 1, 4, 9, 15, 22, 32, 34. The OGR vector used is then [1, 4, 9, 15, 22, 32, 34], which has to be rearranged. We place all elements in the odd position into the initial modified OGR vector. Therefore, the initial modified OGR vector will contain [1, 9, 22, 34]. Starting from the last element of the OGR vector, append each element in the even position into the initial modified OGR vector. The initial modified OGR vector will then contain [1, 9, 22, 34, 32, 15, 4]. The sum of the elements is 117. Next, we set the Incrementation factor to 1. The first channel is always set at the start of the bandwidth. The rest of the channels, starting from Channel 2 to 8 are allocated using the following formula.

Channel N frequency = Channel (N-1) frequency + Initial Channel Spacing + (N^{th} element of modified OGR vector / Sum of elements) x Post-allocate Bandwidth (2)

After computing the frequency for all the channels, these frequencies will be considered as the first allocation set. At this first allocation set, the channels nearer the edges of the bandwidth will experience higher ICI as the channel spacing is much smaller than those nearer the center of the bandwidth. The subsequent allocation sets are obtained by incrementing each element of the modified OGR vector with the Incrementation Factor and then using the above formula to compute the channel frequencies. Note here that the Incrementation Factor is considered significant relative to the first few elements of the OGR vector. For example, the next modified OGR vector will be [2, 10, 23, 35, 33, 16, 5] which translates to OGR vector of [2, 5, 10, 16, 23, 33, 35]. The first element will be increased by 100% but the last element is only increased by 3%. These channel allocations based on the subsequent modified OGR vector will therefore, wider the spacing of the channels nearer to the edge of the bandwidth by utilizing the wider spacing allocated nearer the center frequency initially. This reduces the ICI effect of the channels nearer the bandwidth edges gradually with each new allocation set. After multiple iterations, all elements will reach a state whereby they are approximately the same. At this state, the channel allocation will be near the equally spaced channel allocation. This is the point whereby the FWM effect is significant. Therefore, the objective is to arrive at a state whereby the crosstalk introduced by both the ICI and FWM is minimal.

3. Simulation

The 8-channel x 10Gbps, 50GHz spacing for equal channel spacing allocation, WDM system to be simulated, was designed. The 200km fiber has an EDFA after each 100km span of non-zero dispersion shifted fiber to compensate for the attenuation loss of 0.2dB/km. The average power of each laser was set to 1mW.

With a pre-allocated bandwidth of 50%, and dispersion value of 3 and 6ps/nm.km at 1550nm, the algorithm was iterated for 50 rounds. To compute the BER improvement of the new allocation set achieved over the equally spaced channel allocation (old), the BER Improvement Factor was used.

$$BER\ Improvement\ Factor = \log\ (BER_{Old} / BER_{New}) \qquad (3)$$

For the simulation with dispersion value of 3ps/nm.km, allocation set 13 results in the highest improvement with the average BER Improvement Factor of 1.75. Among the 8 channels, Channel 6 had the highest BER improvement factor of 5.39. Except for Channel 1, 3 and 5, which degraded by a factor of 0.41, 0.36 and 0.3 respectively, the other 5 channels had shown improvement in the BER using the proposed method. Table 1 shows the BER values for the equally spaced allocation and the allocation set by the proposed method with the highest improvement. With the allocation set, simulation was performed by increasing the length of the system till comparable performance with equal spacing was achieved. The results showed an increase of 3.8km in system length while still maintaining positive average BER Improvement Factor (0.03). This translates to allowable input power increase of 0.76dB. Figure 1 shows the simulation in terms of distance increase for Channel 2. The first and second iterations were for the equally spaced allocation and allocation set 13 for zero increase in distance. Subsequently, total length of the fiber was increased at 0.2km per iteration.

Table 1. BER values for simulation with 3ps/nm.km dispersion

	Ch 1	***Ch 2***	***Ch 3***	***Ch 4***	***Ch 5***	***Ch 6***	***Ch 7***	***Ch 8***
Equal Spacing	1.8089 E-07	2.9358 E-04	2.8253 E-09	4.1942 E-05	2.9912 E-10	3.4078 E-04	1.5668 E-04	1.7873 E-09
Allocation Set 13	4.6803 E-07	7.7981 E-09	6.5204 E-09	1.7519 E-07	5.9585 E-10	1.3833 E-09	4.0556 E-07	1.3477 E-09

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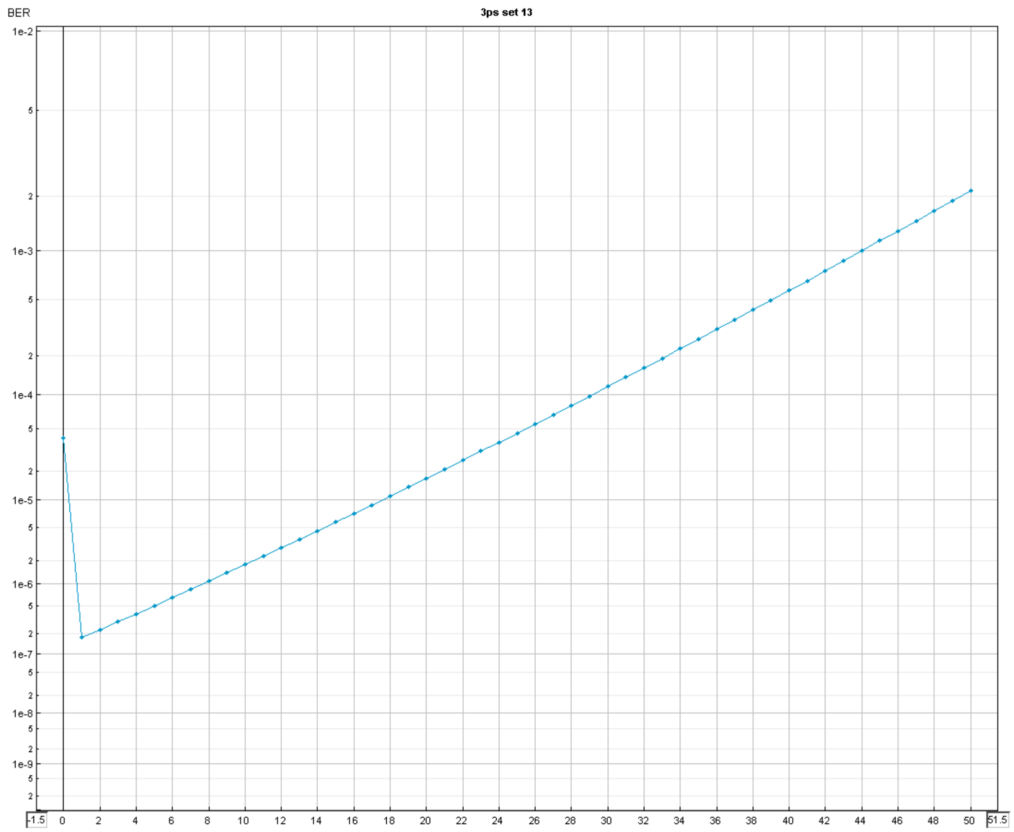

Fig. 1. Simulation on length increase with 3ps/nm.km dispersion

For the simulation with dispersion value of 6ps/nm.km, allocation set 19 results in the highest improvement with the average BER Improvement Factor of 0.97. Among the 8 channels, Channel 4 had the highest BER improvement factor of 3.02. Except for Channel 6, which degraded by a factor of 0.20, the other 7 channels had shown improvement in the BER using the proposed method. Table 2 shows the BER values for the equally spaced allocation and the allocation set by the proposed method with the highest improvement. With this allocation set, simulation was performed by increasing the length of the system till comparable performance with equal spacing was achieved. The results showed an increase of 2.2km in system length while still maintaining positive average BER Improvement Factor (0.06). This translates to allowable input power increase of 0.44dB. Figure 2 shows the simulation in terms of distance increase for Channel 5. The first and second iterations were for the equally spaced allocation and allocation set 19 for zero increase in distance. Subsequently, total length of the fiber was increased at 0.2km per iteration.

Table 2. BER values for simulation with 6ps/nm.km dispersion

	Ch 1	***Ch 2***	***Ch 3***	***Ch 4***	***Ch 5***	***Ch 6***	***Ch 7***	***Ch 8***
Equal Spacing	1.8901 E-04	2.3622 E-04	4.2877 E-06	1.2901 E-04	1.6909 E-06	3.1704 E-08	4.9590 E-04	8.8026 E-05
Allocation Set 13	1.4837 E-04	1.7540 E-05	5.5585 E-07	1.2233 E-07	1.0366 E-07	4.9899 E-08	1.6857 E-05	7.1258 E-05

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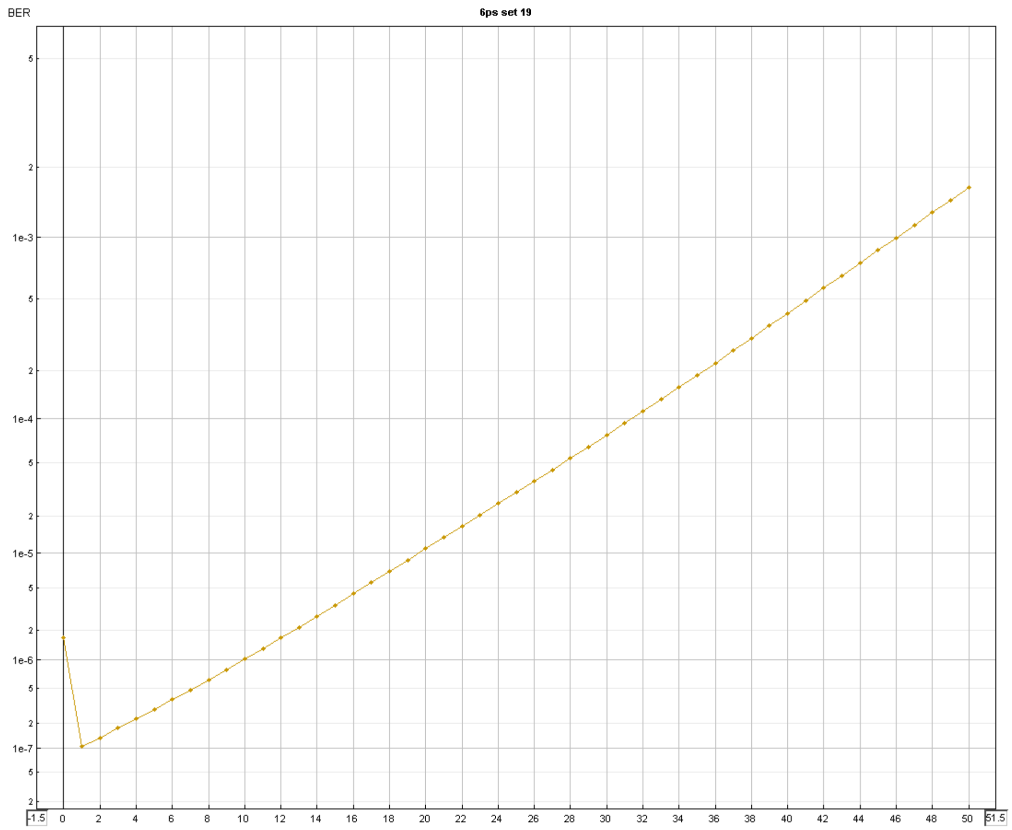

Fig. 2. Simulation on length increase with 6ps/nm.km dispersion

Simulation results showed a higher effectiveness of the method on the system with lower dispersion value. This is due to the fact that FWM increases as dispersion decreases, due to phase matching. The effectiveness of this method relies on the initial channel spacing allocated to the equally spaced allocation too. As the channel spacing increases, the interchannel interference will be reduced. Therefore, it would increase the performance of the system. Simulation performed for the 3ps/nm.km dispersion value with initial channel spacing of 100GHz, which is 2 times that used for the simulations here, was shown to achieve an average BER Improvement Factor of 2.09.

However, this scheme is currently at experimental phase, and considerations of the impact of the scheme on system deployment would have to be taken care of, such as the ITU-T frequency grid recommendations and devices' specifications.

4. Conclusion

In this paper, a novel unequally spaced channel allocation algorithm was presented. Simulation results showed that an average BER Improvement Factor of 1.75, or a 3.8km increase in system length (or 0.76dB increase in input power) could be achieved for a WDM system with 3ps/nm.km dispersion. For the simulation with 6ps/nm.km dispersion, the achievable average BER Improvement Factor was 0.97, or a 2.2km increase in system length (or 0.44dB increase in input power). The difference in the impact of the method on the two simulations was due to the fact that FWM increases as dispersion decreases, due to phase matching. However, we've proved that bandwidth efficiency could be maintained using this algorithm, while enhancing the system performance. This is unlike existing unequally spaced channel allocation methods (which totally eliminated FWM effect), where a 1.6 times bandwidth expansion would be required.

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