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Reduction of Four-Wave Mixing in WDM Links Using Unequal Spacing

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Abstract— When multiple wavelength channels are coupled into a single optical fibre, four-wave mixing (FWM) generates new light at new frequencies. Many of these new frequencies fall right on top of other channels and if the channels are evenly spaced they just become noise. In this study we examine whether this problem can be solved using an unequal channel spacing based on a Golomb ruler. We simulate an eight-channel, 10 Gbps WDM link over ten 80 km spans of non-zero dispersion-shifted fibre using a simple FWM power model and a bit-level Monte-Carlo model giving the Q-factor and the eye diagram. Three channel layouts are compared: a Golomb-ruler plan on the same 50 GHz grid, an equal-spacing plan with the same overall width as the Golomb plan, and equal 50 GHz spacing. The worst channel has -27.5 dBm FWM power at 0 dBm per channel and 124 FWM products fall on channels with equal 50 GHz spacing, up to 18 on one channel. The Q-factor is below the limit Q = 6 at +2 dBm/channel and above, and peaks at 16.0 dB around 0 dBm. With the Golomb plan, the Q-factor increases to 17.4 dB without FWM limit up to +14 dBm and no FWM product hits any channel. The Golomb plan costs 4.9 times more than the spectrum. The Golomb ruler eliminates the last weak products completely and a large equal spacing of the same width produces about the same Q-factor. So the biggest advantage is that the channels are further apart. The study also shows the dependence of the advantage on the unit size of the ruler and the dispersion of the fibres.

Index Terms— *four-wave mixing, WDM, unequal channel spacing, Golomb ruler, Q-factor, fiber nonlinearity, channel allocation.*

I. Introduction

Wavelength-division multiplexing (WDM) has been the fundamental method behind the increase in fibre capacity over the past several decades [1], [2]. WDM enables a single optical fibre to carry multiple channels simultaneously. Designers increase the number of channels, pack them closer and inject more power into the fibre to increase the overall capacity [3]. With these steps the signal is entering the nonlinear region of the fibre where the channels are no longer able to move independently. Thus, the performance of the optical communications is limited by the nonlinear effects of the fibre [4] and a lot of work aim to minimise their damage [5], [6].

One nonlinear effect in the fibre is four wave mixing (FWM). When three channels with frequencies fi, fj and fk travel together, a new wave of frequency fi+fj-fk is generated. There are many of such waves for N channels. Fig. 1 shows them for eight channels. The new frequencies are on a regular grid, with equal spacing between channels (top and bottom plots). Because they have the same frequency as the desired signal, many of them fall exactly on the channels (red lines) and no filter can remove them. They close the channel's eye and add noise to it. The additional frequencies are located between the channels (grey lines) in uneven spaces (middle figure) and can be removed by an optical filter in the receiver.

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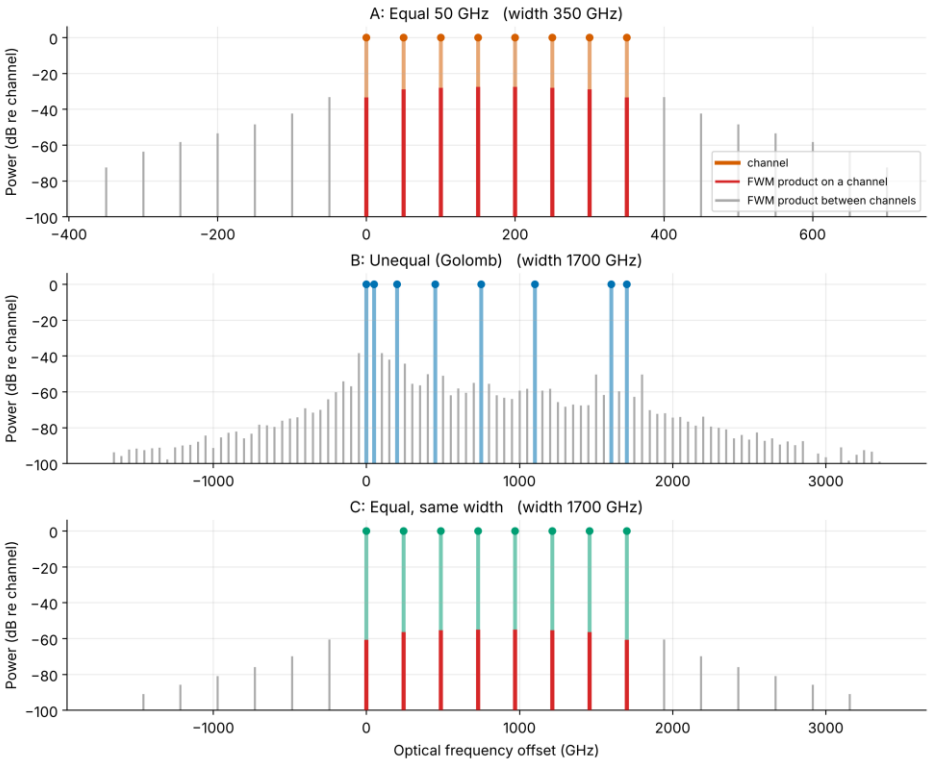


Fig. 1. Channels and FWM products for three channel plans.

The strength of FWM depends strongly on two things: the channel spacing and the dispersion of the fiber. Fig. 2 shows the FWM efficiency of one fiber span. The efficiency falls quickly when the spacing or the dispersion becomes larger, because the interacting waves then travel at different speeds and lose their phase match. Dense channel grids and fibers with low dispersion, such as dispersion-shifted fibers, are therefore the worst case. This is why FWM remains a topic of interest in dense WDM systems and in passive optical networks [7]–[12].

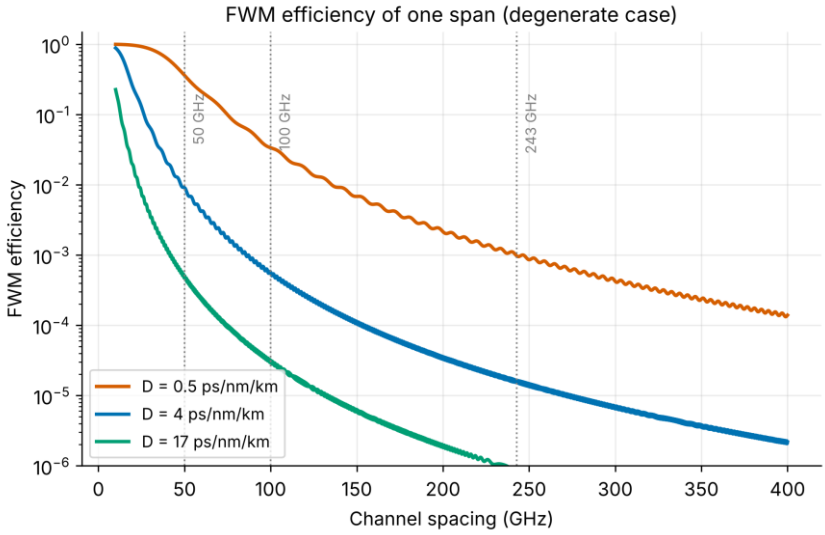


Fig. 2. FWM efficiency of one span versus channel spacing.

There are various ways to reduce FWM. You can use fibres with higher dispersion, reduce the launch power, install optical filters or cleverly arrange the channels. The last approach is attractive because it only changes the channel frequencies and does not need any new hardware. Channel plans for quantum key distribution systems avoiding equal spacing have been studied with odd-even channel

arrangements [10], and optimum Golomb rulers found by metaheuristic search [8], [9]. Other works study the effects of FWM in passive optical networks [12] or reduce it by modulation formats, filters and time division techniques [11].

In general, these studies do not differentiate between the two effects and many report results for one single plan. One consequence is that an unequal design is often wider, so the channels are usually farther apart, and this by itself makes the FWM weaker. The second effect is the real gain of the asymmetrical pattern which avoids the falling of the FWM products into channels. For a fair investigation, you must have a control of the same overall width and spacing. We present a simple and repeatable comparison including such a control, reporting Q-factor, eye diagram, and spectrum cost.

The main contributions are:

(1) a short proof that a Golomb-ruler channel plan has no FWM product on any channel, and a check of this property by direct counting;

(2) a simulation that links a standard FWM power model with a bit-level Monte-Carlo receiver, so that the effect of FWM is shown as Q-factor and eye diagrams;

(3) a three-way comparison of equal 50 GHz spacing, a Golomb-ruler plan and an equal plan of the same width, which separates the effect of width from the effect of the pattern; and

(4) a study of how the results change with the fiber dispersion, the equal spacing and the size of the ruler unit.

The paper is organised as follows. Section II reviews related work. Section III gives the theory. Section IV describes the system and the simulation. Section V presents the results, Section VI discusses them together with the limits of the model, and Section VII concludes.

II. Related Work

The growth and limits of fibre transmission are presented in several overviews [1]–[3] and the limits due to fibre nonlinearity are reviewed in detail in [4]. Much of the literature deals with reducing nonlinear distortion through digital signal processing at either the transmitter or receiver [5], [6]. These techniques work on one or a group of channels and need coherent detection and extra processing power. The method of this paper is different, because it acts on the channel plan and needs no signal processing .

FWM-induced channel allocation has a long history. The idea is to choose channel frequencies such that no two channel pairs have the same frequency difference. Sun et al. reduced FWM noise in a WDM system for quantum key distribution by using interleaved and unequally spaced channels, where the weak quantum signal is very sensitive to noise from the strong classical channels [7]. Bansal et al. studied the generation of optimal Golomb ruler (OGR) sequences, which are precisely the sets of marks with all different distances, and compared several nature-inspired search algorithms for finding near-optimal rulers for WDM channel allocation [8]. In a following work, more algorithms were compared and the algorithms were applied for FWM crosstalk elimination [9]. Salim et al. suggested an odd-even arrangement of the channels to suppress FWM [10]. These works show the value of the idea but mostly report the number of products or the bandwidth of the plan. They do not often report the impact on the Q-factor and the eye of a receiver that has been modelled, and they do not make use of an equal-width control.

Other methods work at the physical layer. Ivaniga and Ivaniga studied the FWM mitigation in a fully optical system [11]. Saleh and Karlık demonstrated the effect of FWM on the uplink of a dense WDM passive optical network [12]. These works confirm that FWM remains important in dense systems with low-dispersion fibres, which is the case studied here.

For the design of real links the nonlinear noise has to be known with small error, so that the system margin can be kept low [13]. Closed form models of nonlinear interference, extended to include stimulated Raman scattering, provide such estimates for wide bandwidths [14], [15], and open source tools now help to estimate the quality of transmission in networks [16]. These models take into consideration the sum of all the nonlinear terms. The present paper looks instead at the single FWM products, because their position in frequency is the key to the channel-plan method.

III. Theoretical Background

A. FWM Products

Consider N channels with optical frequencies f_1, …, f_N. Three channels i, j and k, with k different from i and j, create a product at the frequency

$$f_{ijk} = f_i + f_j - f_k \,. \quad (1)$$

The case i = j is called the degenerate case. Counting the unordered pairs {i, j} and the index k gives the total number of different products

$$M = N(N-1) + [N(N-1)/2](N-2) = N^2(N-1)/2 \,. \quad (2)$$

For N = 8 this gives M = 224 products. A product harms channel m when its frequency lies inside the receiver filter of that channel, that is, when f_{ijk} is close to f_m. The worst case is $f_{ijk} = f_m$, because then no filter can separate the two.

B. Power of a Product

For a single fiber span of length L with equal channel power P, the power of one product is given by the standard expression

$$P_{ijk} = \eta\, (d\, \gamma\, L_{eff}\, P)^2\, P \,, \quad (3)$$

where γ is the nonlinear coefficient, d = 1 for i = j and d = 2 for i ≠ j, and $L_{eff} = (1 - e^{-\alpha L})/\alpha$ is the effective length for the power attenuation coefficient α. The factor η is the FWM efficiency. For a fiber with loss it is

$$\eta = [\alpha^2/(\alpha^2 + \Delta\beta^2)]\, \{1 + 4e^{-\alpha L} \sin^2(\Delta\beta L/2) / (1 - e^{-\alpha L})^2\} \,, \quad (4)$$

where the phase mismatch is, when the dispersion slope is neglected,

$$\Delta\beta = 2\pi\, (\lambda^2/c)\, |\Delta f_{ik}|\, |\Delta f_{jk}|\, D \,. \quad (5)$$

Here λ is the wavelength, c is the speed of light, D is the dispersion parameter, and $\Delta f_{ik} = f_i - f_k$. Equation (5) shows why the FWM is strong for closely spaced channels and low dispersion: the mismatch Δβ is then small and η approaches one. Equation (3) also shows that the product power grows with the cube of the channel power, so a change of 1 dB in the launch power changes the product power by 3 dB.

C. Many Spans and Receiver Filter

In a link with N_s identical spans and an amplifier after each span, the products made in each span are amplified and carried to the end of the link. The phases of the products of different spans are not locked to each other, so their powers are added. The power at the end of the link is then $N_s\, P_{ijk}$. This is a common simple assumption and it gives a reasonable estimate when the spans are many. The receiver filter is described by a power transmission T(Δf), where Δf is the distance of the product from the channel centre. The FWM power that reaches channel m is

$$P_{FWM,m} = N_s \Sigma\, P_{ijk}\, T(f_{ijk} - f_m) \,, \quad (6)$$

where the sum is taken over all products. This paper uses a super-Gaussian filter, $T(\Delta f) = \exp[-\ln 2\, (2\Delta f/B_o)^4]$, with a 3 dB bandwidth B_o = 40 GHz.

D. Golomb Ruler Condition

A Golomb ruler is a set of integer marks $a_1 < \ldots < a_N$ in which all differences $a_p - a_q$ (p > q) are different. Equivalently, all sums $a_p + a_q$ of two marks (including p = q) are different. Such a set is also called a Sidon set. Put the channels at the frequencies $f_n = a_n\, f_0$, where f_0 is the ruler unit. A product lands exactly on channel m when

$$f_i + f_j = f_k + f_m \,, \quad (7)$$

A Golomb ruler is equivalent to ai + aj = ak + am. Different sums are distinct, so the two pairs must be the same, {i, j } = {k, m}. Therefore k must be either i or j. This is not in the definition of a product. So, no FWM product can fall on a channel of a Golomb-ruler plan. The receiver filter must be narrow enough that a product is not close to a channel, say one unit away. The smallest ruler for N = 8 has length 34 units [8], [9] and the marks [0, 1, 4, 9, 15, 22, 32, 34]. The total width is 1700 GHz and fits the 50 GHz ITU grid with f0=50 GHz.

E. Cost in Spectrum

Section III-D imposes a cost on the condition. A set with N marks and all possible differences has a length of at least $N(N-1)/2$ units, a much greater value than the $N-1$ units of an equally spaced set. For eight channels, the optimal ruler is 34, or 4.86 times more spectrum, instead of 7 units. Therefore, the designer has to choose between a wide plan with no FWM and a dense layout with FWM. The extent of this numerical gap is demonstrated in Section V.

IV. System Model and Simulation

A. Link and Parameters

The link simulated is shown in Fig. 3. Eight transmitters transmit 10 Gbps non-return-to-zero on-off keying signals. The multiplexer puts them on a channel plan of the three . The link consists of ten spans of 80 km non-zero dispersion-shifted fibre

(NZ-DSF). power is amplified by an erbium doped fibre amplifier (EDFA) after each span. At the receiver, an optical filter selects one channel and is detected by a photodiode. FWM is robust due to the low dispersion of the fibre and provides a challenging test case. The parameters are given in Table I.

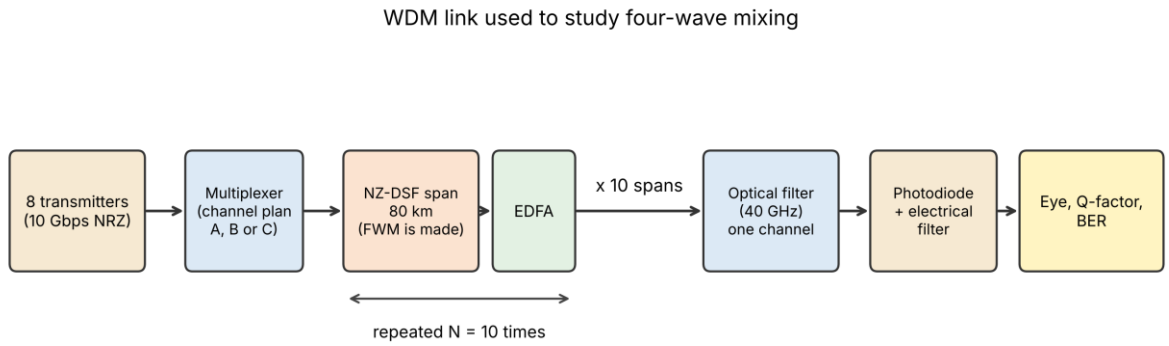


Fig. 3. Block diagram of the simulated WDM link.

TABLE I. Simulation parameters.

Parameter	Value	Parameter	Value
Channels	8	Bit rate / format	10 Gbps NRZ
Span length	80 km	Number of spans	10
Fiber loss	0.2 dB/km	Dispersion D	4 ps/(nm·km)
Nonlinear coeff. γ	1.9 $W^{-1}km^{-1}$	Effective length	21.2 km
Wavelength	1550 nm	Noise figure	5 dB
Optical filter (3 dB)	40 GHz	Electrical filter	0.75 × bit rate
Extinction ratio	12 dB	Thermal noise	10 pA/√Hz
Polarisation	Aligned (worst case)	Runs per point	5 (2048 bits)

B. Channel Plans

Three channel plans are compared (Table II). Plan A has equal 50 GHz spacing, the usual dense grid. Plan B uses the Golomb ruler [0, 1, 4, 9, 15, 22, 32, 34] with a unit of 50 GHz, so that all channels stay on the 50 GHz grid. Plan C has equal spacing with the same total width as plan B (1700 GHz), which is 242.9 GHz between channels. Plan C is the control of this study: it has the same width as plan B but no special pattern. A direct count confirms that the 28 distances between the eight marks of the ruler are all different.

TABLE II. Channel plans.

Plan	Channel frequencies (GHz, relative)	Smallest spacing (GHz)	Width (GHz)
A: Equal 50 GHz	0, 50, 100, 150, 200, 250, 300, 350	50	350
B: Golomb ruler	0, 50, 200, 450, 750, 1100, 1600, 1700	50	1700
C: Equal, same width	0, 243, 486, 729, 971, 1214, 1457, 1700	242.9	1700

C. Bit-Level Monte-Carlo Model

The power model of Section III shows how strong the products are. To show their effect on the signal, a bit-level model is used for one target channel. The steps are as follows.

(1) Random bit sequences (2048 bits, 16 samples per bit) are made for all eight channels. Each bit stream is shaped by a Gaussian modulator filter with a bandwidth of 0.75 times the bit rate, and the extinction ratio is 12 dB. The interfering channels are not synchronised with the target channel, so each of them receives a random time shift.

(2) Every FWM product that lands in the receiver filter of the target channel is added to the optical field of the target channel. Its amplitude follows the product of the three bit waveforms of the channels i, j and k, so the product exists only when all three channels send a "1". Its power comes from (3) and (6), and its phase is random.

(3) The total field is detected by a square-law photodiode and filtered by an electrical Gaussian filter with a bandwidth of 0.75 times the bit rate.

(4) Receiver noise is added. It has a thermal part and a signal–ASE beat part. The optical signal-to-noise ratio (OSNR) at the end of the link is taken from the amplifier chain as

$$\mathrm{OSNR_{dB}} = 58 + P_{\mathrm{dBm}} - A_{\mathrm{span}} - \mathrm{NF} - 10\log_{10} N_s \,, \quad (8)$$

where $A_{\mathrm{span}} = 16$ dB is the span loss and NF = 5 dB is the noise figure. At 0 dBm per channel the OSNR is 27 dB. The Q-factor of the target channel is then found at the best sampling instant as

$$Q = (\mu_1 - \mu_0) / (\sigma_1 + \sigma_0) \,, \quad (9)$$

where μ and σ are the mean and the standard deviation of the current samples for the received "1" and "0" bits. The standard deviation includes the signal spread caused by the FWM products and the added noise. The Q-factor in dB is 20 $\log_{10}$ Q, and Q = 6 (15.6 dB) corresponds to a bit error ratio of about 10^{-9}. Each point is the average of five random runs.

D. Procedure

For each plan the channel with the largest FWM power is found from (6) and called the worst channel. All Q-factor results refer to this channel. The launch power per channel is changed from −10 dBm to +14 dBm. The power limit of a plan is the highest launch power for which the Q-factor stays above 6 (15.6 dB) before FWM closes the eye. If Q does not fall below 6 up to +14 dBm, the limit is written as ">14".

V. Results

A. FWM Products on the Channels

Fig. 1 shows the 224 products of each plan for a launch power of 0 dBm per channel. plan 124 goods Fall on the grid, fall on a channel with a 50 GHz step. The maximum per channel for the middle channels is 18. The signal is 27.5 dB down from the strongest product in a channel, or −27.5 dBm. Plan B has no product on a channel. Each channel is separated by at least 50 GHz from the nearest product, and the 40 GHz receiver filter attenuates it by more than 100 dB. 124 products on channels in plan C. As with any equal spacing the enormous separation means they are significantly weaker: the poorest channel is at −55.0 dBm at 0 dBm per channel. The figures are summarised in Table III.

TABLE III. Comparison of the three channel plans.

Plan	Width (GHz)	Width vs. A	Products on channels	Worst FWM at 0 dBm (dBm)	Power limit (dBm)
A: Equal 50 GHz	350	1.00	124 (max. 18 per channel)	−27.5	+2
B: Golomb ruler	1700	4.86	0	none	>14
C: Equal, same width	1700	4.86	124 (max. 18 per channel)	−55.0	>14

B. Signal-to-FWM Ratio and Distribution over Channels

Fig. 4 shows the ratio between the signal power and the FWM power in the worst channel. For each extra dB of launch power, the ratio drops by 2 dB, because the products grow with the cube of the power. In plan A the ratio is 27.5 dB at 0 dBm and drops below 20 dB at +3.7 dBm. Plan C is still at 27 dB at +14 dBm and 55 dB at 0 dBm, an improvement of 27.5 dB. Since there is no FWM power in any channel in plan B, the ratio is infinite and the curve is not shown.

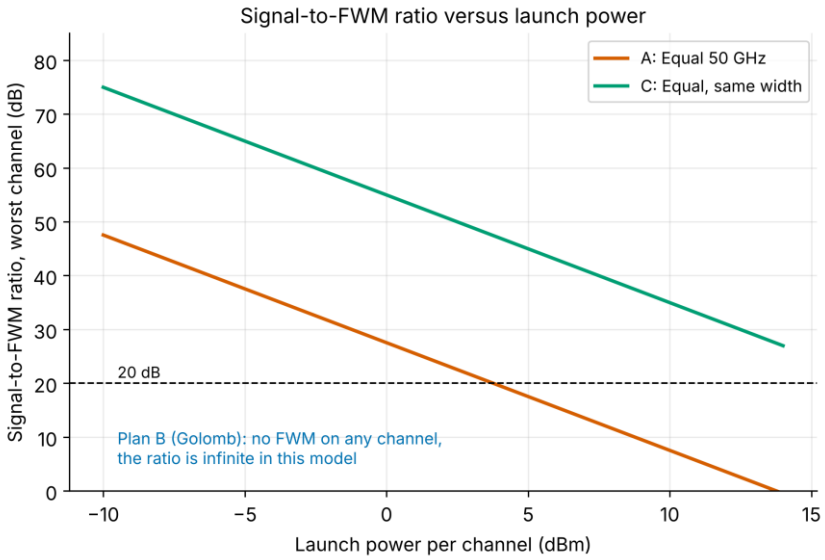


Fig. 4. Signal-to-FWM ratio of the worst channel.

Fig. 5 shows how the FWM power is shared between the channels at +4 dBm per channel. In plan A the middle channels receive the most (−15.5 dBm for channels 4 and 5), and the edge channels receive about 5.7 dB less (−21.2 dBm), because fewer combinations of other channels can reach them. Plan C has the same shape at a much lower level (−42.9 dBm for the middle channels). Plan B has no bar at all. Equal spacing therefore penalises the middle of the band, which is the most valuable part of a WDM system.

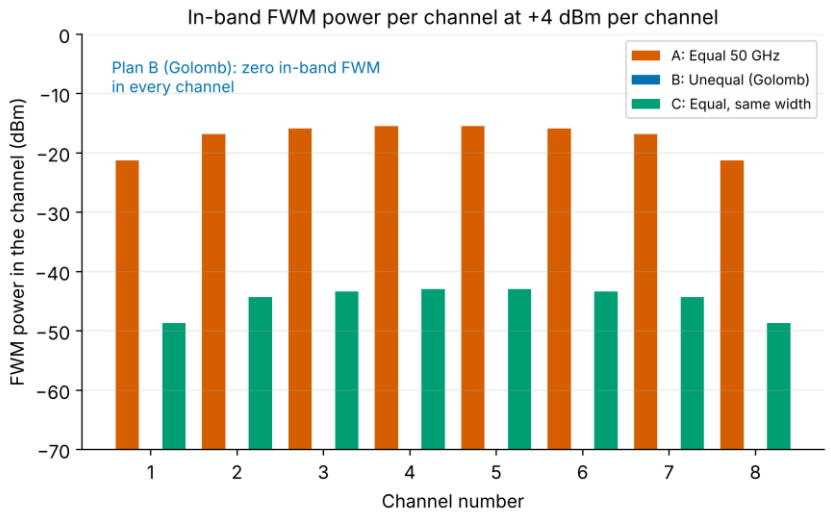


Fig. 5. In-band FWM power per channel at +4 dBm per channel.

C. Q-Factor versus Launch Power

Fig. 6 shows the Q-factor of the worst channel for the three plans, and Table IV gives selected values. For low power, the three plans are the same, because the amplifier noise limits the Q-factor and it rises with the power. For plan A the Q-factor reaches a maximum of 16.0 dB near 0 dBm, and it then falls, because FWM grows faster than the signal. It crosses the Q = 6 line (15.6 dB) between +2 and +3 dBm, so the power limit is +2 dBm, and it reaches only 10.0 dB at +8 dBm and 6.3 dB at +10 dBm. Above +12 dBm the eye is almost closed. The window of useful launch power for plan A is narrow: the Q-factor is above the limit only between about −3 dBm and +2 dBm.

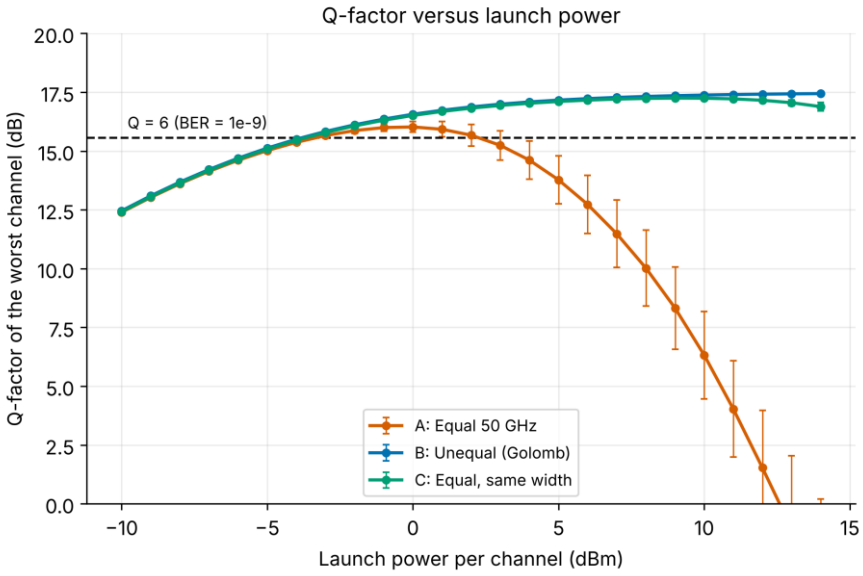


Fig. 6. Q-factor of the worst channel versus launch power.

TABLE IV. Q-factor (dB) of the worst channel.

Power (dBm)	A: Equal 50 GHz	B: Golomb ruler	C: Equal, same width
-10	12.4	12.5	12.4
-5	15.0	15.1	15.1
0	16.0	16.6	16.5
+3	15.2	17.0	16.9
+6	12.7	17.2	17.2
+9	8.3	17.4	17.3
+12	1.5	17.4	17.2
+14	-3.5	17.4	16.9

The Q-factor of Plan B keeps increasing, and saturates at a value of 17.4 dB, which is limited by the modulator, extinction ratio and filters, and not by noise or FWM. In this work, the power limit is not until +14dBm. Plan C has a curve that is almost identical to plan B, 17.3 dB at +9 dBm but with a small decline (16.9 dB at +14 dBm) since it still has weak products. Plan B is better than Plan C by 0.5 dB at +14 dBm. This implies the larger spacing for this connection provides most of the gain and the ruler's pattern eliminates the residual weak products.

D. Eye Diagrams

Fig. 7. Eye diagrams for the worst channel at +8 dBm/channel launch power from a single random run with added receiver noise. Plan A: The eye is badly damaged. The Q-factor for this run is 9.4 dB. Plan B and Plan C have open eyes with Q-factors of 17.3 dB and 17.2 dB, respectively. We cannot see any difference between designs B and C at this power from Fig. 6.

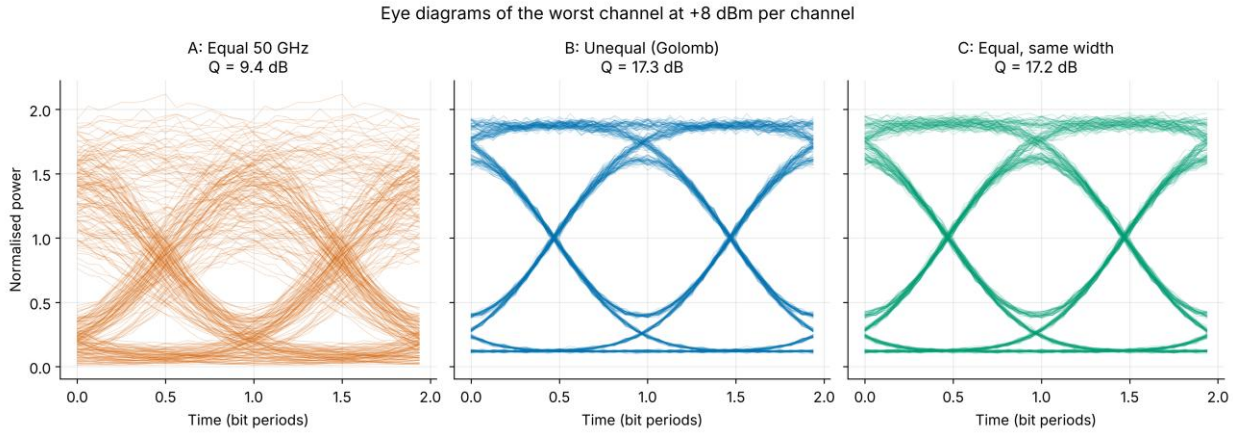


Fig. 7. Eye diagrams of the worst channel at +8 dBm.

E. Effect of Widening an Equal Spacing

A designer may ask whether a simple increase of the equal spacing is enough. Table V shows the answer. Going from 50 GHz to 75 GHz reduces the worst FWM by 7.1 dB and raises the power limit from +2 dBm to +6 dBm. At 100 GHz the limit is +9 dBm, and at 150 GHz it is +13 dBm. For a spacing of 200 GHz or more, the limit is above +14 dBm. Each step costs spectrum in the same way as the Golomb plan: a spacing of 100 GHz needs twice the width of plan A, and a spacing of 243 GHz needs 4.86 times. Widening gives a smooth trade-off between spectrum and power limit, while the Golomb pattern

gives a limit above +14 dBm at a width of 1700 GHz, equal to the widest equal plan.

TABLE V. Equal spacing for different widths.

Spacing (GHz)	Width (GHz)	Worst FWM at 0 dBm (dBm)	Power limit (dBm)
50	350	−27.5	+2
75	525	−34.6	+6
100	700	−39.6	+9
150	1050	−46.6	+13
200	1400	−51.6	>14
242.9	1700	−55.0	>14

F. Effect of Fiber Dispersion

Table VI repeats the study for fibers with different dispersion. In a fiber with a very low dispersion of 0.5 ps/(nm·km), plan A never reaches Q = 6 at any power in the range, because the FWM is already strong at low power. For dispersion of 2, 4, 8 and 17 ps/(nm·km), the power limit of plan A rises from −2 dBm to +2, +6 and +9 dBm. Standard single-mode fiber, with 17 ps/(nm·km), is therefore much more tolerant, in agreement with Fig. 2. Plan B has no limit up to +14 dBm for all values. Plan C has a limit of +7 dBm only for the lowest dispersion. The unequal plan is therefore most useful where the fiber has a low dispersion, which is just the case where dense equal spacing fails.

TABLE VI. Power limit (dBm) for different dispersion.

D (ps/(nm·km))	A: Equal 50 GHz	B: Golomb ruler	C: Equal, same width
0.5	none	>14	+7
2	−2	>14	>14
4	+2	>14	>14
8	+6	>14	>14
17	+9	>14	>14

G. Effect of the Ruler Unit

The ruler unit f_0 can be changed. Table VII shows the result for the same ruler. For a unit of 25 GHz the total width is 850 GHz, and the products fall 25 GHz from the nearest channel. The 40 GHz filter does not block them well (the filter transmission at 25 GHz is 0.18), and the worst FWM power is −34.1 dBm, so the power limit is only +6 dBm. For a unit of 37.5 GHz the products are 37.5 GHz away, the filter transmission is about 2×10^{-4}, and the worst FWM is −70.6 dBm. For 50 GHz and above, the products are filtered out completely. The unit must therefore be large compared with the filter bandwidth. The condition of Section III-D guarantees that products never land on a channel, and the filter must remove those which land beside it.

TABLE VII. Golomb plan for different ruler units.

Unit (GHz)	Width (GHz)	Worst FWM at 0 dBm (dBm)	Power limit (dBm)
25	850	−34.1	+6
37.5	1275	−70.6	>14
50	1700	none	>14
75	2550	none	>14
100	3400	none	>14

VI. Discussion and Limitations

A. Interpretation

The results provide a three-part answer to the question posed by the paper. First, FWM limits a dense equal grid in a low dispersion fibre and the useful launch power window is only of the order of 5 dB wide. Second, the eye stays open at all tested powers and the Golomb ruler removes any product that would fall into a channel. Third, most of the improvement is due to the wider spacing: an equal layout of the same width does almost as well in this link. Hence the ruler is better seen as the instrument to carry the job through. An equal plan relies on the weakness of the products, but it guarantees a result that is independent of the exact values of the power and dispersion. This assurance is useful when the power requirements are high or specifications of fibre are not known.

B. Practical Considerations

The main cost of the uneven plan is the spectrum. The equal-50-GHz plan requires 350 GHz and the Golomb plan requires 1700 GHz for 8 channels. This leads to fewer channels in a system with a fixed bandwidth. Thus, the plan is most attractive in systems with a large unused band and few channels, e.g., low-count passive optical networks and quantum-key-distribution links where a weak quantum signal and strong classical channels share a fibre [7], [12]. The same fixed-grid equipment can be used, as all plan B channels are still on 50 GHz grid, only the choice of the used slots changes. Gaps between the channels could also be filled by channels from other systems, if their products were analysed in the same way. The search techniques of [8] and [9] produce wider rulers for more channels.

C. Limitations

The study has the following limitations. There is one model . FWM . For some of them, closed-form models exist, but they do not consider self-phase and cross-phase modulation, stimulated Raman scattering, and the dependency of the nonlinear noise on the modulation format [4], [14], and [15]. The dispersion slope and the walk-off between channels are neglected and it is assumed that the polarisation is aligned for all channels giving the strongest FWM. We assume that the FWM of different spans is added in power, which is a common and simple, but not very accurate assumption. The results for the tiny ruler unit of 25 GHz should be taken with caution as other linear impairments such as polarization-mode dispersion are not modelled [17] and the linear crosstalk between neighbouring channels is not included. The noise is modelled as a Gaussian approximation and the receiver filter is a fixed super-Gaussian. Finally, the results are from a numerical model, not from an experiment. The results can be compared to a full network model using open source tools. Validation using measurements or a split-step simulation would increase the certainty of the values [16].

VII. Conclusion

Three channel plans were investigated for an eight-channel, 10 Gbps WDM link over ten spans of low-dispersion fibre: an equal 50 GHz spacing, a Golomb-ruler plan and an equal plan of the same width. Direct counting showed that a Golomb ruler avoided all FWM items on a channel (0 of 224 goods on any channel, compared to 124 for the equal plans). The Q-factor is maximum at 16.0 dB, power limit is +2 dBm and worst channel receives -27.5 dBm FWM power at 0 dBm per channel with equal 50 GHz spacing. With the Golomb design, the Q-

factor increases to 17.4 dB with no FWM limit up to +14 dBm. It costs 4.86 times more. The Golomb pattern guarantees 0% in-band FWM and a small 0.5 dB gain at the highest power. The equal plan of the same width results in nearly the same result, indicating that the larger spacing is responsible for the majority of the gain. It requires a large ruler unit in relation to the filter bandwidth. The advantage is the largest for fibres with low dispersion.

Further study could include the effect of self-phase and cross-phase modulation, full-field split-step simulation, coherent formats with higher bit rate, more channel counts with their rulers and a joint search for the plan which minimises at the same time the width and the FWM. An experimental test with a dispersion shifted fibre would also reinforce the numerical conclusions.

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