Effective Channel Allocation to Reduce Inband FWM Crosstalk in DWDM Transmission Systems

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***Abstract*—An accurate analysis of the four-wave mixing (FWM) impact on dense wavelength-division multiplexing optical systems is carried out for different types of fibers. Particular channel allocations on the ITU grid are studied to reduce the inband FWM crosstalk and guarantee high performances in different types of optical fiber. These schemes, with respect to the other known channel allocations, allow one to find an optimum tradeoff between the required bandwidth expansion and the maximum inband FWM crosstalk. A comparison between the system spectral occupation and the signal-to-crosstalk ratio (SXR) versus the channel input power for the equal channel spacing and the proposed channel allocations validates the proposed solutions in the case of single-mode, nonzero dispersion-shifted, and dispersion-shifted fiber. For a 32-channel system, SXR improvements up to 4 dB without bandwidth expansion, and bandwidth savings up to 15 nm with a guaranteed minimum SXR of 25 dB, are obtained with respect to an equally spaced channel allocation.**

***Index Terms*—Fiber-optic transmission systems, four-wave mixing effect, unequal channel spacing.**

I. Introduction

To fully exploit the transmission bandwidth in dense wavelength-division multiplexing (DWDM) systems, a channel spacing reduction is wished. A 12.5-GHz spaced system has started already to appear [1]. However, as the channel distance decreases, the fiber's four-wave mixing (FWM) effect becomes a big impairment for system performance, especially for high launched powers. The performance worsens as the chromatic dispersion gets smaller. Consequently, we consider especially two different types of optical fiber: nonzero dispersion-shifted (NZDS) and dispersion-shifted (DS) fiber. In addition, we verify the proposed channel allocation's efficiency on the most typical single-mode fiber (SMF) for very high input powers. The commonly used equal channel spacing (ECS) minimizes the system bandwidth occupation. On the other hand, ECS is most sensitive to FWM, since essentially all FWM terms appear as inband crosstalk disturbances, reducing the signal-to-crosstalk ratio (SXR) as a consequence. Suppression of all inband FWM crosstalk terms implies an unequal channel allocation [2], [3] that requires a prohibitively large system bandwidth for the number of channels of current interest. The common approach followed by known channel allocation schemes considers as a key parameter the number of intermodulation products falling into the channel bandwidth [3]–[7]. Such schemes still require a large bandwidth expansion. Moreover, the estimation of the inband FWM crosstalk requires a complex computation [6], [7]. An interesting solution was proposed by Guo *et al.* [8] using wavelength encoding to reduce channel crosstalk. Good effectiveness is paid with a sensible increase in the transmitter and receiver complexity.

An alternative effective design strategy can consider unequal channel allocation based on the minimization of the total inband FWM crosstalk instead of the number of intermodulation products. This directly leads one to calculate FWM efficiency that strongly depends on fiber characteristics. Following this approach, in this paper, we analyze the FWM impact on DWDM systems for different types of fibers, and we propose a simple three-channel code (TCC) to minimize the FWM crosstalk. It is a new unequal ITU grid-based channel allocation scheme for the most common fiber spans that eliminates all the most efficient inband FWM terms. This simple and modular scheme requires a modest bandwidth expansion factor, which depends on the acceptable level of SXR. We give below the SXR for a fix bandwidth occupation, and the required system bandwidth for a fixed SXR, versus the launched power per channel and compare it to the ECS scheme for different types of fiber.

This paper is organized as follows. In Section II, FWM theory is reported and formalized considering a discrete channel allocation. In Section III, TCC is introduced and some key parameters calculated. Section IV shows a comparison between ECS and TCC for different kind of fibers.

II. Theory

The FWM power P_{ijk}, generated by three continuous-wave channels of input powers P_i, P_j, P_k at frequencies f_i, f_j, f_k at the output of a fiber with attenuation α and length z, is [9]

$$P_{ijk} = d_{ijk}^2 \gamma^2 L_{\text{eff}}^2 P_i P_j P_k \eta_{ijk} \mathrm{e}^{-\alpha z} \tag{1}$$

where d_{ijk} is the degeneracy factor, taking a value of one or two for degenerate $(i = j)$ and nondegenerate $(i \neq j)$ terms, respectively; L_{eff} the effective length; γ the nonlinear coefficient; and η_{ijk} the efficiency. The last two quantities are defined as

$$\gamma = \left(\frac{2\pi n_2}{A_{\text{eff}} \lambda_0}\right)^2$$
$$\eta_{ijk} = \frac{\alpha^2}{\alpha^2 + \Delta\beta_{ijk}^2} \left[1 + \frac{4e^{-\alpha z} \sin^2(\Delta\beta_{ijk} z/2)}{(1 - e^{-\alpha z})^2}\right] \tag{2}$$

where n_2 is the fiber nonlinear coefficient, λ_0 the comb central wavelength, A_{eff} the core effective area, and $\Delta\beta_{ijk}$ the phase-matching coefficient.

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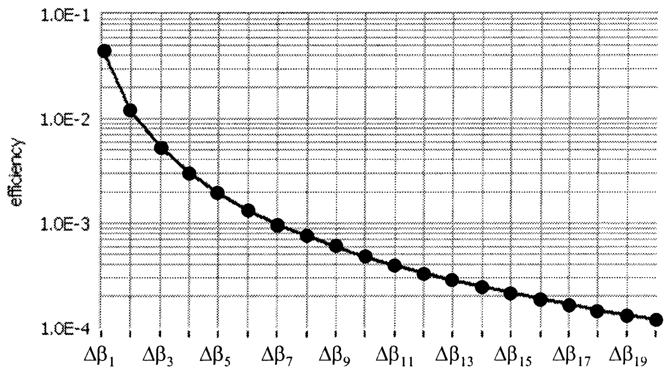

Fig. 1. FWM efficiency analytic values versus $\Delta\beta_n$.

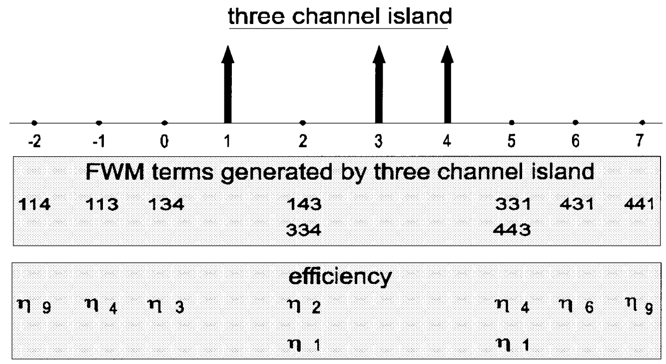

Fig. 2. FWM terms and corresponding efficiencies η_n for a three-channel comb.

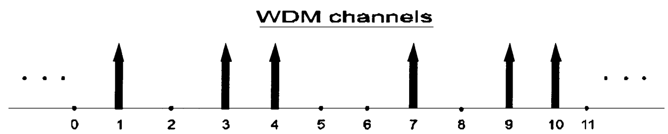

Fig. 3. TCC channel allocation obtained by repetition of three-channel islands, spaced k slots apart ($k = 2$ in this example).

The efficiency can be approximated, for long enough fiber spans, as [10]

$$\eta_{ijk} = \frac{\alpha^2}{\alpha^2 + \Delta\beta_{ijk}}. \tag{3}$$

The phase-matching coefficient $\Delta\beta_{ijk}$ is

$$\Delta\beta_{ijk} = (f_i - f_k)(f_j - f_k)\frac{2\pi\lambda_0^2}{c} \cdot \left\{-D_c + \frac{\lambda_0^2}{2c}\frac{\partial D_c}{\partial\lambda}[(f_i - f_d) + (f_j - f_d)]\right\} \tag{4}$$

where D_c is the fiber chromatic dispersion, $(\partial D_c/\partial\lambda)$ its slope, and f_d the zero dispersion frequency.

Away from the zero dispersion region, (4) becomes

$$\Delta\beta_{ijk} = \frac{2\pi c}{\lambda_0^2} D_c \Delta\lambda_{ik}\Delta\lambda_{jk} \tag{5}$$

where $\Delta\lambda_{ik}$ and $\Delta\lambda_{jk}$ are the wavelength spacing between channels i and k, and j and k. This approximation is valid for the SM and NZDS fiber in the C-band. In the case of channels arranged on the equally spaced grid, as the ITU grid, $\Delta\beta_{ijk}$ takes the discrete values

$$\Delta\beta_n = n\left(\frac{2\pi c}{\lambda_0^2}\right) D_c \Delta\lambda^2 \tag{6}$$

and thus also the efficiency becomes $\eta_n = \eta(\Delta\beta_n)$, where $n = |i-k|\,|j-k|$ is the efficiency order and $\Delta\lambda$ is the selected ITU grid resolution, typically a multiple of 0.4 nm.

In Fig. 1, the FWM efficiency η_{ijk} is plotted versus the discrete values of $\Delta\beta_n$ in the case of $\Delta\lambda = 0.4$ nm and $z = 100$ km. The efficiency takes on quantized values $\eta_n = \eta(\Delta\beta_n)$, which rapidly decrease when n increases, as $1/n^2$ over NZDSFs and (SMFs).

III. Three-Channel Codes

To introduce the new allocation scheme, we first consider the allocation on the ITU grid of only three channels, placed at slots 1, 3, and 4 as shown in Fig. 2. A slot corresponds to the selected grid resolution $\Delta\lambda$. In the figure, all FWM terms are also summarized. Each term is represented by the indexes ijk of the three channels involved in the product.

For instance, the term 134 falling on slot 0 labels the FWM contribution jointly generated by the channels at slots 1, 3, and 4. For each FWM term, the corresponding efficiency η_n is also marked in Fig. 2. We can see that no FWM term falls on the three channels, and the efficiency of the FWM terms decreases with their distance from the "three-channel island" composed of slots 1–4.

The typical TCC scheme adds more channels to the WDM comb by repeating as many three-channel islands as needed, spaced k slots apart from each other, as shown in Fig. 3. The bandwidth occupied by an N-channel WDM system is therefore

$$B = [4Q + k(Q-1) + (k+R)\min(1,R)]\Delta\lambda \tag{7}$$

where Q and R are the quotient and the remainder of the division of N by three, namely, $N = 3Q + R$.

Note that, by construction, the inband FWM terms falling on a channel within a specific island appear because of the presence of channels belonging to different islands. Thus, by increasing the slot distance k between islands, the efficiency of the inband FWM terms decreases, at the expense of an increase of the system bandwidth B. We define a fractional bandwidth expansion ε_B as the ratio between the bandwidth needed in the TCC spacing WDM system and in the equally spaced WDM system, so

$$\varepsilon_B = \frac{B_{\text{TTC}}}{N\Delta\lambda} \tag{8}$$

where $\Delta\lambda$ is the grid resolution (the minimum channel spacing in ECS case). For typically large values of N

$$\varepsilon_B \cong \frac{(k+4)}{3} \tag{9}$$

depending only on k.

It is easy to verify that, in the case of TCC scheme, the *smallest* efficiency order n of the inband FWM terms is one when $k = 0$, four when $k = 1$, and $n = k + 4$ for $k \geq 2$.

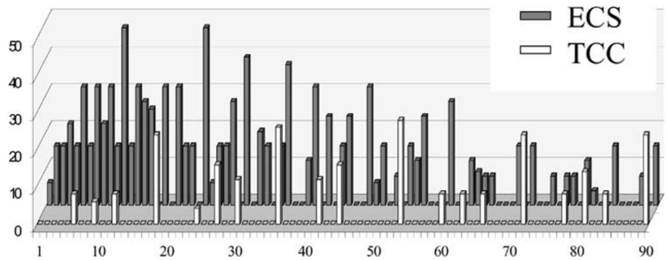

Fig. 4. Number of FWM terms with efficiency η_n versus efficiency order n for (black) an ECS system and (white) a TCC system with island spacing $k = 2$, on the worst channel. $N = 32$ channels.

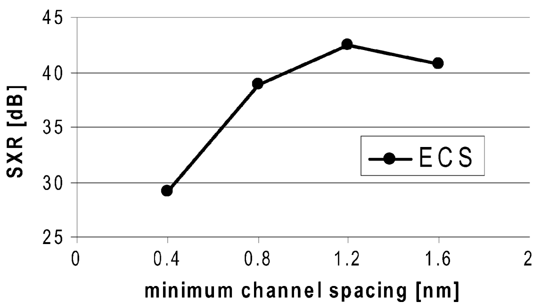

Fig. 5. SXR for a ECS 32-channel system vs. the grid resolution, for a NZDS fiber and a average input power of 2 dBm.

IV. Comparison Between ECS and TCC Codes

In Fig. 4 we show the number of FWM terms falling on the worst channel of an $N = 32$ channel system (each nondegenerate term counted as four) plotted versus the efficiency order n, both for the ECS scheme (black bars) and for the TCC scheme with $k = 2$ (white bars). Clearly, the TCC scheme shifts the inband FWM terms to higher orders, thus reducing the FWM penalty. Note that there are 280 more terms with $n > 90$, up to $n = 240$, for the ECS scheme, and 560, up to $n = 930$, for the TCC scheme, not shown in the figure.

When the transmitted power levels are low, the ECS is the best scheme, i.e., the one that minimizes the system bandwidth. As the per channel power increases, the SXR quickly decreases below a tolerable threshold value $\mathrm{SXR}_{\min}$ for some channels of the comb, especially for fibers with low dispersion value, as NZDF or DSF. Nevertheless, for very high input powers, also in the SMF a intolerable SXR reduction is experienced. At this point, if we want to keep an equal channel allocation, the grid resolution $\Delta\lambda$ must be increased. This process must be repeated as the input power increases further. Fig. 5 shows the SXR of the worst channel in a NZDS fiber, for an equally channel allocation versus the grid resolution. The transmitted signals are 10-Gbit/s pseudorandom modulated NRZ signals. The SXR increases with the minimum channel spacing, but with a further increase in channel distance, the comb bandwidth includes the zero dispersion wavelength, producing a drastic worsening of the system performances. Therefore it is necessary to minimize the spectral occupation, reducing the FWM crosstalk with an opportune unequal channel allocation.

A. NZDS Fiber

Concerning the NZDS fiber, in Fig. 6, we consider an ECS with grid resolution of 0.8 nm and a TCC with a minimum channel spacing of 0.4 nm to obtain two channel allocation code with about the same spectral occupation, 25.6 and 24.8 nm, respectively. We compare the worst channel SXR obtained for a 32-channel transmission on a single span of 100 km of NZDSF, attenuation $\alpha = 0.2$ dB/km, and nonlinear coefficient $\gamma = 2\ \mathrm{W}^{-1}\mathrm{km}^{-1}$ in the two different cases versus the average input power per channel. The chromatic dispersion value is $D_c = 2$ ps/nm/km at the center of the channel comb. The considered signals are always 10-Gbit/s pseudorandom modulated NRZ signals. The curves' behavior is similar, but the TCC allows one to obtain an improvement higher than 3 dB with a fractional bandwidth expansion <1.

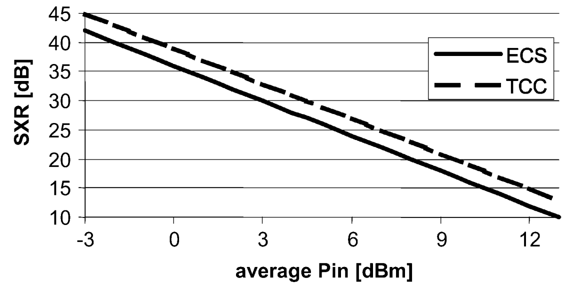

Fig. 6. SXR versus the average input power per channel for the worst comb channel in an NZDS fiber using ECS (dark curve) or TCC (light curve).

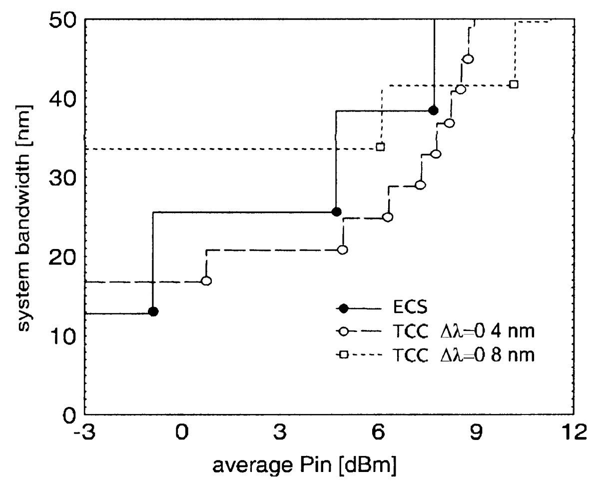

Fig. 7. System bandwidth versus average input power per channel for a target $\mathrm{SXR}_{\min} = 25$ dB in a 100-km NZDS fiber with $|D_c| = 2$ ps/nm/km, both for ECS and for TCC, for various grid resolutions. $N = 32$ channels.

The ECS system bandwidth obtained by increasing the grid resolution to guarantee a target $\mathrm{SXR}_{\min} = 25$ dB is plotted in Fig. 7 versus the average input channel power. In the case of low power, the grid resolution is 0.4 nm, increasing in steps of 0.4 nm at each discontinuity in the curve. Note that from the SXR we can easily infer the Q-penalty from [10, Fig. 5] by using the relation $(k\sigma_1)^2 < 1/(2\,\mathrm{SXR})$, where $k\sigma_1$ is the standard deviation of the signal-crosstalk beat in the notation of [10]. An $\mathrm{SXR} = 25$ dB guarantees a penalty below about 1 dB for one span. In the same figure we show the system bandwidth of the TCC scheme for the same fiber parameters and $\mathrm{SXR}_{\min}$. Consider first the TCC with grid resolution of 0.4 nm. As the power increases, $\mathrm{SXR}_{\min}$ is reached by some channels, and the island distance k is increased by one unit at each discontinuity, starting at low power with $k = 0$. Up to average input power per channel

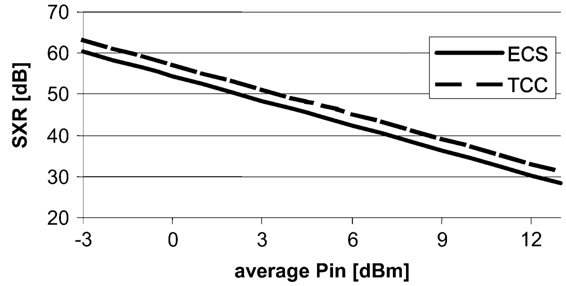

Fig. 8. SXR versus the average input power per channel for the worst comb channel in a SM fiber using ECS (dark curve) or TCC (light curve).

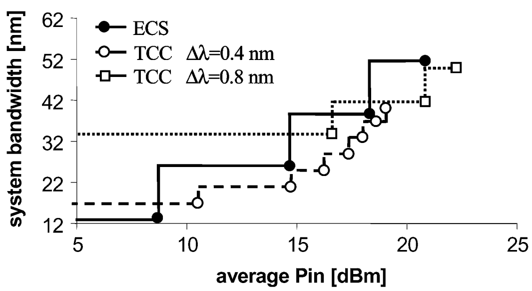

Fig. 9. System bandwidth versus average input power per channel for a target $\mathrm{SXR}_{\min} = 25$ dB in a 100-km SM fiber with $|D_c| = 17$ ps/nm/km, both for ECS and TCC, for various grid resolutions. $N = 32$ channels.

$\mathrm{P_{in}} = -1$ dBm, the ECS is the best scheme. For higher values, up to about 9 dBm, the TCC with ITU grid resolution of 0.4 nm is the most efficient in terms of system bandwidth. However, as the island spacing k becomes large, even the TCC becomes inefficient, and a simple way to recover bandwidth efficiency is to adopt a TCC scheme with a higher grid resolution, i.e., by enlarging the grid slots. The system bandwidth for the TCC scheme with resolution 0.8 nm is also shown in the figure. Using the TCC, it is possible to reduce the bandwidth up to 15 nm in respect to the ECS.

In the calculations, we considered the dispersion value constant along the fiber, the channel polarizations aligned as a worst case, and a dispersion slope $S = 0.04$ ps/nm^2/km, which keeps the zero dispersion wavelength λ_0 sufficiently away from the WDM comb in all considered cases.

B. SM Fiber

The same comparisons have been made for transmission system on SM fiber. In this case the higher chromatic dispersion value makes the FWM effect of minor impact on the system performances. But also in this case, the use of an appropriate unequal channel spacing produces an SXR improvement useful especially for high lunched powers.

In Fig. 8, the SXR obtained with the two different channel allocation codes, and in the same conditions described for the NZDS fiber, is reported. Also in this case the improvement introduced by the TCC is about 3 dB, which for low SXN translates, according to [10], to more than 2 dB of penalty decrease.

Fig. 9 shows the bandwidth needed to obtain an SXR of 25 dB using the ECS and TCC on the SM fiber, versus the average input power per channel. Up to 8.7 dBm is suitable to use an equally channel spacing to minimize the spectral occupation, whereas for higher input power levels the most compact channel allocation is TCC with a grid resolution of 0.4 nm. As the TCC k parameter increases beyond six, the best scheme, in terms of bandwidth, is the TCC using the minimum channel spacing 0.8 nm. The comparison demonstrates that the introduction of the unequal TCC permits a bandwidth savings up to 14 nm in particular cases.

C. DS Fiber

In the DS fibers, the efficiencies do not take discrete values, because the approximation for the phase-matching coefficient, expressed in (5), is not valid. Therefore the complete phase-matching expression in (4) must be considered. Consequently, it is important to consider not only the channel spacing but also the zero dispersion wavelength position to determine the FWM terms' efficiencies. In Fig. 10, the SXR concerning all system channels is reported for different zero dispersion wavelength values in the case of ECS considering an average input power of -9 dBm. Typically the channels near the zero dispersion are affected by FWM effect more than the distant channels. Fig. 10 shows the worst case channels following the zero dispersion position. The channels closer to the zero dispersion region are more affected by the FWM crosstalk because the channels involved in the inband low-order FWM terms find smaller dispersion values. Consequently, the FWM efficiency of these terms increases.

Therefore, an efficient channel allocation must avoid that the FWM terms, involving the slots near the zero dispersion channels, fall into the signal band. For this reason the ECS scheme introduces an unacceptable system penalty.

To reduce this degradation, we consider an asymmetric ECS (AECS) with respect to the zero dispersion position. As shown in Fig. 11 at the left of the zero dispersion wavelength, we allocate the channels by an ECS using a minimum channel spacing equal to the double of the grid resolution, we avoid the zero dispersion slot, indicated as slot 0, and, to the right side, we repeat the ECS scheme, shifting the comb by one slot to obtain the asymmetry.

The channel comb wavelengths, to the right (λ_i^+) and to the left (λ_j^-) of the zero dispersion position, will be, respectively

$$\lambda_i^+ = \lambda_d + (2i-1)\Delta\lambda \quad \text{and} \quad \lambda_j^- = \lambda_d - 2(j)\Delta\lambda \tag{10}$$

where λ_d is the zero dispersion wavelength, $\Delta\lambda$ is the grid resolution, and i and j are integer numbers varying from one to $i_{\max}$ and $j_{\max}$, respectively, to obtain $i_{\max} + j_{\max} = N$ with N equal to the channel number.

By this allocation, all FWM terms involving two left channels, in respect to the zero dispersion, falling on the opposite side if they are degenerate or falling on the same side if they are nondegenerate, are outband terms. The same behavior is verified for the terms due to two right signals.

Decreasing the inband FWM terms number, we can reduce the FWM impairment with a fractional bandwidth expansion

$$\varepsilon_B = \frac{B_{\mathrm{AECS}}}{N\Delta\lambda} = \frac{2N}{N} = 2. \tag{11}$$

Fig. 12 summarizes the channel allocation technique; by simulation we found that the best solution is for λ_d, corresponding

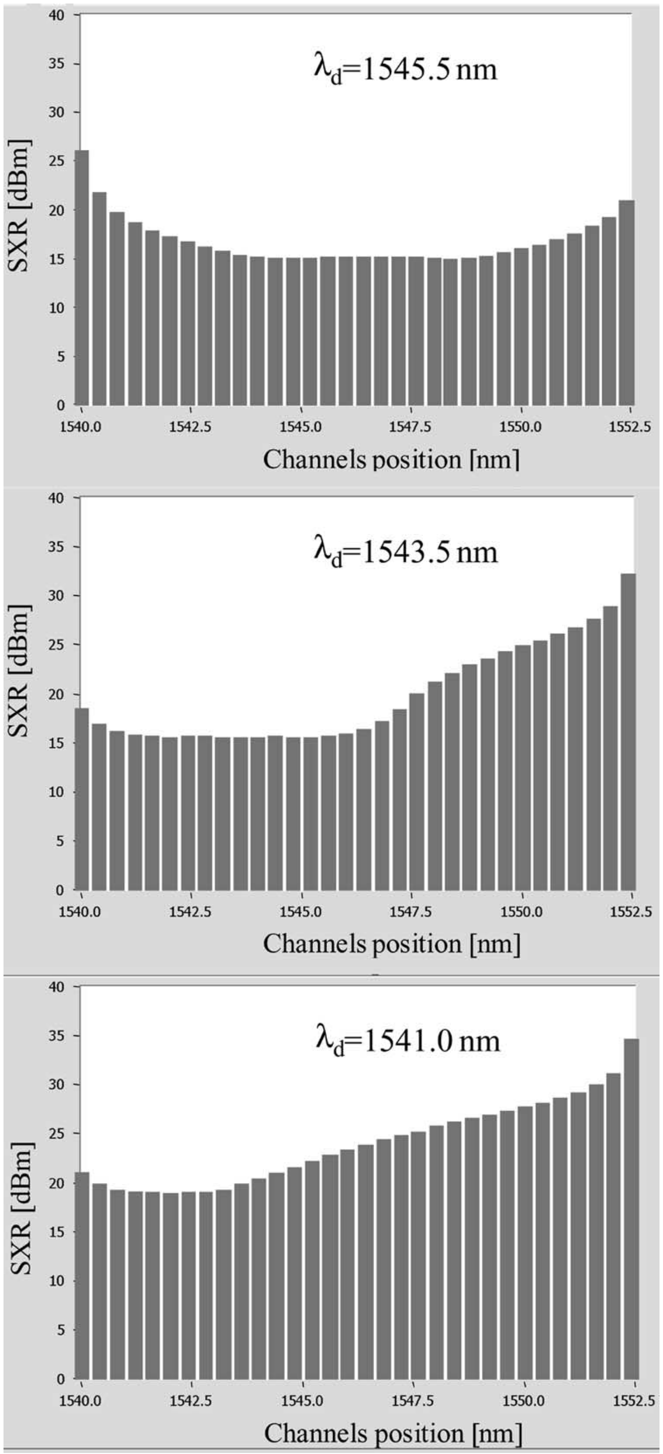

Fig. 10. SXR for a 32-channel ECS scheme for different zero dispersion position.

to the last empty slot in the range of h slots between the two nearest islands.

The needed bandwidth in this case is

$$B = [4Q + k(Q-2) + h + (k+R)\min(1,R)]\Delta\lambda. \quad (12)$$

For $\mathrm{N} \gg 1$, the fractional bandwidth expansion is the same as that for normal TCC.

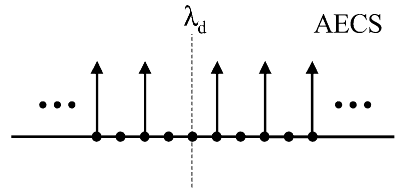

Fig. 11. Asymmetric ECS scheme optimized for the zero dispersion region.

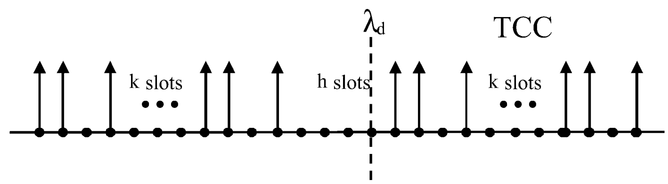

Fig. 12. Asymmetric TCC scheme optimized for the zero dispersion region.

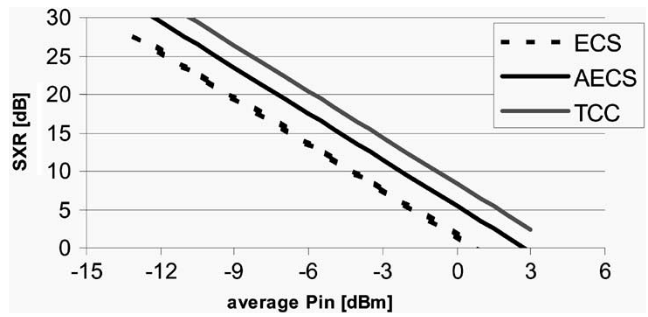

Fig. 13. SXR versus the average input power per channel for the worst comb channel in a DS fiber using ECS (dotted curve), AECS (dark curve) or TCC (light curve).

Fig. 13 shows the comparison between the SXR obtained with ECS and AECS schemes versus the average input power per channel, for the worst channel in the zero dispersion region using, in both cases almost the same spectral occupation. Both channel allocations are realized using a grid resolution of 0.4 nm and a minimum channel spacing of 0.8 nm. Consequently, the occupied bandwidth is 25.6 and 26 nm for ECS and AECS, respectively. The asymmetry introduction allows one to obtain an SXR improvement of 4 dB, or a penalty reduction higher than 2.5 dB, with a fractional bandwidth expansion equal to 1.016 and independently on the lunched power.

The TCC scheme, reducing further the inband FWM terms, is a suitable channel allocation technique also for transmission on DS fiber. In this case we consider a three-channel repetition at distance k slot, maintaining the zero dispersion wavelength external to any three-channel islands, in order to avoid that two channels experience a dispersion value near to zero. In this case, in fact, the two channels originate a higher efficiency FWM term. We introduce also a different spacing, h slots, between the zero dispersion adjacent island to optimize the channel position in respect to the zero dispersion wavelength.

In Fig. 13, we report the SXR versus the average input power per channel in DS fiber, also for the adjusted TCC scheme in the case of $k = 2$ and $h = 3$.

The spectral occupation is 25.2 nm, very close to that of the other schemes. The proposed TCC, even requiring a fractional bandwidth <1, allows one to obtain a further SXR improvement

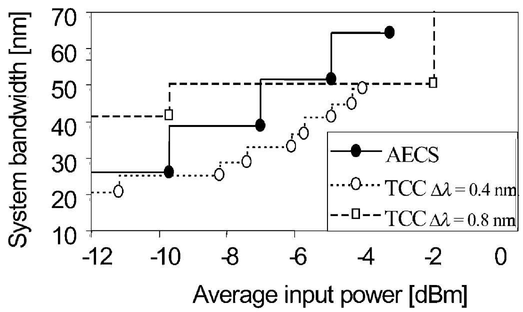

Fig. 14. System bandwidth versus average input power per channel for a target $\mathrm{SXR}_{\min} = 25$ dB in a 100-km DS fiber with $D_c = 0$ ps/nm/km, for AECS and TCC, for various grid resolutions. $N = 32$ channels.

of 3 dB, which means a penalty reduction of more than 2 dB with respect to the AECS, independent of the input channel power. We compare also, in Fig. 14, the system bandwidth needed to guarantee a fixed SXR of 25 dB for all channels versus the average input power per channel in the case of AECS and TCC.

The curve concerning the AECS was obtained for channel spacings multiple of 0.4 nm, in order to respect the ITU grid, whereas for the other curves we increased the k and h values. In particular

$$h = k + (1 - R(k/2)) \quad \text{and} \quad k = 1, \ldots, 8 \qquad (13)$$

where $R(k/2)$ is the remainder of the division of k by two.

Up to -11.2 dBm, the most efficient allocation code is the TCC on the 0.4-nm grid with a bandwidth savings of more than 5 nm. In the range $-11.2 : -9.7$ dBm, it is almost equivalent to using AECS or TCC on the 0.4-nm grid. For lunched powers higher than -9.7 dBm, up to -4 dBm, the last one requires the minimum spectral occupation, reducing the bandwidth up to 19.6 nm. To transmit more than -4 dBm, it is convenient to use a TCC on the 0.8 grid, decreasing the bandwidth of 14 nm.

The zero dispersion wavelength was assumed to be into a known slot. Commercial fiber data sheets give imprecise information about that because the zero dispersion position changes along the real fiber. However, it is possible to experimentally characterize the fiber and measure the correct zero dispersion wavelength value to be considered in the system design.

V. Conclusion

An analysis of FWM impact on DWDM optical systems is carried out for different types of fibers. The new approach consists in optimizing channel allocation considering the total in-band FWM crosstalk and not only the number of intermodulation products falling into the channel bandwidth. A new unequal channel allocation based on three-channel islands has been proposed and compared with equally spaced systems. The behaviors, numerically obtained, of the SXR for a fixed system bandwidth and of the spectral occupation to guarantee a fixed SXR have been reported for NZDS, SM, and DS fiber.

The numerical results show an SXR improvement of at least 3 dB (for low SXR, this assures a penalty reduction of more than 2 dB) in the case of TCC with respect to ECS, using the same bandwidth, for all types of fiber. Moreover, the new allocation code allows savings of up to 15 nm of spectral occupation, assuring the same SXR.

In the case of DS fiber, the TCC results have been compared also with an asymmetric ECS to take into account the zero dispersion position.

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