Power pre-emphasis for suppression of FWM in coherent optical OFDM transmission

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Abstract: Four-wave-mixing (FWM) due to the fiber nonlinearity is a major limiting factor in coherent optical OFDM transmission. We propose to apply power pre-emphasis, i.e. to allocate the transmitted power non-uniformly among subcarriers in order to suppress the FWM impairment. The proposed technique was numerically investigated for both single channel 15.6 Gbs CO-OFDM transmissions and 7-channel WDM transmissions, showing that up to 1 dB improvement in the system's Q-factor can be achieved without considering sophisticated power loading algorithms developed for wireless communications.

OCIS codes: (060.2330) Fiber optics communications; (060.4370) Nonlinear optics, fibers.

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1. Introduction

In multicarrier transmission systems power allocation among channels is an important problem attracting a great deal of attention [1–15]. According to the channel conditions and properties the transmitted power of each subcarrier can be adjusted to maximize the bit rate [1–4], the energy efficiency [5–8] or to improve the overall system performance [9–15].

In wireless communication systems with link adaptation, the modulation format, coding rate and transmitter power can be selected in order to improve the transmission performance. For example, in a frequency-selective fading channel, different subcarriers will generally experience different channel attenuations. Thus, to maximize the information transmission rate the transmitter power should be allocated among the subcarriers carefully according to the instantaneous channel state information (CSI) available at the transmitter. It has been shown that the data rate of a single OFDM system can be maximized if the transmission power is adapted with the help of the water-filling algorithm [2–4]. The water-filling algorithm is applied by allocating more power on subcarriers with larger gain to noise ratios (GNR) [2]. Various other power allocation algorithms have also been investigated to maximize the energy efficiency subject to a capacity constraint [5–8].

In optical wavelength-division-multiplexing (WDM) transmission systems pre-emphasis of the input-channel powers has been considered as an effective technique to solve the problem of gain equalization due to the non-uniform wavelength-dependent gain profile of erbium-doped fiber amplifiers (EDFA) [9–11]. As the EDFA gain profile is not flat in the operating region, WDM links could experience significant gain variations over the active signal comb [15]; as a result, if all WDM channels are transmitted with the same power, at the receiver they typically show different output-power values and different optical-signal-to-noise ratios (OSNR) [15]. This leads to unacceptable bit-error-rate (BER) performance of some channels [9]. A power allocation technique was first proposed in [9] to equalize the output powers and the output OSNR of all WDM channels. This method is attractive because of its simplicity as no equipment, upgrades or adjustments are required at intermediate amplifier sites [9]. In addition, in WDM transmission, power pre-emphasis can also be used to compensate for different channels evolution due to the Raman effect in silica.

Coherent optical OFDM (CO-OFDM) has been considered as a promising candidate for high capacity optical networks [16]. CO-OFDM provides an efficient way to compensate for inter-symbol interference caused by both chromatic dispersion (CD) and polarization-mode dispersion (PMD) and uses a simple channel estimation and compensation scheme [17, 18]. However, one major drawback of CO-OFDM is that it suffers from a number of nonlinear effects, especially four-wave-mixing (FWM) due to the narrow and equal spacing of subcarriers [19–21]. Mitigating the impact of FWM on the performance of CO-OFDM transmission is the motivation of this work.

It has been shown that in CO-OFDM transmission the power density of FWM noise is higher in the center of the OFDM band than at the edge [20–22]. Similarly, the contributions of different subcarriers to the FWM noise, in general, are different. As a result, the power of the FWM noise depends strongly on the power distribution among the OFDM subcarriers. Therefore, power allocation algorithms can be applied to suppress the impact of FWM on the performance of CO-OFDM systems. Unfortunately, most of the existing bit and power loading algorithms [1–15] developed for wireless systems were designed for linear channels and, thus, cannot be applied effectively to optical communication systems because of the fiber nonlinearity [23]. Since the nonlinear distortion depends on the transmitted power, changing the transmission parameters of an arbitrary subcarrier will influence the other subcarriers. In addition, existing power loading algorithms are sophisticated and thus are not suitable for high speed optical communications. Therefore, a simple and effective strategy of applying power pre-emphasis for CO-OFDM transmission is of great interest.

In this work, we propose an effective power allocation technique to mitigate the FWM impairment subject to a power constraint in CO-OFDM transmissions. This simple technique is based on allocating less power to subcarriers that have larger contributions to the FWM impairment, and thus, reducing the total power of FWM noise. In CO-OFDM transmission power allocation algorithms can be implemented directly in the frequency domain before the IFFT block, which generates the time-domain signal. In the proposed technique, the system performance can be optimized by adjusting only two parameters, independently of the total number of subcarriers.

2. Impact of FWM on CO-OFDM transmission

In CO-OFDM systems with narrow frequency spacing, the strongly phase matched interaction can be considered. The power of a single FWM product created at ($f_g = f_i + f_j$-f_k) after N_A fiber spans can be calculated as [19]:

$$P_{ijk} = \left(\frac{D_{\deg}}{3} \cdot \gamma \cdot L_{eff} \right)^2 P_i P_j P_k \cdot \eta, \tag{1}$$

where $D_{deg} = 6$ for non-degenerate and $D_{deg} = 3$ for degenerate FWM products, $L_{eff} = (1 - e^{-\alpha L})/\alpha$ is the nonlinear effective length (P_i, P_j, P_k) are the powers of subcarriers, η is the FWM coefficient which strongly depends on the relative frequency spacing between the FWM components given by $\eta = \eta_1 \eta_2$. η_1 is responsible for intra-span FWM coefficient and η_2 is responsible for inter-span nonlinear interference. The expressions for η_1 and η_2 are given in [19]. Note that η_1 and η_2 are independent of the OFDM subcarriers' power.

It can be seen from Eq. (1) that under the condition $P_i + P_j + P_k$ = constant, the power of this FWM product is strongest when the total power is distributed equally among these three subcarriers ($P_i = P_j = P_k = P/3$). As a result, equally allocating power among subcarriers, in fact, is not an optimum option in terms of mitigating the FWM impairments.

In CO-OFDM systems, the exact number of FWM products, both degenerate and non-degenerate, falling on a given subcarrier can be readily calculated [20]. The number of FWM products falling on the i'th subcarrier is:

$$M(i, N) = \frac{1}{2}(N^2/2 - 2 \cdot N + Ni - i^2 + i), \tag{2}$$

where N is the number of OFDM subcarriers, $i = 1 \ldots N$ is the subcarrier index.

Let $S(g, N)$ denote the number of FWM products created with the contribution of the g'th subcarrier. It is obvious that for every non-degenerate FWM product falling on the g'th subcarrier ($f_g = f_i + f_j$-f_k) we can accordingly find 3 FWM products, which are created with the contribution of this g'th subcarrier, namely ($f_j = f_g + f_k$-f_i), ($f_i = f_g + f_k$-f_j) and ($f_k = f_i + f_j$-

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f_g). Similary, for every degenerate FWM product falling on the g'th subcarrrier we can accordingly find 2 FWM products, which are created with the contribution of this subcarrier. Based on these arguments and taking into account the fact that the number of non-degenerate FWM products is much bigger than the number of degenerate FWM product [20], the number of FWM products created with the contribution of the g'th subcarrier can be calculated approximately:

$$S(g,N) = 3M(g,N) = \frac{3}{2}\cdot(\frac{N^2}{2} - 2N + Ng - g^2 + g). \tag{3}$$

It should be noticed from (1) that the power of a single non-degenerate FWM product is 4 times larger than the power of a single degenerate FWM product. As a result, expression (3) can be used with high accuracy to analyse the contribution of each subcarrier to the total FWM noise falling into the OFDM band. In Fig. 1(a) the dependence of $S(g,N)$ on the subcarrier index is shown in the case of an OFDM system with 128 subcarriers. The result was obtained using both simulation with a MATLAB program and Eq. (3). In the simulation, we calculated the exact number of possible combinations of 3 subcarriers (f_i, f_j, f_k), the interaction among which creates FWM products ($f_g = f_i + f_j$-f_k) falling into the OFDM band. It can be seen in Fig. 1(a) that almost no mismatch between the analytical and numerical results is observed, which verifies that Eq. (3) provides very high accuracy, especially when the number of OFDM subcarriers is large. In the case considered with 128 subcarriers, the 68th subcarrier plays a role in around 18000 FWM combinations while the 1st and the 128th subcarriers have contribution to only approximately 12000 FWM combinations.

Figure 1(b) shows the total FWM power for each subcarrier for a single span (80km) transmission, which confirms that centre subcarriers have a much larger contribution to the FWM noise in comparison with subcarriers at the edges. As a result, the power of FWM noise can be reduced simply by allocating less power to the centre subcarriers and more power to the subcarriers at the edges. If the transmitted power is distributed among subcarriers carefully in this way we are able to improve the signal-to-noise ratio (SNR) of subcarriers at the edges while keeping the SNR of the centre subcarriers almost unchanged, thus improving the system's performance. Moreover, the power pre-emphasis can be easily optimized and adjusted in a flexible way for any required transmission distance. This idea is similar to the water-filling algorithm when the transmitted power is allocated such that the SNR of subcarriers with higher gains are further increased. However, the difference is that the water-filling algorithm aims to maximize the bit rate while our proposal aims to improve the system's tolerance to fiber nonlinearity.

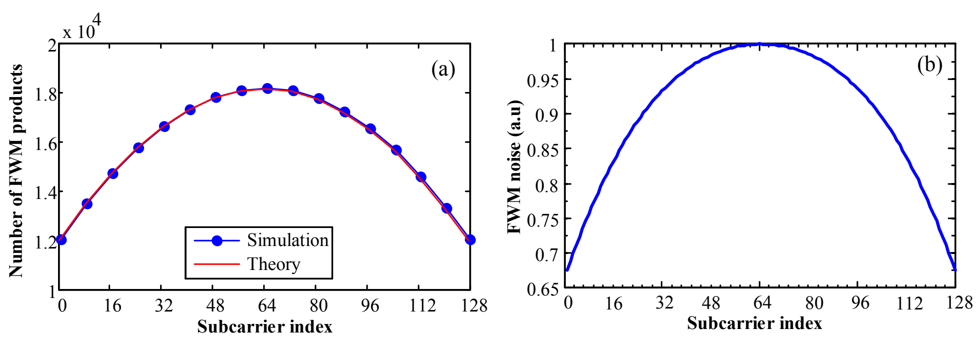

Fig. 1. (a) Dependence of *S(g, 128)* on the subcarrier indicies, (b) The total FWM power for each subcarrier for a single span (standard single mode fiber, 80km) in a CO-OFDM system with 100 MHz frequency spacing and 128 subcarriers

3. System description and analysis

In a CO-OFDM system the signal consists of a large number of subcarriers. In the transmission line these subcarriers can interact with each other, creating thousands of FWM products. As a result, finding the optimum way to allocate the transmitted power among the subcarriers to minimize the impact of FWM on the system's performance is a very complex problem. This is especially true in the presence of ASE noise and is not analytically soluble. A simple heuristic approach to this problem is to allocate the transmitted power among subcarriers using a simple analytical function, the parameters of which are then optimized in order to achieve the best performance. If a power distribution function is already chosen then the power allocation algorithm can be applied simply by multiplying the information symbol after modulation or data mapping with a fixed coefficient before the IFFT block. For convenience we set the amplitude distribution among the subcarriers by a function $A(k)$, and then the power distribution among subcarriers can be easily obtained by $P(k) = A(k)^2$.

We consider in this work the following particular amplitude distribution function $A(k)$ which has a "Super Gaussian hole" in the centre:

$$A(k) = 1 - a \cdot \exp(-b(k - N/2)^x), \tag{4}$$

where (a, b, x) are the three parameters of the distribution function, which are required to be optimized in order to achieve the best performance. The distribution (4) is chosen for analysis because of its simplicity and possibility to use 3 free parameters to change the depth, width and roll-off of the power distribution curve in order to optimise the system's performance.

It is obvious that by varying (a, b, x) the transmitted power can be allocated among subcarriers in various ways. Figure 2 shows some options of allocating power among subcarriers using the distribution function (4) for the case of 100 subcarriers ($N = 100$). The equal power distribution can also be obtained by setting ($a = 0$) or ($b = 0$) [Fig. 2(a)].

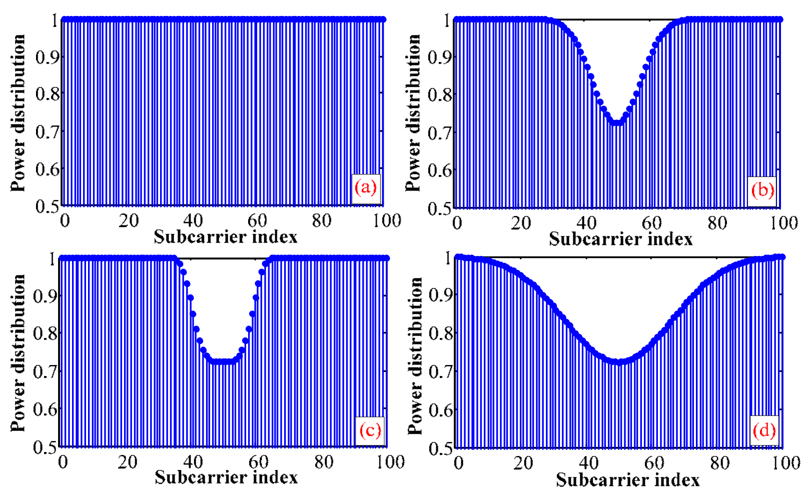

Fig. 2. Various power allocation methods for CO-OFDM with 100 subcarriers using distribution of Eq. (4), (a) ($a = 0$) or ($b = 0$), (b) ($a = 0.15$, $b = 0.01$, $x = 2$), (c) ($a = 0.15$, $b = 0.001$, $x = 4$), (d) ($a = 0.15$, $b = 0.002$, $x = 2$)

4. Single channel transmissions and optimization

In this section, in order to investigate the benefit of allocating the total transmitted power among the subcarriers using Eq. (4) we first set up a single polarization 15.6 Gbs CO-OFDM system as shown in Fig. 3.

A 15.6 Gbs data stream is first mapped mapped onto 100 subcarriers using the QPSK modulation format with Gray coding and subsequently transferred to the time domain by an

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IFFT of size 256. Only 100 subcarriers from the 15th to 114th are modulated while zeros occupy the remainder. The total OFDM symbol duration is 12.8 ns. A cyclic prefix of length 64 is used to accommodate dispersion. The fiber link is assumed to consist of 35×80-km spans of standard single mode fiber (SSMF) with the loss parameter of 0.2 dB/km and PMD coefficient of 0.1 ps/km$^{0.5}$. The fiber nonlinearity coefficient and dispersion are 1.22 W^{-1}km^{-1} and 16 ps/nm/km respectively. The fiber span loss is compensated by Erbium-doped optical amplifiers (EDFA) with 16 dB of gain and a noise figure of 6 dB. In the simulation the ASE noise is added inline after each fiber span. The transmitter and receiver lasers have the same linewidth of 100 kHz. The laser phase noise is modeled as a Wiener-Levy process with a variance $\sigma^2 = 2\pi\upsilon t$ where υ is the combined laser linewidth and t is the time difference between two samples. The simulated time window contains 6000 OFDM symbols. The channel estimation and equalization is performed with the assistance of an initial training sequence using the zero forcing estimation method. The common phase error due to laser phase noises is estimated and compensated using a pilot-aided technique by inserting 8 pilot subcarriers in each OFDM symbol.

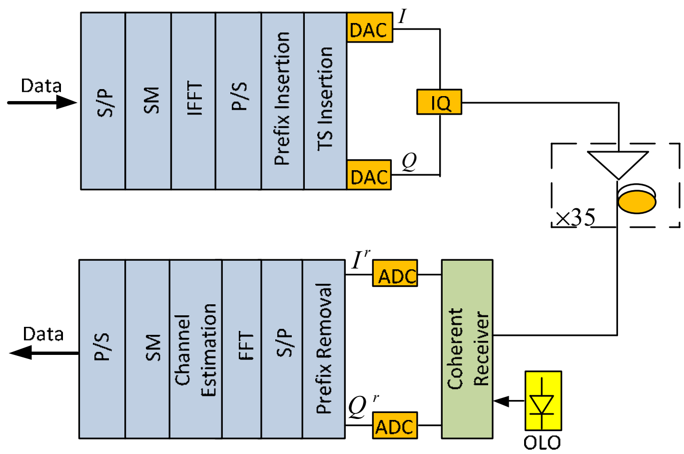

Fig. 3. Block diagrama of 15.6Gbs CO-OFDM transmissions.S/P: serial/parallel conversion, P/S: parallel/serial conversion, SM: symbol mappings, TS: training symbol, DAC: digital-to-analog converter, I/Q: I/Q modulator, OLO: optical local oscilator

We compare the performance of this CO-OFDM system with the four methods of power allocation, which are shown in Fig. 2 (the four distributions will be referred to as a, b, c, and d). In these system simulations we perform Monte Carlo calculations to directly evaluate the system's BER through error counting. The performance of the CO-OFDM system is then characterised using the effective Q-factor in dB, which is delivered from the system's BER by the expression [24]:

$$Q_{BER} = 20\log[\sqrt{2}\cdot erfc^{-1}(2BER)]. \quad (5)$$

The performance of the 15.6 Gbs CO-OFDM system with different power distribution methods among the subcarriers is shown in Fig. 4. It can be seen that by allocating less power in the middle of the OFDM band the system's performance can be significantly improved. The power distribution (d) [Fig. 2(d)] shows the best performance, which gives around 1 dB improvement in the system's Q-factor in comparison with the case of equal power distribution. By applying this power allocation method the system's tolerance to fiber nonlinearity can be also improved by approximately 1 dB. The distributions (b) and (c) [Figs. 2(b) and 2(c)] show almost the same performance. At the optimum launch power level these power distributions do not show significant advantage over the equal power distribution. However, in the nonlinear limited transmission regime both power allocation methods (b) and (c) [Figs. 2(b) and 2(c)] can give around 0.7 dB improvement in the system's Q-factor.

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The similarity of curves (b) and (c) in Fig. 4 suggests that the shape of the distribution function is not critical. The improvement in the curve (d) in Fig. 4 shows that the width is more important. In order to verify and confirm the improvement in the system's Q-factor when the power distribution is adjusted we perform 50 realizations for every Q-calculation. The obtained results indicate that the statistical distribution of each Q-factor calculation in general has a width smaller than 0.3 dB. The statistical distribution of Q-factor improvement in dB is shown in Fig. 5 for various values of a, b and the launch power. It can be seen that the improvement in general is stable. The mean Q-factor improvements for (a = 0.15, b = 0.002, x = 2) are 0.91 dB and 1.56 dB when $P = -7$ dBm and $P = -4$ dBm respectively. For the second and the third power distributions shown in Fig. 2 the mean Q-factor improvements when $P = -4$ dBm are 0.63 dB and 0.62 dB respectively.

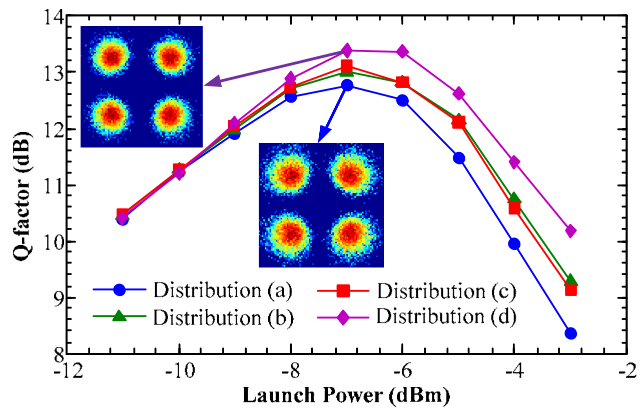

Fig. 4. Performances of 15.6Gbs CO-OFDM system with different power distribution methods among subcarriers after 2800km of transmission distance

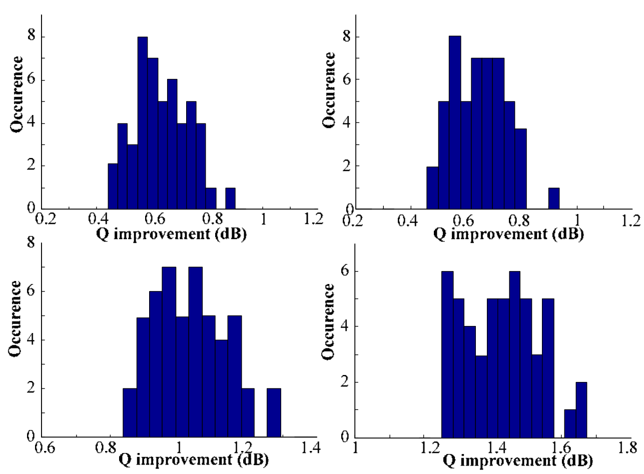

Fig. 5. Statistical distribution of Q-factor improvement in dB when the power distribution is adjusted. (a) (a = 0.15, b = 0.01, x = 2, P = -4 dBm), (b) (a = 0.15, b = 0.01, x = 4, P = -4 dBm), (c) (a = 0.15, b = 0.002, x = 2, P = -7 dBm), (d) (a = 0.15, b = 0.002, x = 2, P = -4 dBm)

Let us now move to the discussion of optimizing the parameters of the power distribution function. Simulation results (not presented here) show that using higher order ($x>2$) distributions does not improve the system's performance in comparison with the second order (x = 2) distribution. Therefore, we further consider only the second order case and present the optimization results for the two remaining parameters (a, b).

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Figures 6, 7, and 8 show the system's Q-factor as a function of (*a, b*) for three values of the launch powers representing three transmission regimes, namely $P = -9\ dBm$ for the ASE noise limited regime [Fig. 6], $P = -7\ dBm$ for the optimum launch power point [Fig. 7] and $P = -4\ dBm$ for the nonlinear limited regime [Fig. 8]. One should notice that the conventional method of equally allocating power among subcarriers can be obtained by setting $a = 0$ or $b = 0$. Therefore, in Figs. 6–8 $a = 0$ or $b = 0$ can be considered as the reference points showing which values of a, b can be used to improve the system's performance.

The simulation result shown in Fig. 6 indicates that modifying the power distribution cannot be applied to improve the system's performance when the launch power is too low ($P = -9dBm$). When $a<0.15$ the system's performance is almost independent of *b*. However, when $a>0.15$, the system performance starts to getting worse. This is because the SNR of the centre subcarriers decreases substantially due to the low power allocated in the middle of the OFDM band.

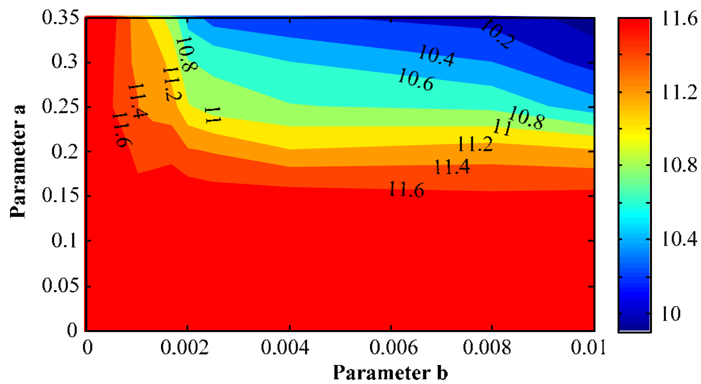

Fig. 6. Dependence of Q-factor on (*a, b*), $P = -9dBm$, after 2800km of transmission distance

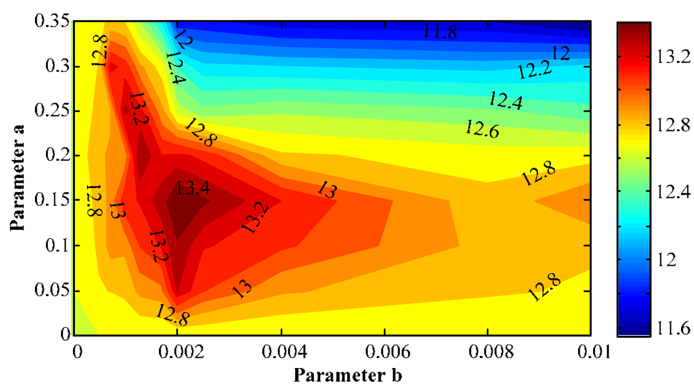

Fig. 7. Dependence of Q-factor on (*a, b*), $P = -7dBm$, after 2800km of transmission distance

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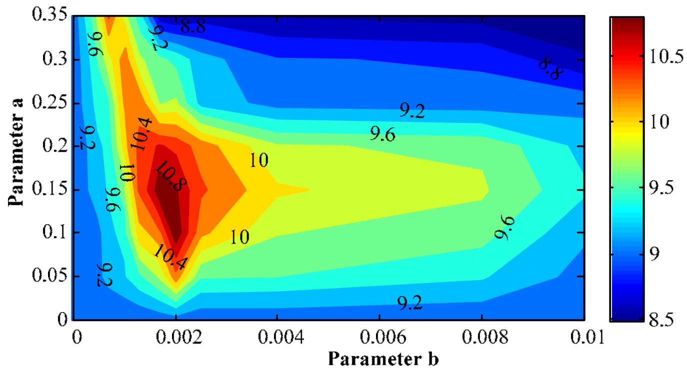

Fig. 8. Dependence of Q-factor on (*a, b*), *P = –4dBm*, after 2800km of transmission distance

When the transmitted power is set around its optimum value (*P = –7dBm*) the chosen power distribution function can improve the system's performance in a wide range of (*a, b*). In this case FWM noise due to the fiber nonlinearity is also an important limiting factor as well as ASE noise introduced by optical amplifiers. Therefore, the system's performance will improve if the FWM noise is suppressed. The optimum values of (*a, b*) are found to be (*a = 0.15, b = 0.002*), which offer around 1dB advantage in the received signal quality. A larger improvement (around 1.6 dB) can be obtained in the nonlinear limited regime *P = –4dBm* as shown in Fig. 8. In this case, the dominant limiting factor is FWM noise. By applying the power distribution function with (*a = 0.15, b = 0.002*) the system's Q-factor can be improved to 12.2 dB in comparison with 10.6 dB for the conventional equal power distribution. This indicates that the modified power distribution is effective in mitigating the impact of FWM noise on the transmission performance. However, there is a trade-off in applying this technique. The power of FWM noise can be significantly reduced by using a large value of *a*, however, in this case the transmitted power of the centre subcarriers becomes too small, thus increasing the number of errors falling on these subcarriers due to its low SNR. The optimum value of *a* is found to be *a = 0.15*, according to a power suppression ratio of 0.72 for the centre subcarrier.

Generally, by allocating less power in the centre subcarriers the total FWM power can be reduced. However, if the powers of the center subcarriers are too small the SNR of these subcarriers will be lower in comparison with the case of uniform power distribution due to the ASE noise. In this case, the system's performance can be worse. In the absence of ASE noise and if the OFDM frequency spacing is small (the strongly phase matched interaction can be considered), Eq. (3) suggests that the optimum power distribution among subcarriers should be: $P(g) = S_0/S(g,N)$, where S_0 is a constant. If this power allocation method is applied the power suppression ratio of the centre subcarrier will be around 0.66 (when the number of subcarriers is large). However, in the presence of ASE noise (6 dB of noise figure) the optimum power suppression for the centre subcarrier in the investigated system was found to be 0.72, slightly higher than the value when ASE noise is not considered. This result indicates that for a particular application the optimum power allocation method should be defined flexibly in order to balance the impact of FWM and ASE noise.

5. WDM transmissions and discussions

In order to verify the effectiveness of the proposed power allocation technique, we also investigate the impact of non-uniform power allocation among OFDM subcarriers in 7-channel WDM transmissions with 12.5 GHz of channel spacing, centred at 1550 nm. The WDM signal spectrum is shown in Fig. 9.

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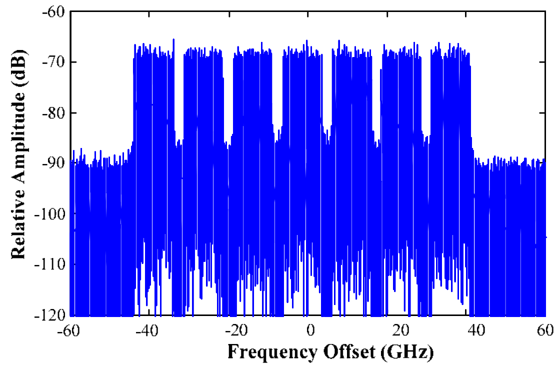

Fig. 9. Spectrum of 7-channel WDM CO-OFDM transmissions, system, the central carrier is at 1550 nm.

In this simulation set up, for each channel, the OFDM signal is generated with the same parameters as shown in the previous section. At the receiver, after coherent detection, the channel was filtered using a filter with 11 GHz of bandwidth. We consider here only the optimum power allocation strategy obtained in the previous section. This power allocation technique is applied to all WDM channels. In addition, all WDM channels are considered with the same power.

Figure 10 compares the performances of the centre channel (4th) when the uniform and non-uniform power allocation strategies are applied. Even in the presence of nonlinear impairment from the neighbouring channels, the optimum non-uniform power allocation method still offers around 0.7 dB advantage (at the optimum launch power) over the traditional uniform power allocation technique. The optimum non-uniform power allocation technique effectively supresses the FWM noise falling in the considered WDM channel. In addition, the nonlinear interaction among subcarriers at the edge of a WDM channel with subcarriers in other WDM channels does not significantly increase when more power is allocated to these subcarriers because of the frequency guard band between adjacent WDM channels. As a result, the proposed non-uniform power allocation technique still can be applied effectively in WDM transmissions.

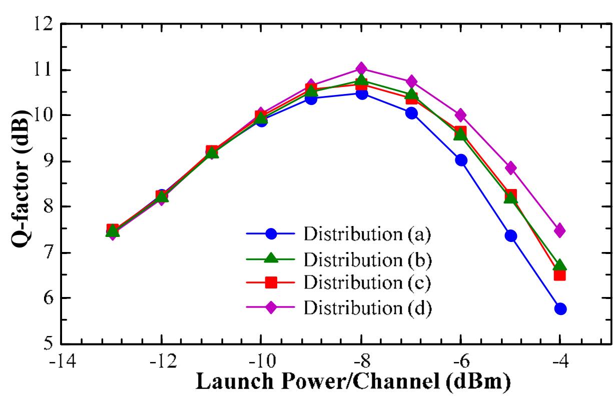

Fig. 10. Performance comparison of uniform and optimum non-uniform power allocation methods among subcarriers for the center channel (4th) in WDM transmissions, after 2800km of transmission distance

6. Conclusion

We have proposed a novel power pre-emphasis method for coherent optical OFDM, which can reduce the impact of FWM on the system performance. In this method the transmitted

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power is allocated unequally among subcarriers by a simple power distribution function, which has a “Super Gaussian hole” in the centre. This technique is attractive because of its simplicity in comparison to existing power loading techniques developed for wireless communication. The technique can be simply implemented as part of the transmitter DSP and represents very low additional cost. Numerical simulations of a 15.6 Gbs CO-OFDM system with 100 subcarriers and 7-channel WDM have shown that up to 1dB improvement in the system Q-factor can be obtained when this power allocation method is applied. We believe that the proposed power pre-emphasis technique can be also successfully combined with the constrained channel coding [25, 26] to suppress other detrimental nonlinear and linear impairments such as patterning effects due to inter carrier interference.

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