Transmission simulation of coherent optical OFDM signals in WDM systems

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Abstract: In this letter, we first present the theoretical basis for coherent optical OFDM systems in direct up/down conversion architecture. We then demonstrate the transmission performance through simulation for WDM systems with coherent optical OFDM (CO-OFDM) including the fiber nonlinearity effect. The results show that the system Q of the WDM channels at 10 Gb/s is over 13.0 dB for a transmission up to 4800 km of standard-single-mode-fiber (SSMF) without dispersion compensation. A novel technique of partial carrier filling (PCF) for improving the non-linearity performance of the transmission is also presented. The system Q of the WDM channels with a filling factor of 50 % at 10 Gb/s is improved from 15.1 dB to 16.8 dB for a transmission up to 3200 km of SSMF without dispersion compensation.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.1660) Coherent communications; (0606.5060) Phase modulation

References and links

1. S. Hara and R. Prasad, *Multicarrier Techniques for 4G Mobile Commmications,* (Artech House, Boston, 2003).
2. W. Shieh and C. Athaudage, "Coherent optical orthogonal frequency division multiplexing," Electron. Lett. **42,** 587 – 588 (2006).
3. J. Lowery, L. Du, and J. Armstrong, "Orthogonal frequency division multiplexing for adaptive dispersion compensation in long haul WDM systems," in Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference, Technical Digest, (Anaheim, CA, USA, 2006), Paper PDP39.
4. I. B. Djordjevic and B. Vasic, "Orthogonal frequency division multiplexing for high-speed optical transmission," Opt. Express **4,** 3767-3775 (2006).
5. "Supplement to IEEE standard for information technology telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements. Part 11: wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: high-speed physical layer in the 5 GHz band," in IEEE Std 802.11a-1999, (1999)
6. E. Ip, J. P. Kahn, D. Anthon and J. Hutchins, "Linewidth measurements of MEMS-based tunable lasers for phase-locking applications," IEEE Phot. Technol. Lett. **17,** 2029 – 2031 (2005).
7. J. D. Berger, D. Anthon, S. Dutta, F. Ilkov, and I. -F. Wu, "Tunable MEMS Devices for Reconfigurable Optical Networks," in Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference, Technical Digest (CD) (Optical Society of America, 2005), paper OThD1. http://www.opticsinfobase.org/abstract.cfm?URI=OFC-2005-OThD1.
8. G. Charlet, N. Maaref, J. Renaudier, H. Mardoyan, P. Tran, S. Bigo, "Transmission of 40Gb/s QPSK with coherent detection over ultra long haul distance improved by nonlinearity mitigation," in Tech. Dig., ECOC'2006 (Cannes, France, 2006), post-deadline paper, Th.4.3.6.
9. N. S. Bergano, "Wavelength division multiplexing in long-haul transoceanic transmission systems," J. Lightwave Technol. **23,** 4125-4139 (2005).

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1. Introduction

Orthogonal frequency division multiplexing (OFDM) has been widely employed into numerous digital standards for broad-range of applications such as digital audio/video broadcasting and wireline/wireless communication systems [1]. Recently it has been shown that OFDM can be applied in optical long haul transmission systems and had many advantages over conventional single-carrier modulation format [2-4]. Many key merits of the OFDM techniques have been studied and proven in the communications industry. Firstly, the frequency spectra of OFDM subcarriers are partially overlapped, resulting in high spectral efficiency. Secondly, the channel dispersion of the transmission system is easily estimated and removed, and thirdly, the signal processing in the OFDM transceiver can take advantage of the efficient algorithm of FFT/IFFT with low computation complexity. Recently, an equivalent optical-domain multi-carrier format, called coherent optical OFDM (CO-OFDM) has been proposed for long haul transmission [2]. In the mean time, incoherent optical OFDM (IO-OFDM) has also been proposed independently, and has been shown to have similar dispersion tolerance with a much simpler detection scheme [3]. However, the CO-OFDM is superior to IO-OFDM in spectral efficiency, OSNR requirement, and PMD insensitivity. It is well-known that OFDM is generally susceptible to nonlinearity and phase noise owing to high peak to average power ratio (PAPR) [1]. Therefore it is critical to investigate and improve the CO-OFDM system transmission performance including fiber nonlinearity, in order to ascertain its suitability for optical transmission. In this letter, we intend to answer two important questions for CO-OFDM WDM system, (i) what is the achievable system Q value ?, and (ii) what is the optimal launch power at various transmission distances ?. We first present the theoretical basis for coherent optical OFDM systems in direct up/down conversion architecture. We then demonstrate the transmission performance through simulation for WDM systems with coherent optical OFDM (CO-OFDM) including the fiber nonlinearity effect. The results show that the system Q of the WDM channels at 10 Gb/s is over 13.0 dB for a transmission up to 4800 km of standard-single-mode-fiber (SSMF) without dispersion compensation. A novel technique of partial carrier filling (PCF) for improving the non-linearity performance of the transmission is also presented. The system Q of the WDM channels with a filling factor of 50 % at 10 Gb/s is improved from 15.1 dB to 16.8 dB for a transmission up to 3200 km of SSMF without dispersion compensation.

2. WDM transmission systems with CO-OFDM

The basic WDM CO-OFDM transmission system is shown in Fig. 1. A generic CO-OFDM system consists of an OFDM transmitter, an optical link, and an OFDM receiver. Inside the OFDM transmitter, the input data bits are mapped onto corresponding information symbols of the subcarriers within one OFDM symbol, and the digital time domain signal *s(t)* is obtained by using IFFT [1-2]:

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{k=N_{sc}} c_{ik} \Pi(t - iT_s) \exp(j2\pi f_k (t - iT_s) \tag{1}$$

$$f_k = \frac{k-1}{t_s} \tag{2}$$

$$\Pi(t) = \begin{cases} 1, & (-\Delta_G < t \le t_s) \\ 0, & (t \le -\Delta_G,\ t > t_s) \end{cases} \tag{3}$$

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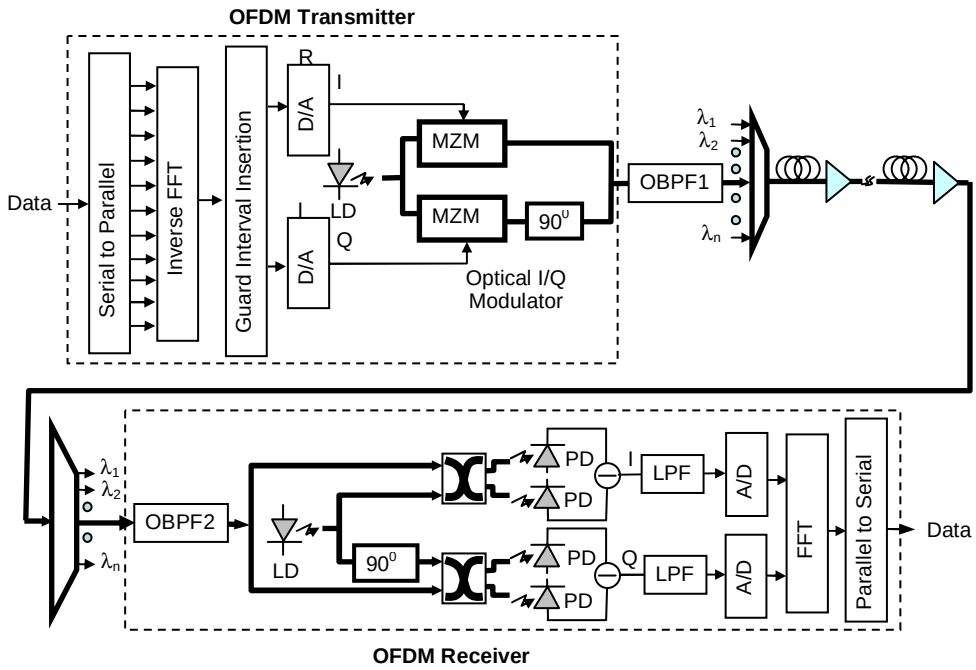

Fig. 1. Conceptual diagram of a CO-OFDM system

Where C_{ik} is the *ith* information symbol at the *kth* subcarrier, f_k is the frequency of the subcarrier, N_{sc} is the number of OFDM subcarriers, T_s, ΔG, and t_s are the OFDM symbol period, guard interval length and observation period respectively. To efficiently reduce the transmitter and receiver bandwidth, the subcarrier frequency of OFDM symbol is preferred to be between $-f_{BW}/2$ and $f_{BW}/2$, where f_{BW} is the bandwidth of OFDM symbols. The popular form of base band OFDM signal, *s(t)* can be generated as [5]

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=-N_{sc}/2+1}^{k=N_{sc}/2} c_{ik} \Pi(t - iT_s) \exp(j2\pi f_k (t - iT_s) \tag{4}$$

The digital time domain signal *s(t)* is then inserted with a guard interval and subsequently converted into real time waveform through digital-to-analogue converter (DAC) [1]. The guard interval is to eliminate the inter-symbol interference (ISI) and its interval length ΔG should satisfy the condition:

$$\Delta_G \geq \frac{c|D_t|Nsc}{f^2 t_s} \tag{5}$$

where f is the frequency of the optical carrier, c is the speed of light, D_t is the total accumulated chromatic dispersion in units of ps/pm, and N_{sc} is the number of OFDM subcarriers. The OFDM electrical-to-optical conversion is achieved by applying respectively the real and imaginary components of *s(t)* on to I and Q ports of an optical I/Q modulator. The two Mahnch-Zender (MZ) optical modulators biased at zero output power and a 90 degree phase shifter are used. Multiple WDM channels with CO-OFDM modulation format are launched into the optical link. The optical link consists of multi-span SSMF fibers and Erbium doped fiber amplifiers (EDFA) to compensate the fiber transmission loss. In contrast to the conventional link design, the CO-OFDM system may not use any dispersion compensation fiber. The WDM channels are demultiplexed and detected using two optical coherent detectors which serve as an optical-to-electrical OFDM I/Q converter. In the OFDM receiver,

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the OFDM signal will be sampled using an ADC, and demodulated by performing FFT to recover the data.

3. Transmission performance

A Monte Carlo simulation is conducted to identify the transmission performance of a CO-OFDM system. The OFDM parameters are OFDM symbol period of 25.6 ns, 128 subcarriers, a guard interval equal to one quarter of the observation period, QPSK encoding for each subcarrier. We apply commonly used system parameters for our simulation: WDM channel spacing of 50 GHz, 80 km span distance, fiber chromatic dispersion of 16 ps/nm/km, 0.2 dB/km loss, and a nonlinear coefficient of 2.6×10^{-20} m^2/W. The fiber span loss is compensated by an EDFA with a gain of 16 dB and noise figure of 6 dB. The linewidth of the LD1 and LD2 are assumed to be 100 kHz, which is close to the value achieved with commercially available semiconductor lasers [6-7]. A commercial Intel laser with a similar linewidth has been recently used for coherent experiment [8]. In this simulation, we choose optical filters, both OBPF1 and OBPF2, as easily available second-order Gaussian filters with 40 GHz bandwidth. The simulation shows the result of transmission of 8 WDM channels with the middle (the 4th) channel detected. Simulation of larger WDM channel number (>8) gives almost the same result. Although the traditional DFB lasers have a linewidth of about 1 MHz and will not be fit for CO-OFDM transmission, we believe that this is not a major issue because the trend is that the tunable lasers with narrow linewidth will gradually replace the traditional single-wavelength DFB laser in the market, and massive production of tunable lasers such as Intel lasers has already driven the cost down to the level of telecomm usage. In the mean time, we are also working on the algorithms to further improve the linewidth tolerance for CO-OFDM, and will report the findings in further publication.

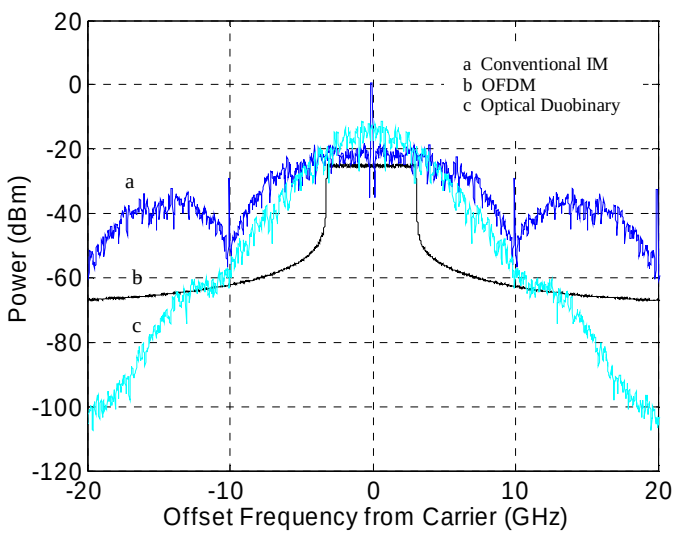

Fig. 2. Optical Spectra for 10 Gbit/s CO-OFDM, optical duobinary and conventional IM signal with the same average power

Figure 2 shows the optical spectrum of an OFDM signal. For reference, the spectra of conventional intensity modulation (IM) signal and the optical duobinary signal are shown with the same average power. The 20 dB bandwidth of OFDM signal is around 6.8 GHz in contrast with 18 GHz for conventional IM, and 12 GH for optical duobinary signal. This signifies that CO-OFDM has potential to achieve high spectral efficiency.

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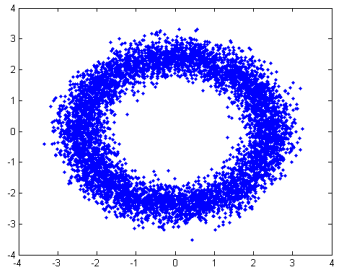

Fig. 3. Constellation of received data

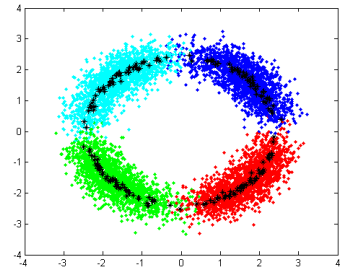

Fig. 4. Constellation of received data after removing chromatic dispersion. Stars show the average of each OFDM symbol

Figure 3 shows the received constellations of 51 OFDM symbols after transmitting 3200 km fiber. The constellation is rotated with respect to each other owing to a phase shift from fiber chromatic dispersion [2-3]. The phase shift due to chromatic dispersion is

$$\phi = \frac{1}{2}\beta_2 \omega^2 L \tag{6}$$

$$\beta_2 = -\frac{\lambda^2}{2\pi c} D \tag{7}$$

Where β_2 is group velocity dispersion parameter, D is fiber dispersion parameter, L is the fiber length, ω is the optical frequency at each subcarriers. The phase shift can be estimated by using training sequences and compensated. The constellations of 51 OFDM symbols after removing chromatic dispersion is shown in Fig. 4, where the stars show the average of each OFDM symbol. The constellation of received OFDM information symbol drifts between each OFDM symbol showing smearing of constellation, and this is due to the phase noise of the transmitter and receiver lasers.

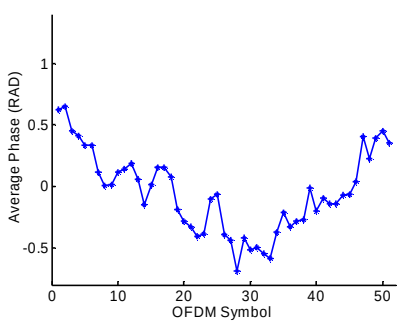

Fig. 5. OFDM symbol phase evolution

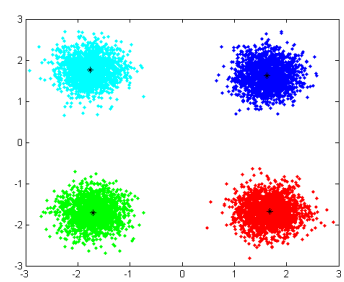

Fig. 6. Constellations of received data after removing chromatic dispersion and average phase noise of one OFDM symbol

Figure 5 shows the 51 OFDM symbol phase after transmitting 3200 km fiber. The OFDM symbol phase ϕ_i is estimated by averaging over the phases of 128 subcarriers given by

$$\phi_i = \langle 0.25 \mathrm{mod}(4 \arg(C'_{ik}), 2\pi) \rangle \tag{8}$$

where $arg(C'_{ik})$ is the phase of the received information symbol C'_{ik} at the *kth* subcarrier in the *ith* OFDM symbol [2]. The OFDM symbol phase ϕ_i mainly comes from the phase noise of lasers, and it is critical to have ϕ_i estimated and compensated. Fig. 6 shows the constellation

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of 51 OFDM symbols after the phase compensation, where the stars show the center of each OFDM symbol. A clear constellation is recovered with four distinct clusters of data points representing corresponding four QPSK information symbols. The residual noises spreading each OFDM constellation point now are mainly from nonlinearity of optical fibers, amplified-spontaneous-noise (ASE) in transmission system, and intra-carrier interference (ICI) due to the intra-symbol phase noise of lasers. Assuming the noises spreading each information symbol is Gaussian noise, the Q-factor is related to the system's BER through the complementary error function erfc( ) given by 0.5×erfc(q/$\sqrt{2}$), and Q(dB)=20log(q) [3], [9]. The q factor was calculated as the ratio between the amplitude of the received QPSK information symbol, divided by the standard deviation of each information symbol as:

$$q = \left(\frac{1}{NN_{SC}} \sqrt{\sum_{i=1}^{N} \sum_{k=1}^{N_{SC}} \frac{\left| C'_{ik} - C'_{i,AVG} \right|^2}{\left| C'_{i,AVG} \right|^2}} \right)^{-1} \tag{9}$$

$$C'_{i,AVG} = \left\langle C'_{ik} \right\rangle_k \qquad \backslash \tag{10}$$

where C'_{ik} is the received information symbol for the *kth* subcarrier in the *ith* OFDM symbol, $C'_{i,AVG}$ is average of received information symbol, N and N_{SC} are the number of OFDM symbols and subcarriers in each OFDM symbol respectively. The bit error rate of 0.5×erfc(q/$\sqrt{2}$) matches with our numerical simulation results. 510 OFDM symbols are simulated equivalent to 510×128 bits for each Q computation. We find that the simulated Q value is very stable for different pseudorandom data and different random phase noise of laser.

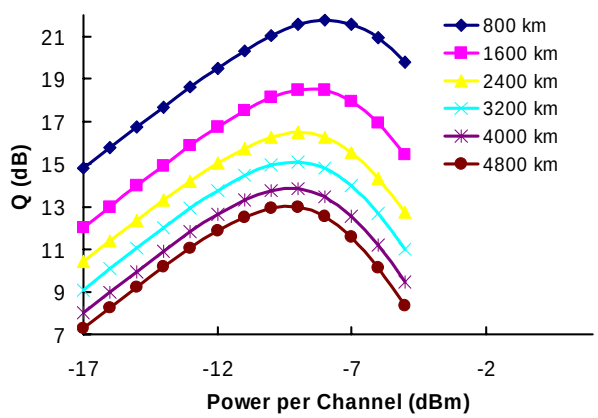

Fig. 7. System Q versus the optical power of each WDM channel

Figure 7 shows the system Q of the received data versus the optical launch power of each WDM for different fiber lengths. It can be seen from Fig. 7 that the optimal optical launch power of each WDM channel is from -10 dBm to – 8 dBm.

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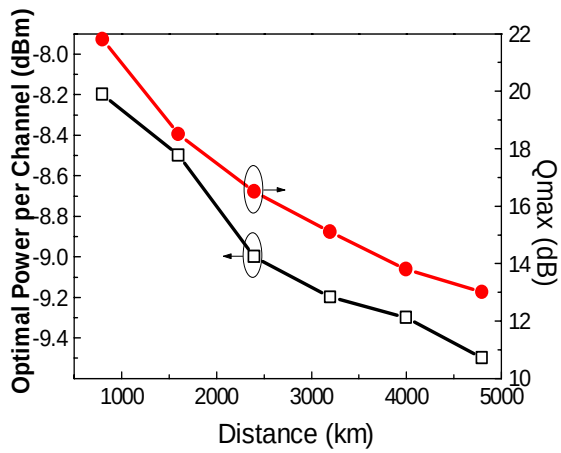

Fig. 8 Optimal optical power of each WDM channel and maximum system Q versus fiber transmission distance

Figure 8 shows the optimal optical launch power and the optimal Q value at different fiber transmission distances. As the transmission distance increases, the optimal optical launch power decreases due to the increase of fiber non-linearity. The optimal Q varies from 21.8 dB to 13.0 dB as the fiber link reach increases from 800 km to 4800 km. We stress that the CO-OFDM system is more power efficient than IO-OFDM counterpart because it does not need to transmit the main optical carrier, which usually consumes 50% of the optical power [3]. This eases the requirement of optical amplifiers for high pump power and also removes nonlinear degradation caused by transmission of optical carrier [3].

4. Partial carrier filling (PCF) for improvement of fiber nonlinearity performance

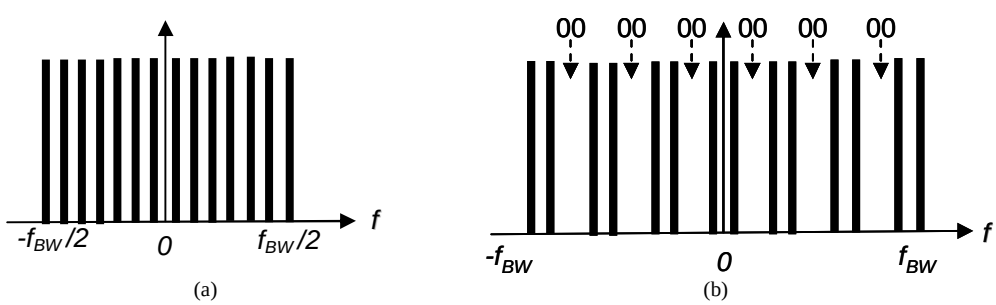

Fig. 9 (a) Original OFDM symbol. (b) OFDM symbol after filling zeros

The impact of system nonlinearity on the OFDM symbol could be moderated by partially filling the OFDM spectrum, or in practice, assigning redundant zero values to certain OFDM subcarrier as shown in Fig. 9. We define a filling factor (FF) as the number of effective subcarriers (with data) divided by the total number of the subcarriers in each OFDM symbol. Fig. 9 shows the case of a filling factor of ½. As shown in Fig. 9, there are zero subcarriers between every two data subcarriers. A large proportion of the spurious components generated by fiber nonlinearity – four wave mixing will be located in the unfilled (zero) subcarriers, which has no impact on the filled (data) subcarriers. Therefore inter-subcarrier and inter-channel cross talk due to fiber nonlinearity are reduced by partial carrier filling. This scheme takes advantage of the powerful signal processing capability of the OFDM and would be

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difficult to implement in single-carrier system, where a large number of very fine electrical filters have to be employed for the same purpose.

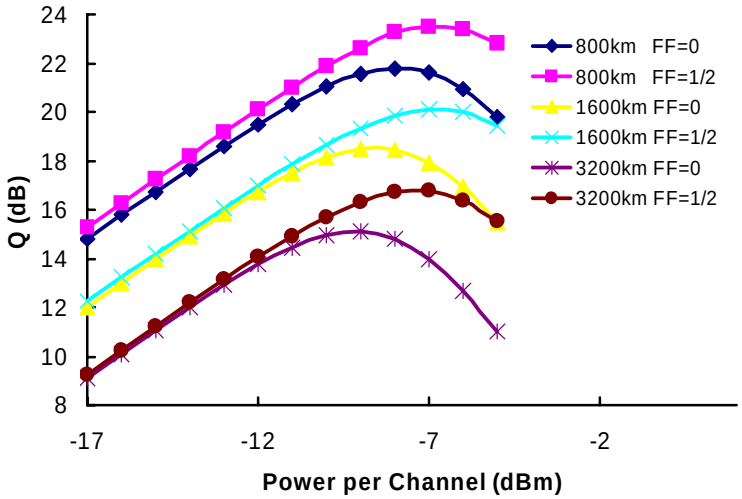

Fig. 10. System Q versus the optical power of each WDM channel with and without partial filling

Figure 10 shows the system Q of the received data versus the optical power of each WDM channel launched into the fiber link of 3200 km with a filling factor of 0 and filling 50 %. With the increase of optical launch power, the improvement of Q by PCF increases for all transmission distance from 800 km to 3200 km. The increase of maximum Q is over 1.5 dB with the partial filling. The optimal optical lunch power is also increased from -9 dBm to -7 dBm by filling zeros in the code.

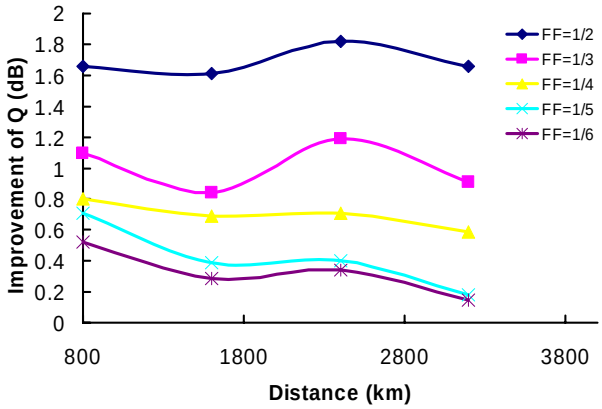

Fig. 11. Maximum system Q for different filling factors

Figure 11 shows the maximum system Q at different filling factors. As the filling factor increases, the maximum system Q increases. Increase of filling factor also leads the increase of electrical and optical bandwidth of transmitting data. Figure 12 shows the optical spectrum of an OFDM signal with a filling factor of ½. For reference, the spectra of an OFDM signal without filling, conventional intensity modulation (IM) signal and the optical duobinary signal are shown with the same average power. Although partial carrier filling broadens the bandwidth of an OFDM signal, due to its high spectral efficiency, the 20 dB bandwidth of

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OFDM signal with a filling factor of ½ is around 13 GHz, which is still comparable with conventional IM of 18 GHz, and optical duobinary signal of 12 GHz.

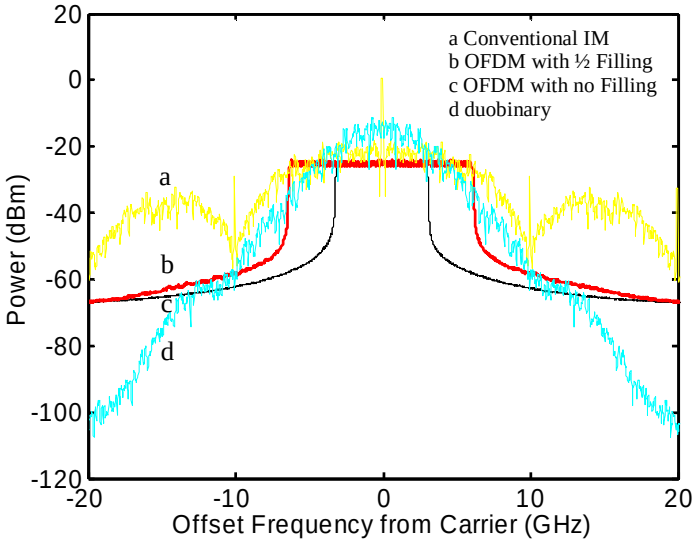

Fig. 12. Optical Spectra for 10 Gbit/s CO-OFDM of filling zero factor ½, CO-OFDM without filling zeros, optical duobinary and conventional IM signal with the same average power

5. Conclusions

Transmission performance for WDM systems with coherent optical OFDM (CO-OFDM) is simulated including the fiber non-linearity effect. The simulation shows that the system Q of the WDM channels at 10 Gb/s is over 13.0 dB for a transmission up to 4800 km of standard-single-mode-fiber (SSMF) without dispersion compensation. The CO-OFDM system may simplify the long-haul link design and maintenance without a need for chromatic dispersion compensation. The performance of CO-OFDM long haul transmission could be improved by partial carrier filling (PCF) in the OFDM symbol. The simulation shows the system Q increase from 15.1 dB to 16.8 dB for 3200 km transmission by filling ½ of zeros into data. OFDM signal has high frequency efficiency. Although filling zeros broaden the bandwidth of an OFDM signal, the bandwidth of OFDM signal with filling zero of ½ is still comparable with conventional IM and optical duobinary signal.

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