

Comparison Study of Long-haul 100-Gb/s DDO-OFDM and CO-OFDM WDM Systems

Ling Liu¹, Shilin Xiao^{1*}, Meihua Bi^{1,2}, and Lu Zhang¹

¹State Key Laboratory of Advanced Optical Communication System and Networks,
Shanghai Jiao Tong University, Shanghai 200240, China

²College of Communication Engineering, Hangzhou Dianzi University, Hangzhou 310018, China

(Received May 16, 2016 : revised August 30, 2016 : accepted September 28, 2016)

In this paper, for the first time, the transmission performances of long-haul 100-Gb/s direct detection optical OFDM (DDO-OFDM) and coherent optical OFDM (CO-OFDM) wavelength division multiplexing (WDM) systems are compared by simulation. It provides specific guides for system parameter selection to get a high-performance and cost-effective OFDM WDM system. Specifically, the comparison involves three aspects: launched power is investigated to achieve better system performance; laser linewidth is numerically investigated to choose cost-effective laser; system dispersion tolerances with different laser linewidths are analyzed to further reveal the advantages and disadvantages of these two detecting methods, direct detection and coherent detection, in long-haul OFDM WDM system.

Keywords : Direct detection optical orthogonal frequency division multiplexing (DDO-OFDM), Coherent optical OFDM (CO-OFDM), Wavelength division multiplexing (WDM) system

OCIS codes : (060.0060) Fiber optics and optical communications; (060.4510) Optical communications

I. INTRODUCTION

To satisfy the increasing bandwidth demand in high-speed fiber-optic communication networks, optical orthogonal frequency division multiplexing (O-OFDM) has been widely considered as a promising technology for long-haul high-speed optical transmission systems [1, 2], due to its properties of high spectral efficiency, robustness to chromatic dispersion and flexibility on dynamic bandwidth allocation [3]. There are two forms of detecting methods for long-haul optical OFDM systems: direct detection optical OFDM (DDO-OFDM) and coherent optical OFDM (CO-OFDM) [4, 5]. However, OFDM is quite susceptible to phase noise, which will cause severe inter-carrier interference (ICI) [6]. Since laser phase noise induced by laser linewidth [7, 8] will be converted to intensity noise along a dispersive fiber [9], there is a trade-off between laser linewidth and fiber transmission distance, especially for the CO-OFDM system where the transmission signal and the local oscillator (LO) signal must track the phase and frequency of each other. Therefore, it is crucial to investigate the impact of laser linewidth on an OFDM system to find

a cost-effective laser with appropriate linewidth. Moreover, fiber nonlinearity can enhance the conversion of phase noise to intensity noise by fiber transmission [10], which is more significant in long-haul optical transmission systems. Thus the study of fiber launched power, which can not only improve the system optical signal to noise ratio (OSNR) but also induce the fiber nonlinearity, is essential as well. Also, the fiber chromatic dispersion accumulated over long-haul transmission, together with the linewidth-induced noise will worsen the system performance, so the system dispersion tolerance is measured.

In our previous work [11, 12], a low-cost, symmetric 40-Gb/s stacked WDM- OFDM-PON system was demonstrated experimentally. To further study the OFDM technology in long-haul 100-Gb/s fiber-optic transmission, in this paper, transmission performances of 100-Gb/s long-haul DDO-OFDM and CO-OFDM WDM systems have been compared through simulation. Since the impacts of fiber launched power, laser linewidth and chromatic dispersion on long-haul OFDM system exist, relevant simulations have been carried out to achieve a high-performance and cost-effective system. Results show

*Corresponding author: slxiao@sjtu.edu.cn

Color versions of one or more of the figures in this paper are available online.



This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/3.0/>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

that the system performance of CO-OFDM is better than DDO-OFDM, while its laser linewidth requirement is far more stringent. Thus, for applications such as backbone network which needs performance improvement, CO-OFDM can be used, for passive optical network and datacenter optical interconnect which are cost-sensitive, DDO-OFDM can be used. This paper provides specific guides of system parameter selection for different applications over various transmission distances.

II. SYSTEM ARCHITECTURE

Following the system configuration of Fig. 1, the simulation was established on the commercial simulation software OptiSystem 7.0 combined with the MATLAB program. In the DDO-OFDM architecture showed by Fig. 1(a), for one channel, single Mach-Zehnder modulator (MZM) biased at quadrature point is driven by the baseband electrical OFDM signal generated offline by MATLAB to generate O-OFDM signal for direct detection. After transmission, the O-OFDM signal is detected by a photo diode (PD) and offline processed in MATLAB. In the direct up/down conversion CO-OFDM architecture illustrated by Fig. 1(b), for one channel, I/Q modulator biased at null point is driven by the in-phase (I) and quadrature (Q) components of OFDM signal [13]. The coherent receiver consists of a LO laser, a 2×4 90° optical hybrid and a pair of balanced photo diodes (BPDs). Then I and Q components of the electrical signal are offline processed in MATLAB. The procedures of OFDM signal generated and processed are described in the inset (i) and inset (ii) of Fig. 1 respectively, using the synchronization

TABLE 1. Parameter setting of the OFDM signals in MATLAB

Sample rate	10-GS/Sample
IFFT size	128
CP length	16
Modulation format	square-16QAM
Data subcarriers	40
Number of symbols	2000
Pilot symbols	Periodically inserted, 1 out of 100 symbols
Sequence length	131072

and channel estimation algorithm we proposed in [14, 15].

The bitrate of the OFDM signal in each WDM channel is 12.5 Gb/s, then the bitrate of this WDM system is 100 Gb/s (8×12.5 Gb/s). Details of OFDM parameters are showed in Table 1.

Eight 100 GHz-spaced laser diodes (LDs) working between 193.1 THz and 192.4 THz are used as downstream optical sources. The transmission link comprises loops of 80-km standard single mode fiber (SMF) and an erbium doped fiber amplifier (EDFA) with 16 dB-gain and 6 dB-noise figure. Note that, all the optical device noises and system noises are taken into consideration in this work.

III. SIMULATION AND ANALYSIS

3.1. System Performances with Different Fiber Launched Powers

To improve system budget and minimize the impact of

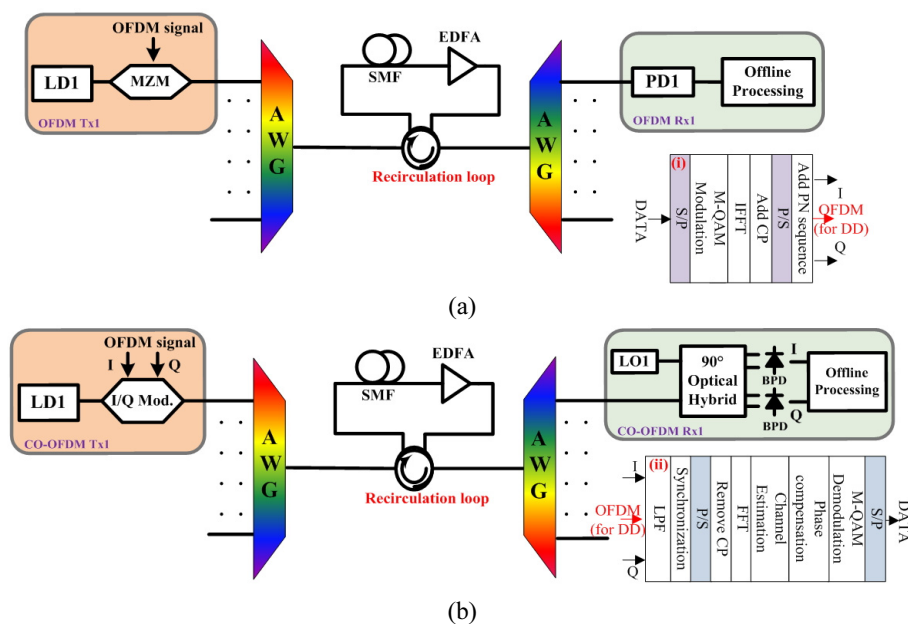


FIG. 1. Architecture of the (a) DDO-OFDM and (b) CO-OFDM WDM systems. Inset (i) and (ii) are OFDM signal generation and process procedures in MATLAB program.

fiber nonlinearity, in this section, from the aspect of fiber launched power, the transmission performances of 100-Gb/s long-haul DDO-OFDM and CO-OFDM systems are compared and analyzed. To make a fair comparison, we set the laser linewidth to 0.01 MHz and the power of LO laser to 10 dBm. System transmission distances from 1-loop (80-km) to 6-loop (480-km) are simulated respectively. To determine the optimum fiber launched power, we vary the fiber launched power from -7 dBm to +13 dBm. It is noted that, we only select the worst channel among the eight WDM channels to analyze.

Taking 100-Gb/s 480-km CO-OFDM system for an example, the system bit error rate (BER) performance with the fiber launched power as parameter is presented in Fig. 2(a). It can be seen that, for a fixed transmission distance, with the increase of fiber launched power, BER performance becomes better at first, and then gets worse as high error floor occurs. These results can be explained in that higher fiber launched power can provide higher OSNR, but when it is too high, non-linear impairments in the fiber, such as cross-phase modulation and four-wave mixing [16], will be large enough to degrade the system performance. Similar results are obtained in DDO-OFDM system.

It is noted that, since the BER error floor is as high as 3.15×10^{-2} when transmission distance is larger than 3 loops (240 km) in DDO-OFDM system, we only present simulation results of 1-loop (80-km) and 2-loop (160-km) transmission

of DDO-OFDM system in this paper. Fig. 2(b) and (c) demonstrate the optimal system performances of WDM-OFDM system over different fiber length transmission, namely, the situation when their optimum fiber launched powers are applied respectively. The receiver sensitivity of 80-km CO-OFDM system is improved by ~ 9.3 dB at forward error correction (FEC) threshold [17] of $\text{BER} @ 3.8 \times 10^{-3}$ in comparison with 80-km DDO-OFDM system. The receiver sensitivity of 160-km CO-OFDM system is improved by ~ 10.9 dB compared with 160-km DDO-OFDM system. Seen from Fig. 2(b) and (c), there is no doubt that the advantage of CO-OFDM is notable in the long-haul high-speed WDM system.

To present more visibly, simulation results are summarized in Table 2. Firstly, it is obvious that for both DDO-OFDM and CO-OFDM systems, the optimum fiber launched power and receiver sensitivity decrease with the increasing fiber length. This can be attributed to longer distance, which may induce larger system noise and remarkable fiber nonlinearity. Secondly, for the same fiber length, the optimum launched power in CO-OFDM system is lower while the optimum receiver sensitivity at BER of 3.8×10^{-3} is higher than that in DDO-OFDM case, that is, lower optical signal power can provide better performance in the CO-OFDM system than in the DDO-OFDM case. The reason is that, CO-OFDM is highly susceptible to fiber nonlinearity. It also reveals the better interference rejection capacity of the CO-OFDM system.

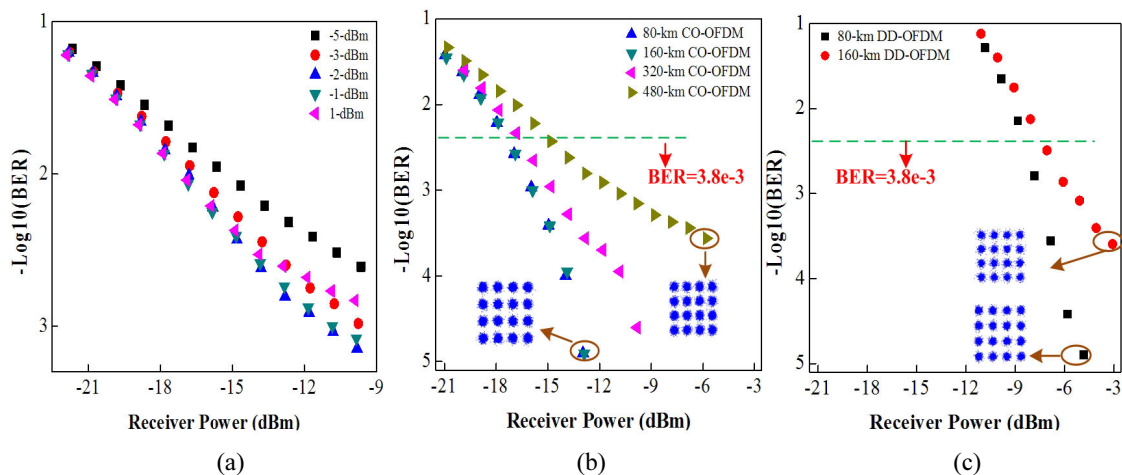


FIG. 2. (a) BER performances with different fiber launched powers applied in 100-Gb/s CO-OFDM system over 480-km SMF. BER curves with optimum fiber launched powers applied for different fiber lengths transmission in 100-Gb/s (b) CO-OFDM and (c) DDO-OFDM systems.

TABLE 2. Optimum fiber launched power, optimum receiver sensitivity @ $\text{BER} = 3.8 \times 10^{-3}$ and power-offset tolerance for a power penalty of 1dB @ $\text{BER} = 3.8 \times 10^{-3}$ in 100-Gb/s WDM-OFDM system

	DDO-OFDM		CO-OFDM			
	80 km	160 km	80 km	160 km	320 km	480 km
Optimum launched power (dBm)	9	5	3	1	-1	-2
Optimum receiver sensitivity (dBm)	-8.6	-6.9	-18	-17.8	-16.8	-14.3
Power-offset tolerance (dB)	>14	10.5	>14	10.3	6	3

Furthermore, the tolerance of optimum launched power shift is also evaluated. Figure 3 demonstrates the power penalty versus power offset with the transmission distance as parameter. The reference of fiber launched power offset is the optimum fiber launched power for each transmission system respectively, using the results from Table 2. The power penalty is defined as the decrease in receiver sensitivity at BER of 3.8×10^{-3} when compared to the situation that its optimum fiber launched power is applied. For a fixed power penalty of 1dB, the power-offset tolerances are listed in Table 2. For both DDO-OFDM and CO-OFDM systems, it can be seen that the increase in transmission distance will decrease the tolerance of fiber launched power shift for the

same power penalty. The reason is that, owing to the increased fiber nonlinearity in longer-distance transmission, the susceptibility of the system performance to variation in power increases.

3.2. System Performances with Different Laser Linewidths

To get a cost-effective system, from the aspect of laser linewidth, the transmission performances of long-haul DDO-OFDM and CO-OFDM systems are compared and analyzed in this section. The relationship between laser phase error variance and 3-dB laser linewidth is given as follows [7, 8],

$$\sigma_{\phi}^2(T) = \{\phi(t) - \phi(t-T)\}^2 = 2\pi f_{3dB}T \tag{1}$$

where f_{3dB} is 3-dB laser linewidth, $\phi(t)$ is the laser phase noise, T is the relative delay. Namely, laser phase noise depends on linewidth. Since OFDM is sensitive to phase noise, undoubtedly, narrower linewidth will provide better performance in OFDM system, especially in CO-OFDM system. However, narrower linewidth means a more expensive laser. The aim of this subsection is to provide guides for engineering trade-offs, choosing cost-effective laser with appropriate linewidth by investigating the impact of linewidth on OFDM system.

In this section, power of LO laser is set to 10 dBm. Optimum fiber launched powers are applied in each system respectively. Laser linewidths from 0-MHz to 5-MHz are applied respectively (linewidths of the signal laser and the LO laser in CO-OFDM system are the same). Taking 100-Gb/s 480-km CO-OFDM system for an example, the BER performances with the laser linewidth as parameter are presented in Fig. 4(a). To be specific, system error floors with 5-MHz laser linewidth are listed in Table 3. It is obvious that, for the same transmission distance, the wider the linewidth is, the worse the BER performance becomes and the higher the error floor is. It is attributed to the fact that, the dominant

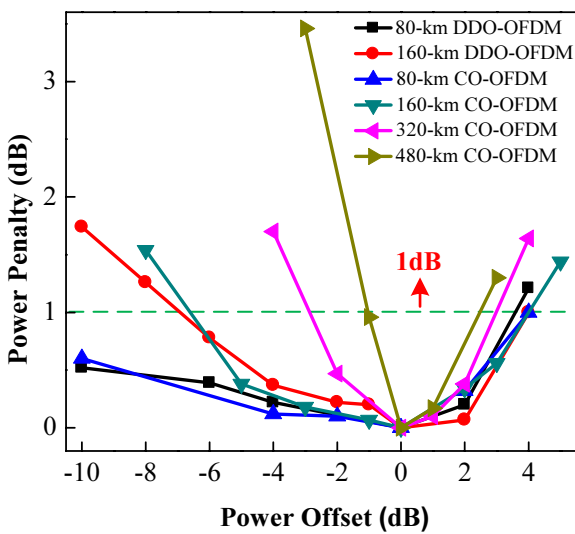


FIG. 3. Power penalty of BER@ 3.8×10^{-3} versus optimum power offset for different transmission distances in 100-Gb/s DDO-OFDM and CO-OFDM systems.

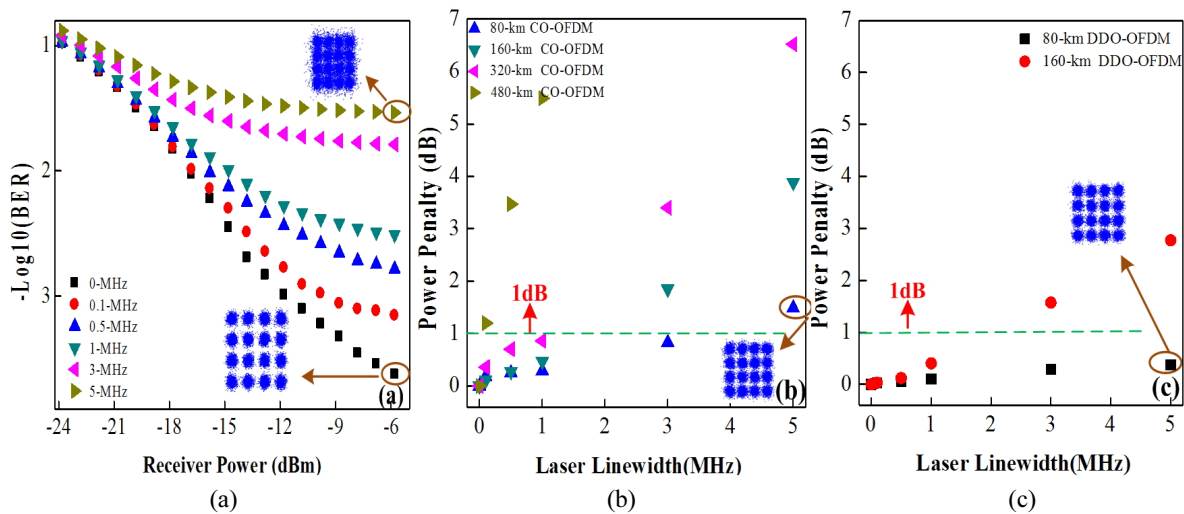


FIG. 4. (a) BER performances with different laser linewidths applied in 100-Gb/s 480-km CO-OFDM system. Receiver power penalty of BER@ 3.8×10^{-3} versus laser linewidth for different transmission distances in 100-Gb/s (b) CO-OFDM and (c) DDO-OFDM systems.

TABLE 3. Linewidth requirement for a power penalty of 1dB at BER= 3.8×10^{-3} and system error floor with 5-MHz laser linewidth

	DDO-OFDM		CO-OFDM			
	80 km	160 km	80 km	160 km	320 km	480 km
Linewidth requirement (MHz)	>5	2	3.5	1.7	1.1	0.1
Error floor with 5-MHz laser linewidth	1×10^{-5}	3×10^{-4}	5×10^{-5}	5×10^{-4}	2.5×10^{-3}	2.5×10^{-2}

TABLE 4. Dispersion tolerance in 100-Gb/s DDO-OFDM and CO-OFDM systems for a power penalty of 2dB at BER= 3.8×10^{-3}

	DDO-OFDM	CO-OFDM
Dispersion tolerance with 0.01-MHz laser linewidth (ps/nm)	-2400~2400	-13500~11500
Dispersion tolerance with 1-MHz laser linewidth (ps/nm)	-2400~2400	-4400~3600

noise term for coherent detection is the LO-spontaneous beat noise which is dependent on laser linewidth, larger phase noise induced by wider linewidth will worsen the system performance, interacted with fiber dispersion.

Figure 4(b) and (c) show the receiver power penalty versus laser linewidth with transmission distance as parameter. The power penalty is defined as the decrease in receiver sensitivity at BER of 3.8×10^{-3} for each case as compared to the situation when ideal laser, i.e., 0-MHz linewidth laser, is used. The requirements of laser linewidths can be obtained. For a fixed power penalty of 1dB @BER= 3.8×10^{-3} , the linewidth requirement is showed in Table 3.

Firstly, it can be seen that linewidth requirement of DDO-OFDM system is relaxed in comparison with CO-OFDM system for the same transmission distance. Especially for 80-km 100-Gb/s transmission, there is barely any power penalty for DDO-OFDM systems with different laser linewidths. The reason can be explained as follows. After fiber transmission, for direct detection which is based on the square law detection of the received signal, optical carrier and the subcarriers both experience the same dispersion effect; for coherent detection, the spectrum of received signal broadens owing to the combined effect of dispersion and phase noise, that is, spectral widths of received signal and LO signal are not the same, so the beat of received signal and the LO signal will bring larger phase noise. Furthermore, combined with the inter-channel interference in WDM system, the performance deteriorates further.

Secondly, it can be seen from Fig. 4(b) and (c) that, the tolerance of linewidth decreases with the increasing transmission distance. The reason is that the effect of phase noise is more remarkable after longer-fiber length transmission. When the transmission distance is relatively shorter, the performance deterioration mainly arises from inter-channel interference; when the transmission distance is relatively longer, fiber dispersion combined with the laser phase noise is the dominant factor.

3.3. System Dispersion Tolerance

To compare the 100-Gb/s long-haul optical transmission in DDO-OFDM and CO-OFDM WDM system comprehensively,

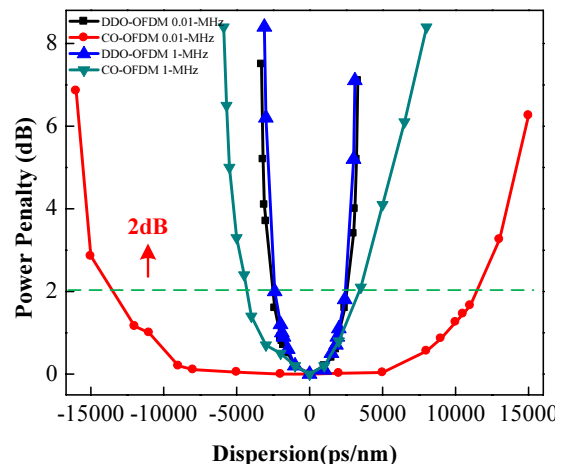


FIG. 5. Receiver power penalty of BER@ 3.8×10^{-3} versus dispersion for different laser linewidths in 100-Gb/s DDO-OFDM and CO-OFDM systems.

in this section, system chromatic dispersion tolerance is analyzed since accumulated chromatic dispersion after long-haul SMF transmission will worsen the system performance severely. To make a fair comparison, fiber launched power and the fiber dispersion slope stay the same in DDO-OFDM and CO-OFDM WDM systems.

To calculate the dispersion tolerance, the OFDM signal is detected after a variable amount of accumulated dispersion. Figure 5 depicts the receiver power penalty versus dispersion for different laser linewidths in 100-Gb/s DDO-OFDM and CO-OFDM systems. The power penalty is defined as the decrease in receiver sensitivity at BER of 3.8×10^{-3} for each case as compared to the situation when ideal SMF, i.e., zero-dispersion fiber, is used. The chromatic dispersion tolerance range for a power penalty of 2dB @BER= 3.8×10^{-3} is listed in Table 4.

It can be seen that the chromatic dispersion tolerance range of CO-OFDM system is larger than DDO-OFDM system. Moreover, the dispersion tolerance of CO-OFDM system varies with the laser linewidth while dispersion tolerance of DDO-OFDM system almost stays the same. These results

further reveal that the CO-OFDM system is more suitable for long-haul transmission while susceptible to laser linewidth.

IV. CONCLUSIONS

Transmission performances of long-haul 100-Gb/s DDO-OFDM and CO-OFDM WDM systems are compared for the first time. The comparison is based on system parameters: fiber launched power, laser linewidth and fiber dispersion. Simulation results show that, the CO-OFDM has better performance and larger chromatic dispersion tolerance range than DDO-OFDM while it has a stricter laser linewidth requirement and its dispersion tolerance is more susceptible to laser linewidth. To achieve a high-performance and cost-effective long-haul 100-Gb/s OFDM WDM system, this paper provides specific guides for engineering trade-offs by choosing appropriate detecting methods, fiber launched power and a cost-effective laser with appropriate linewidth for different applications over various transmission distances.

ACKNOWLEDGMENT

This work was jointly supported by the National Nature Science Fund of China (No.61271216, No. 61221001, No.61501157 and No.61090393), China Postdoctoral Science Foundation (No.2013M540361) and the National "863" Hi-tech Project of China (No.2013AA013602 and No.2012AA011301).

REFERENCES

1. S. Azou, Ş. Bejan, and P. Morel, "Performance improvement of a SOA-based coherent optical-OFDM transmission system via nonlinear companding transforms," *Opt. Commun.* **336**, 177-183 (2015).
2. H. Bao and W. Shieh, "Transmission simulation of coherent optical OFDM signals in WDM systems," *Opt. Express.* **15**(8), 4410-4418 (2007).
3. N. Cvijetic, "OFDM for next-generation optical access networks," *J. Lightwave Technol.* **30**(4), 384-398 (2012).
4. Yi X, W. Shieh, and Ma Y, "Phase noise effects on high spectral efficiency coherent optical OFDM transmission," *J. Lightwave Technol.* **26**(10), 1309-1316 (2008).
5. L. Nadal, M. S. Moreolo, and J. M. Fàbrega, "Low complexity PAPR reduction techniques for clipping and quantization noise mitigation in direct-detection O-OFDM systems," *Opt. Fiber Technol.* **20**(3), 208-216 (2014).
6. Y. Ha and W. Chung, "A Feedforward Partial Phase Noise Mitigation in the Time-Domain using Cyclic Prefix for CO-OFDM Systems," *J. Opt. Soc. Korea* **17**(6), 467-470 (2013).
7. K. Kikuchi, "Effect of $1/f$ -type FM noise on semiconductor-laser linewidth residual in high-power limit," *IEEE J. Quantum Electron.* **25**(4), 684-688 (1989).
8. K.-P. Ho, *Phase-Modulated Optical Communication Systems* (Springer Science & Business Media, New York, 2005).
9. Z. Zan, M. Premaratne, and A. J. Lowery, "Laser RIN and linewidth requirements for direct detection optical OFDM," in *Proc. Conf. on Lasers and Electro-Optics and Quantum Electronics and Laser Science Conf. (CLEO/QELS) 2008* (San Jose, California, United States, May 2008), paper CWN2.
10. A. Cartaxo, B. Wedding, and W. Idler, "Influence of fiber nonlinearity on the phase noise to intensity noise conversion in fiber transmission: theoretical and experimental analysis," *J. Lightwave Technol.* **16**(7), 1187 (1998).
11. M. Bi, H. He, S. Xiao, J. Li, and W. Hu, "Bidirectional stacked 40-Gb/s WDM-OFDM-PON system using the electronic controlled liquid crystal tunable filter," in *Proc. 2013 18th Opto Electronics and Communications Conf. (OECC)/2013 International Conf. on Photonics in Switching (PS)* (Kyoto International Conference Center, Kyoto, Japan, Jul. 2013), Paper MP 1-5.
12. M. Bi, S. Xiao, H. He, J. Li, L. Liu, and W. Hu, "Power Budget Improved Symmetric 40-Gb/s Long Reach Stacked WDM-OFDM-PON System Based on Single Tunable Optical Filter," *IEEE Photonics J.* **6**(4), 7900708-7900717 (2014).
13. W. Shieh, H. Bao, and Y. Tang, "Coherent optical OFDM: theory and design," *Opt. Express* **16**(2), 841-859 (2008).
14. Y. Tian, M. Bi, H. He, J. Li, and W. Hu, "Power Budget Improvements using Grouped Pilot Channel Estimation for OFDM-PON," in *Proc. Asia Communications and Photonics Conf. 2013* (Beijing Conference Center, Beijing, China, Nov. 2013), Paper AF1G. 5.
15. M. Bi, S. Xiao, H. He, J. Li, and Z. Zhao, "A new symbol timing synchronization scheme for direct modulation optical OFDM PON," in *Proc. Asia Communications and Photonics Conf. 2011* (Shanghai International Convention Center, Shanghai, China, Nov. 2011), pp. 830926-830926.
16. T. Tokle, C. Peucheret, and P. Jeppesen, "Advanced modulation formats in 40 Gbit/s optical communication systems with 80 km fibre spans," *Opt. Commun.* **225**(1), 79-87(2003).
17. ITU -T Recommendation G.975.1, Appendix I.9 (2004).