

# PERFORMANCE IMPROVEMENT OF NONLINEARITY COMPENSATION USING OPTICAL PHASE CONJUGATION FOR METRO DWDM SYSTEMS WITH OPTICAL ADD DROP MULTIPLEXERS

*Nguyen Duc Binh<sup>1</sup>, Nguyen Van Dien<sup>2</sup>, Nguyen Tan Hung<sup>2</sup>,  
Nguyen The Quang<sup>1</sup>, Nguyen Hong Kiem<sup>1</sup>, Vuong Quang Phuoc<sup>3</sup>*

## Abstract

Wavelength Division Multiplexing (WDM) has been widely applied in optical add-drop multiplexing (OADM) fiber metro systems with an increasing number of wavelength channels and sufficiently narrow channel spacing. The problem that appears here is the signal distortion produced by dispersion and nonlinearity effects. To cope with these effects, many compensation solutions have been introduced, such as digital compensation (DC) solutions on technology of digital signal processing (DSP) or optical phase conjugation (OPC) on all-optical domain. In fact, research on using OPC to compensate for dispersion and nonlinearity in metro transmission systems are incomplete, especially with large number multiplexing systems. In this paper, we propose to use OPC for dispersion and nonlinear compensation in DWDM metro systems. Specifically, we focus on two common types of modulation signals: QPSK and 16-QAM; operations in 16- and 32-channel dense WDM system. The simulation results show that the system quality increases significantly when using OPC to compensate for dispersion and nonlinearity, e.g. when transmitting 16-QAM signals in a 32-channel system passing through 20 add/drop nodes, the gain of Q factor is greater than 2 dB.

## Index terms

Optical Add-Drop Multiplexing, metro system, Optical phase conjugation, Nonlinear compensation, Wavelength Division Multiplexing.

## 1. Introduction

**T**HE emergence of many applications, which require large bandwidth, e.g. cloud computing, video on demand, IoT, 5G, and big data, increases exponentially the global data traffic recently [1, 2]. These put tremendous pressure on the information network, which widely used the fiber optic transmission backbone network. Moreover, as the increasing demand of high-speed services, the capacity of the metro optical

---

<sup>1</sup>Le Quy Don Technical University, Ha Noi, Vietnam, <sup>2</sup>The University of Danang – University of Science and Technology, Danang, Vietnam, <sup>3</sup>Hue University of Sciences, Thua Thien-Hue, Vietnam

transmission network need to significantly improve. In response to these requirements, the optical metro network has changed rapidly over time. Starting with purposefully built systems to expand the capacity/reach of time-division multiplexing (TDM), data and storage services, they are evolving to utilize Modular optical transport platform with integrated optical and electronic switching capabilities [3]. Optical transport networks are hierarchically structured and comprise several network tiers. Typically, there is a meshed core/backbone network which connects to multiple metro network domains. Commonly used network architectures is meshed, ring, and point-to-point [3-6]. In some specific cases a linear topology can be used (e.g. considering each specific wavelength channel, or considering the protective linkage direction). A metro network is a broadband data network designed for geographic areas, cities, or towns. The distance is usually less than 100 kilometers up to several hundred kilometers. Along with that, the application of R-OADM (Reconfigurable – Optical Add/Drop Multiplexer) node structures has made optical channel add/drop and wavelength switching more flexible [3-6]. For metro systems, to increase the capacity of the system, several techniques have been applied, such as dense wavelength division multiplexing (DWDM) technology with a large number of channels (16, 32, ...) [3-6] or higher modulation format order techniques (quadrature phase shift keying - QPSK, M-quadrature amplitude modulation - M-QAM ...) [7, 8].

When transmitting light signals in optical fibers, system performance is affected by three phenomena: attenuation, dispersion and Kerr nonlinearity effect [9, 10]. For systems with low transmission rates, the dispersion effects are quite small and Kerr effects can be ignored. However, with high-speed transmission systems, these phenomena greatly affect the system performance, especially with multichannel systems. To deal with these effects, many dispersion compensation solutions are proposed, such as electrical dispersion compensation (EDC or DC), digital back propagation (DBP), and phase conjugated twin wave (PCTW) [11-14]. However, these solutions cannot perfectly apply for DWDM systems with large number of channels, narrow channel spacing, and high transmission speed [14]. In addition, for an ordinary metro system, as the transmission distance of each route is quite short with several tens of kilometers, the number of optical add-drop multiplexing (OADM) nodes is quite small, e.g. 5, or 6 nodes, the EDC technology is suitable for dispersion compensation. If the number of OADM nodes increases (e.g. 10-20 nodes), and the transmission speed of each wavelength also increases (e.g. 50 GBaud), then the negative effects of nonlinearities and optical filters in OADM on the received signal will accumulate larger and degrade the performance of the system.

Another solution is to use optical phase conjugation (OPC) set placed on the transmission line. It will compensate for dispersion and nonlinearity for DWDM backbone systems [15-21]. However, to the best of our knowledge, there is no research for the application of OPC to metro DWDM systems. In [22], we had some preliminary assessments of the efficiency of using OPC for a metro WDM system, but that only applied for a simple metro system.

In this paper, we investigate the system performance of WDM metro networks when using OPC for high-speed optical signals and high modulation levels. We conducted a quality investigation of 16-channel, and 32-channel OADM metro WDM systems using QPSK and 16-QAM optical signal with Baudrate of 50 GBaud. The simulation results show that when using OPC, the system performance is considerably improved. In particular, with the 32-channel system, the gain of Q factor is more than 2 dB, when the 16-QAM signal is transmitted through 20 add/drop nodes.

## 2. Principle of dispersion and nonlinearity compensation using OPC

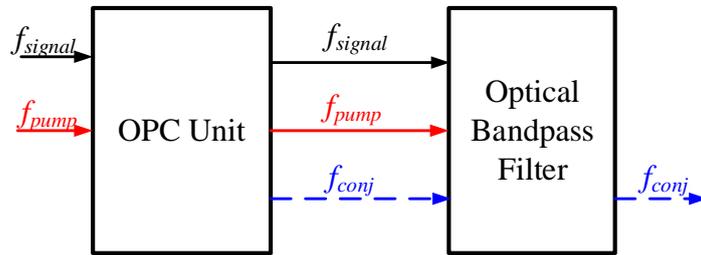


Figure 1. Diagram of the OPC operation.

Fig. 1 shows the operation of an OPC. Input signal and pump signal with frequency of  $f_{signal}$  and  $f_{pump}$  are combined in an OPC unit. At the OPC unit output, the conjugated signal, which combined two these input signals, has a frequency of  $f_{conj}$ . After passing through optical bandpass filter, the desired conjugated signal with frequency  $f_{conj}$  is calculated as follows Eq. 1 [5].

$$f_{conj} = 2 * f_{pump} - f_{signal} \quad (1)$$

Fig. 2 shows an optical transmission system that uses OPC to compensate the non-linearity phenomena. OPC is used to perform signal conjugation at the midpoint of the optical link for reversing and compensating signal distortion, as impairments occur in the first half of the link through the transmission of the second half of the link.

To present the signal transmitted along the fiber, we use the nonlinear Schrödinger equation (NLSE), which is written as Eq. 2 [5]:

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A - \frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{1}{6}\beta_3 \frac{\partial^3 A}{\partial t^3} + i\gamma|A|^2A \quad (2)$$

where  $A$  is the complex envelope of the optical field;  $z$  is the transmission distance;  $\alpha$  is the attenuation coefficient;  $\gamma$  is the nonlinear coefficient, and is calculated as [3]:

$$\gamma = \frac{n_2\omega_0}{cA_{eff}} \quad (3)$$

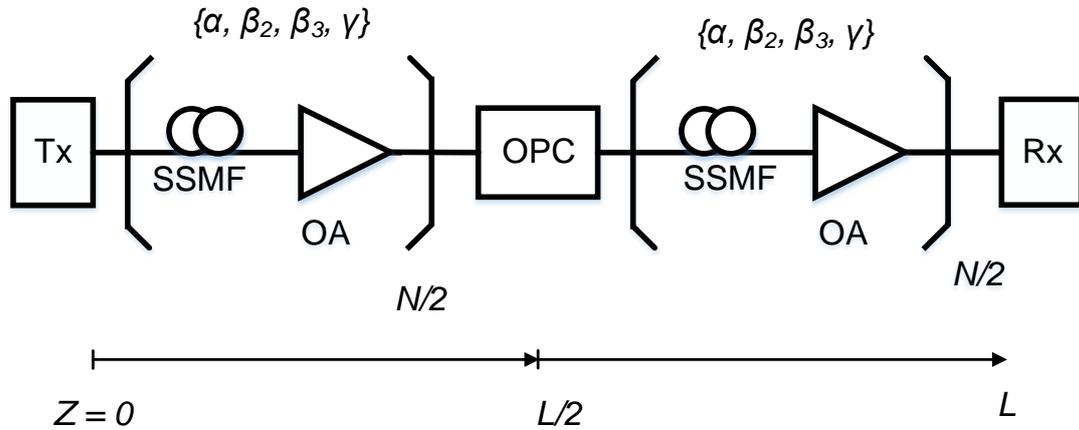


Figure 2. Diagram of OPC-based transmission.

where  $A_{eff}$  is the effective area of the fiber core, there are different values depending on fiber type, e.g.  $80\mu m^2$  for SSMF.

When the OPC is located at position  $z_0$  on the transmission line, the phase conjugation is described as [5]:

$$A(z_0 + \sigma) = A^*(z_0 - \sigma) \quad (4)$$

where  $\sigma$  is the minimum transmission distance in OPC.

After the OPC, the conjugated signal are propagated for another half of single mode fiber length and can be described as Eq. 5 [5, 23, 24]:

$$\frac{\partial A^*}{\partial z} = -\frac{\alpha}{2}A^* + \frac{i}{2}\beta_2\frac{\partial^2 A^*}{\partial t^2} + \frac{1}{6}\beta_3\frac{\partial^3 A^*}{\partial t^3} - i\gamma|A^*|^2A^* \quad (5)$$

Ability for dispersion and nonlinear compensation of OPC technique are expressed by two NLSE equations (2), (5), that are applied before and after OPC respectively [5].

Note that the sign of attenuation in two cases is unchanged, so the OPC does not compensate for the attenuation loss. In contrast, the signs of GVD and Kerr effect are inverted by OPC, the influences of these two effects are compensated for when the signal passes through the transmission path after the OPC. Therefore, we have a comparison in Table 1.

Table 1. The influences of different effects on the optical signal

Effect	Before OPC	After OPC
Attenuation	$-\frac{\alpha}{2}A$	$-\frac{\alpha}{2}A^*$
GVD	$-\frac{i}{2}\beta_2\frac{\partial^2 A}{\partial t^2}$	$\frac{i}{2}\beta_2\frac{\partial^2 A^*}{\partial t^2}$
S	$\frac{1}{6}\beta_3\frac{\partial^3 A}{\partial t^3}$	$\frac{1}{6}\beta_3\frac{\partial^3 A^*}{\partial t^3}$
Kerr-effect	$i\gamma A ^2A$	$-i\gamma A^* ^2A^*$

### 3. System configuration

Fig. 3 shows two system configurations of the metro system with DBP and OPC. Fig. 3a is the simulation system using dispersion and nonlinearity compensation by DC. In simulation, we use QPSK and 16-QAM optical signal with symbol rate of 50 GBaud. In particular, transmitted speed is from 100 to 200 Gbps, which is modulated into QPSK and 16-QAM optical signal 50 GBaud at the multiplexer input (MUX), using 100 GHz grid of wavelength. Detailed diagram of the M-QAM transmitter is shown in Fig. 4a. On the transmitter side, M modulated signals of QPSK or 16-QAM are first put into the MUX, then transmitted to the optical transmission line using Standard Single Mode Fiber (SSMF). For metro system, we set the distance of each transmission line from 10 to 50 km. An optical channel add/drop block and an amplifier is put at the end of each section. A highlight characteristic feature of the metro system is the emergence of multiple add/drop nodes with optical filters. At this time, their effects will be accumulated when the signal is transmitted over many optical transmission lines. This makes the signal separation on the receiver side and the ideal condition of the OPC affected. In this paper, we set the bandwidth value for the optical filter as 75 GHz.

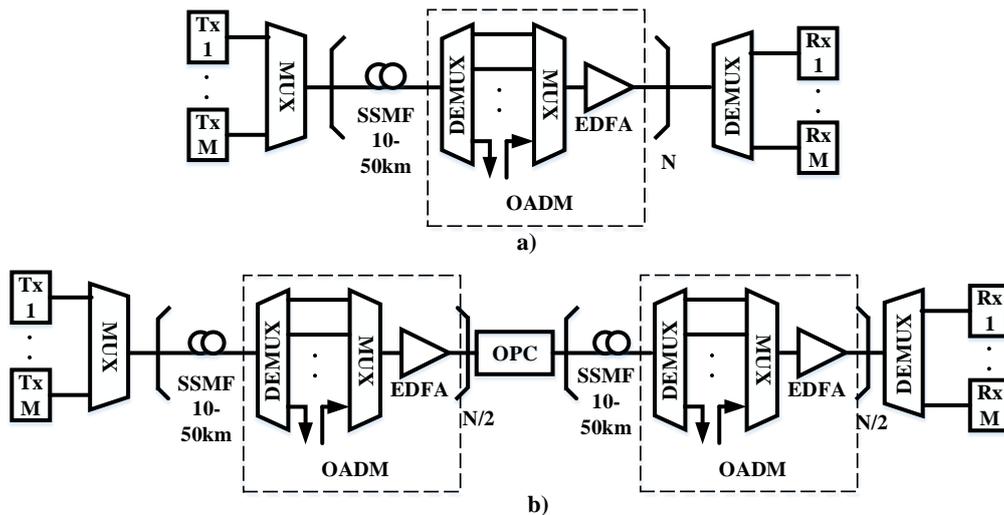


Figure 3. Configuration of the OADM metro system when dispersion compensation using OPC: a, without OPC; b, using OPC.

Fig. 3b is the configuration using OPC to compensate for dispersion and nonlinearity. The function of blocks is similar to that shown in Fig. 3a. However, at the receiver side, dispersion and nonlinear compensation are not performed in DSP block. Instead, we put an OPC in the middle of an optical transmission line, then it compensates the dispersion and deals with nonlinear effect appear in transmission.

In the transmission link, we used amplifier as erbium-doped amplifier (EDFA). In addition, we put in each span of single mode fiber optic (SMF) line with a MUX/DEMUX,

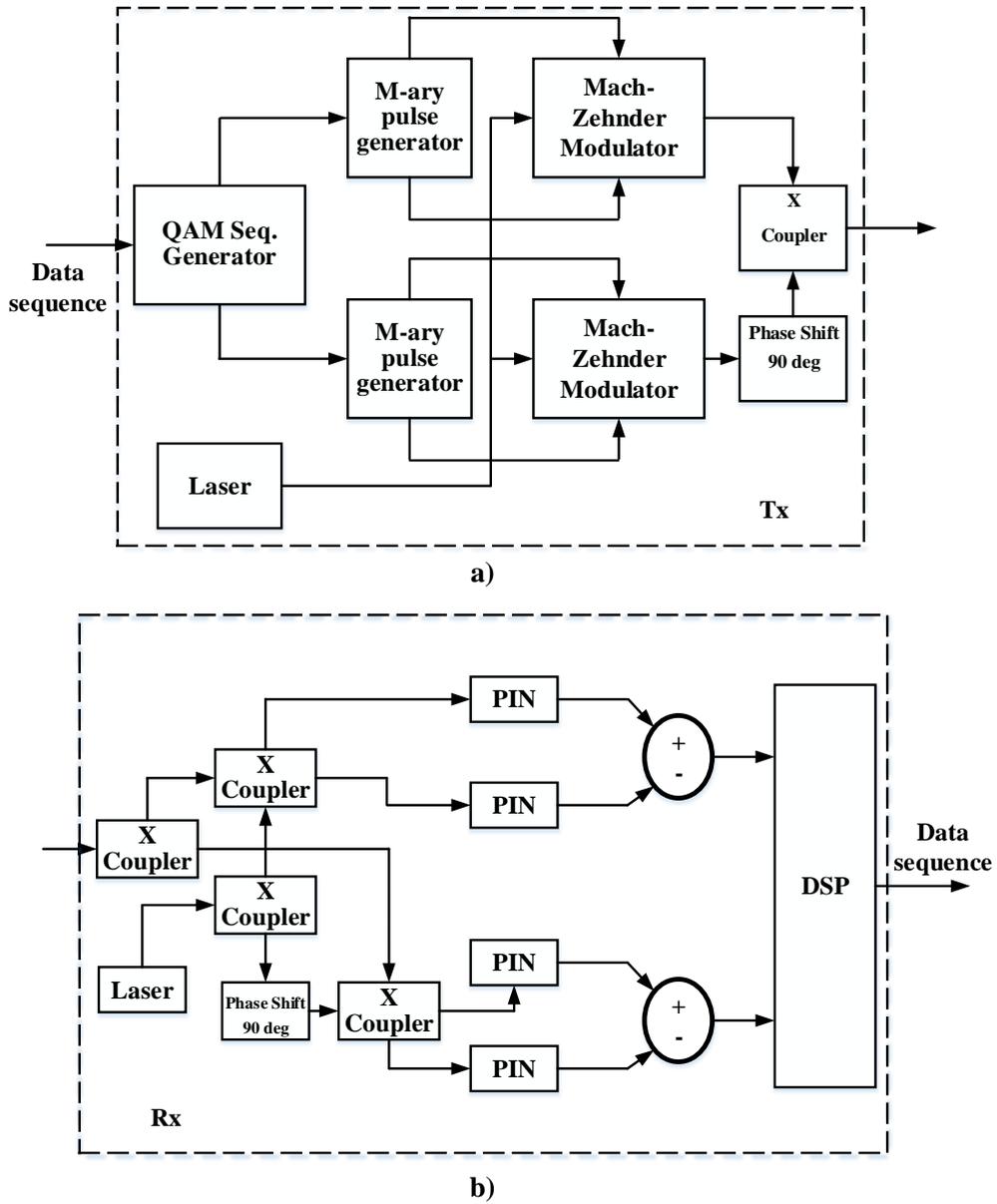


Figure 4. Schematic diagram of M-QAM transmitter and receiver.

grid of channel as  $100GHz$ , numbers of channel  $M = 16, 32$ . The loss, dispersion (at  $1550\text{ nm}$ ), dispersion slope (at  $1550\text{ nm}$ ), and nonlinearity coefficients of the optical fiber are:  $\alpha = 0.2\text{dB/km}$ ,  $D = 17\text{ps/km/nm}$ ,  $S = 0.075\text{ps/km/nm}^2$ , and  $\gamma = 1.2\text{W}^{-1}.\text{km}^{-1}$ , respectively. To compensate for all losses, EDFA with noise figure of  $6\text{dB}$  is used. In this configuration, the number of span ( $N$ ) is changed on a case-by-case basis to perform a system quality investigation. An OPC is located in the middle of the transmission line, after the first  $N/2$  span.

To represent the simulation results we used Q factor (dB), which is calculated using the error vector magnitude EVM (%) received from the constellation of the receiver signal which are shown as [25]:

$$EVM = \frac{\frac{1}{N_0} \sum_{n=1}^{N_0} \|S_n - S_{0,n}\|^2}{\frac{1}{N_0} \sum_{n=1}^{N_0} \|S_{0,n}\|^2} \quad (6)$$

$$BER = \frac{(1 - M^{-1/2})}{\frac{1}{2} \log_2 M} * \text{erfc} \left[ \sqrt{\frac{\frac{3}{2}}{(M-1)EVM^2.k^2}} \right] \quad (7)$$

$$Q = 20\lg(\sqrt{2}(\text{erfcinv}(2BER))) \quad (8)$$

where  $S_n$  is the normalized  $n$ th symbol in the stream of measured symbols,  $S_{0,n}$  is the ideal normalized constellation point of the  $n$ th symbol,  $N_0$  is the number of unique symbols in the constellation,  $M$  is the number of points on the signal constellation.  $k$  is the coefficient depending on the type of modulation, and calculated as the table 2.

Table 2. The calculation of  $k$  with some modulation

Format	QPSK	16QAM	32QAM	64QAM
$k$	1	$\sqrt{9/5}$	$\sqrt{17/10}$	$\sqrt{7/3}$

#### 4. Simulation results and Discussion

The performance of nonlinear compensation using OPC is considered through two types of optical signal modulation, QPSK and 16-QAM for Baud rate as  $50\text{ GBaud}$ . The number of channels is 16 and 32, respectively. In DWDM, some channels at middle of bandwidth will be influenced by the strongest nonlinear effects. Therefore, we focused on evaluating the variation in the quality of these channels with non-linear compensation using OPC.

#### 4.1. QPSK-based DWDM metro system

Fig. 5 to Fig. 10 show simulation results of using OPC to compensate for dispersion and nonlinear effects. Firstly, we examine the variation of system quality (Q factor) according to the value of the optical power to launch into fiber (Fig. 5 and Fig. 6). Next, we change the number of nodes add/drop, then conduct a system quality assessment and compare two scenarios, with OPC and without OPC (Fig. 7 to Fig. 10).

*4.1.1. Impact of launched power on the system performance:* In this simulation, the value of the number of add/drop nodes (N) is 10. Then, we change the optical launched power value to survey the Q value. Fig. 5 show the results of the system quality survey (Q factor) according to the optical power to launched into fiber for the case of a 16-channel optical multiplexing system, when the distance of each transmission segment is 10 or 50 km. And Fig. 6 show the results for the 32-channel multiplexing system. Insets show the signal constellation at the receiving side at the nonlinear threshold; left side is not using OPC and right side is using OPC.

It can be seen from Fig. 5 (10 and 50 km add/drop line ) that the use of OPC offers a clear increase (over the Q factor survey) compared to using DC, with Q factor increasing by more than 1 dB in both cases. Moreover, when comparing the use of OPC with DC, the system's nonlinear threshold (the value of power coupled into the optical fiber to Q factor reaches its maximum) is increased by about 3 dB (15 dBm of OPC compared to 12 dBm of DC). The system's nonlinear threshold is the value of transmit power at which quality (Q) is best. When the capacity is above this threshold, the quality of the system does not increase or even decrease. The reason is that when the transmit power increases, the nonlinearity of the system also increases rapidly, which leads to the OSNR at the receiver side decreasing. When the power is greater than the nonlinear threshold, the OSNR degradation occurs faster than the receiver compensation, which results in a rapid drop in system quality.

Fig. 6 shows the simulation results of system quality (Q factor) according to the optical power to launch into fiber for the case of a 32-channel optical multiplexing system. The nonlinear threshold of the system using OPC is pushed up quite high (approximately 18 dBm).

*4.1.2. The performance benefit of OPC for different number of add/drop nodes:* In this simulation, we change the number of nodes add/drop (N in Fig. 3), from 4 to 20 nodes. Then, we investigate the Q value when dispersion and nonlinearity are compensated by DC or OPC. The results are shown in Fig. 7 (16-channel system) and Fig. 9 (32-channel system).

Fig. 7 shows the general trend when using OPC and DC is the decrease in system quality (Q factor) as the number of nodes increases. However, it is clear that the reduction in OPC use is slower than DC. The more the number of nodes is used, the better the advantages of OPC are shown. When comparing the use of OPC with DC, the increase of the Q factor value from using 4 nodes to 20 nodes are 0.51 dB and 0.93 dB, respectively (for 10 km transmission distance per span). The results for 50 km

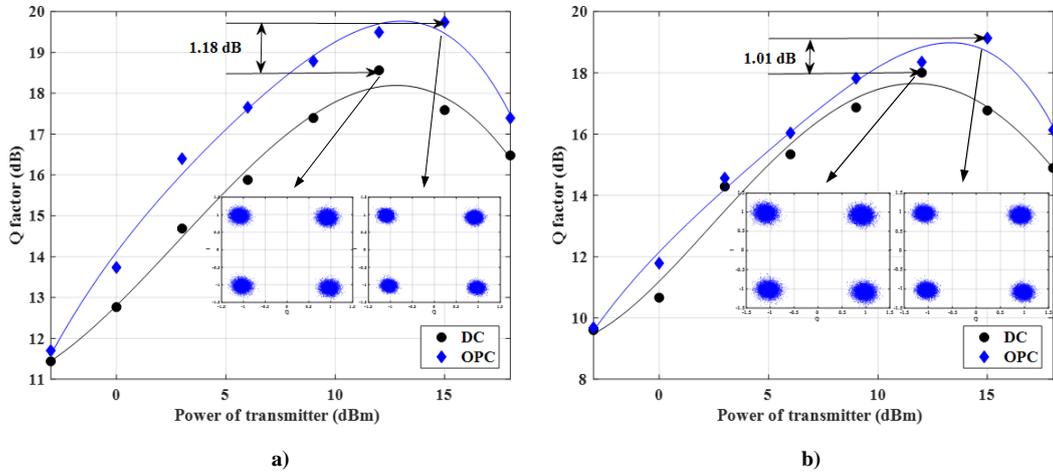


Figure 5. *Q* factor varies with the launched power into the optical fiber with 16-channel metro DWDM system using QPSK signal (Insets are constellations at nonlinear threshold):  
 a) 10 km per add/drop line; b) 50 km per add/drop line

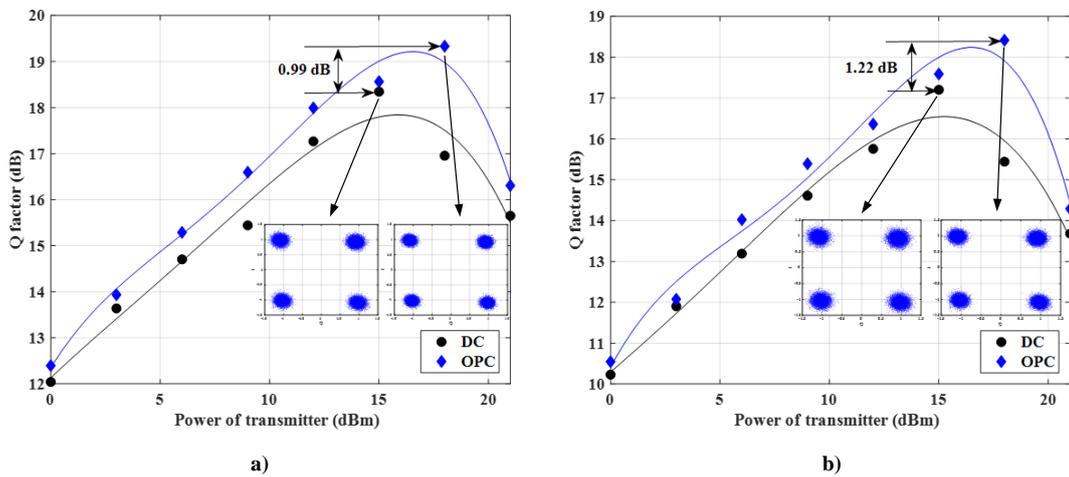


Figure 6. *Q* factor varies with the launched power into the optical fiber with 32-channel metro DWDM system using QPSK signal (Insets are constellations at nonlinear threshold):  
 a) 10 km per add/drop line, b) 50 km per add/drop line

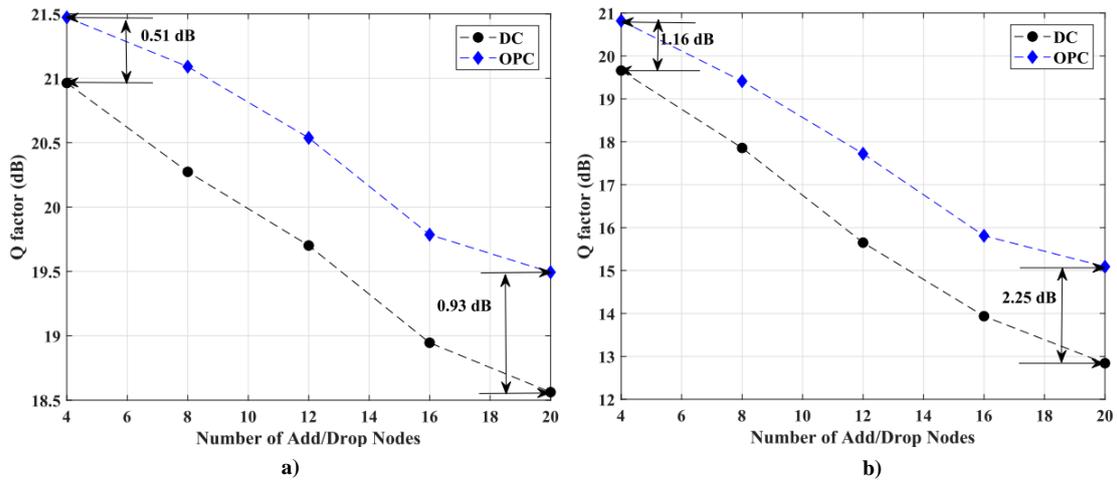


Figure 7. Q factor varies with the number of add/drop nodes with 16-channel metro DWDM system using QPSK signal: a) 10 km per add/drop line; b) 50 km per add/drop line

transmission distance per span are 1.16 dB and 2.25 dB, respectively. In addition, we can see the result through the power spectrum of the receiving signal, e.g. in Fig. 8.

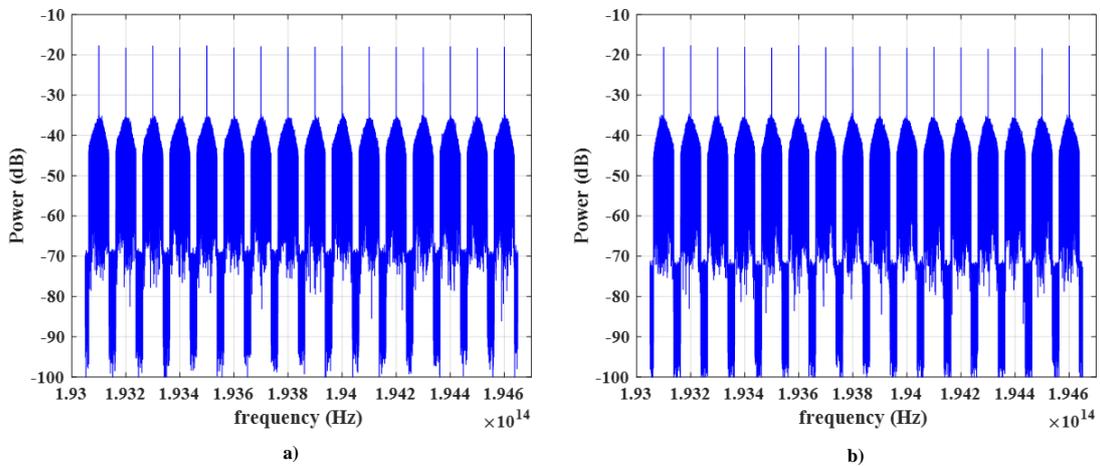


Figure 8. Spectrum of received signal for 16-channel system: a) without OPC; b) with OPC

In Fig. 9, the simulation results show the clear effect of using OPC, when the number of add/drop nodes increases for the DWDM metro system. The increase of the Q factor value using OPC compared to when using DC in the case of 20 nodes and 4 nodes are 1.13 dB and 0.63 dB, respectively (for 10 km transmission distance per span); for 50 km transmission distance per span, result are 2.24 dB and 1.28 dB, respectively.

Also, similar to the case of a 16-channel system, Fig. 10 shows the received signal spectrum when transmitted through 20 OADM nodes.

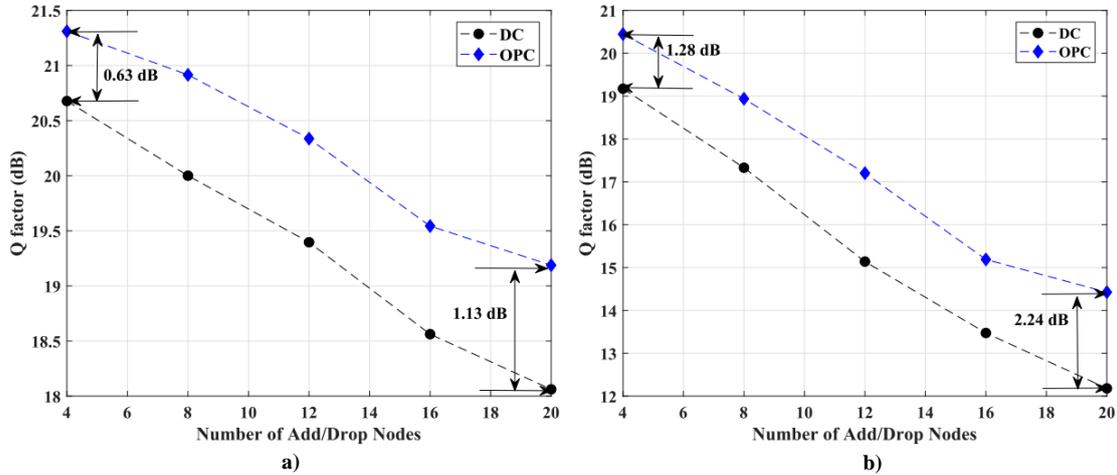


Figure 9. Q factor varies with the number of add/drop nodes with 16-channel metro DWDM system using QPSK signal: a) 10 km per add/drop line; b) 50 km per add/drop line

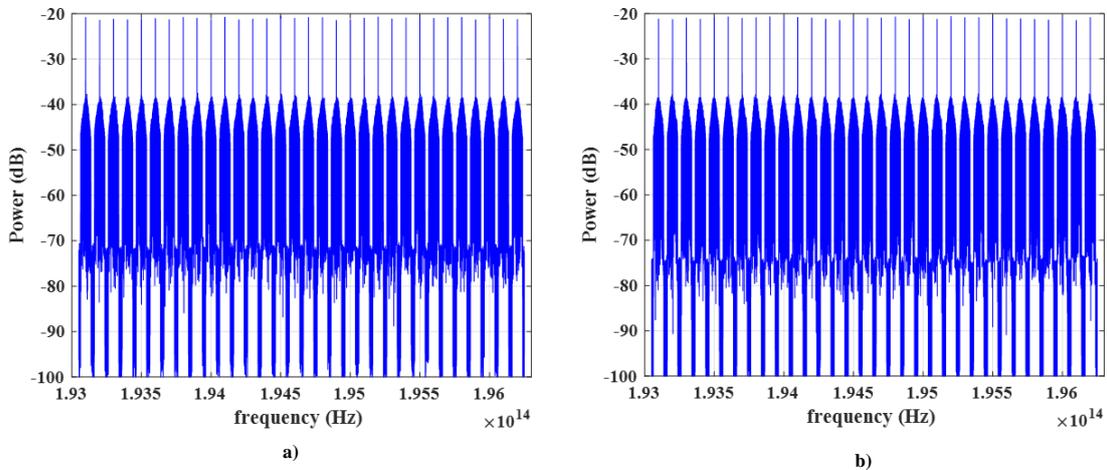


Figure 10. Spectrum of received signal for 16-channel system: a) without OPC; b) with OPC

#### 4.2. 16-QAM-based DWDM metro system

Next we will examine DWDM systems using 16-QAM signals. For 16-QAM signal, the simulation setup is similar to the ones using the QPSK signal. The simulation results are shown in Fig. 11 to 16.

4.2.1. *Impact of launched power on the system performance:* In the case of using 16-QAM signal, we see the effect of using OPC compared to DC, similar to the system using QPSK signal. We also realize that the nonlinear threshold value achieved when using OPC is also higher than DC (similar to the case of QPSK signal). Simulating two systems: 16-channel and 32-channel, the Q value (surveyed by the power of fiber-optic signal) in the case of using OPC is much higher than that of using DC, specifically up to 1 dB with a 16-channel system (Fig. 11); even reaches approximately 2 dB for a 32-channel system (Fig. 12). At the same time, the nonlinear threshold of the system when using OPC also increased compared to the ones using DC, about 3 dB.

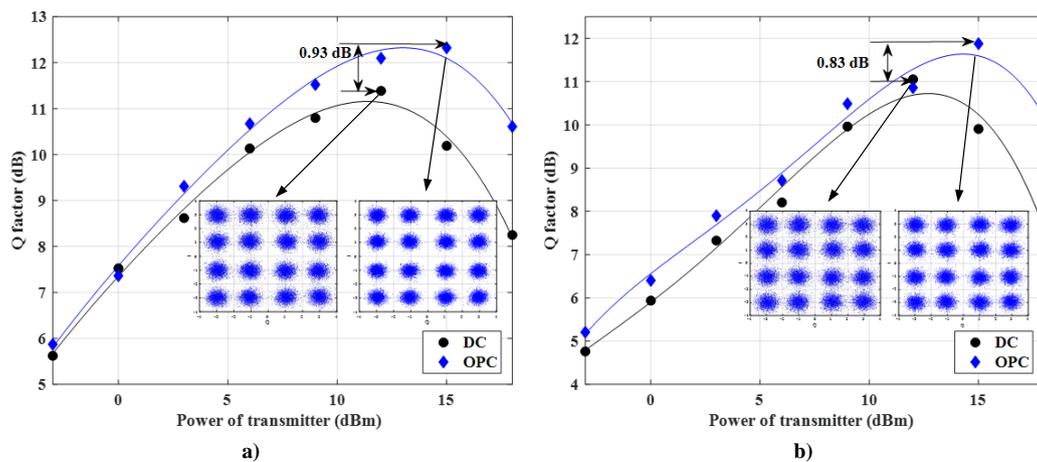


Figure 11. Q factor varies with the launched power into the optical fiber with 16-channel metro DWDM system using 16-QAM signal (Insets are constellations at nonlinear threshold):  
 a) 10 km per add/drop line; b) 50 km per add/drop line

Insets in Fig. 11 and Fig. 12 show the constellation of the received signal at the nonlinear threshold, which can be seen as an improvement in the use of OPC. This improvement is more noticeable than in case of QPSK.

4.2.2. *The performance benefit of OPC for different number of add/drop nodes:* Because 16-QAM signal has amplitude modulation, it is therefore strongly affected by non-linear distortion. Therefore, when the number of add/drop nodes increases (transmission length increases), the system quality (Q factor) decreases very quickly; we can see this very clearly in Fig. 13 to 16.

Along with that, as the number of add/drop nodes increases (from 4 to 20), the use of OPC to compensate for dispersion and nonlinearity becomes even more effective, reflected in the improvement in value of Q factor, specifically, the achieved simulation results are: increase from 0.74 dB to 1.927 dB for 16-channel system when transmission distance as 10 km per span (Fig. 13a); from 0.87 dB to 2.003 dB for 16-channel system when transmission distance as 50 km per span (Fig. 13b); from 0.92 dB to 2.257 dB for

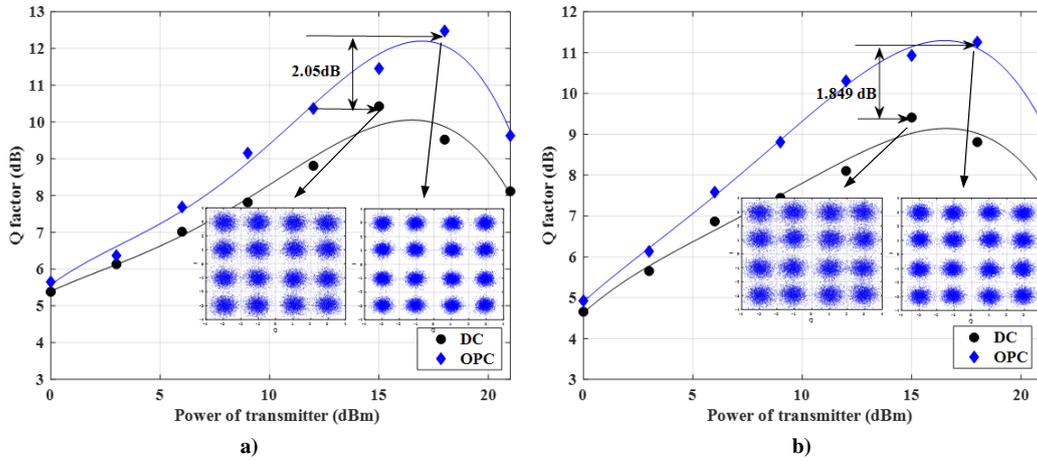


Figure 12.  $Q$  factor varies with the launched power into the optical fiber with 16-channel metro DWDM system using 32-QAM signal (Insets are constellations at nonlinear threshold):  
 a) 10 km per add/drop line; b) 50 km per add/drop line

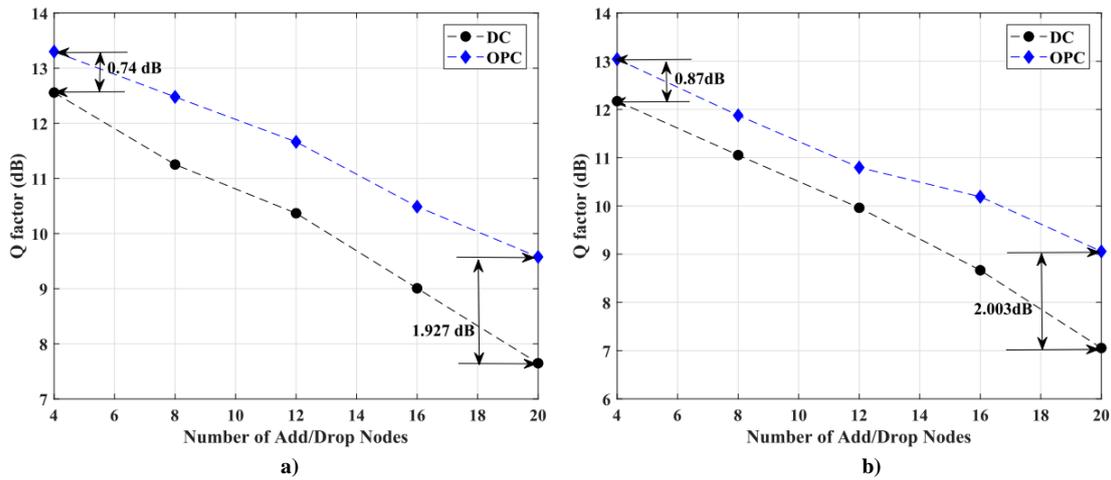


Figure 13.  $Q$  factor varies with the number of add/drop nodes with 16-channel metro DWDM system using 16-QAM signal: a) 10 km per add/drop line; b) 50 km per add/drop line

32-channel system when transmission distance as 10 km per span (Fig. 15a); and from 1.01 dB to 2.286 dB for 32-channel system when transmission distance as 50 km per span (Fig. 15b). Fig. 14 and 16 show the results of the received signal spectrum when transmitted through 20 OADM nodes for 16- and 32-channel system, respectively.

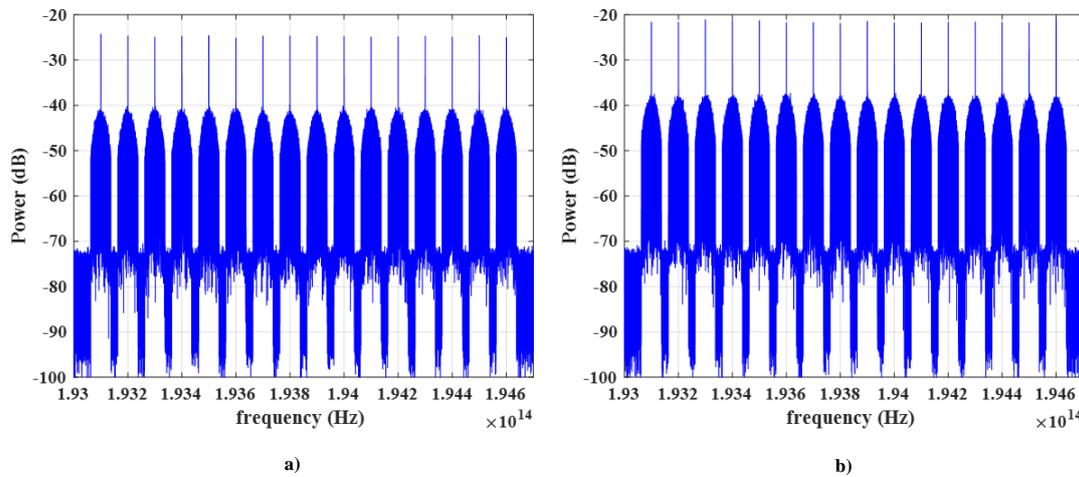


Figure 14. Spectrum of received signal for 16-channel system: a) without OPC; b) with OPC

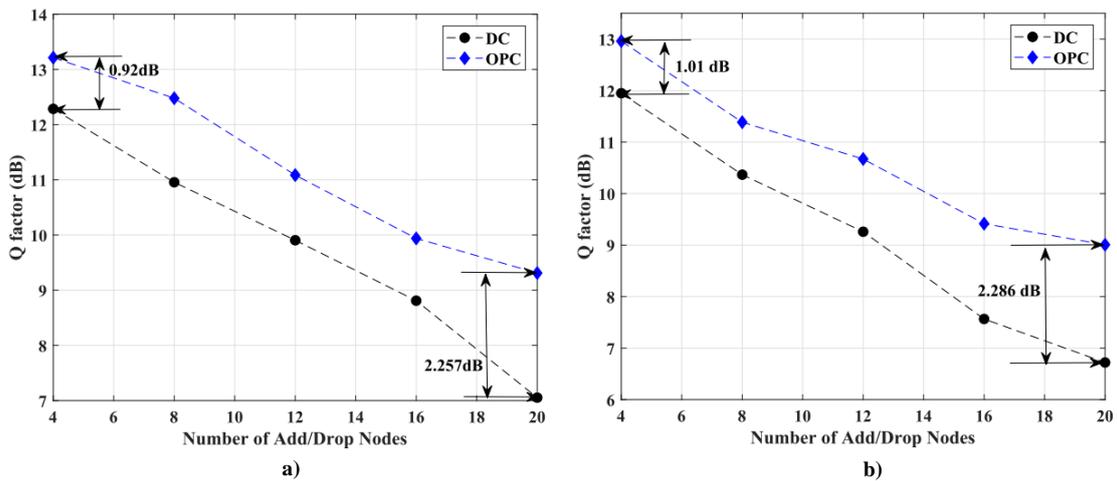


Figure 15. Q factor varies with the number of add/drop nodes with 32-channel metro DWDM system using 16-QAM signal: a) 10 km per add/drop line; b) 50 km per add/drop line

## 5. Conclusion

We have presented the improvement of signal quality (via Q factor) of the DWDM metro system with two cases (16 and 32 channels) when using DC and OPC. Simulations are performed for QPSK and 16-QAM modulation signal types and Baudrate equal as 50 GBaud. Numerical results show that the superiority of signal quality when dispersion and nonlinearity compensation by OPC than DC; e.g. with metro system using 16-QAM signal, multiplexing 32 channels and transmitting through 20 add / drop nodes; the

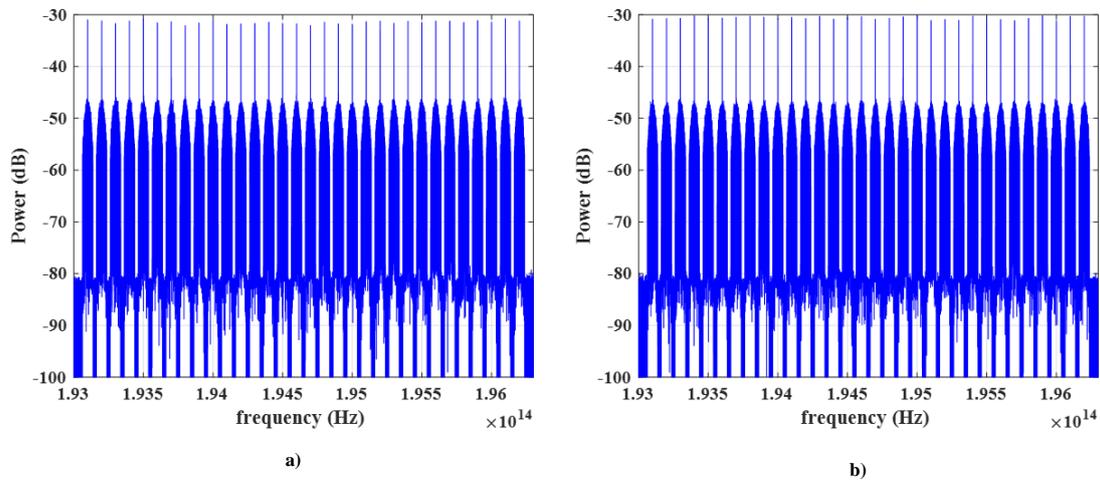


Figure 16. Spectrum of received signal for 16-channel system: a) without OPC; b) with OPC

gain of Q factor can reach more than 2dB. However, when we increase the number of channels in the system, the efficiency of nonlinear compensation of OPC is also reduced, especially channels in the middle of the signal spectrum.

## References

- [1] J. Gantz and D. Reinsel, "The digital universe in 2020: big data, bigger digital shadows, and biggest growth in the far east," *IDC IVIEW, EMC Corporation*, pp. 1-16, 2012.
- [2] Cisco System, "Cisco Visual Networking Index: Forecast and Trends 2017-2022," *Cisco White Paper*, 2018.
- [3] Jörg-Peter Elbers, Klaus Grobe, "Optical metro networks 2.0," *Proceedings of SPIE - The International Society for Optical Engineering*, Jan. 2010. DOI: 10.1117/12.847079.
- [4] Alexandros Stavdas, "Core and metro network," *Wiley Series in Communication Networking & Distributed Systems*, John Wiley & Sons Ltd., 2010. ISBN: 978-0-470-51274-6.
- [5] Yi chen, Mohammad T. Fatehi, Humberto J. La Roche, Jacob Z. Larsen, Bruce L. Nelson, "Metro Optical Networking," *Bell Labs Technical Journal*, vol. 4, no. 1, jan. - mar. 1999.
- [6] Shinji Matsuoka, "Ultrahigh-speed Ultrahigh-capacity Transport Network Technology for Cost-effective Core and Metro Networks," *NTT Technical Review*, Vol. 9, No. 8, Aug. 2011.
- [7] P. J. Winzer, "High-spectral-efficiency optical modulation formats," *Journal of Lightwave Technology* 30(24), 3824–3835, 2012.
- [8] Marek Jaworski, "Optical Modulation Formats for High-speed DWDM Systems," *Proceedings of 2003 5th International Conference on Transparent Optical Networks*, 2003.
- [9] G. P. Agrawal, "Nonlinear Fiber Optics, Second Edition," *Academic Press, San Diego, USA*, 1995.
- [10] A. D. Ellis, M. E. McCarthy, M. A. Z. A. Khateeb, M. Sorokina, N. J. Doran, "Performance limits in optical communication due to fiber nonlinearity," *Adv. Opt. Photonics*, vol. 9, pp. 429-503, 2017.
- [11] A.D. Ellis, S.T. Le, M.A.Z. Al-Khateeb, S.K. Turitsyn, G. Liga, D. Lavery, T.Xu, P. Bayvel, "The Impact of Phase Conjugation on the Nonlinear-Shannon Limit: The Difference Between Optical and Electrical Phase Conjugation," *IEEE Summer Topicals Meeting Series (SUM)*, Nassau, 2015, pp. 209–210. <http://dx.doi.org/10.1109/SUM.2015.7362201>.
- [12] Hung Nguyen Tan, Son Thai Le, "On the effectiveness of nonlinearity compensation for high-baudrate single-channel transmissions," *Optics Communications*, Volume 433, pp 36-43, 15 February 2019.
- [13] E. Ip, J. M. Kahn, "Compensation of dispersion and nonlinear impairments using digital back propagation," *J. Lightwave Technol.*, vol. 26, pp. 3416-3425, 2008.

- [14] E. Temprana, E. Myslivets, L. Liu, A. W. V. Ataie, B. p. P. Kuo, N. Alic, S. Radic, "Two-fold transmission reach enhancement enabled by transmitter-side digital back propagation and optical frequency comb-derived information carriers," *Opt. Express*, vol. 23, pp. 20774-20783, 2015.
- [15] I. D. Phillips, et al., "Exceeding the nonlinear-shannon limit using raman laser based amplification and optical phase conjugation," in Proc. *Optical Fiber Communications Conference and Exhibition (OFC)*, pp. 1-3, San Francisco, CA, USA, 2014.
- [16] A. Yariv, D. Fekete, and D. M. Pepper, "Compensation for channel dispersion by nonlinear optical phase conjugation," *Opt. Lett.*, vol. 4, no. 2, pp. 52-54, Feb. 1979.
- [17] K. Solis-Trapala, M. Pelusi, H. N. Tan, T. Inoue, S. Namiki, "Optimized WDM transmission impairment mitigation by multiple phase conjugation," *J. Lightwave Technol.*, vol. 34, pp. 431-440, 2016.
- [18] S. Yoshima, Z. Liu, Y. Sun, K. R. Bottrill, F. Parmigiani, P. Petropoulos, and D. J. Richardson, "Nonlinearity Mitigation for Multi-channel 64-QAM Signals in a Deploy Fiber Link through Optical Phase Conjugation," in Proc. *Optical Fiber Communications Conference and Exhibition (OFC)*, Paper Th4F4, 2016.
- [19] Hao Hu, Robert M. Jopson, Alan H. Gnauck, Sebastian Randel, and S. Chandrasekhar, "Fiber nonlinearity mitigation of WDM-PDM QPSK/16QAM signals using fiber-optic parametric amplifiers based multiple optical phase conjugation," *Opt. Express*, vol. 25, pp. 1618-1628, 2017.
- [20] S. Watanabe, T. Chikama, G. Ishikawa, T. Terahara, and H. Kuwahara, "Compensation of pulse shape distortion due to chromatic dispersion and Kerr effect by optical phase conjugation," *IEEE Photon. Technol. Lett.*, vol. 5, no. 10, pp. 1241-1243, Oct. 1993.
- [21] C. Lorattanasane, and K. Kikuchi, "Design theory of long-distance optical transmission systems using midway optical phase conjugation," *Journal of Lightwave Technology*, vol. 15, no. 6, pp. 948-955, 1997.
- [22] Binh Nguyen Duc, Nguyen Van Dien, Hung Nguyen Tan, and Quang Nguyen-The, "Nonlinearity compensation in DWDM metro systems using optical phase conjugation," *International Conference on Advanced Technologies for Communications (ATC)*, 2019.
- [23] Shu Namiki, Karen Solis-Trapala, Hung Nguyen Tan, Mark Pelusi, and Takasi Inoue, "Multi-channel cascaded parametric signal processing for wavelength conversion and nonlinearity compensation," *Journal of Lightwave Technology*, vol. 35, no. 4, pp. 815-823, Feb. 2017.
- [24] Son Thai Le, Hung Nguyen Tan, and Henning Buelow, "Imperfection Induced Bandwidth Limitation in Nonlinearity Compensation," *European Conference on Optical Communication (ECOC)*, Gothenburg, Sweden, paper P2.SC6.23, 2017.
- [25] W. Freude, et al., "Quality metrics for optical signals: Eye diagram, Q factor, OSNR, EVM, and BER," in Proc. *14th International Conference on Transparent Optical Networks (ICTON)*, Coventry, pp. 1-4, 2012.

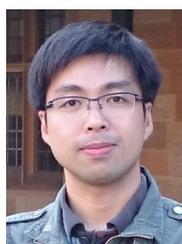
*Manuscript received: 12-08-2020; Accepted: 16-12-2020.*



**Nguyen Duc Binh** was born in Bac Giang, Vietnam, in 1984; received B.E. degree from Le Quy Don Technical University, Vietnam, in 2008, and M.E. degree in 2013 from Le Quy Don Technical University, Vietnam. From 2013 to 2015, he worked as an operator and manager engineer of optical transmission network at the High-tech Communication Center, Communications Command. He is currently a Ph.D student at Le Quy Don Technical University, Hanoi, Vietnam.



**Nguyen Van Dien** was born in Da Nang, Vietnam, in 1980. He received the B.E. degree from Ho Chi Minh City University of Technology and the Diplom-Ingenieur degree from University of Stuttgart, Germany in 2003 and 2011, respectively. He is now a Ph.D. candidate at The University of Danang – University of Science and Technology. His research interests include fiber-optics communications, radio-over-fiber and microwave photonics for next generation access networks.



**Nguyen Tan Hung** was born in Da Nang, Vietnam, in 1980. He received the B.E. degree from The University of Danang – University of Science and Technology, Da Nang, Vietnam, in 2003, and the M.E. and Ph.D. degrees from the University of Electro-Communications, Tokyo, Japan, in 2009 and 2012, respectively. From 2012 to 2016, he was a researcher with the National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan, where he worked on ultrafast and spectrally efficient all-optical network technologies, and development of an all-optical wavelength converter. In 2016, he joined the University of Da Nang, Da Nang, Vietnam, where he is currently an Associate Professor and the Vice-Director of The University of Danang – Advanced Institute of Science and Technology. His research interests include optical communications and networking, all-optical signal processing and photonic integrated circuits. He is a member of the IEEE Photonics Society.



**Nguyen The Quang** was born in 1978. He received B.E. degree from National Defense Academy, Japan, in 2004, M.E. degree in 2009 and the Ph.D. degree in 2012 from the University of Electro-Communications, Tokyo, Japan. From 2012 to 2014, He worked as a postdoctoral fellow at the Department of Communication Engineering and Informatics, the University of Electro-Communications, Tokyo, Japan. He was a recipient of the Young Scientist Award at the 15th OptoElectronics and Communications Conference (OECC 2010) presented by the IEEE Photonics Society Japan Chapter. His research interest is all-optical signal processing based on nonlinear fiber optics for WDM and OTDM systems. He is currently a lecturer at Le Quy Don Technical University, Hanoi, Vietnam.



**Nguyen Hong Kiem** was born in Ha Nam, Vietnam, in 1979. He received the B.E. degree from Telecommunications University, Nha Trang, Vietnam, in 2005, and the M.E. degree from the Telecommunications Institute of Technology, Vietnam, in 2011. From 2009 to 2017, He was a lecturer, Department of telecommunications engineering, Telecommunications University, Nha Trang, Vietnam. He is currently a PhD student, Le Quy Don Technical University, Hanoi, Vietnam.



**Vuong Quang Phuoc** was born in Hue, Thua Thien-Hue, in 1990. He received B.E. degree from Hue University of Sciences, in 2013, and the M.E. degree from the University of Danang – University of Science and Technology, in 2018. He is currently a lecturer at Hue University of Sciences.

# NÂNG CAO HIỆU QUẢ BÙ PHI TUYẾN SỬ DỤNG BỘ LIÊN HỢP PHA QUANG CHO CÁC HỆ THỐNG METRO GHÉP KÊNH PHÂN CHIA BƯỚC SÓNG MẬT ĐỘ CAO CÓ BỘ XEN – RỄ QUANG

## Tóm tắt

Ghép kênh phân chia theo bước sóng (WDM) đã được ứng dụng rộng rãi trong các hệ thống ghép kênh xen/rễ quang (OADM) với số lượng kênh bước sóng ngày càng tăng và khoảng cách kênh đủ hẹp. Vấn đề xuất hiện ở đây là sự biến dạng tín hiệu do hiệu ứng tán sắc và phi tuyến trong sợi quang. Để giải quyết những ảnh hưởng này, nhiều giải pháp bù đã được đưa ra như giải pháp bù kỹ thuật số (DC) trên công nghệ xử lý tín hiệu số (DSP) hay giải pháp bù trên miền tín hiệu toàn quang như kỹ thuật sử dụng OPC đã tỏ ra hiệu quả. Trên thực tế, các nghiên cứu về việc sử dụng OPC để bù tán sắc và phi tuyến trong hệ thống truyền dẫn metro chưa nhiều và chưa thực sự đầy đủ, nhất là với các hệ thống ghép kênh với số lượng kênh lớn. Trong bài báo này, chúng tôi thực hiện khảo sát đánh giá việc sử dụng OPC để bù tán sắc và phi tuyến trong hệ thống metro DWDM. Đánh giá tập trung vào hai loại tín hiệu điều chế phổ biến: QPSK và 16-QAM, hoạt động trong hệ thống DWDM 16 và 32 kênh. Kết quả mô phỏng cho thấy chất lượng hệ thống tăng lên đáng kể khi sử dụng OPC để bù tán sắc và phi tuyến. Ví dụ: khi truyền tín hiệu 16-QAM trong hệ thống 32 kênh đi qua 20 nút xen/rễ, tham số chất lượng Q có thể cải thiện đến hơn 2 dB.