Nonlinearity compensation in DWDM metro systems using optical phase conjugation

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***Abstract*—Many studies have shown that the use of the optical phase conjugation (OPC) to perform dispersion and nonlinear compensation for high-speed fiber optic transmission systems is highly effective. Especially in backbone systems, the use of mid-link OPC sets has proved a clear advantage. When OPC is in the middle of the transmission line, it will immediately create a complex conjugate of the OPC forward signal (the signal is transmitted on the first half of the transmission line). This new signal will be transmitted on the second half of the transmission line, and therefore dispersion and nonlinear effect will be compensated. Recently, with the rapid increase in the demand for user traffic, the capacity of metro systems has also increased rapidly. Dense Wavelength Division Multiplexing (DWDM) metro systems have characteristics such as short transmission distances, multiple add/drop node numbers, multiple optical amplifiers (mostly Erbium Doped Fiber Amplifier (EDFA)); however, the optical signals in them are also greatly affected by the dispersion and nonlinear effects. In this paper, we examine the efficiency of using OPC for dispersion and nonlinear compensation for optical signals in DWDM metro systems. This will be very important in understanding applications of OPC in actual systems later.**

Keywords*—Fiber optic communication, Dense Wavelength Division Multiplexing, Optical phase conjugation, Nonlinear compensation.

I. INTRODUCTION

The emerging of many bandwidth hungry applications, e.g. cloud computing, video on demand, IoT, 5G, and Big Data, has made the global data traffic increase exponentially in the past [1, 2]. Along with that, the demand of using high-speed services of customers is increasing. These have put tremendous pressure on today's information network, whose widely used backbone architecture is the fiber optic transmission network. As a result, improving the capacity and reach of fiber-optic transmission systems is essential to satisfying the increase in the desired data capacity. Similar to the backbone system, the transmission capacity of metro systems is also expanding [3-5]. The need to increase the capacity of the system, resulting in an inevitable problem is the application of DWDM technology and high-level modulation into metro systems [4,5]. In the last decade, a lot of research efforts have been made to understand the capacity of point-to-point optical channels [6]. However, the ultimate capacity and performance of optical channels depends on many factors, including fiber nonlinear Kerr effects such as four-wave mixing, self-phase modulation and cross-phase modulation [7]. These effects are somewhat more serious when symbol rates, modulation format levels, and number of channels are increased for large capacity transmission.

There have been many research of methods to eliminate the effects of nonlinear distortion caused by Kerr effects through digital and optical compensation techniques; such as digital back propagation (DBP) [8, 9], optical phase conjugation (OPC) [10-14]. DBP uses digital signal processing (DSP) technology in digital coherent receiver. In practice, the DBP is usually done for a single channel with narrow bandwidth. Because, the real-time computing power of DSP technology currently do not meet the computing power to conduct DBP for the transmission of multiple wavelength division multiplexing (WDM) channels. Therefore, the effectiveness of the DBP is still limited. Another common method is to use an OPC located in the middle of the path to compensate for nonlinear distortion [10-14]. The advantage over DBP, OPC has wide bandwidth, can operate effectively for multiple WDM signals, so it has high energy efficiency. Some studies show that, if many OPCs are used on transmission lines, the efficiency of OPC will increase significantly; for example, the ability to compress the time and phase translation in the Solution transmission system [15, 16]. Studies have also shown that distortion of the nonlinear signal phase can be decreased through the use of multiple OPCs on the transmission path, because the nonlinear interactions between the signal and the amplified spontaneous emission (ASE) are partially compensated through OPC layers [17]. In principle, OPC technique is required a symmetry for signal propagating in the fist and second half to obtain a perfect nonlinear and chromatic dispersion [18-20]. In fact, the first studies suggested and demonstrated that optical phase conjugation (OPC) has the ability to compensate for signal distortion due to chromatic dispersion and nonlinear effects since 1979 [21-23]. Usually, OPC is placed in the middle of a transmission link, and then OPC is used to create behind it a phase-conjugated signal with the previous signal; for the purpose of reversing or compensating for signal distortions due to chromatic dispersion and nonlinear effects appearing in the first half (span 1) to the second-half of the link (span 2).

In this paper, we investigate the signal quality of DWDM metro networks when using OPC for high-speed optical signals and high modulation levels. We conducted a quality survey of DWDM 4, 16 channel metro system for 16QAM optical signal 50GBaud. The simulation results show that when using OPC, the signal quality of DWDM channels in the metro network is clearly improved, in addition to the channels in the middle of the bandwidth, this improvement is particularly high.

II. System configuration

Fig. 1 shows the system configuration of the metro system with OPC, used to simulate the investigations in the paper. In simulation, we use 16QAM optical signal with symbol rate of 50 GBaud for two values of optical channel numbers equal to 4 and 16. In particular, we describe the transmitter details from the bit sequence with a speed of 200 Gbps, which is modulated into 16QAM optical signal 50 GBaud at the multiplexer input (MUX). Detailed diagram of the 16QAM transmitter is shown in the drawing on the upper left of Fig. 1.

After that, the amplifier used on fiber link is erbium-doped amplifier (EDFA); in addition, we put in each span of 20km single mode fiber optic (SMF) line with a MUX/DEMUX, grid of channel as 100 GHz, numbers of channel M = 4, 16. The loss, dispersion (at 1550nm), dispersion slope (at 1550nm), and nonlinearity coefficients of the optical fiber are α = 0.2 dB/km, D = 17 ps/km/nm, S = 0.075 ps/km/nm^2, and γ = 1.2 W^{-1}.km^{-1}, respectively. To compensate for all losses, due to fiber and MUX/DEMUX per span, EDFA with noise figure of 6dB 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 N/2 span.

At the receiver, optical signals, after demultiplexing, are passed through the coherent optical receiver, converted into electrical signals to be included in digital signal processing (DSP). DSP performs signal processing steps such as frequency recovery, phase, timing, and chromatic dispersion compensation. Detailed diagram of the 16QAM receiver is shown in the drawing on the upper right of Fig. 1.

Results such as error vector magnitude (EVM) value, bit error rate (BER), and Q factor of detected signals are calculated from the constellation of the receiver signal [24].

III. Simulation Results and discussion

The performance of nonlinear compensation using OPC is considered through two metro system configurations, 4 channels and 16 channels; with 16QAM optical signal, symbol rate 50GBaud. In DWDM, some channels at middle of bandwidth will be influenced by the strongest nonlinear effects; therefore we focused on investigating the variation in the quality of these channels when non-linear compensation using OPC.

A. Four channels DWDM system

Fig. 2 shows the change in the quality of middle channels when using dispersion compensation technique with DBP and OPC. In this case, to investigate the Q factor according to the transmitter power, we set the transmission distance to 20 km, with a add/drop of channel, and an EDFA to compensate the loss due to add/drop cause. We can see that the Q difference in the two cases is small (0.84 dB). The reason for this is that the nonlinear effect in this case is quite small, mainly due to the EDFA and the interaction between channels, so the effectiveness of OPC is not clearly shown. In addition, when using DBP or OPC, we all have an optimal transmit power value, where we have the best system quality (largest Q); as with DBP is 0 dBm, and with OPC is 3 dBm. This power value is called the nonlinear threshold; if the transmit power is greater than that, the quality of the system does not increase but also decreases quite quickly.

When we increase the transmission distance, the number of add / drop nodes increases, we can clearly see the change when using OPC and DBP. This is shown in Fig. 3. At this point, the nonlinear effect on the wavelength channels (especially channels between bandwidth) will increase significantly, because of the effect of nonlinear effects. Kerr is produced when the signal passes through the fiber. This is shown in more detail in Fig. 4; this figure clearly shows the constellation of signals collected in 4 specific cases using two dispersion compensation methods, DBP and OPC. Specifically with the spectrum of 4 signal channels, we can compare the two cases of DBP and OPC through fig. 5 and fig. 6. Fig. 5 shows the receiver signal spectrum, before putting into the DEMUX, when using DBP to compensate dispersion; meanwhile, Fig. 6 shows the signal spectrum when using OPC to compensate for dispersion.

B. Sixteen channels DWDM system

In the case of 16 channels (M = 16), Fig. 7 shows the change in Q factor by transmitter power when using DBP and OPC to compensate for dispersion on the transmission line. Similar to the case of 4 channels, the best power value, or nonlinear threshold, is 3 dBm and 6 dBm in the case of using DBP and OPC for dispersion and nonlinear compensation, respectively.

Fig. 7 shows the superiority of OPC compared to DBP when used to compensate transmission dispersion. With a 16-channel system, the nonlinear effect occurs with the wavelengths between bandwidths being very large, thus using DBP when the number of nodes increases (longer transmission range, larger EDFA number), signal quality (Q factor) fast decrease. For OPC, due to the good nonlinear compensation capability, resulting in quality transmission (Q factor) is much more positive than DBP (Q increases by 3.5 dB when the number of nodes is 10).

Furthermore, Fig. 9 shows the constellation of signals obtained when using DBP and OPC to compensate dispersion in a 16-channel metro system. And similar to the case of a 4-channel system, Fig. 10 and 11 show the spectrum of the received signal when transmitted through 20 nodes of add/drop, respectively in two cases using DBP and OPC to compensate for nonlinearity.

IV. Conclusions

We have presented the improvement of signal quality (via Q factor) of the DWDM metro system in two 4 and 16 channel cases when dispersion and nonlinear compensation using DBP and OPC. Simulations are performed for 16QAM modulation signal type and symbol speed equal to 50GBaud. Simulation results show high efficiency when using OPC for dispersion and nonlinear compensation in multi-channel metro DWDM systems. However, when we increase the number of channels in the system, the efficiency of nonlinear compensation of OPC is also reduced. Next, we will more clearly examine the effect of nonlinear compensation by OPC in the DWDM metro system, giving higher symbol speeds (100, 200 GBaud, ...), the number

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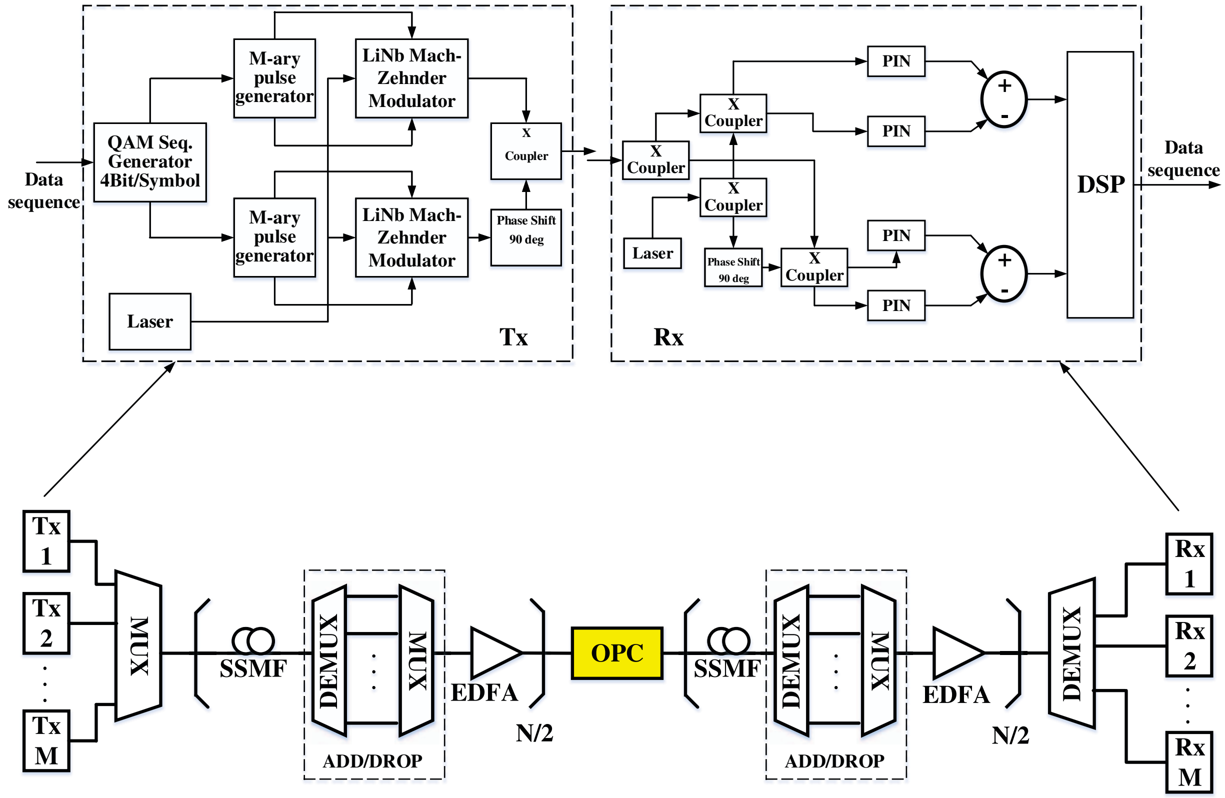

Fig. 1. Configuration of the metro system when dispersion compensation using OPC.

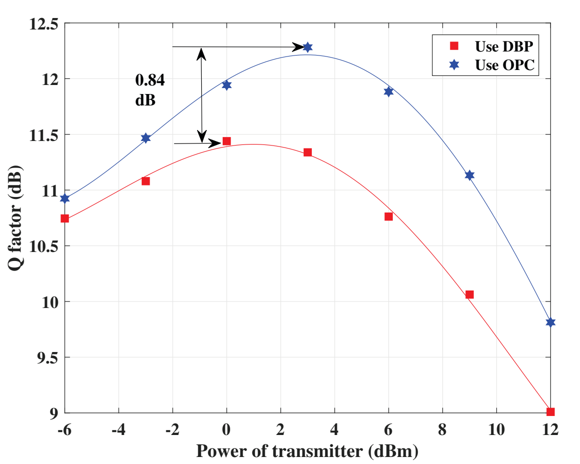

Fig. 2. Average Q factor of middle channels follow transmitter power when used DBP and OPC.

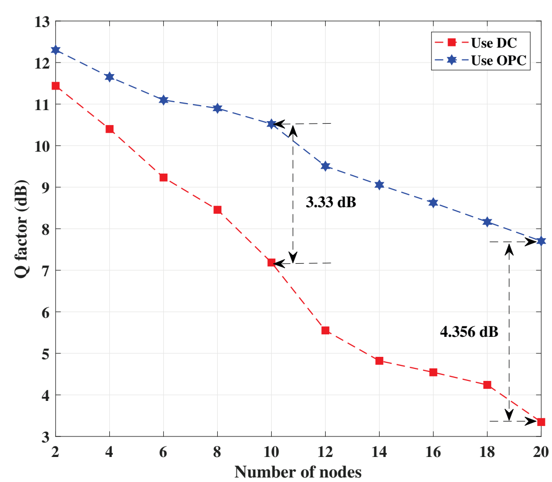

Fig. 3. Average Q factor of middle channels follow numbers of add/drop nodes when used OPC and DBP.

of larger channels (24, 32 channel, ...), and higher modulation level (64QAM). In addition, the study to apply OPC to systems using dual polarization modulation signals (DP-M-QAM) is a very interesting and important problem.

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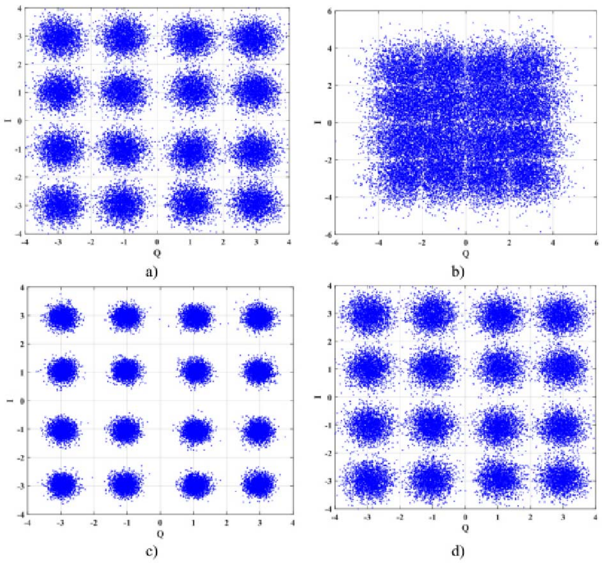

Fig. 4. Contellation of receiver signals when dispersion compensation using (a) DBP in 10 node case; (b) DBP in case of 20 nodes; (c) OPC in case of 10 nodes; and (d) OPC in case of 20 nodes.

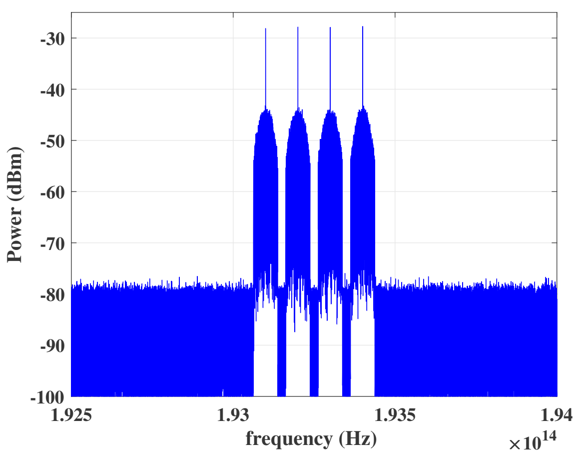

Fig. 5. Spectrum of receiver signals when used DBP for dispersion compensation for 20 nodes add/drop.

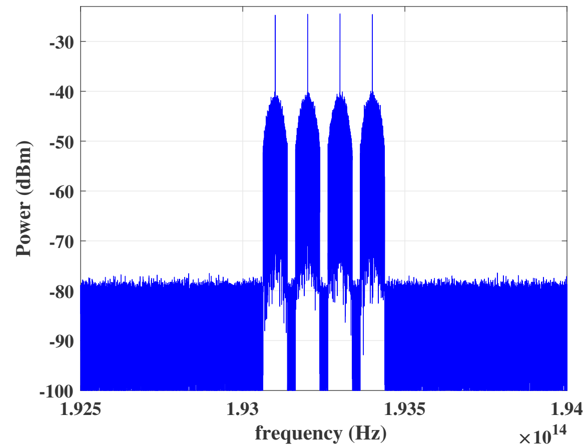

Fig. 6. Spectrum of receiver signals when used OPC for dispersion compensation for 20 nodes add/drop.

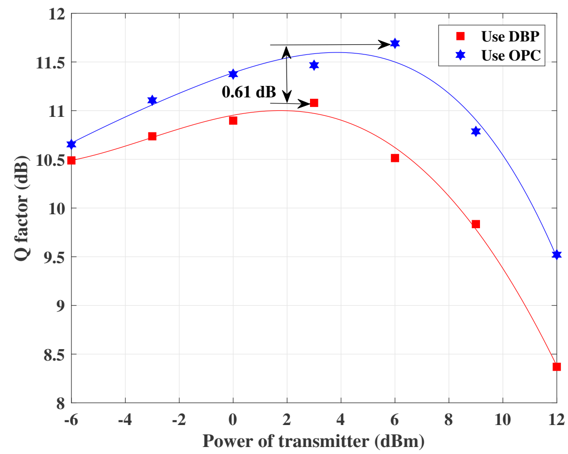

Fig. 7. Compare average Q factor of middle channels follow transmitter power when used OPC and DBP.

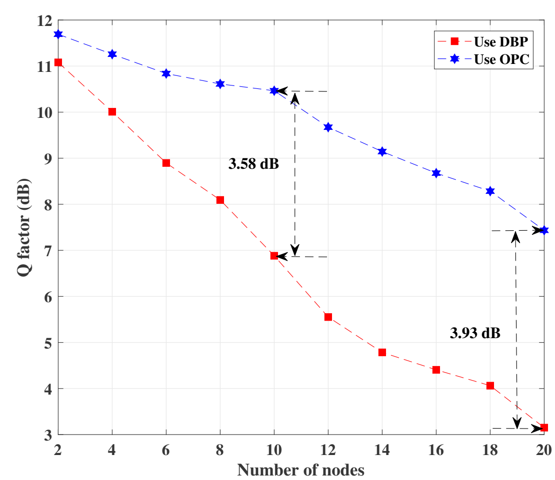

Fig. 8. Compare average Q factor of middle channels follow numbers of add/drop nodes when used OPC and DBP.

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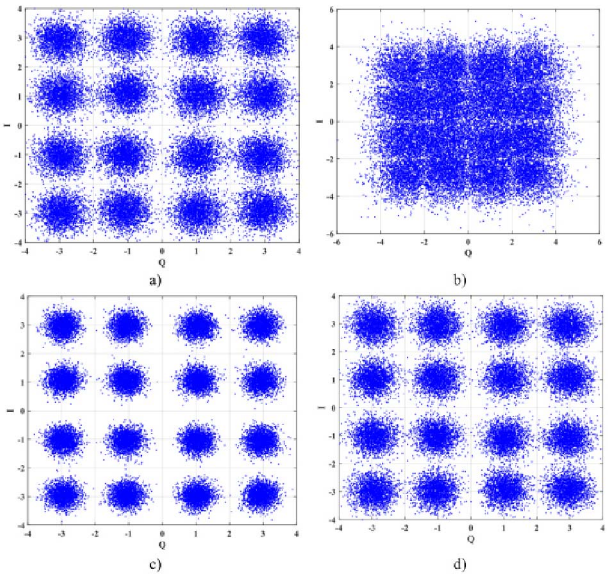

Fig. 9. Contellation of receiver signals when dispersion compensation using (a) DBP in 10 node case; (b) DBP in case of 20 nodes; (c) OPC in case of 10 nodes; and (d) OPC in case of 20 nodes.

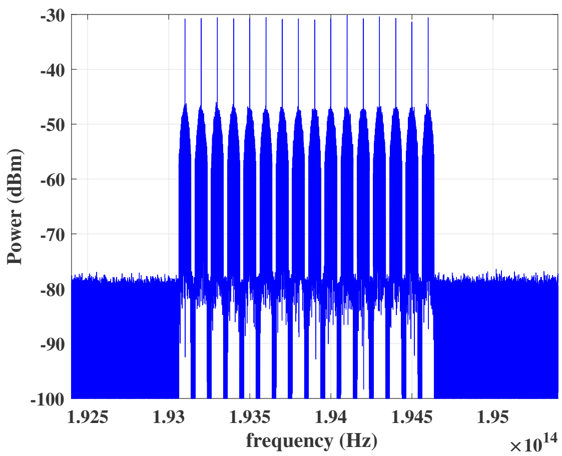

Fig. 10. Spectrum of receiver signals when used DBP for dispersion compensation for 20 nodes add/drop.

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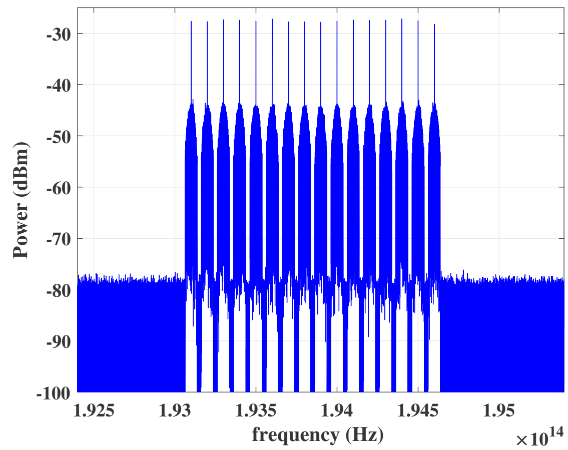

Fig. 11. Spectrum of receiver signals when used OPC for dispersion compensation for 20 nodes add/drop.

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