Performance evaluation of modulation formats in 40×40-Gb/s WDM repeaterless transmission systems

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Transmission performance of six modulation formats is numerically compared in 40 × 40-Gb/s wavelength division multiplexing (WDM) repeaterless systems. The results indicate that return-to-zero differential phase shift keying (RZ-DPSK) (33% duty cycle) demonstrates the best performance among all the formats when the accumulated amplified spontaneous emission power (AASEP) is small. But with the increasing of AASEP, the superiority of RZ-DPSK transmission performance over the other five modulation formats is vanished. AASEP is justified to be the major source for the deterioration of the superiority.

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Recently, the wavelength division multiplexing (WDM) repeaterless transmission system has attracted much attention[1−5]. Remote pumped amplifiers[1−3], bidirectional pumped Raman amplification[4], and ultra-large effective area ($A_{\rm eff}$) fibers[5] have been included in transmission system, and dramatically promoted the capacity-length production of repeaterless transmission systems. Some advanced modulation formats are also included in unrepeated transmission[1]. Considering that most of the fibers practically installed are standard single mode fiber (SSMF), it is important to find an economic way to upgrade the repeaterless transmission system by adopting novel techniques, such as advanced modulation formats.

In this paper, transmission performance of several modulation formats, such as non-return-to-zero (NRZ), carrier suppressed return-to-zero (CSRZ), return-to-zero (RZ) (with 33% duty cycle), NRZ differential phase shift keying (NRZ-DPSK), CSRZ-DPSK and RZ-DPSK, is numerically compared in a traditional 40 × 40-Gb/s WDM repeaterless system with hybrid Raman erbium-doped-fiber-amplifier (EDFA) amplification. And the impact of noise effects, mainly nonlinear phase noise and accumulated ASE noise, on transmission performance is theoretically analyzed.

The system setup is shown in Fig. 1. The transmitter is composed of 40 lasers, whose wavelengths range

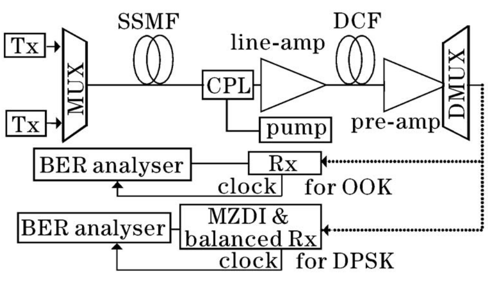

Fig. 1. Repeaterless transmission system configuration with OOK receiver for NRZ and RZ signal, and DPSK receiver for DPSK signal respectively. Tx: transmitter; CPL: couplers; line-amp: line-amplifier; pre-amp: pre-amplifier; MUX: multiplexer; DMUX: demultiplexer; Rx: receiver; MZDI: Mach-Zehnder delayed interferometer.

from 1529.55 to 1560.6 nm, and channel spacing is 100 GHz. The parameters of SSMF and dispersion compensating fiber (DCF) in the system are listed in Table 1 (α: fiber loss; D_{1550}: fiber dispersion at 1550 nm; S_{1550}: fiber dispersion slope at 1550 nm; $A_{\rm eff}$: fiber effective area). The back-forward distributed Raman amplification is achieved by coupling a pump in front of the line-amplifier, with equivalent noise figure, $n_{\rm RA}$= 0 (dB). In the receiver part, there are two branches, of which one is for on-off keying (OOK) signals, such as NRZ, CSRZ, and RZ, and the other for DPSK signals. A typical balanced DPSK receiver is same as that in Ref. [6]. All the PIN detectors in receivers are with a same parameter: bit error rate (BER) 10^{-11} at 12 dBm for NRZ.

Usually, the amplified spontaneous emission (ASE) noise is equivalent to receiver for system's BER evaluation. For OOK system, ASE noise can be taken as white Gaussian noise in the course of optical signal detection, however, for DPSK system, ASE noise should be taken as the random noise with nonzero χ^2 distribution[7], i.e., a non-central quadratic form of Gaussian random variables. In addition, the following system BER is the mean BER of 40 channels.

The receiver sensitivity of the six modulation formats in the back to back receiving is given in Fig. 2. It can be seen that the required received power to reach a BER of DPSK formats is about 3 dB lower than that of OOK formats due to the superior receiver sensitivity of DPSK.

In simulation, all the launch power per channel is preliminarily set a same value $P_{\rm lau}$ = 2 dBm, which is optimized for NRZ-DPSK system in 180-km repeaterless transmission. And the optical power injected into the receiver is traditionally set as $P_{\rm rec}$ = −8 dBm. The repeaterless transmission length ranges from 120 to 300 km.

Table 1. Parameters of the Fibers

Fiber	α (dB/km)	D_{1550} (ps/(nm·km))	S_{1550} (ps/(nm^2·km))	$A_{\rm eff}$ (μm^2)
SSMF	0.2	17	0.9	80
DCF	0.5	−102	−0.54	30

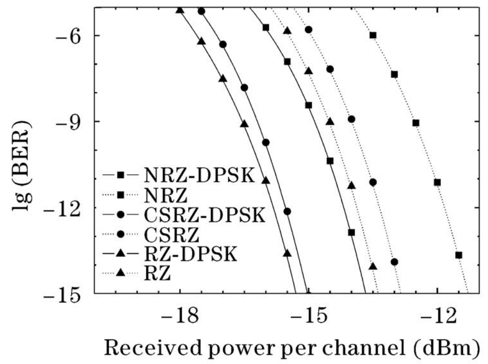

Fig. 2. Receiver sensitivity for different modulation formats (back to back).

The Raman amplifier (RA) is set to provide a maximum gain of $G_{\mathrm{RAMax}} = 15$ dB. To avoid high nonlinearity effect in DCF, the maximum gain of pre-amplifier is set as $G_{\mathrm{pre}} \leq G_{\mathrm{preMax}}$, where $G_{\mathrm{preMax}} = 15$ dB. According to different link loss, l, the three amplifiers' gains are arranged as

$$G_{\mathrm{RA}} = G_{\mathrm{pre}} = G_{\mathrm{line}} = 0, \qquad l < \delta P_0, \tag{1}$$

$$\begin{cases} G_{\mathrm{RA}} = l - \delta P_0, \\ G_{\mathrm{pre}} = G_{\mathrm{line}} = 0 \end{cases}, \qquad \delta P_1 > l > \delta P_0, \tag{2}$$

$$\begin{cases} G_{\mathrm{RA}} = G_{\mathrm{RAMax}} \\ G_{\mathrm{pre}} = l - \delta P_1 \\ G_{\mathrm{line}} = 0 \end{cases}, \qquad \delta P_2 > l > \delta P_1, \tag{3}$$

$$\begin{cases} G_{\mathrm{RA}} = G_{\mathrm{RAMax}} \\ G_{\mathrm{pre}} = G_{\mathrm{preMax}} \\ G_{\mathrm{line}} = l - \delta P_2 \end{cases}, \qquad l > \delta P_2, \tag{4}$$

where $l = l_{\mathrm{SMF}} + l_{\mathrm{DCF}}$ stands for the total signal power loss in SSMF and DCF, $\delta P_0 = P_{\mathrm{lau}} - P_{\mathrm{rec}}$ is the power margin between launch power, P_{lau}, and signal power at receiver, P_{rec}; and $\delta P_1 = P_{\mathrm{lau}} - P_{\mathrm{rec}} + G_{\mathrm{RAMax}}$ is the power margin with the maximum gain of Raman amplifier, G_{RAMax}, incorporated; and $\delta P_2 = P_{\mathrm{lau}} - P_{\mathrm{rec}} + G_{\mathrm{RAMax}} + G_{\mathrm{preMax}}$ is the power margin with both the G_{RAMax} and G_{preMax} incorporated.

The preliminary transmission performance of six modulation formats is compared in Fig. 3. When the transmission length is over 210 km, the performances of both the OOK and DPSK modulated systems deteriorate quickly, and the superiority of DPSK to OOK disappears gradually.

For a launch power optimized NRZ-DPSK system with a fixed length L, when transmission length is less than L, the nonlinear phase noise effect is larger than that of ASE noise, and it will be less than that of ASE noise when transmission length is longer than L. When ASE noise is not considered in the simulation, the performances of all six modulation formats system in 300-km transmission are free of error. So, the ASE noise is the main source for the BER deterioration in distance longer than 180-km domain, as shown in Fig. 3.

By using the Eqs. (1)—(4) and the equivalent noise power spectral density function[8], the accumulated amplified spontaneous emission power (AASEP) can be written as

$$P_{\mathrm{ASE}} = \left[G_{\mathrm{line}}\left(G_{\mathrm{RA}} - 1\right) n_{\mathrm{RA}} + \left(G_{\mathrm{line}} - 1\right) n_{\mathrm{line}}\right] \cdot 2 \cdot h\nu_i l_{\mathrm{DCF}} G_{\mathrm{pre}} B_{\mathrm{o}} + 2 \cdot \left(G_{\mathrm{pre}} - 1\right) n_{\mathrm{pre}} h\nu_i B_{\mathrm{o}}, \tag{5}$$

where n_{RA}, n_{line}, n_{pre} are the noise figure of Raman amplifier, line amplifier, and preamplifier respectively, l_{DCF} is the signal loss in DCF fiber, h is the Plank constant, ν_i is the ith channel frequency, B_{o} is the spectra width of the optical Bessel filter at the receiver.

The relation between the AASEP entering into receivers and the transmission length is given in Fig. 4. The solid line with squares is the calculated accumulated ASE noise power after demultiplexing with $n_{\mathrm{RA}} = 0$ (dB) and $n_{\mathrm{line}} = n_{\mathrm{pre}} = n_{\mathrm{EDFA}} = 4$ (dB); the dashed line with circles is the results with $n_{\mathrm{RA}} = n_{\mathrm{line}} = n_{\mathrm{pre}} = -1$ (dB), i.e., all the optical amplifiers are supposed to be Raman amplifiers with very low noise. It can be seen that the difference between them is very small. The long transmission distance is always accompanied with exponentially grown noise power in this transmission scheme. With the span length increasing, nonlinear phase noise becomes smaller due to the weak power at the end of transmission link; however, the ASE power strength grows exponentially. So, it can be seen that AASEP is the major source for the deterioration of the superiority of RZ-DPSK to the other formats.

According to the simulation results above, it can be found from Fig. 3 that RZ-DPSK and CSRZ-DPSK show better performance than NRZ-DPSK, RZ, CSRZ and NRZ, which can be explained by the high receiver

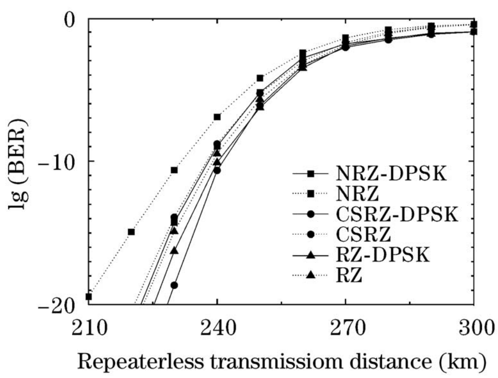

Fig. 3. 40 × 40-Gb/s WDM repeaterless transmission performance of different modulation formats.

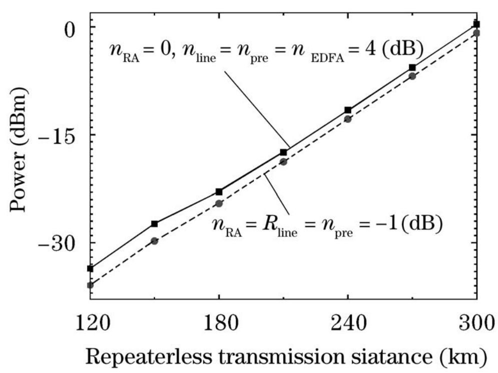

Fig. 4. Demultiplexed ASE noise power versus repeaterless transmission distance for different noise figures.

sensitivity of DPSK and high nonlinearity tolerance of narrow pulse width. Figure 5 shows the 210-km receiver sensitivity. It can be found that the demultiplexed received optical power of RZ-DPSK is over 1 dB lower than that of other formats when BER is 10^{-15}.

To further investigate the superiority of RZ-DPSK, by taking into account its high receiver sensitivity, an optimization of launch power and demultiplexed received optical power is performed, and the results are listed in Table 2. The transmission performances of RZ-DPSK system and CSRZ-DPSK system are given in Fig. 6. The solid line with circles is the BER performance of optimized CSRZ-DPSK system, and the solid line with triangles is that of optimized RZ-DPSK, where RZ-DPSK shows better nonlinearity tolerance than CSRZ-DPSK

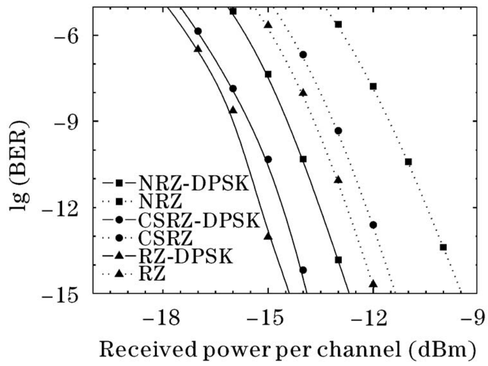

Fig. 5. Comparison of receiver sensitivity after 210-km transmission for the different modulation systems as a function of demultiplexed received optical power.

Table 2. Optimized Launch Power and Demultiplexed Received Power per Channel for RZ-DPSK and CSRZ-DPSK Modulated System in 270-km Repeaterless Transmission

	CSRZ-DPSK	RZ-DPSK
$P_{\rm lau}$ (dBm)	8.5	8.0
$P_{\rm rec}$ (dBm)	−12	−12

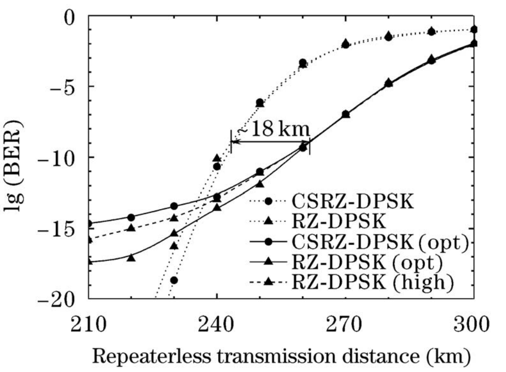

Fig. 6. Performance comparison of CSRZ-DPSK and RZ-DPSK modulated system at different launch and received power with optimization and without optimization in 270-km repeaterless transmission respectively.

when the transmission distance is shorter than 270 km. The two solid lines coincide when distance is longer than 270 km due to ASE noise. Even if the launch power for RZ-DPSK system is increased, the transmission performance does not improve obviously, as shown by the dashed line with triangles in Fig. 6. From the line, when $P_{\rm lau}$ = 8.5 dBm, BER performance of RZ-DPSK system deteriorates.

It can be found that the optimized values of launch power and received power have correspondence with a specific transmission distance. Receiving before that distance, fiber nonlinearity affects BER more than ASE noise does, and inversely, while receiving after that distance, ASE noise affects system BER more than fiber nonlinearity does.

Because of the wider spectra of RZ-DPSK than that of CSRZ-DPSK, the AASEP tolerance of RZ-DPSK system is worse than that of CSRZ-DPSK, as shown by the two dotted lines in Fig. 6, while the nonlinearity tolerance of RZ-DPSK system is better than that of CSRZ-DPSK system as shown by the two solid lines.

In conclusion, the transmission performance of six modulation formats is numerically compared in 40 × 40-Gb/s WDM repeaterless systems with the span length ranging from 120 to 300 km. RZ-DPSK demonstrates higher nonlinearity tolerance, higher receiver sensitivity and lower power penalty. Simulation results indicate that RZ-DPSK demonstrates the best performance among all the formats when the AASEP is small. But with the increasing of AASEP, the superiority of RZ-DPSK transmission performance over the other five modulation formats is vanished. AASEP is justified to be the major source for the deterioration of the superiority.

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