Spectral Efficiency Improvement of the Optical Communication Systems

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***Abstract* –** In this paper, different amplitude and phase modulation formats are investigated and compared to find the optimum one among them for high spectral efficiency (SE) Wavelength Division Multiplexing (WDM) systems with an acceptable value of the Bit Error Rate (BER). Also, the effectiveness of using the polarization interleaving scheme in minimizing the nonlinear effects in the optical fiber channel for the various modulation formats is investigated. (Optisystem v 7.0) A simulation package is used to simulate the system. The simulation results show the effectiveness of using the polarization interleaving in decreasing the nonlinear effects. RZ modulation formats are found to give a better BER value than the corresponding NRZ formats but with a smaller value of the SE. Among the compared modulation formats, RZ-AMI and the RZ-DQPSK are the only formats that are found to give the optimal performance for high capacity WDM networks.

Keywords –Spectral Efficiency, Optical modulation formats, Polarization Interleaving.

1. Introduction

In order to meet the ever-increasing demand in telecommunication capacity, fiber optic communication systems have been evolving dramatically over the past decade. The fiber optic communication traffic growth has been at a rate of about 2 dB per year, representing a traffic increase of a factor of 100 in 10 years. The capacity increase in fiber optic communication systems has been achieved mainly by deploying more fiber links, populating more wavelength channels per fiber link through Dense Wavelength Division Multiplexing (DWDM), and increasing the data rate per wavelength channel [1].

Transmission through optical fiber cables plays an important role in the communication networks of nowadays. The main motivation for this is the enormous potential bandwidth of optical fiber (>100 THz), which is several orders of magnitude larger than the bandwidth of copper media like coaxial cables or twisted wire pairs [2].

2. SE Improvement in Optical Communication Systems

The use of WDM can increase the system capacity because it transmits multiple bit streams over the same fiber simultaneously. When N channels at bit rates B_1, B_2 … B_N are transmitted simultaneously over a fiber of length L, the total bit rate of the WDM link becomes:

$$B_T = B_1 + B_2 + \cdots B_N \qquad (1)$$

For equal bit rates, the system capacity is enhanced by a factor of N. The most relevant design parameters for a WDM system are the number of channels N, the bit rate B at which each channel operates, and the frequency spacing Δv_{ch} between two neighboring channels. The product NB denotes the system capacity and the product $N\Delta v_{ch}$ represents the total bandwidth occupied by a WDM system [3].

The spectral efficiency (η_s) is defined as:

$$\eta_s = B/\Delta v_{ch} \qquad (2)$$

Where B is the single-channel bit rate and Δv_{ch} is the channel spacing.

The throughput of a DWDM transmission system can be increased in many ways by using a wider optical bandwidth, by increasing spectral efficiency, or by some combination of the two. Utilizing a wider bandwidth typically requires additional amplifiers and other optical components, therefore; raising spectral efficiency is often the more economical alternative [4]. Different modulation formats are introduced to enhance the spectral efficiency of the optical communication systems. Spectrally efficient modulation formats are used to decrease the channel dispersion and crosstalk among the adjacent channels.

There are different factors that should be considered for the right choice of modulation format such as: spectral efficiency, power margin and tolerance against group-velocity dispersion (GVD) and against fiber nonlinear effects like self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), and stimulated Raman scattering (SRS) [5]. A wide variety of works to compare the modulation formats to high spectrally efficient WDM systems are done. J.-X. Cai et al, [6] in 2005, compared the performance of the RZ-, CSRZ-, and NRZ-DPSK formats at 40 Gb/s over transoceanic distances using a non-slope-matched test-bed. RZ-DPSK was more nonlinear tolerant than CSRZ-DPSK, but CSRZ-DPSK performed the best for co-polarized channels with 100 GHz channel spacing.

M. Secondini et al, [7] in 2005, theoretically investigated and analytically compared different modulation formats in terms of robustness to the combined effect of the CD and PMD, and the impact of the narrow optical filtering. They found that DQPSK is quite robust to both PMD and CD, and is not degraded when channel spacing is set to be as in current 10 Gb/s WDM systems.

C. R. da Silveira et al, [8] in 2009, presented a theoretical comparison among six types of modulation formats applied to a 40 Gb/s transmission through the 170 km long KyateraTestbed. NRZ-OOK is the only format, which has not presented adequate BER, while all the others resulted in a BER lower than 10-12, each one for a different range of transmitted power. For the WDM configuration, NRZ-OOK and CSRZ had not reached a satisfactory performance. The NRZ-DPSK has been the less impacted format in the WDM configuration in comparison to its results in the single-channel configuration.

C. R. da Silveira et al, [9] in 2011, theoretically evaluated different optical modulation formats at 40 Gb/s are under three transmission constraints: spectral narrowing due to filter cascading, chromatic dispersion and self-phase modulation. Modulation schemes such as DPSK & DQPSK, are found to provide the best performance.

3. Proposed Simulated System

The modulation formats are simulated in 8 × 40 Gb/s WDM system and are divided into two parts:

Simulation of 8-channels at 100 GHz channel spacing with 40 Gb/s bit rate.

Simulation of 8-channels at 50 GHz channel spacing with 40 Gb/s bit rate.

The reason of simulating the system at two different channel spacing is to analyze the performance of the modulation formats at smaller system bandwidth and narrower channel spacing where the crosstalk arising from neighboring channels is enhanced.

The polarization interleaving scheme is used to reduce the nonlinear effects and the crosstalk between the adjacent channels. The block diagram of the polarization interleaving system is shown in Fig. 1. The simulated system is shown in Fig. 2. The odd and even number channels are multiplexed together into two separate branches, whose states of polarization (SOPs) are adjusted using polarization controllers, so that they are orthogonal. A polarization beam combiner or a device known as the channel polarization interleaver is then used to create a WDM signals whose neighboring channels are orthogonally polarized [10].

An ITU-T G.652 optical fiber is used in simulation because it is found in a previous works like [11] and [12] to be the optimal fiber type against the fiber nonlinearities as compared to the other types of optical fibers. In order to decrease the pulse broadening resulting from the chromatic dispersion effects, a dispersion compensating fiber (DCF) is used in the simulation of the fiber channel. A symmetrical dispersion compensation scheme is used as it is found in previous works like [13] and [14] to be the optimal type of dispersion compensation scheme. The optical fiber channel consists of an SMF with an attenuation coefficient value of 0.2 dB/km, a dispersion coefficient value of 17 ps/(km.nm) and dispersion slope coefficient of 0.075 ps/(km.nm^2). The length of the SMF is 25 km with an effective area of 22 μm^2.

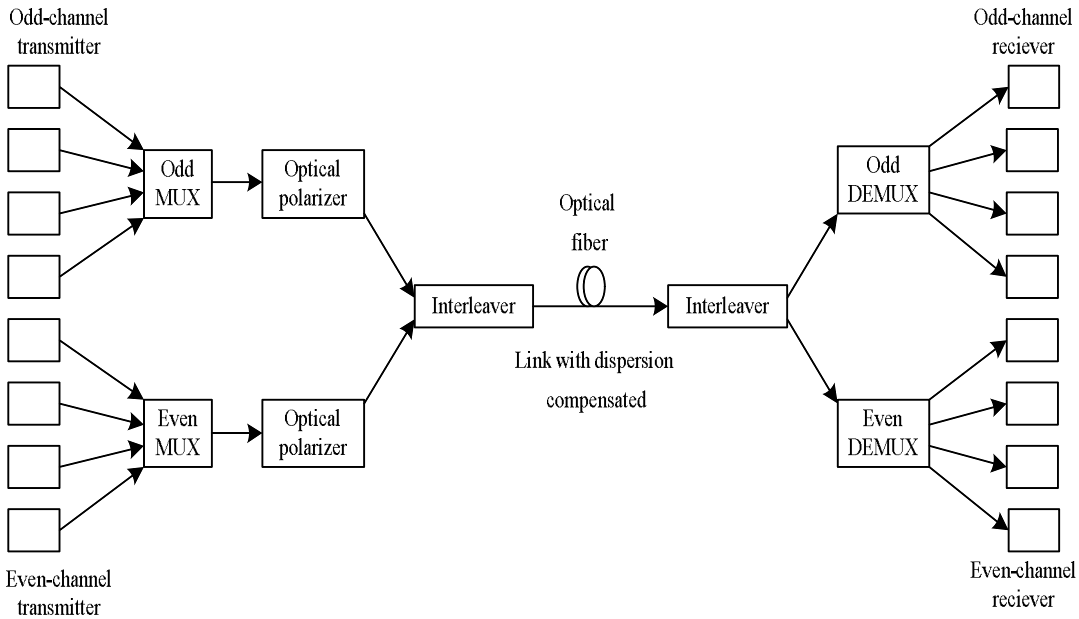


Figure 1. Block diagram of the polarization interleaved WDM system [10].

Then it is followed by a DCF with a length of 5 km. It's attenuation constant is 0.5 dB/km, the dispersion coefficient value is -85 ps/(km.nm) and the dispersion slope coefficient is -0.3 ps/(km.nm^2). The effective area of the DCF is 70 μm^2. The value of the effective area of the DCF is larger than that of the SMF in order to alleviate the nonlinear effects incurred in the DCF. Then, the DCF is followed by a second DCF with the same parameters of the first one. the attenuation, and the losses of the connectors and the splicers. An attenuator is placed before the EDFA to simulate the connector and the splicer losses of the fibers. The value of the connector loss and the splicer loss are taken as 0.25 dB and 0.15 dB

Then, a second SMF with the same parameters of the first SMF is inserted at the end of the fiber channel. This configuration forms the symmetrical dispersion compensating scheme.

The value of the DGD parameter for all the fiber types is 0.1 ps/km$^{1/2}$. The span length is taken as 60 km. An EDFA is used at the end of each span with a gain value of 30 dB to compensate the losses incurred in the optical fiber channel, which result from

respectively. A minimum acceptable value to compare the modulation formats is taken as 1×10^{-12} which corresponds to a Q factor of 17 dB. The simulation parameters of the optical fibers channel are listed in table1.

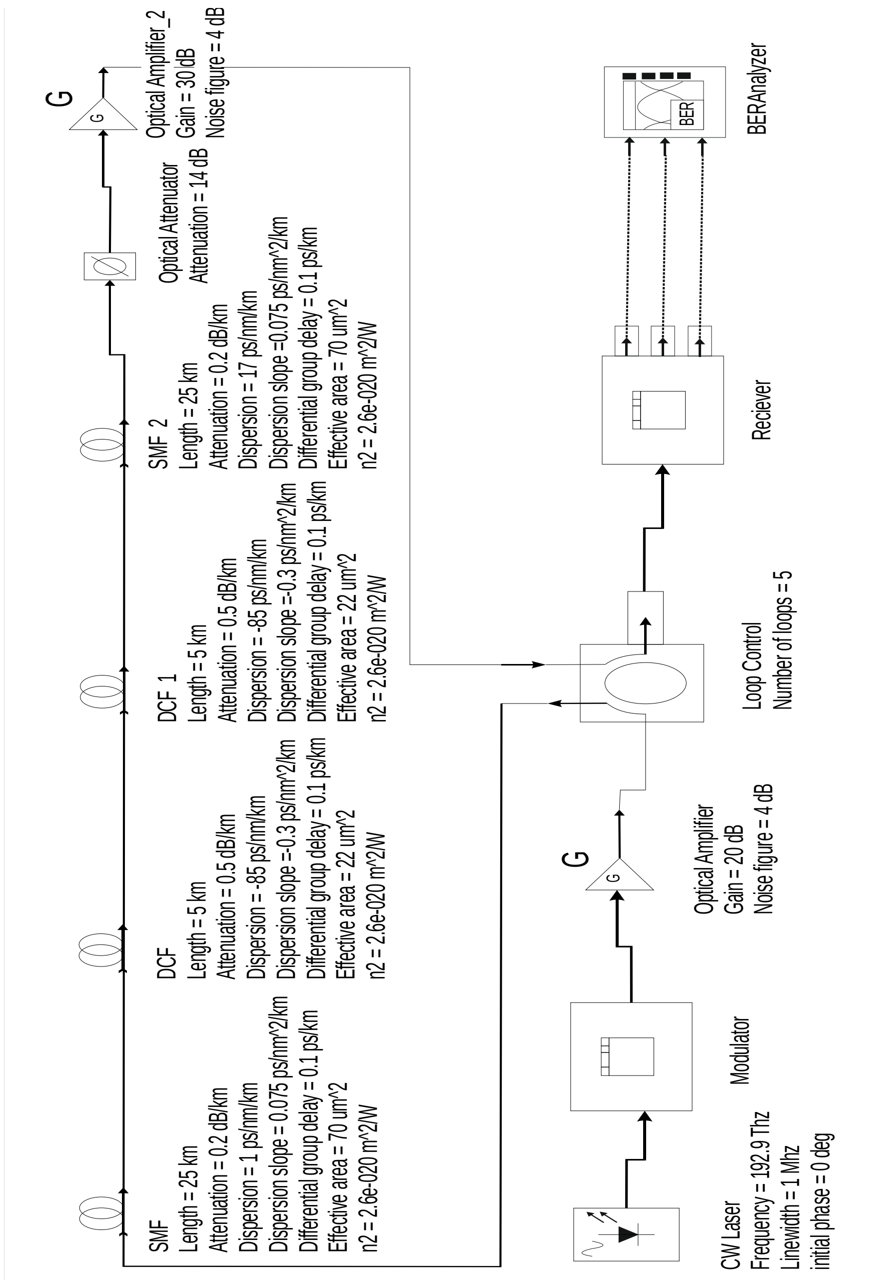


Figure 2. The simulated optical communication system.

Table1. System Parameters.

Parameter	Value
Reference bit rate	40 Gb/s
Number of channels	8 channels
Frequency spacing	100 GHz (0.8 nm) and 50 GHz (0.4 nm)
Center frequency	192.9 THz
Span length	60 km
Source line width	1 MHz
PRBS	2^k-1=7
CW power	from 0 dBm to 20 dBm
NF of EDFA (dB)	4
Photodiode type	APD
APD gain	5
Sensitivity	Better than -40 dBm
ITU-T G.652 Fiber parameters	
α (dB/km)	0.2
Dispersion parameter D (ps/(nm.km))	17
Dispersion slope S (ps/(km.nm^2))	0.075
Effective area (μm^2)	70
DGD parameter (ps/$\sqrt{km}$)	0.1
n_2 (m^2/W)	2.6e (-20)
DCF parameters	
α (dB/km)	0.5
Dispersion parameter D (ps/(nm.km))	-85
Dispersion slope S (ps/(km.nm^2))	-0.3
Effective area (μm^2)	22
DGD parameter (ps/$\sqrt{km}$)	0.1
n_2 (m^2/W)	2.6e (-20)

4. Simulation Results

Figure 3 shows the optical spectrum and waveform of the various modulation formats considered in the simulations at 40 Gb/s. Table2 shows the SE of the modulation formats considered. It shows that in general DQPSK formats have the highest values of the SE among the compared modulation formats because of their reduced bandwidth.

Figures 4 and 5 show the eye diagrams of the system at the input (to the left), without polarization interleaving (in the middle), and with polarization interleaving (to the right) at 100 GHz channel spacing and 50 GHz channel spacing respectively.

The eye height is larger with the polarization interleaving system with a lower crosstalk, which shows the effectiveness of using the polarization interleaving in reducing the nonlinear effects.

Figures 6 and 7 show a comparison of the amplitude and phase modulation formats in 100 GHz channel spacing respectively. The results are summarized in table2.

From figure 6 and table 2, it is found that among the amplitude and the pseudo multilevel formats, RZ-AMI is found to have the maximum value of the Q factor and power range with the maximum value of the SE as in the case of the single channel system. 33% RZ-OOK and 67% RZ-OOK have nearly the same Q factor, but at higher power region, 33% RZ-OOK shows a better performance than 67% RZ-OOK. This is because as the bit duration is decreased, its robustness to PMD and the CD effects is increased. NRZ-OOK and RZ-DUO show the worst performance and they did not reach the 17 dB threshold (BER=1×10^{-12}).

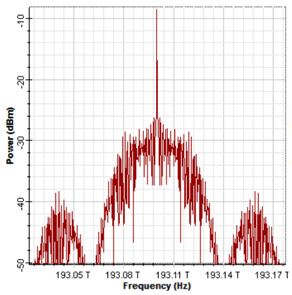
From figure7, it is shown that the maximum Q factor of RZ-DQPSK formats are higher than RZ-DPSK formats because the bandwidth occupied by the RZ-DQPSK formats is half that of the DPSK formats with a higher SE. Although NRZ-DQPSK has the highest SE among all the modulation formats, it does not reach the 17 dB threshold because it is affected by noise and it requires a high OSNR.

Figure 8 and figure 9 show a comparison of the amplitude and phase modulation formats in 50 GHz channel spacing respectively. The results are summarized in table2.

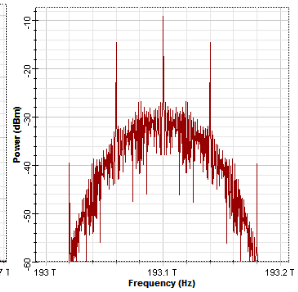
From figure 8 and table2, it is shown that only RZ-AMI and 67% RZ-OOK have reached the 17 dB threshold. RZ-AMI is found to give the best performance among the amplitude and pseudo multilevel formats giving the highest Q factor and power range just as the case in the system with 100 GHz channel spacing. The performance of 33% RZ-OOK and 67% RZ-OOK in the 100 GHz channel spacing is nearly the same, but at 50 GHz channel spacing, the performance of 67% RZ-OOK is better than that of 33% RZ-OOK which does not reach the 17 dB threshold. This can be attributed to the large bandwidth of the 33% RZ-OOK which leads to degrade its performance in tighter channel spacing.

For the phase modulation formats, at 100 GHz channel spacing, RZ-DQPSK are found to give a larger Q factor than RZ-DPSK and NRZ-DPSK is better than NRZ-DQPSK. In 50 GHz channel spacing, the formats with a tighter bandwidth perform in a better way. It is seen from figure 9, that all the DQPSK formats perform better than DPSK formats. It is also shown that the performance of DPSK formats at 50 GHz channel spacing is nearly the same as that of the amplitude and pseudo multilevel formats. This is because as the channel spacing is decreased, the formats with the tighter bandwidth (the higher SE) perform the best. This shows the advantage of employing DQPSK formats as the channel spacing is decreased.

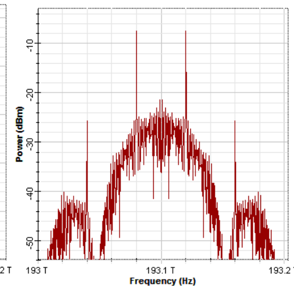
From figure 9 and table2, it is shown that only RZ-DQPSK formats reached the 17 dB threshold. RZ-AMI and RZ-DQPSK are the only formats that reached the 17 dB threshold with a maximum Q factor to 33% RZ-DQPSK and a maximum SE to 67% RZ-DQPSK. Therefore, the right choice of the modulation format between them is a compromise between the Q factor and the SE.



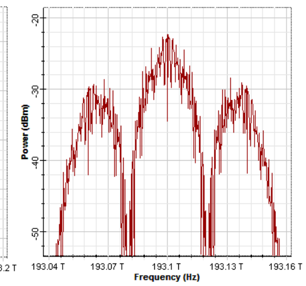
NRZ-OOK



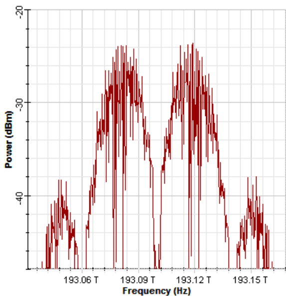
33% RZ-OOK



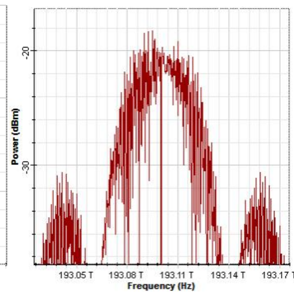
67% RZ-OOK



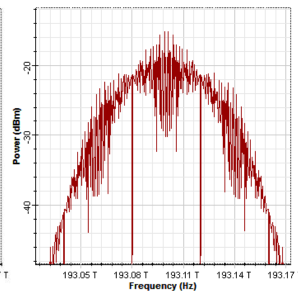
RZ-DUO



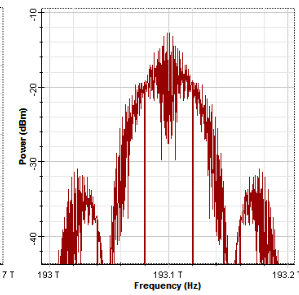
RZ-AMI



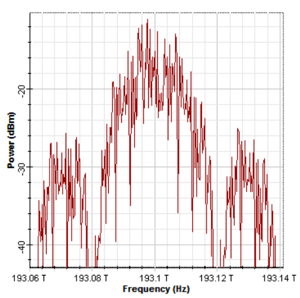
NRZ-DPSK



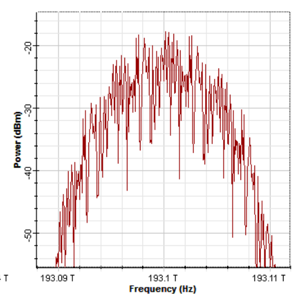
33% RZ-DPSK



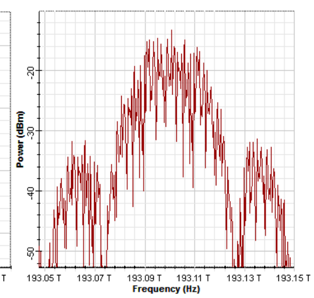
67% RZ-DPSK



NRZ-DQPSK



33% RZ-DQPSK



67% RZ-DQPSK

Figure3. Optical Spectrum and waveform of the simulated modulation formats at 40 Gb/s.

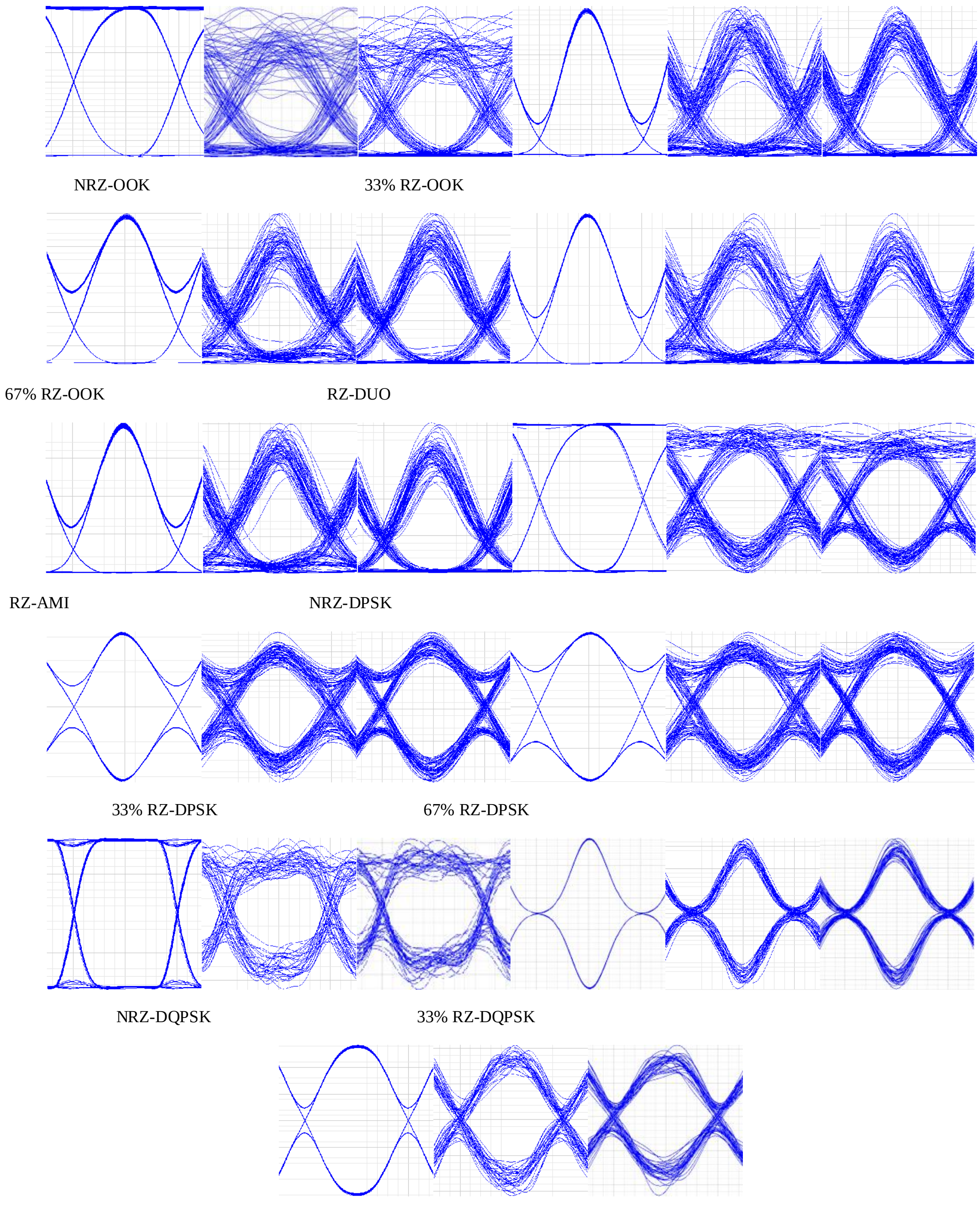
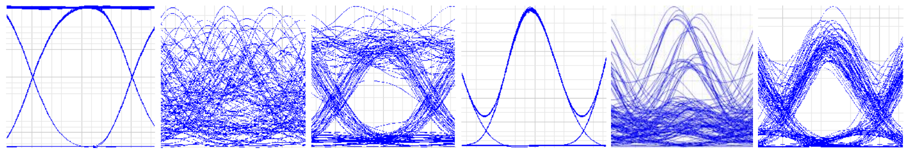
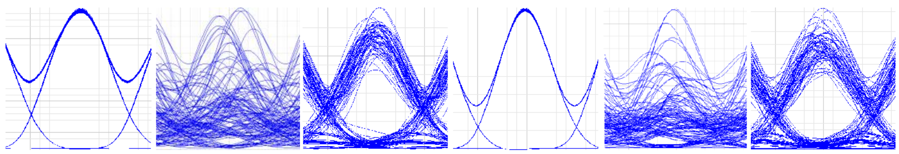


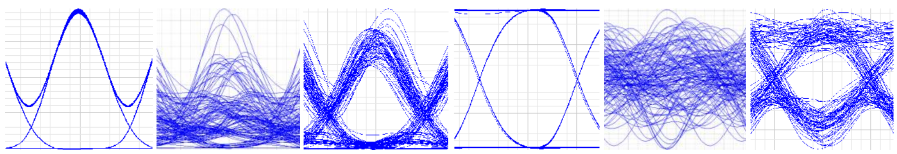
Figure4. Eye diagrams of the 8-channel system at the input (to the left), without polarization interleaving (in the middle) and with polarization interleaving (to the right) at 100 GHz channel spacing.



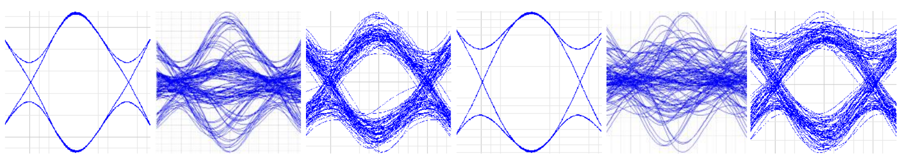
NRZ-OOK 33% RZ-OOK



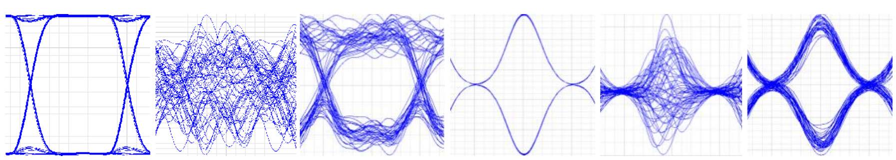
67% RZ-OOK RZ-DUO



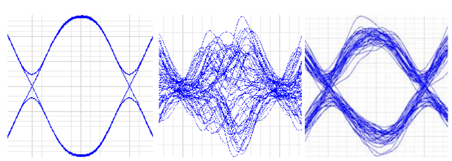
RZ-AMI NRZ-DPSK



33% RZ-DPSK 67% RZ-DPSK



NRZ-DQPSK 33% RZ-DQPSK



67% RZ-DQPSK

Figure 5. Eye diagrams of the 8-channel system at the input (to the left), without polarization interleaving (in the middle) and with polarization interleaving (to the right) at 50 GHz channel spacing.

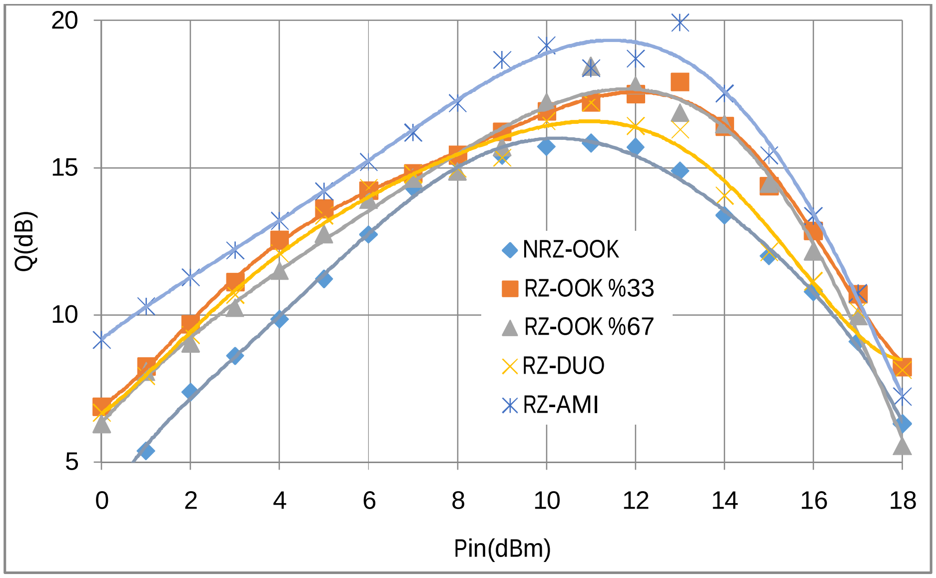


Figure 6. Comparison between amplitude modulation formats at 100 GHz.

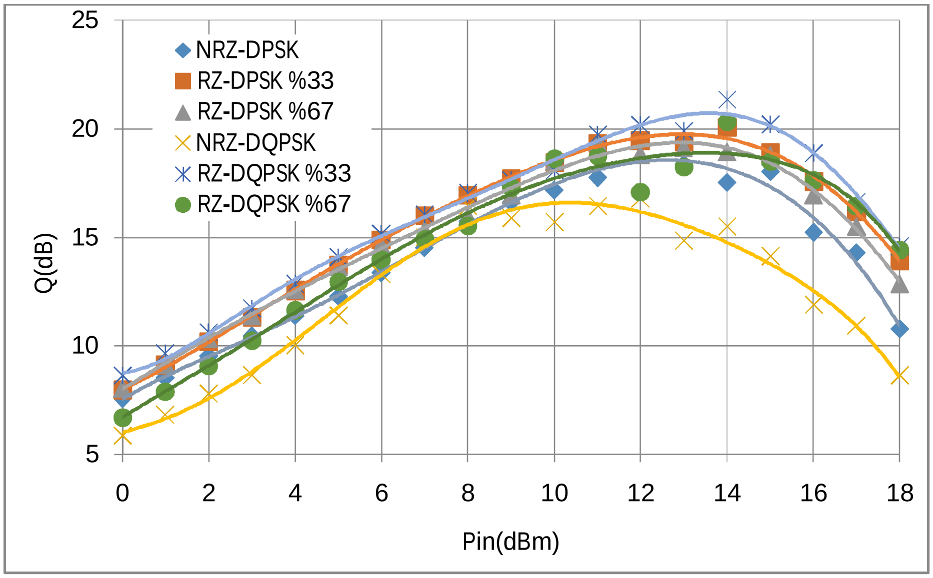


Figure 7. Comparison between phase modulation formats at 100 GHz.

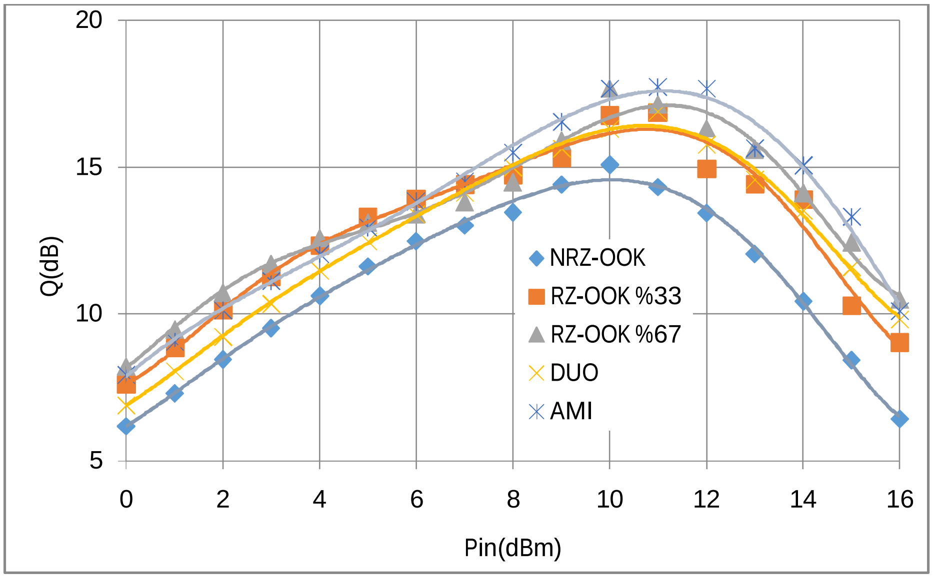


Figure 8. Comparison between amplitude modulation formats 50 GHz.

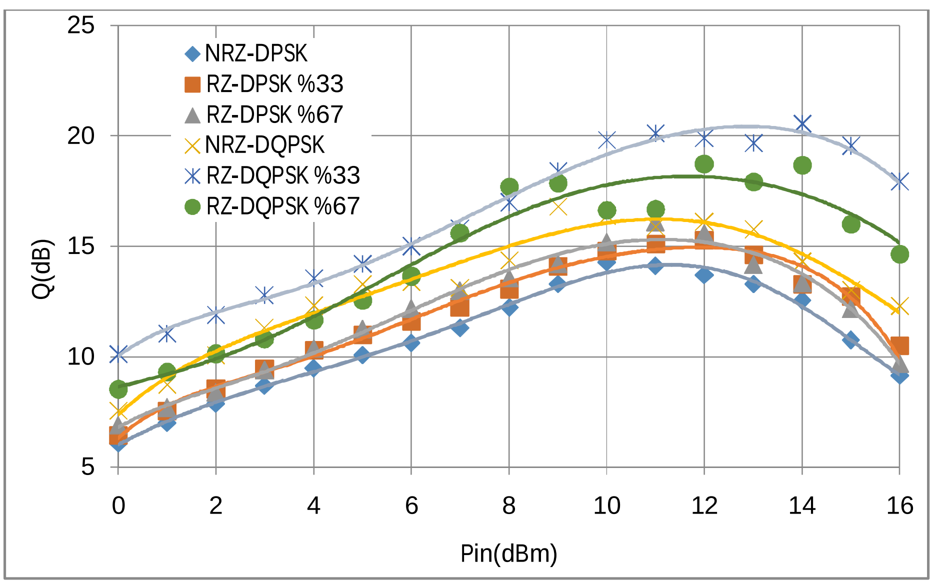


Figure 9. Comparison between phase modulation formats at 50 GHz.

Table 2. Maximum Q factor of the simulated modulation formats at single channel, 100 GHz and 50 GHz channel spacing systems with the corresponding power range and spectral efficiency

Modulation Format	100 GHz		50 GHz		SE (b/s/Hz)
	Max. Q	P (dBm)	Max. Q	P (dBm)	
NRZ-OOK	16	----------	14.6	----------	0.5
33% RZ-OOK	17.8	10.2-13.4	16.5	----------	0.27
67% RZ-OOK	17.8	10-13.4	17.1	10.7-11.5	0.33
RZ-DUO	16.6	------------	16.5	----------	0.33
RZ-AMI	19.4	7.6-14.4	17.6	9.6-12.4	0.5
NRZ-DPSK	18.6	9.4-15.3	14.2	------------	0.5
33% RZ-DPSK	19.7	8.1-16.5	15	------------	0.25
67% RZ-DPSK	19.4	8.7-16.1	15.4	------------	0.4
NRZ-DQPSK	16.6	------------	16.2	------------	1
33% RZ-DQPSK	20.7	8.2-17	20.4	7.8-16.4	0.5
67% RZ-DQPSK	18.9	9-17	18.2	8.8-14.4	0.8

5. Conclusions

The eye diagrams show the effectiveness of using the polarization interleaving in reducing the nonlinear effects and the crosstalk especially at low channel spacing. Among all the simulated modulation formats, RZ-AMI, 33% RZ-DQPSK and 67% RZ-DQPSK are the only formats that give a suitable value of the SE and their Q factor remains above the 17 dB threshold from the 100 GHz channel spacing system to the 50 GHz channel spacing system. This shows that these formats are suitable for long-haul WDM networks.

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