Comprehensive Assessment of New Modulation Techniques in 40Gb/s Optical Communication Systems

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Abstract. In this paper, comprehensive assessments are proposed for intensity modulations and phase modulations respectively. Several key performance features, like receiver sensitivity, chromatic dispersion tolerance, nonlinearity tolerance, and noise sensitivity were compared among these modulation techniques. Results show that 66% duty cycle RZ signal so-called the carrier-suppressed return-to-zero (CSRZ) format has the best performance in the intensity modulations. In phase modulations, the most outstanding modulation is DPSK. DQPSK modulation is also a very promising choice if the effect of noise could be resolved. The combination of intensity modulation and phase modulation will compromise the performance advantages of both.

1. Introduction

In modern optical communication systems, modulation format has a great impact on system performance. NRZ (non-return-to-zero) modulation format is widely used in the 10G and lower rate optical communication system. Compared with other modulation formats, NRZ modulation is simple and convenient, and requires lower cost. But when it comes to the 40Gb/s and higher speed, transmission capacity is restricted because of the optical signal-to-noise ratio (OSNR) tolerance and nonlinear effects of NRZ. Therefore NRZ modulation is no longer suitable for the application of 40Gb/s or higher rate long-distance transmission systems. 40Gb/s long-distance transmission systems need spectrum-efficient modulation formats. For the current 40Gb/s commercial wavelength division multiplexing (DWDM) systems, special modulation formats are used, such as optical duo binary (ODB), return-to-zero (RZ), carrier-suppressed return-to-zero (CSRZ), differential phase shift keying(DPSK), and differential quadrature reference phase shift keying (DQPSK), etc. New modulation techniques have become a research focus in high-speed long haul transmission systems. Compared to NRZ, the most significant advantage of new modulation formats is to improve the N × 40Gb/s WDM transmission system for the most limiting factors (such as dispersion, nonlinear effects, back to back OSNR, etc.), and significantly expand the system's transmission distance\(^1\).

This paper combines simulation contrast and theoretical analysis to reveal the features and application conditions for each intensity modulation and phase modulation. Moving a further step, a best combination of them is concluded.
2. Simulation Setup
All the simulations are performed using the commercial simulation software package OptiSystem Software. 40Gb/s optical communication systems with diverse modulation formats discussed are established and shown in Figure 1, Figure 2, Figure 3, and Figure 4, respectively. In these diagrams, PRBS represents a pseudo random bit sequence binary generator, which generates $2^9$ (512 bites) long sequences. NRZ is a converter changing binary to electrical NRZ signal. OBPF is an optical band pass filter, as it is used as a second order Gaussian filter, the full width at half maximum (FWHM) bandwidth is optimised for individual modulation formats. V-Att is a variable attenuator. ELPF represents an electric low pass filter, which is fifth order and the -3 dB bandwidth is optimised for individual modulation formats. The frequency and power of the CW laser diode are set at 193.1 THz and 1 mW, respectively. Extinction ratio of Mach-Zehnder intensity modulators (MZM) is set at 30 dB. The link consists of a 100km span of standard single mode fiber (SSMF) with group velocity dispersion (GVD) of 17ps/nm/km, an attenuation coefficient of 0.2dB/km, an effective area $A_{eff}$ of $70\mu m^2$, and a nonlinear index $n_2$ of $2.6\times10^{-20}m^2/W$. The chromatic dispersion compensation is performed by dispersion compensation fiber (DCF). Erbium doped fiber amplifier (EDFA) is used to compensate the attenuation generated by SSMF fibers. A PIN photodetector with dark current of 10 nA and thermal noise of $1.0e^{-11}W/Hz$ is assumed.

In order to generate RZ signals with different duty cycles, one MZM is used to generate an NRZ format first, then another MZM is applied on top of the NRZ signal to obtain the corresponding RZ signals with different duty cycles (like 33%, 50% and 66% RZ signals), using RF clock signals with different amplitudes and frequencies.

The realization of DQPSK is a little complex, which comprises one phase modulator (PM) and one MZM in series, with 90 and 180 degree phase shift, respectively.

3. Comparison of Intensity Modulations
3.1. Nonlinearity Tolerance
High-speed and long-distance transmission requires higher launch power of the transmitter, which will result in more severe nonlinear effects[2]. Therefore, the nonlinear effects become an important constraint to 40Gb/s or higher rate long-distance transmission.

The changes of nonlinear effects are achieved by controlling the launch power. Figure 5(a) reflects how the nonlinear effects impact bit error rate (BER) using different intensity modulation formats.

The four curves in Figure 5(a) all decrease at first and then increase in the simulation process. If the input optical power is small, the system will reach a high BER because the OSNR is too low. With the rising of input power, the BER continues to fall and finally arrives at the lowest point, where the system has the optimal performance. After that, the BER increases again, because the nonlinear effects become the dominant influence factor in the system. Hence, the lowest point represents the best launch power. We can see from the figure that best launch power of NRZ is 6dBm, while the RZ formats with 66%, 50% and 33% duty cycle have the best launch power of 8dBm, 9.3dBm, and 10.5dBm, respectively.

3.2. Dispersion Tolerance
The dispersion means that the phase velocity of a wave depends on its frequency, or alternatively, the group velocity depends on the frequency. It will cause inter-symbol interference and result in error bits during transmission[3].

Ignoring the polarization mode dispersion (PMD) effects and nonlinear effects, we set the launch power to the 4dBm. By adjusting the length of DCF, the chromatic dispersion (CD) can be changed from less compensation to over compensation. When the length of DCF is 10KM, chromatic dispersion is fully compensated, while less than 10KM means less compensation. The optical attenuator is adjusted to make the BER comparable.

The simulation results are shown in Figure 5(b). When the BER reaches at 10e-9, the residual dispersion that the system can tolerate is calculated as follow:

\[
D = \left| (L - 10\text{km}) \times (-80\text{ps/nm/km}) \right|
\]

(1)

Where L is the length of DCF in different modulation systems.

It can be calculated that dispersion tolerance of NRZ is 32ps/nm, while that of RZ format of 66% duty cycle is 20ps/nm. RZ formats of 50% and 33% duty cycle have approximately equal dispersion tolerance, which is 12ps/nm and has become an important constraint.

3.3. Receiver Sensitivity
Receiver sensitivity is defined as the minimum average optical power required for the optical receiver to satisfy the communication quality conditions (BER or OSNR), and plays an important role in the measurement of receiver performance[4].

The thermal noise of PIN photodetector is set to \( \frac{1}{2} \times e^{-\frac{W}{10}} \text{W/Hz} \). The simulation results are shown in Figure 5(c). When the BER reaches at 10e-9, the receiver sensitivity of NRZ modulation format is -9.2dBm, while that of RZ format of 66%, 50% and 33% duty cycle are -10.5dBm, -11dBm and -11.7dBm, respectively.
Figure 5(a). Nonlinear tolerance Comparison in intensity modulations. Figure 5(b). Dispersion tolerance Comparison in intensity modulations. Figure 5(c). Comparison of receiver sensitivity in intensity modulations.

Table 1 shows the comparison of intensity modulations. It can be seen that a smaller duty cycle of the intensity modulation brings about a chain of positive reactions, such as more intensive energy, stronger nonlinear tolerance and higher receiver sensitivity. However, on the downside, the poorer dispersion tolerance will arise. The RZ signal with 66% duty cycle which is called CSRZ is proposed to be the best trade-off among all the above performances in various intensity modulations.

|                  | best launch power | dispersion tolerance | receiver sensitivity |
|------------------|-------------------|----------------------|----------------------|
| NRZ              | 6dBm              | 32ps/nm              | -9.2dBm              |
| RZ50             | 8dBm              | 20ps/nm              | -10.5dBm             |
| RZ66(CSRZ)       | 9.3dBm            | 12ps/nm              | -11dBm               |
| RZ33             | 10.5dBm           | 12ps/nm              | -11.7dBm             |

4. Comparison of Phase Modulations

4.1. Noise Tolerance
Noise tolerance is an important performance index of phase modulations\(^5\). Considering the condition of full compensation and no nonlinear effects, we set the optical launch power to 4dBm, and the optical attenuator to 8.43db. By changing the thermal noise of PIN photodetector, the simulation results are shown in Figure 6(a).

We can see from the figure that, the BER of DPSK modulation is much lower than that of OOK(On-Off Keying) modulation system. When the BER reaches at 10\(^{-9}\), the noise that can be tolerated is \(1.5e^{-3}W/Hz\) in OOK system and \(2.5e^{-3}W/Hz\) in DPSK system. However, the noise can be tolerated in DQPSK system is nearly zero in the simulation condition we set.

4.2. Nonlinear Tolerance
The thermal noise of PIN photodetector is set to \(1.0e^{-3}W/Hz\) and the optical attenuator is adjusted to allow the system BER comparable. Figure 6(b) reflects how the nonlinear effects impact on BER in different phase modulation formats.

Similarly to the intensity modulations, the trends of the three curves in Figure 5 all decrease at first and then increase in the process. The best launch power of DPSK is 10dBm, while that non-linear tolerance of OOK and DQPSK are both 12dBm.

4.3. Dispersion Tolerance
The simulation results are shown in Figure 6(c). According to the formula (1), we can calculate that the dispersion tolerance of OOK is 8ps/nm, while that of phase modulation DPSK and DQPSK are improved to 13.6ps/nm and 32ps/ns, respectively.

Table 2 shows the comparison of phase modulation. Compared with the intensity modulations, the performance of phase modulations does not have strong nonlinear tolerance, but performs well in dispersion tolerance, especially DQPSK, for its half-reduced symbol rates. Compared with OOK, DPSK’s noise tolerance enhanced greatly for the reason that the amplitude’s variation range is expanded to from -1 to 1. DQPSK is particularly sensitive to noise as its phase is equally divided into four parts. Using more phases in phase modulation is accompanied with a lower symbol rate, stronger anti-dispersion ability, but higher noise sensitivity. The system noise can be reduced by coordinating with Raman amplifier[6].

Compromising all the performance indexes mentioned above, DPSK is the most outstanding one in various phase modulations. If the impact of noise can be effectively reduced, multi-system phase modulation, such as DQPSK, is also very promising for its two positive characteristics: a performance enhancement and a low requirement of the electronic devices’ speed, though its implementation is with high complexity.

5. Conclusions
Comprehensive assessment has been done in this article. Considering all performance indicators that have been simulated, the most outstanding intensity modulation format is CSRZ, while DPSK is the best in the phase modulations. If the effect of noise can be effectively solved, DQPSK modulation is also very promising. The combination of intensity modulation and phase modulation combines their performance advantages and will be the trend of modulation used in 40Gb/s optical communication systems.

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