Analysis the Speciality of Modulation Format in WDM-PON System

Li Li
Departments of Electronic Information and Electrical Engineering, Anyang Institute of Technology/ Anyang, China 455000

Corresponding author: lilifkb@163.com

Jijun Zhang1 and Aihan Yin2
1Departments of Electronic Information and Electrical Engineering, Anyang Institute of Technology/ Anyang, China 455000
Email: hnayzjj@yahoo.com.cn

2School of Information Engineering, East China Jiaotong University/ Nanchang, China 330013;
Email: wufanedu@163.com

Abstract—In the wavelength division multiplexing passive optical network (WDM-PON) system, the modulation format was important. While three different modulation formats including not-return-to-zero (NRZ), return-to-zero (RZ), carrier-suppressed return-to-zero (CS-RZ) and the optical differential quadrature reference phase shift keying (DQPSK) modulation format of each code are introduced in the article. A method of their modulated signal generation with computer is described, and a comparison of their spectra and waveforms is made. The 40 Gbps signal transmitted in 200 km G.652 fiber by way of single channel with erbium-dope-fiber-amplifier (EDFA) is simulated for these three formats. It shows that the ability of anti-dispersion and anti-PMD (Polarization Mode Dispersion) is better in the CS-RZ-DQPSK modulation format, and this format has the smallest eye-opening penalty with a wider range of power into the optical fiber.

Index Terms— Optical communication; Modulation format; NRZ (Not Return-to-Zero); RZ (Return-to-Zero); CS-RZ (Carrier-Suppressed Return-to-Zero); DQPSK (Differential Quadrature Reference Phase Shift Keying); Dispersion

I. INTRODUCTION

With the rapid development of the next generation of optical fiber transmission information system, 40Gbps optical fiber transmission system and its wavelength division multiplexing (WDM) system have been the focus of research. In order to enhance the capacity of the system and diminish the degradation of performance which would be caused by the loss of transmission, systems engineering and optimization would be important. Thereinto, the optical code-pattern would be the important factor which decides the spectrum efficiency, transmission quality and the dispersive tolerance of the system. Thus, the chosen of code-pattern is the first factor in the high speed optical transmission system [1-3].

The application of optical fiber transmission system and dense-wavelength-division-multiplexing (DWDM) system make the dispersive tolerance markedly decrease, and the non-linearity effect has an impact on the system performance. Traditional NRZ code-pattern might not have met the demand, while needs other new modulation format. People propose many code-patterns in terms of 40Gbps optical transmission system [4-11], such as RZ [3], and also propose the RZ of the carrier suppressive (CS-RZ), single sideband-RZ (SSB-RZ), duodecimal-RZ (D-RZ), mend duodecimal-RZ (MD-RZ) [6], RZ-DPSK [5-6], full spectrum return-to-zero (FSRZ) and chirp return-to-zero (CRZ). DPSK and RZ are better than NRZ in the term of anti-noise. RZ-DPSK is better than NRZ at the influence of anti-dispersive. CS-RZ, CRZ and the DPSK are better than NRZ in the term of nonlinear effect. SSB is better than NRZ in term of spectrum effectiveness. Recently, some code-patterns appeared which include differential quadrature phase keying (DQPSK) [7], intensity modulation-DPSK (IM-DPSK) [8], and the Prefiltered CS-RZ [9]. NRZ-DPSK, RZ-DPSK and CS-RZ-DPSK use the phase change of the close codes showing the signal “0” and “1”. Their spectrums are smoothness and do not have any linear spectrum. IM-DPSK is to diminish the optical intensity change of close codes, in order to decrease the chatter and non-linearity. Differential quadrature phase keying (DQPSK) makes the phase change in the code of two bytes. Prefiltered CS-RZ is used to filter the CS-RZ in order to decrease the width of the spectrum and enhance the spectrum efficiency. DQPSK modulation format with a four-level phase modulation and approximation constant envelope in intensity is helpful to resist nonlinear effects [10]. In comparison with the traditional phase modulation format DPSK, inserting the reference phase “π/2” in the DQPSK between the phase of “0” and “π” helps to double spectrum utilization. In the DQPSK modulation format, using two bits to represent each symbol not only reduce the transmission speed and lower the electric drive component cost, but also greatly enhance the flexibility towards PMD. Under the same condition of symbol rate, the transmission capacity of DQPSK system is twice of DPSK modulation format [11]. In contrast to the binary OOK modulation format, DQPSK has a good ability to resist nonlinear effects by nature. By using the balanced receiver, the sensitivity of DQPSK can be enhanced by 3dB and the requirements towards OSNR can also be
reduced [4-5]. Besides, without the polarization multiplexing the channel utilization of DQPSK can be surpassed to 0.8b/s/Hz. Under using the polarization multiplexing, the spectrum effectiveness of 2b/s/Hz can be achieved in the DWDM transmission system, without giving rise to additional loss. Thus, code modulation formats for high speed optical communication transmission system are of great significance.

In the paper, take the 40Gbps for example, the way of modelization of NRZ, RZ and CS-RZ with computer analyzes the optical spectrum. The 40 Gbps signal transmitted in 200 km G.652 fiber by way of single channel with erbium-dope-fiber-amplifier (EDFA) is simulated for these three formats. Thus, we can get the better code-pattern with high spectrum efficiency and high tolerance for the optical noise and the non-linearity effect.

II. THE PRINCIPLE AND CHARACTERISTIC OF THE CODE-PATTERN

A. The principle of chosen code pattern

There are three principles for the modulation format that we should follow: firstly, the compact modulation signal spectrum is good at enhancing the operating factor of the spectrum and the dispersive tolerance of group velocity; secondly, a high non-linearity tolerance; thirdly, the structure of the transmitter and receiver are simple as soon as possible.

B. The principle of NRZ

We usually use the Mach-Zehnder modulator (MZM) and the consecutive wave (CW) laser in the modulation system. Except for the NRZ, their appearance would be performed by the two concatenation of MZM. These two concatenations of MZM play different roles. The first MZM is used to bring various pulses by the drive of the clock signal. The second one is used to load the data.

Figure 1 is the frame of the NRZ signal of the optics. When transmitted the “1” in the NRZ, optical signal impulse occupies a whole bit-time; when there is no optical pulse, the signal is “0”. The realization of the coding is simple, only needing a high speed exterior modulator that can work effectively at the speed of 10Gbps. The advantage of NRZ is the simplicity of application, low cost and high spectrum efficiency, which can be used widely into the synchronous digital hierarchy (SDH) and wavelength division multiplexing (WDM) system. Under the 10Gbps system, we use the NRZ modulation model. The disadvantage of NRZ is that the transition does not return zero between two codes, the sensitivity for transmission loss. So it is not suitable for high speed and the extra long-distance transmission.

C. The principle of RZ and CS-RZ

Figure 2 is the frame about the principle of the generation of RZ and CS-RZ, which is all composed by the two concatenation of MZM. The technology of RZ code prevails recently, which is used in the high speed of 40Gbps optical transmission system. In the pulse sequence of RZ code, the transition area which connects “1” amplitude of electric field has the independent time envelope. Because modulation format of RZ has different transition all the time in the code bits, thus it can bring more “neatness” optical signal in order to unscramble the receiver. The advantage of RZ is the low average of optical power; higher ability on anti-non-linearity effect and anti-polarization mode dispersion (PMD) [12]. RZ code is also more conducive to clock recovery. Because the consecutive “1” of NRZ is a whole, the eye pattern of RZ code stretches bigger, the better ability of anti-error-code performance, and the greater improvement on 3dB of the optical signal noise ratio (OSNR), providing

The CS-RZ code is based on the traditional RZ code, and join the phase separation of π in each adjacent sign bit (no matter the sign bit is “0” or “1”). The phase separation of the carrier can be regarded as the signal with a minus but the carrier is invariability. The typical value of this signal with positive and negative ambipolar is ‘0’, so there is no pinnacle in the zero frequency because of not having Δ function (impulse function), after multiplying the according carrier, and there is also no pinnacle in the carrier. In the CS-RZ, because the sign about consecutive code of amplitude of electric field is reversed, it can get the low width of spectrum. With the high power, it not only increases the dispersive capacity, but also enhances the resist of the non-linearity of self-phase modulation (SPM) and four-wave-mixing (FWM), and so on.

D. The principle of DQPSK

A precoding component is needed in the optical DQPSK system to avoid iteration decoding, incorrect transmission and lower the complexity of hardware, ensuring the receiving signal could be detected accurately in demodulation. Because of different coding having different modulations, precoding is essential for the optical DQPSK transmission system.
A 40Gbit/s signal is produced by a Pseudo-Random Binary Sequence (PRBS) generator, as in Figure 1 the PRBS is executed serial to parallel exchange, making \( U_i \) and \( V_i \) to be the input signals. The following equations are the rules of precoding:

\[
I_i = (Q_{i-1} \oplus I_{i-1})(U_i \oplus I_{i-1}) + (Q_{i-1} \oplus I_{i-1})(V_i \oplus I_{i-1})
\]

\[
Q_i = (Q_{i-1} \oplus I_{i-1})(U_i \oplus I_{i-1}) + (Q_{i-1} \oplus I_{i-1})(U_i \oplus I_{i-1})
\]

As the signals after precoding, there are four choices in the I and Q. That is (00, 01, 10, 11), corresponding to four phases (0, \( \pi/2 \), \( 3\pi/2 \)) or (\( \pi/4 \), \( 3\pi/4 \), \( 5\pi/4 \), \( 7\pi/4 \)). \( \Delta \Phi \) is used as the differential phases of continuous bits in DQPSK and its value is (0, \( \pi/2 \), \( 3\pi/2 \)). The way of differential coding is effective to avoid incorrect decision which is caused by the inverting phase of the receiver.

E. The Modulation mode of optical DQPSK

Three different modulation modes are currently researched: using two MZMs separately in series way and in parallel connections, besides, the third way is only using one signal phase modulator (PM) \(^{(13)}\). As shown in Figure 4, the series connection way is analyzed in the paper below. After the precoding, the branches of I and Q are respectively sent into two MZMs for four levels phase modulation. The phase modulation is made in branch I and Q, when the output of branch I is 0 or 1, and the phase of optical signal is separately according to 0 and \( \pi \). The phase difference of branch I is \( \pi \), but in branch Q the phase difference is \( \pi/2 \). That’s to say, the output of branch Q is 0 or 1, which is separately according to 0 and \( \pi/2 \).

When the joint output of branch I and Q are (00, 01, 10, 11), the joint modulation of four level phases are (0, \( \pi/2 \), \( \pi \), \( 3\pi/2 \)) which is the same as the series way. The output phase difference of DQPSK is \( \pi/2 \), and the modulation way is inseparably related to the precoding.

III. CODE TYPE WAVE SHAPE AND SPECTRAL ANALYSIS

### A. The wave analysis of code type

At present, it researchers often use MZM to produce modulation code; MZM is the coupler about two-interconnected-3dB. While a \( \Delta L \) optical path difference is existed between two wave-guides, there can be phase modulation which produced by the two signals at the output. Such as the figure1, with the Mach-Zehnder interferometer (MZI) modulator modulating for CW laser lamp-house, the electric 40Gbps NRZ signal (2'-1 pseudo-random binary sequence) would become 40Gbps NRZ optical signal. For the figure2, the first MZI has the same working theory as MZI of the figure1, only changing the electric 40Gbps of NRZ into RZ (dutyfactor is 0.5); the second MZI should be controlled by the sine-wave clock and voltage bias on two spur track of MZI, getting through to modulate the amplitude, frequency, phase and the voltage bias, then we can get the optical signal of RZ and CS-RZ.

Thus, we might as well input light field:

\[
E_{in}(t) = |E_o|e^{j\omega t}
\]

(1)

Passing the MZM, after the phase modulation, the light field would be:

\[
E_{out}(t) = \frac{E_{in}(t)}{2} \left[ e^{j\varphi_1(t)} + e^{j\varphi_2(t)} \right]
\]

(2)

\[
\varphi_1(t) = \frac{\pi}{2} \cdot \frac{1}{V_s} \left[ V_{in} \sin(\omega_t + \Psi) + V_1 \right]
\]

(3)

\[
\varphi_2(t) = \frac{\pi}{2} \cdot \frac{1}{V_s} \left[ V_{in} \sin(\omega_t + \Psi) + V_2 \right]
\]

(4)

where the \( V_{in} \), \( \omega_t = 2\pi f \), \( \Psi (i=1,2) \) are the amplitude, angular frequency, phase of the clock signal on two spur track of MZI separately. \( V_1, V_2 \) can provide the voltage bias on two spur track of MZI separately. When the single arm works cause the appearance of phase separation, \( V_{\pi} \) is the switch voltage from the max to the min. In order to make the MZM working at the station without chirp, researchers can add the voltage of two single arms to a fixed voltage bias. That is \( V_1(t) + V_2(t) = V_{bias} \), thus the output of the light field is:

\[
E_{out}(t) = \frac{E_{in}(t)}{2} \cos \left[ \frac{\pi}{2V_s} \left( V_{in} - V_{bias} \right) \right] e^{j\frac{\pi V_{bias}}{2V_s}}
\]

(5)

The output of the light intensity is:
\[ P_{\text{out}}(t) = P_{\text{in}}(t) \cos \left[ \frac{\pi (V_{\text{in}} - V_{\text{bias}})}{2V_x} \right] \]  

(6)

RZ code with the duty factor 50% can set the input of the electrical clock signal:

\[ V_{\text{in}} = \frac{V_x}{2} \sin \omega_0 t \]  

(7)

Then the light field and light intensity of RZ is by equation (3), (4):

\[ E_{\text{out}}(t) = E_{\text{in}}(t) \cos \left( \frac{\pi}{2} \sin \omega_0 t \right) \]  

(8)

\[ P_{\text{out}}(t) = P_{\text{in}}(t) \left[ 1 + \cos \left( \pi \sin \omega_0 t \right) \right] \]  

(9)

With the above formula: the optical impulse cycle is \( \frac{2\pi}{\omega_0} \), the angle frequency is \( \omega_0 \), the full width at half maximum (FWHM) is \( \frac{\pi}{\omega_0} \).

CS-RZ code would be set the input of electrical clock signal:

\[ V_{\text{in}} = \frac{V_x}{2} \sin \omega_0 t \]  

(7)

Then the light field and light intensity of RZ is by equation (3), (4):

\[ E_{\text{out}}(t) = E_{\text{in}}(t) \cos \left( \frac{\pi}{2V_x} \left( V_x \sin \omega_0 t - V_x \right) \right) e^{-\frac{t^2}{2\sigma^2}} \]  

(10)

\[ P_{\text{out}}(t) = P_{\text{in}}(t) \sin^2 \left( \frac{\pi}{2} \sin \omega_0 t \right) \]  

(11)

From the above formula: the optical impulse cycle is \( \frac{\pi}{\omega_0} \); angle frequency is \( 2\omega_0 \); the FWHM is \( \frac{\pi}{\omega_0} \).

B. Optical spectrum analysis of the code pattern

According to the above academic expression of various code-models, using the method of optical spectrum towards random signal in the communication theory, the power spectrum density of the random pulse sequence concludes two parts: consecutive spectrum \([P_u(\omega)]\) and linear spectrum \([P_v(\omega)]\). Through computing the power spectrum of NRZ code is:

\[ P_s(f) = \frac{1}{2} T_s \alpha \left( \pi (f_c - f) T_s \right)^2 + \frac{1}{2} \delta(f_c - f) \]  

(12)

\[ P(f) = f_0 \left[ \sum_{n=0}^{\infty} J_{2n+1} \left( \frac{\pi}{f_0} \right)^2 \frac{2n+1}{2\pi(f-f_0)\left[(f-f_0)^2-(2n+1)^2f_0^2\right]} \right] \times \cos \left[ \frac{\pi(f-f_0)}{f_0} \right]^2 + \sum_{n=0}^{\infty} \delta(f - f_c \pm 2(2n-1)f_0) \]  

(13)

From the above analysis, the CS-RZ optical spectrum has a distance of stair linear spectrum that is 40GHz. There is no linear spectrum existing, which is caused by the change of \( \pi \) phase between the two pulses. The power spectrum of the RZ code is:

\[ g(t) = e^{-\frac{t^2}{2\sigma^2}} \left[ J_0 \left( \frac{\pi}{f_0} \right) \right] + \sum_{n=0}^{\infty} J_n \left( \frac{\pi}{f_0} \right) \cos(2nf_0 t) - 2 \sum_{n=0}^{\infty} J_n \left( \frac{\pi}{f_0} \right) \sin \left[ (2n+1)\pi f \right] \]  

(14)

From the expression of the RZ optical spectrum, we can know the linear spectrum existed in the RZ optical spectrum.

From the formula, the FWHM of the NRZ signal is 25ps; the FWHM of RZ is 12.5ps and CS-RZ is 12.5ps, too. The figure below is the spectrum of modulation format; figure 3 is the wave and the spectrum of NRZ; the spectrum width of NRZ is about 80GHz (the distance between secondary line spectrum); figure 4 is the wave and the spectrum of RZ code; and spectrum width is 160GHz; figure 5 is the wave and the spectrum of CS-RZ code, and spectrum width is 120GHz with no carrier wave. This section through comparing of NRZ, RZ and CS-RZ between the single pulse wave and the spectrum, gets the concrete transmission characteristic of various modulations formats [5][10].

C. The analysis of spectrum by three kinds of modulation formats

The impulse width of NRZ is the biggest in these six kinds of modulation formats, so it is easy to occur intersymbol interference, sensitive to the transmission loss, infective to the non-linear effect, but the spectrum of
NRZ is narrow which is good for decreasing the interference of inter-channel WDM system.

The duty-factor of RZ code will reduce; impulse width is smaller than NRZ, which can restrain the non-linear effect of optical fiber, suitable to work in the high-power and long-distance transmission condition, but the spectrum of RZ code is wide, dispersive capacity decreases markedly, which is not good for management.

The impulse width of CS-RZ is smaller than NRZ; spectrum width is between the NRZ and RZ. The part of carrier wave is prohibited, it is not only becoming smaller and increasing the dispersive capacity, but also becoming stronger on the ability of resisting the non-linear effect.

The spectrum of NRZ is the most compact in the one-lever sideband and baseband, which results in the cost of eye pattern stretch becoming smaller comparatively caused by the wave variation and the interference. Because NRZ spectrum contains the residual carrier element, it would be affected by the FWM interference in the low dispersive optical fiber.

The spectrum of RZ has the linear spectrum obviously in the one-lever sideband and baseband; one-lever sideband will overlap in the adjacent channel of WDM system which has minor interval. So it can arouse badly interference between the adjacent channels. Then its optical spectrum width is bigger than NRZ and CS-RZ so as not to assure the optical efficiency in the receiver.

In parallel to NRZ, the optical spectrum shape of CS-RZ is prohibited in the frequency element of carrier wave. But the two interval linear-spectrums with a period of a byte frequency are appeared, which is 40GHz in this article. When the frequency interval of WDM channel is greater than 100GHz, this characteristic can diminish the loss of FWM, but it can result in serious loss of FWM when the frequency interval is 75GHz. The spectrum width of CS-RZ is between NRZ and RZ.

Figure3 (b) is the code type of NRZ-DQPSK. Its spectrum width is narrow which is helpful to suppress the chromatic dispersion and reduce the crosstalk between the channels in the DWDM systems. But the wider pulse width is easy to cause inter-symbol interference (ISI) and nonlinear effects.

From Figure4 (b) we can see that the widest optical spectrum of RZ-DQPSK reduces the tolerance of chromatic dispersion and goes against the control of chromatic dispersion.

In Figure5 (b) the pulse width of CS-RZ-DQPSK is between the other two code types. The narrow spectrum is not only enhancing the spectrum efficiency and transmission capacity, but also having higher tolerance of chromatic dispersion and nonlinear effects. In contrast with the RZ-DQPSK, CS-RZ-DQPSK has better effects on the suppression of crosstalk between channels.

Besides, because of using the DQPSK modulation mode, from the spectrum of different code types we can see that this modulation mode largely reduce the emergence of linear spectrum, which could enhance the receiving accuracy of spectrum and lower the Interference and BER.

IV. THE ANALYSIS OF TRANSMISSION PERFORMANCE

A. The performance of anti-dispersive code format

Figure6 is the anti-dispersion performance comparison of different code types in DQPSK. CS-RZ-DQPSK has the best anti-dispersion performance, and the advantages are more obvious especially when the dispersion index is large. From the above-mentioned optical spectrum we know that the spectrum width of RZ-DQPSK is widest and reduce the tolerance of anti-dispersion performance. As the energy of different duty cycle RZ codes are more concentrated, it is helpful to enhance the sensitivity of the receiver and lower the cross-talk between pulses, which is proper for the high speed transmission. From the following figure5, the difference between the RZ-DQPSK and NRZ-DQPSK is not very big when the chromatic dispersion index is small. But when the chromatic dispersion index is large, due to the wider spectrum of RZ-DQPSK code, the rate of increase with power penalty in the RZ-DQPSK code will pass the NRZ-DQPSK code. Chromatic dispersion is not only affecting the amplitude of the signal, but also the phase, besides enhancing the power penalty.

B. The anti-PMD ability of code format

In the low-speed transmission system the PMD may not be taken into account, but for the speed of system surpassing 40Gb/s, the effects of PMD can not be neglected. In the high-speed transmission system the PMD makes the pulse broadening and causes the power penalty, limiting the transmission distance without repeaters. Because the occurrence of PMD is random, so in this paper we only consider the first-order condition. The parameter of eye-opening penalty (EOP) is used to measure the performance of anti-PMD in the different modulation code types.

From figure7 we can see that the CS-RZ-DQPSK has the best performance of anti-PMD. For the NRZ codes, its pulse width is the largest and the pulse is not sensitive to the difference of delays, decreasing the effects of PMD. But because of the reduction of time slot between pulses, the interaction between pulses is to be strengthened. The energy of RZ codes concentrate on the narrower region of the center of symbols, which requires a greater differential group delay than the NRZ codes causing the inter-symbol interference. So the RZ codes have a greater performance than RZ codes in anti-PMD.

For different codes existing an optimal duty cycle makes the Q factor in the system to the best. When the duty cycle is small, the pulse width is narrow and the margin of the pulse broadening is big, which is helpful to reduce the interaction between pulses. But as the decreasing of the pulse width, the delay difference of the two principal polarization parameters is more vulnerable to the pulse shape, which enhances the effects on PMD and leads to the deterioration of transmission performance. On the whole, the anti-PMD performance of the CS-RZ-DQPSK is better than the other two code types.
V. THE FORMAT OF TRANSMISSION SYSTEM AND THE RESULTS OF SIMULATIONS

Make the system configuration of simulations. Transmitter uses the CW laser, which is with the wavelength of 1550nm. With the input MZM of NRZ electrical signal generates the optical NRZ and can be sent to circuitry; The CS-RZ is composed by two MZM concatenation; the first one produces the NRZ and be sent to the second level; From the output CS-RZ of the second level and the second MZM modulator, RF port transmits the sin clock signals when the transmission speed is the half of the whole. The transmission speed is 40Gbps and the signal sequence is 27-1. The transmission optical fiber is composed by the five different single-mode fibers (SMFs) with the length of 50km, and the whole length is 250km. The dispersion compensation uses the dispersion compensation fiber (DCF). The parameter of SMF and DCF is showed in table1. The various simulations of codes are showed in figure8.

VI. CONCLUSIONS

In this article, it produces 40Gbps optical signals of three modulation formats through computer simulation and compares its wave shape and optical spectrum. Then the performance of dispersion compensation is simulated through the no-zero dispersion shifted fiber by single-channel transmission mode. We can get the results: The results show that under the condition of dispersion compensation CS-RZ-DQPSK with the narrow spectrum has the best dispersion tolerance for PMD, which can be able to suppress the nonlinear effects in the optical fiber and get the smallest EOP with a wider range of power into the fiber. Besides, the modulation mode of optical DQPSK has the better performance on the receiving sensitivity and transmission capacity and lowers the requirements for the high speed of modulator. In the future it can expand more workings on the research from the following aspects to go along the research on the new code: carry on the research on the non-linear phenomena in the high-speed optical fiber transmission and get the way to restrain them. Do our more research on the dispersion management for the better transmission performance.

REFERENCES

of Optical Fiber Communications conference, Anaheim, CA.


Li Li received his B.Sc. degree in 2007 and received his M.Sc. degree from East China Jiaotong University, Nanchang, China, in 2010. He joined the Anyang Institute of Technology in 2010 as a lecturer in the Departments of Electronic Information and Electrical Engineering. He has published some papers in the journals and conference proceedings which were indexed by SCI&EI. His major research interests are in optical communication, WDM-PON, QoS guarantees and security.

Jijun Zhang joined the Anyang Institute of Technology as a professor in the departments of electronic information and electrical engineering. Her major research interests are in electronic technology and control theory.

© 2011 ACADEMY PUBLISHER