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Performance Comparison of alCNRZ and nCRZ Modulation Format for WDM/DWDM System

Rupanjali Banerjee, Naveen Dhillon, Manjit Singh

***Abstract*-Advance Modulation formats like alternate chirped non-return-to-zero (alCNRZ) and novel chirped return-to-zero (nCRZ) are playing a significant role in transmission of an optical signal accurately at its destination. High-speed optical signal transmission over long distance is usually achieved by alCNRZ with enhanced nonlinear tolerance. On the other hand increased spectral efficiency and narrower signal spectrum is obtained through nCRZ. In this paper, the comparison between alCNRZ and nCRZ is made on the basis of their performance in presence of higher-order dispersion compensation and phase modulation. The performance of alCNRZ and nCRZ has been analytically compared on various values of phase modulation and higher-order dispersion term to find out which modulation format is better in this regard.**

***Keywords*-alCNRZ, GVD, nCRZ, RZ**

I. Introduction

The performance regarding transmission of a signal in a system can be enhanced if the optical pulses are pre-chirped at the transmitter side, which causes broadening of the signal spectrum thus reducing the tolerance to residual dispersion and to narrow band filtering. This implementation of the pre-chirp can be realized by using either passive component like fiber-piece, optical fiber or active component like Mach-Zehnder Modulator, phase modulator. [1- 2].

Apparently, the Non Return-to-zero (NRZ) based formats possess the property called reduced non-linear tolerance that primarily profit from the implementation of pre-chirp. It was recently found that the main reason behind the pre-chirping of NRZ pulses may be stated as the induced spectral broadening that results in a stronger impact of group-velocity dispersion (GVD). This effect can be partially removed by choosing a proper amount of phase modulation and then implementing that on the NRZ pulses. [3]

This realization is achieved in an advance modulation format known as Alternate Chirped NRZ (alCNRZ) modulation format. This format can improve the performance of a signal during its transmission to the destination in deployed optical transmission system. Moreover this format is also useful because of its simple generation. The maximum transmission distance can be enhanced by improved non-linear tolerance. The main focus of this format is to enable a high speed optical transmission over long-haul (>400 Km) distances. [4], [5], [6]

Alike NRZ, Return-to-zero (RZ) possess an increased nonlinear tolerance. The RZ pulses are produced by the conventional method where a small amount of additional pre-chirping is done at the transmitter end. [1], [7], [8]

The novel chirped RZ (nCRZ) modulation may be suggested as an alternative method for the generation of alternate chirped RZ pulses. It has found to be possible that by using a phase modulator at the transmitter side, narrower signal spectrum of RZ pulses may be obtained. This enables a higher spectral efficiency and an increased nonlinear tolerance. [7], [8], [9]

II. Analytical Description of alCNRZ and nCRZ Modulation Format

I. Mathematical Modeling of alCNRZ

The complex amplitude of the generated alCNRZ pulses is given by: [6], [7]

$$E_{alCNRZ} = \sqrt{P_{NRZ}} \times \exp\begin{pmatrix} i \times m \times \\ (0 \cdot 5 + 0 \cdot 5 \times \cos(2\pi ft)) \end{pmatrix}$$

(1)

Here i is the current in amperes, m is the phase modulation index in radians, f is the clock frequency in GHz and t is the time period in seconds

To insert dispersion into equation number (1), we can multiply it with $e^{-j\beta L}$

$$E_{alCNRZ} = \sqrt{P_{NRZ}} \times \exp\left(\begin{matrix} i \times m \times \\ (0\cdot 5 + 0\cdot 5 \times \cos(2\pi f t)) \end{matrix}\right) \times e^{-j\beta L} \quad (2)$$

Propagation constant β can be expanded in terms of Taylor's series around $\omega = \omega_0$, then (2) can be written as:

$$\beta = \beta_0 + (\omega - \omega_0)\frac{d\beta}{d\omega} + \frac{1}{2}(\omega - \omega_0)^2 \frac{d^2\beta}{d\omega^2} + \frac{1}{6}(\omega - \omega_0)^3 \frac{d^3\beta}{d\omega^3} + \frac{1}{24}(\omega - \omega_0)^4 \frac{d^4\beta}{d\omega^4} \ldots \quad (3)$$

Now as we know that $\frac{d\beta}{d\omega} = \tau$ is the group delay for unit length and L denotes fiber length by putting the value of β from equation in $\exp(-j\beta L)$, we will get [6], [10] and [11]

$$E_{alCNRZ} = -j\left[1 - jF_2 \frac{\partial^2}{\partial t^2} + F_3 \frac{\partial^3}{\partial t^3} - jF_4 \frac{\partial^4}{\partial t^4}\right] \sqrt{P_{NRZ}} \times \exp(i \times m \times (0\cdot 5 + 0\cdot 5 \times \cos(2\pi f t))) \quad (4)$$

Here the values of F_2, F3, and F4 are the higher order dispersion parameters

$$F_2 = \frac{\lambda^2 L}{4\pi c}\frac{\partial \tau}{\partial \lambda} \quad (5)$$

Is the second order dispersion term.

$$F_3 = -\frac{L}{6}\frac{\lambda^2}{(2\pi c)^2}\left[\lambda^2 \frac{\partial^2 \tau}{\partial \lambda^2} + 2\lambda \frac{\partial \tau}{\partial \lambda}\right] \quad (6)$$

Is the third order dispersion term.

Similarly the value of F_4 can be taken as the fourth order dispersion term

$$F_4 = \frac{L}{24}\frac{\lambda^3}{(2\pi c)^3}\left[\lambda^3 \frac{\partial^3 \tau}{\partial \lambda^3} + 6\lambda^2 \frac{\partial^2 \tau}{\partial \lambda^2} + 6\lambda \frac{\partial \tau}{\partial \lambda}\right] \quad (7)$$

In order to simplify the equation (4)

Let $$E = \sqrt{P_{NRZ}} \times \exp\left(\begin{matrix} i \times m \times \\ (0\cdot 5 + 0\cdot 5 \times \cos(2\pi f t)) \end{matrix}\right) \quad (8)$$

$$E_{alCNRZ} = -j \times \sqrt{P_{NRZ}} \left[E - jF_2 \frac{\partial^2 e}{\partial t^2} + F_3 \frac{\partial^3 e}{\partial t^3} - jF_4 \frac{\partial^4 e}{\partial t^4} + \ldots\right] \quad (9)$$

$\frac{\partial^2 e}{\partial t^2} = E_2$, $\frac{\partial^3 e}{\partial t^3} = E_3$, and $\frac{\partial^4 e}{\partial t^4} = E_4$ respectively.

By using the above equation, (9) becomes

$$E_{alCNRZ} = -j \times \sqrt{P_{NRZ}} \left[\begin{matrix} E - jF_2 E_2 + F_3 E_3 \\ - jF_4 E_4 + \ldots \end{matrix}\right] \quad (10)$$

Now, let us consider our original equation which is given by

$$E_{alCNRZ} = \sqrt{P_{NRZ}} \times \exp\left(\begin{matrix} i \times m \times \\ (0\cdot 5 + 0\cdot 5 \times \cos(2\pi f t)) \end{matrix}\right)$$

It is now required to find up to fourth order derivative of the above expression. From (10) it is clear that the first order derivative is expressed as E_1, second order as E_2, third order as E_3 and fourth order as E_4 respectively.

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Since P_{NRZ} is a constant as well as a common term involved in all the derivatives expression, its value will be put at the expression of the fourth order derivative, i.e. E_4.

Now,

$$E = E_{alCNRZ} = \sqrt{P_{NRZ}} \times \exp\left(i \times m \times \left(0\cdot 5 + 0\cdot 5 \times \cos(2\pi f t) \right) \right) \quad (11)$$

To find the first order derivative

$$E_1 = -i \times m \times \pi \times f\left[E \sin(2\pi f t)\right] \quad (12)$$

To find the second order derivative

$$E_2 = -im\pi f\left[E_1 \sin(2\pi f t) + 2\pi f E \cos(2\pi f t)\right] \quad (13)$$

To find the third order derivative

$$E_3 = -im\pi f \begin{bmatrix} E_2 \sin(2\pi f t) + \\ 4\pi f E_1 \cos(2\pi f t) - \\ 4\pi^2 f^2 E \sin(2\pi f t) \end{bmatrix} \quad (14)$$

To find the fourth order derivative, and putting P_{NRZ} in it, the equation becomes

$$E_4 = -im\pi f \begin{bmatrix} E_3 \sin(2\pi f t) + 6\pi f E_2 \cos(2\pi f t) \\ -12\pi^2 f^2 E_1 \sin(2\pi f t) - \\ 8\pi^3 f^3 E \cos(2\pi f t) \end{bmatrix} \quad (15)$$

Putting the values of E_2, E_3 and E_4 from (13), (14) and (15) in equation number (10) we have

$$E_{alCNRZ} = -j \times \sqrt{P_{NRZ}} \begin{bmatrix} E \\ -jF_2 \begin{bmatrix} -im\pi f \\ \begin{pmatrix} E_1 \\ \sin(2\pi f t) \\ + 2\pi f E \\ \cos(2\pi f t) \end{pmatrix} \end{bmatrix} \\ + F_3 \begin{bmatrix} -im\pi f \\ \begin{pmatrix} E_2 \\ \sin(2\pi f t) \\ + 4\pi f E_1 \\ \cos(2\pi f t) \\ -4\pi^2 f^2 E \\ \sin(2\pi f t) \end{pmatrix} \end{bmatrix} \\ -jF_4 \begin{bmatrix} -im\pi f \\ \begin{bmatrix} E_3 \\ \sin(2\pi f t) \\ + 6\pi f E_2 \\ \cos(2\pi f t) \\ -12\pi^2 f^2 E_1 \\ \sin(2\pi f t) \\ -8\pi^3 f^3 E \\ \cos(2\pi f t) \end{bmatrix} \end{bmatrix} \end{bmatrix} \quad (16)$$

This equation can be further simplified by putting the value of higher-order derivatives in detail.

II. Mathematical Modeling of nCRZ

The complex amplitude of the generated nCRZ pulses is given by: [12], [13]

$$E_{nCRZ} = \sqrt{P_{RZ}} \times \exp\left(i \times m \times \left(\sin(2\pi f t)\right)\right) \quad (17)$$

Here i is the current in amperes, m is the phase modulation index in radians, f is the clock frequency in GHz, t is the time period in seconds

To insert dispersion into equation number (17), we can multiply it with $e^{-j\beta L}$

$$E_{nCRZ} = \sqrt{P_{RZ}} \times \exp(i \times m(\sin(2\pi ft))) \times e^{-j\beta L} \tag{18}$$

Propagation constant β can be expanded in terms of Taylor's series around $\omega = \omega_0$, then (18) can be written as:

$$\beta = \beta_0 + (\omega - \omega_0)\frac{d\beta}{d\omega} + \frac{1}{2}(\omega-\omega_0)^2\frac{d^2\beta}{d\omega^2} + \frac{1}{6}(\omega-\omega_0)^3\frac{d^3\beta}{d\omega^3} + \frac{1}{24}(\omega-\omega_0)^4\frac{d^4\beta}{d\omega^4}\dots \tag{19}$$

Now as we know that $\frac{d\beta}{d\omega} = \tau$ is the group delay for unit length and L denotes fiber length by putting the value of β from equation in $\exp(-j\beta L)$, we will get [10], [11] and [14]

$$E_{nCRZ} = -j\left[1 - jF_2\frac{\partial^2}{\partial t^2} + F_3\frac{\partial^3}{\partial t^3} - jF_4\frac{\partial^4}{\partial t^4}\right]\sqrt{P_{RZ}} \times \exp(i \times m(\sin(2\pi ft))) \tag{20}$$

The values of F_2, F3, and F4 can be referred from equation number (5), (6) and (7).

In order to simplify the equation (20)

Let $$E = \sqrt{P_{RZ}} \times \exp(i \times m(\sin(2\pi ft))) \tag{21}$$

$$E_{nCRZ} = -j \times \sqrt{P_{RZ}}\left[E - jF_2\frac{\partial^2 e}{\partial t^2} + F_3\frac{\partial^3 e}{\partial t^3} - jF_4\frac{\partial^4 e}{\partial t^4} + \dots\right] \tag{22}$$

$\frac{\partial^2 e}{\partial t^2} = E_2, \frac{\partial^3 e}{\partial t^3} = E_3$, and $\frac{\partial^4 e}{\partial t^4} = E_4$ respectively.

By using the above equation, (22) becomes

$$E_{nCRZ} = -j \times \sqrt{P_{RZ}}\begin{bmatrix} E - jF_2E_2 + F_3E_3 \\ -jF_4E_4 + \dots \end{bmatrix} \tag{23}$$

Now, let us consider our original equation which is given by

$$E_{nCRZ} = \sqrt{P_{RZ}} \times \exp(i \times m(\sin(2\pi ft)))$$

It is now required to find up to fourth order derivative of the above expression. From (23) it is clear that the first order derivative is expressed as E_1, second order as E_2, third order as E_3 and fourth order as E_4 respectively.

Since P_{RZ} is a constant as well as a common term involved in all the derivatives expression, its value will be put at the expression of the fourth order derivative, i.e. E_4 .

Now,

$$E = E_{nCRZ} = \sqrt{P_{RZ}} \times \exp(i \times m(\sin(2\pi ft))) \tag{24}$$

To find the first order derivative

$$E_1 = i \times 2 \times m \times \pi \times f[E\cos(2\pi ft)] \tag{25}$$

To find the second order derivative

$$E_2 = 2im\pi f[E_1\cos(2\pi ft) - 2\pi fE\sin(2\pi ft)] \tag{26}$$

To find the third order derivative

$$E_3 = 2im\pi f\begin{bmatrix} E_2\cos(2\pi ft) - 4\pi fE_1\sin(2\pi ft) \\ -4\pi^2 f^2 E\cos(2\pi ft) \end{bmatrix} \tag{27}$$

To find the fourth order derivative and putting P_{RZ} the equation becomes

$$E_4 = 2im\pi f \begin{bmatrix} E_3\cos(2\pi ft) - 6\pi fE_2 \sin(2\pi ft) \\ -12\pi^2 f^2 E_1 \cos(2\pi ft) + \\ 8\pi^3 f^3 E \sin(2\pi ft) \end{bmatrix}$$

(28)

Putting the values of $E_{2,}E_3$ and E_4 from (26), (27) and (28) in equation number (23) we have

$$E_{nCRZ} = -j \times \sqrt{P_{RZ}} \begin{bmatrix} E \\ -jF_2 \begin{bmatrix} 2im\pi f \\ \begin{pmatrix} E_1 \\ \cos(2\pi ft) \\ -2\pi fE \\ \sin(2\pi ft) \end{pmatrix} \end{bmatrix} \\ +F_3 \begin{bmatrix} 2im\pi f \\ \begin{pmatrix} E_2 \\ \cos(2\pi ft) \\ -4\pi fE_1 \\ \sin(2\pi ft) \\ -4\pi^2 f^2 E \\ \cos(2\pi ft) \end{pmatrix} \end{bmatrix} \\ -jF_4 \begin{bmatrix} 2im\pi f \\ \begin{bmatrix} E_3 \\ \cos(2\pi ft) \\ -6\pi fE_2 \\ \sin(2\pi ft) \\ -12\pi^2 f^2 E_1 \\ \cos(2\pi ft) \\ +8\pi^3 f^3 E \\ \sin(2\pi ft) \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

(29)

This equation can be further simplified by putting the value of higher-order derivatives in detail.

Putting the different values of all the constant terms used (i, m, f, P_{RZ}) in equation number (16) and (29) the required graphs are plotted.

III. Results and Discussion

According to the International Telecommunication Union (ITU) Telecommunication Standardization Sector (ITU-T) recommendation [15], it is assumed that $\lambda = 1.55\mu m$ and $\frac{\partial \tau}{\partial \lambda} = 20\, ps / nm.km$, L denotes fiber length. By using all these values the following dispersion parameters are obtained that are represented by equation (5), (6) and (7) respectively.

$$F2 = -12.72(ps)^2 L, \quad F3 = \frac{d^3\beta}{d\omega^3} = 0.00298(ps)^3 L$$

$$F4 = \frac{d^4\beta}{d\omega^4} = -5.32x10^{-5}(ps)^4 L\ .$$

The modified analytical formulation for the alCNRZ and nCRZ modulation format in the presence of higher order dispersion terms is given in equation (16) and (29) respectively. The following graphical representation shows a diverse nature of plot depicting signal strength against distance.

The comparison of both the modulation formats in the presence of higher-order dispersion parameters is shown in figure (1). For distances up to 500 Km, different values of signal strength are obtained in the presence of higher-order dispersion parameters. When F2, F3, F4 are considered for both nCRZ and alCNRZ the value for signal strength for 'nCRZ' line is near to -1400 dB range and for 'alCNRZ' line it is near to -1300 dB range over same distance of 500 Km. Again for F2, F3, F4=0, the value of the 'nCRZ' line is near to -1050 dB and that of 'alCNRZ' line is near to -720 dB. Similarly, for F2, F3=0 and F4=0, the values of 'nCRZ' and 'alCNRZ' line are near to -780 dB and -690 dB respectively. Now after making a comparative study it is found that as distance increases the signal strength got enhanced and improved in alCNRZ than that in nCRZ modulation format.

The comparison of alCNRZ and nCRZ modulation formats in presence of phase modulation index is given in the following figure (2). The values of signal strength with respect to distance of 500 Km is obtained through various phase modulation indices of m=1, m=2 and m=3. For m=1, the 'nCRZ' line has value that is decreasing from -1300 dB to -1320 dB and that of the 'alCNRZ' line has its value decreasing from -1380 dB to -1430 dB respectively with increasing distance from 0 Km to 500 Km. Again for m=2, the 'nCRZ' line has value declining from -1240 dB to -1270 dB and that of 'alCNRZ' line decreasing from -1320 dB to -1340 dB respectively. Similarly for m=3, the 'nCRZ' line has the value that is diminishing from -1320 dB to -1330 dB, while the 'alCNRZ' symbol line has value that is gradually retarding from -1330 dB to -1370 dB. Thus after making a detailed comparison between the two modulation formats it is found that as distance increases the signal strength for nCRZ gives better performance than alCNRZ with different values of phase modulation.

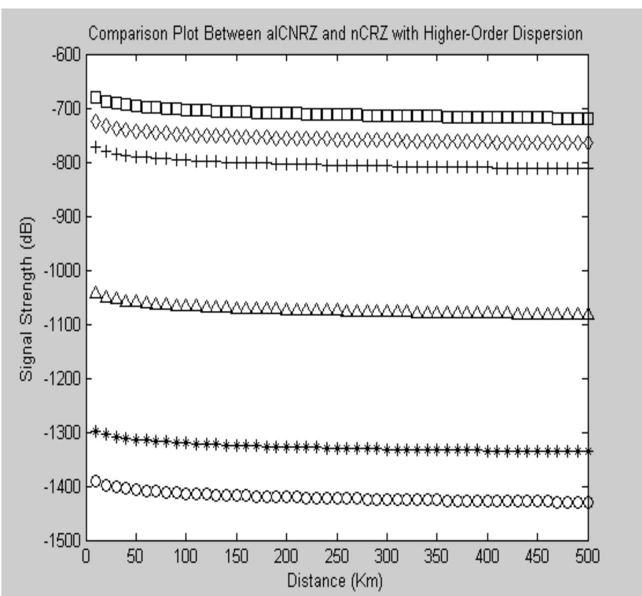

Figure 1. Comparison of alCNRZ and nCRZ with higher-order dispersion compensation. The 'star', 'diamond' and 'square' symbol represent curves for alCNRZ while 'circle', 'upper triangle' and 'plus' symbol represent curves for nCRZ. The 'star' and 'circle' lines are for the case when F2, F3, F4 are considered. Again, the 'diamond' and 'upper triangle' lines are for F2, F3 and F4=0. Similarly, the 'square' and 'plus' lines are considered when F2, F3=0 and F4=0.

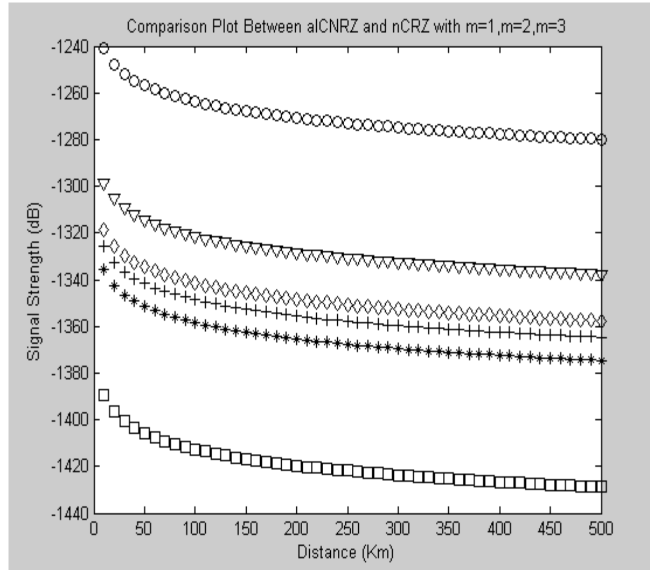

Figure 2. Comparison of alCNRZ and nCRZ with m=1, m=2 and m=3. Here the 'square', 'diamond' and 'star' 'symbolized graphs for alCNRZ while 'lower triangle', 'circle' and 'plus' symbol represent graphs for nCRZ. The 'square' and 'lower triangle' lines are for the case when m=1. Again, the 'diamond' and 'circle' lines are for m=2. Similarly, the 'star' and 'plus' lines are considered when m=3.

IV. Conclusion

The equation number (16) and (29) represents a modified relationship for the signal strength that includes the higher order dispersion effect and the phase modulation for optical alCNRZ and nCRZ based communication system. The effect of higher order dispersion has been evaluated at an operating wavelength of 1.55 μm. It has been observed from the graphical representation that the signal strength is enhanced when the higher order dispersion compensation is considered together for both alCNRZ and nCRZ. The mathematical modeling of both alCNRZ and nCRZ signal may look same but there lies some distinction between the two. After making a detailed comparison between the two, it can be inferred that when higher-order dispersion compensation are considered alCNRZ proves better than nCRZ. While considering phase modulation on the other hand, nCRZ is much better than alCNRZ. The effect of additional pre-chirping in both alCNRZ and nCRZ is found in their distinct graphical analysis whereby the strength of the signal is improved with distance. Thus after comparing the results from the previous model of alCNRZ and nCRZ modulation format, it can be concluded that the signal strength can increase as well as improve if higher order dispersion compensation and phase modulation are equally considered for both of them, while in case of higher-order dispersion compensation, alCNRZ is an optimum choice and nCRZ provides good performance when phase modulation are taken into account.

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