WDM Transmission Performance evaluation for Externally Modulated Coding Formats

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Abstract: Performance evaluation of WDM transmission systems for external electro-optic modulated codes is considered. This has been done for two popular line codes which are return-to-zero (RZ) and non-return-to-zero (NRZ) formats operating at bit rates of 10 and 40 Gbps. The optical channel consisting of a standard single mode fiber was compensated for chromatic dispersion at 1550 nm by a dispersion compensation fiber. Signal attenuation occurring in both fibers has been compensated by adequate optical amplifiers. Performance of considered systems has been evaluated via the analysis of quality factor profiles. Numerical simulations reveal that external modulation using Mach-Zehnder devices affects more RZ coded systems than NRZ coded ones. This is for the case where the average power and data bit rates are the same for the two codes. The overall results show a net superiority of NRZ modulation scheme over RZ scheme for different fiber spans at various data bit rates.

Key words: RZ, NRZ, Mach-Zehnder, WDM, optical modulator, MZM.

1.   Introduction

Optical transmission systems based on WDM approach is dominating the all-optical data transportation with bit rates exceeding several terabit-per-second wire rates to serve the ever increasing next generation Internet Protocol networks [1, 2]. Thus, full operation of these systems will be most important features in the near future.

Some of the main optical networking functions such as routing add and drop multiplexing and demultiplexing and wavelength conversion, need to be functional to encapsulate the IP packet requirements into the optical layer [3]. Simulation of such systems plays an important role in determining expected behaviors of components and devices prior to their implementation and testing. This is a cost effective method for evaluating their performance as experimental set ups involved are still relatively expensive [4].

External modulators are among the interesting devices to be used for implementing some main functions for future optical networks [1, 5-6]. In this regard, different types of modulators have been developed during the last decades to be used for such systems as well as in many other applications involving electro optical signal modulation and demodulation [7-9]. The most popular ones are the Mach–Zehnder Modulators (MZM) used to perform various optical and electro optical functions associated with fiber optic systems. These devices can be used either separately or coupled to semiconductor optical amplifiers (SOA) to perform signal modulation [2].

MZM devices are also used in fiber optic systems to overcome chromatic dispersion, which was the main limiting factor for increasing transmission speed. With dual-terminal driving capabilities, MZM devices are key components for multi-gigabit rate

fiber optic communication systems. Even though a realistic finite MZM DC extinction coefficient can induce some frequency chirp; it has been shown that this chirp can be considerably reduced and therefore, the transmission distance increased [10]. In connection with these devices, a set of coding signals are used to modulate optical data streams. The most popular ones are the non-return-to-zero (NRZ) and return-to-zero (RZ) formats [11-14].

In this paper, the effect of single external modulator on transmission performance of WDM data packet in optical fiber systems is investigated for NRZ and RZ modulation codes. The optical channel considered consists of a standard single mode fiber fully compensated by a dispersion compensation fiber at *1550 nm*. The power attenuation in every span has been compensated using optical amplifiers with adequate gain. The results of modulation effects are analyzed through the quality factor profiles, eye diagrams and bit error rates.

2. Analysis

For an external dual drive optical modulator such as the one shown in figure 1, the optical modulated output field $E_{out}(t)$ can be expressed as a function of the input optical field $E_i(t)$, as [2]:

$$E_{out}(t) = \frac{E_{in}(t)}{2}\left[\exp(j\frac{\pi V_1(t)}{V_\pi}) + \rho\exp(j\frac{\pi V_2(t)}{V_\pi})\right] \quad (1)$$

Where, ρ is a scaling factor between 0 and 1 that accounts for non-ideality of the MZM (note that for an ideal device $\rho=1$). $V_1(t)$ and $V_2(t)$ are dual drive modulating voltages applied to each arm of the MZM and V_π is the switching voltage.
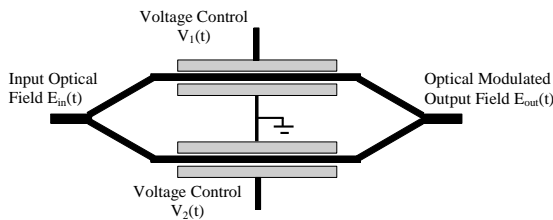

Fig. 1: Simplified layout of a Mach-Zehnder Modulator

The voltage V_π, which is a function of operating wavelength, is an important parameter for the operation of the optical modulator. It is the voltage required to change the output modulated light intensity from its maximum value to its minimum value were the phase shift between the fields of the two arms reaches π radians.

This parameter can be expressed as a function of the optical and physical properties of the MZM as [2]:

$$V_\pi(\lambda) = \left[\frac{\lambda}{n_0^3(\lambda).r_{ij}(\lambda)}\right] \times \left[\frac{d}{\gamma(\lambda).L}\right] \quad (2)$$

Where $n_0(\lambda)$ is the optical index of the modulator active layer at zero applied voltage, $r_{ij}(\lambda)$ is called the electrooptic tensor containing the electrooptic coefficients that depend on the material characteristics, device design and optical polarization. $\gamma(\lambda)$ is the optical confinement factor, d is the gap between the modulator electrodes and L the modulation length.

After performing the needed transformations on equation (1) above, by considering the output optical intensity as the square of the output optical modulated field $|E_{out}(t)|^2$, the transfer function of the MZM for a chirp free balanced modulation ($V_1=-V_2$) can be expressed as a function of the modulating voltage V_m as:

$$H(V_m) = \frac{1}{2} \times \{1 + \cos[\frac{V_m}{V_\pi(\lambda)}\pi + \phi(\lambda)]\} \quad (3)$$

Where $V_m=V_1$ or $V_m=-V_2$ and $\phi(\lambda)$ is the phase shift at a given applied bias voltage.

Equations (2) and (3) show that as the wavelength λ of a WDM signal stream shifts slightly up or down to cover the allocated wavelength range, a change in the voltage V_π occurs as a function of λ and induces a variation in the modulation transfer function. This affects the bias point of the modulator as well as its modulation index which influences the overall performance of the transmission system [10].

It is therefore expected that this wavelength dependent effect could be obtained from the analysis and simulation of

a WDM transmission system using a configuration like the one shown in figure 2. This is because the WDM coded data streams, which are multi-wavelength affect in different ways the output field E$_{out}$(t) and thus have a different effects on transmission performance of the system. The simulation approach and the obtained results are presented in the subsequent section.

3. Results and discussion

Figure 2 shows a simplified schematic diagram of an externally modulated WDM transmission system using an MZM. The optical transmitter is composed of a set of multiplexed WDM wavelengths λ_i varying within the range extending from 1549 nm - 1556 nm. This set of signals is modulated by a dual drive Mach-Zehnder Modulator and driven separately by RZ and NRZ line codes with pseudorandom bit sequences of (2^7-1). The optical amplifiers used for attenuation compensation are set to be wideband to cover the above wavelengths range with noise figure of 6 dB.
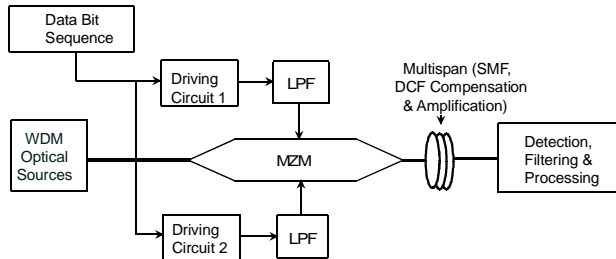

Fig. 2. Block Diagram of WDM transmission system used in simulation.

To minimize any nonlinear effect that might alter the expected results, the power of all wavelengths has been fixed to an average value of 0 dBm. The laser sources used have a full width at half maximum (FWHM) of 10 MHz at data bit rates of 10 Gbps and 40 Gbps. True Wave RS fibers were used in simulation for their low dispersion slope and their high performance in WDM systems. Their attenuation and dispersions at λ=1.5650μm are respectively, 0.21 dB/Km, -97 s/m^3 and 0.25 dB/Km, 97 s/m^3 [16].

A dual-electrode MZM operating in a push–pull mode is used for modulation of input data. The driven data bit sequences are filtered by a low pass filter having an adequate bandwidth with respect to bit rates used. The choice of the filter bandwidth is important for preserving the best performance of the system characteristics. The optical photodetector is a *pin* photodiode with a quantum efficiency of 0.8.

The analysis adopted for simulation of system of figure 2 is based on the solution of the nonlinear Schrödinger equation governing wave propagation through optical fiber systems. The slowly varying electric filed pulse E(t), defined above is obtained by solving the following equation:

$$\frac{\partial E}{\partial z} = -\frac{\alpha}{2}E + i\Gamma \times |E|^2 \times E - \beta_1 \times \frac{\partial E}{\partial t} \\ -\beta_2 \times \frac{i}{2} \times \frac{\partial^2 E}{\partial t^2} + \frac{\beta_3}{6} \times \frac{\partial^3 E}{\partial t^3} \quad (4)$$

Where, E is the amplitude of the envelope of $E(t)$, β_1, β_2 and β_3, are respectively the inverse group velocity, the first and the second order group dispersion velocities. α is the absorption coefficient, and Γ the nonlinear coefficient of the optical fiber for a given span.

The split-step Fourier method technique, used in this work, is based on the fact that propagation of a pulse over the full length of optical fiber is considered by dividing the total length of the fiber into small segments in such a way that changes in the envelopes of optical signals can be considered sufficiently small. Within these segments, the linear and the nonlinear operators in the Schrödinger equation can be considered to act independently of each other. Hence, the effect of propagation along the fiber segment is determined by first using nonlinear operator followed by the linear operator. In this way, the accuracy and efficiency of operator splitting techniques depend on the way discretization is done in time and spatial domains [15].

From the solution of equation (4), Q parameter, eye diagram and bit error rate are derived and used as performance estimators. Note that the Q factor is approximated using mean values and standard deviations of the signal samples as indicated by the following relation:
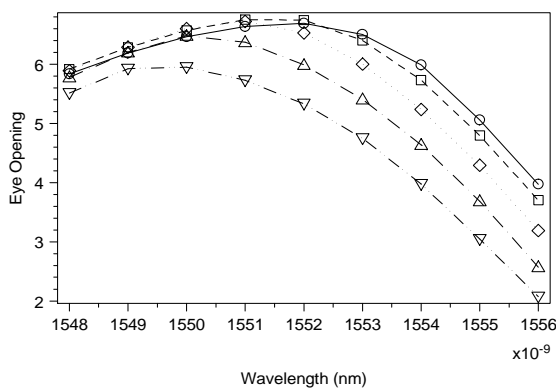
$$Q = \frac{m_1 - m_0}{\sigma_1 - \sigma_0} \qquad (5)$$

where m_1, m_0, σ_1, σ_0 are the mean values and standard deviations of the signal samples when a "1" or a "0" is received respectively.

In order to quantitatively examine the effects of WDM wavelengths' components on the performance of the MZM based fiber system, a set of computer simulations has been performed.
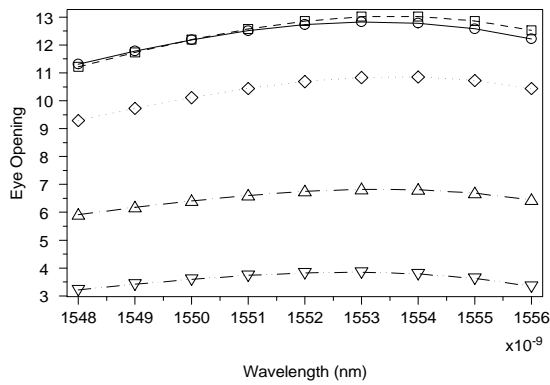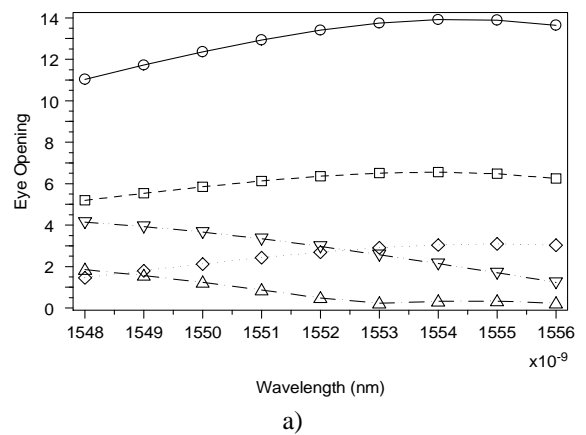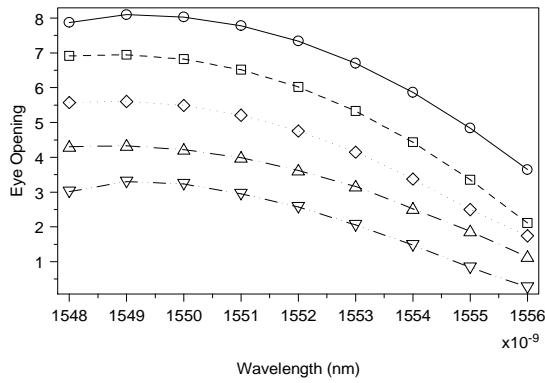

a)

b)

Fig. 3. Eye Openings for system of figure 2 at 10Gb/s. a) RZ code and b) NRZ code for total fiber lengths of 60km (o), 180km (□), 300km (◊), 420km (Δ), 540km (∇).

Figure 3 shows the profiles of the eye opening as a function of operating wavelengths and total SMF fiber span at bit rates of 10 GB/s for RZ and NRZ formats. Note that best performance of transmission is obtained at around *1552 nm*. This is clearly apparent from the relatively higher eye openings at this wavelength as shown in the figure. Note also that as the values of WDM operating wavelengths shift up and down, the eye openings are reduced and the performance of the system is therefore deteriorated. This situation applies for both RZ and NRZ modulation formats with same average optical power and same bit rate. In figure 4 the profiles of the eye openings are shown for the same system and modulation code at bit rates of 40 GB/s. In this case, the fiber spans are kept shorter as the dispersion becomes the dominant effect on transmission performance at longer distances. Note the difference in system performance between NRZ formats as far as the best operating wavelength and performance reduction at different fiber spans.

Note that in all cases, system performance deteriorates as fiber span increases for both RZ and NRZ codes as shown in figures 3 and 4.

a)

Fig. 4. Eye Openings for system of figure 2 at 40Gb/s. a) RZ code and b) NRZ code for total fiber lengths of 20km (o), 30km (□), 40km (◊), 50km (Δ), 60km (∇).

Fig. 6. BER of the system of figure 2 at 10Gb/s for NRZ code and total fiber span of up to 900 km. Upper curves are for larger wavelength changes.

As has been indicated above, analysis has been done for systems operating at 10 and 40 Gb/s. Results for Q-factor parameter profiles are shown in figures 5 for five different wavelengths and fiber spans up to 900Km. In this figure, insensitivity to Wavelength variations of the quality factor is observed at short distances, *i.e.* up to about 250Km. However, when the transmission distances increase above 300Km, the relative change of the profile of Q parameter becomes more affected by the slight wavelength tuning. This will therefore be and extra factor to reduce the overall transmission performance of the system.
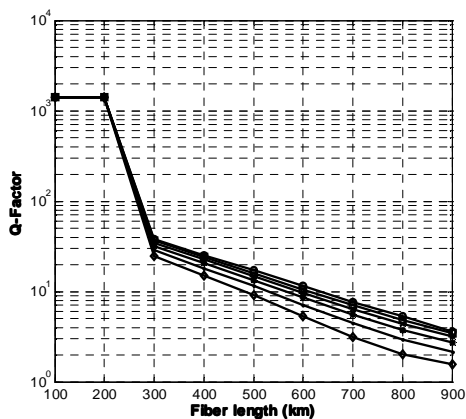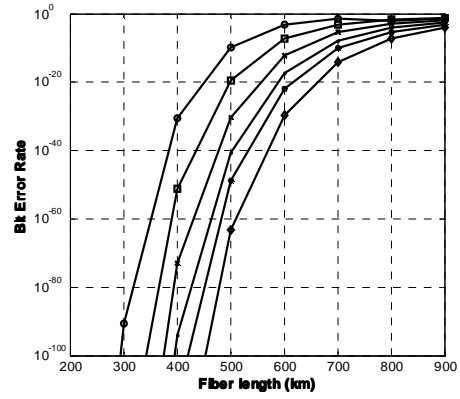
Figure 7 depicts the variations in the eye opening profiles for different operating wavelengths in the range 1548nm -1556nm and fiber spans up to 900km at bit rates of 10GBps. The lower curves correspond to larger wavelength changes with respect to central wavelength.

Fig. 5. Q-Factor of system of figure 2 at 10Gb/s for NRZ code and total fiber span of 900 km.
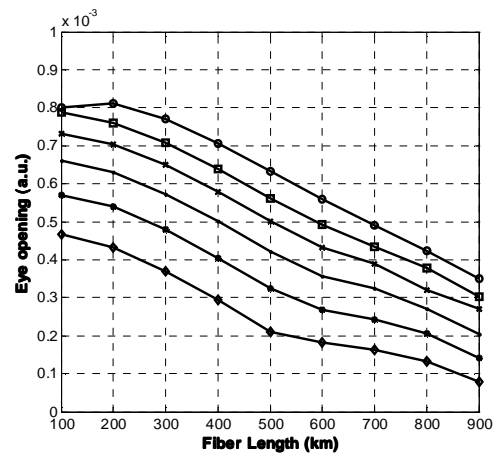
Fig. 7. Eye opening profiles for system of figure 2 at 10Gb/s for NRZ code and total fiber span of up to 900 km. Lower curves correspond to larger wavelength changes.

This appears to be in line with the results shown earlier. Note the deterioration of the BER as the wavelengths deviate from central of 1550nm.

4.   Conclusions

   Simulation of WDM systems using single external electro-optic modulator was considered in this work. This has been done for two most popular line codes which are return-to-zero (RZ) and non-return-to-zero (NRZ) operating at bit rates of 10 and 40 Gigabit per second. Chromatic dispersion as well as signal attenuation in the fibers have been compensated to examine the intrinsic effects due to wavelength detuning in a wide range of wavelengths. It has been shown that wavelength detuning in WDM systems affects significantly the transmission performance. It also appears for the system considered that the NRZ code is better tolerated than the RZ code. This fact has been observed for the two bit rates considered.

References

1. Meccozi A., Wiesenfeld J. M., "The roles of semiconductor optical amplifiers in optical networks", Opt. Photon., **3**, 2001.
2. Li G. L., Yu P. K. L., "Optical Intensity Modulators for Digital and Analog Applications", J. Lightwave Technol. **21**, 2003.
3. Blumenthal D. J., Olsson B.-E., Rossi G., Dimmick T. E., Rau L., Ma¡sanovic´ M., Lavrova O., Doshi R., Jerphagnon O., Bowers J. E., Kaman V., Coldren L. A., and Barton J., "All-Optical Label Swapping Networks and Technologies", J. Lightwave Technol., **12**, 2000.
4. Kolesik M., Matus M., Moloney J. V., "All-Optical Mach–Zehnder-Interferometer-Based Demultiplexer, A Computer Simulation Study", IEEE Photon. Technol. Lett. **15**, 2003.
5. Lizé Y. K., Liu X., and Kashyap R., "Single Modulator Payload/Label Encoding and Node Operations for Optical Label Switching", IEEE Photon. Technol. Lett., **10**, 2006.
6. Weber, C., Fischer J. K., Bunge C.-A. and Petermann K.: Electronic Precompensation of Intrachannel Nonlinearities at 40 Gb/s. IEEE Photon. Technol. Lett., **16**, 2006.
7. Michalak R. J., Kuo Y.-H., Nash F. D., Szep A., Caffey J. R., Payson P. M., Haas F., McKeon B. F., Cook P. R., Brost G. A., Luo J., Jen A. K.-Y., Dalton L. R., and W. H. Steier, "High-Speed AJL8/APC Polymer Modulator", IEEE Photon. Technol. Lett., **11**, 2006.
8. Killey R. I., Watts P. M., Mikhailov M. Glick, and Bayvel P., "Electronic Dispersion Compensation by Signal Predistortion Using Digital Processing and a Dual-Drive Mach–Zehnder Modulator", IEEE Photon. Technol. Lett., **3**, 2005.
9. Chen D.-Y and Phillips J. D., "Analysis and Design Optimization of Electrooptic Interferometric Modulators for Microphotonics Applications", J. Lightwave Technol., **6**, 2006.
10. Kim H., Gnauck A. H., "Chirp Characteristics of Dual-Drive Mach–Zehnder Modulator with a Finite DC Extinction Ratio", IEEE Photon. Technol. Lett. **14**, 2002.
11. Khosravani R., Willer A. E., "Comparison of different modulation formats in terrestrial systems with high polarization mode dispersion", Proc. Optical Fiber communication conference. **2**, 2000.
12. Breuer D., Ennser K., Petermann K., "Comparison of NRZ- and RZ modulation format for 40 Gb/s TDM standard-fiber systems", Proc. ECOC'96, Oslo, Norway, paper TuD.3.3, **2**, 1996.
13. Caspar C., Foisel H.-M., Gladisch A., Hanik N., Kuppers F., Ludwig R., Mattheus A., Pieper W., Strebel B., Weber H. G., "RZ Versus NRZ Modulation Format for Dispersion Compensated SMF-Based 10-Gb/s Transmission with More Than 100-km Amplifier Spacing", IEEE Photon. Technol. Lett. **11**, 1999.
14. Xu L., Chi N., Yvind K., Christiansen L.J., Oxenløwe L.K., Mørk J., Jeppesen P., Hanberg J., " 7 × 40 Gb/s base-rate RZ all-optical broadcasting utilizing an electroabsorption modulator", OSA Optics Express. **12,** 2004.
15. Sinkin V., Holzlohner R., Zweck J., and Menyuk C. R., "Optimization of the split-step Fourier method in modeling optical-fiber communication systems", J. Lightwave Technol., **21**, 2003.
16. http://www.cellco.com.pl/dl/ TrueWave.pdf