

Modulation Formats for High-Speed, Long-Haul Fiber Optic Communication Systems

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1. Introduction

The goal of an optical fiber communication system is to transmit the maximum number of bits per second over the maximum possible distance with the fewest errors. A typical digital fiber optic link is depicted in Figure 1. Electrical data signals are converted to optical signals via a modulator. A “1” is transmitted as a pulse of light while a “0” has no light output. The number of “1’s” and “0’s” transmitted per second determines the speed of the link (bit rate). Glass optical fibers have a wide transmission window over which a number of optical signal channels may be transmitted simultaneously by wavelength division multiplexing (WDM). The power of all the channels combined is boosted by an optical amplifier before being launched into an optical fiber. The launched power generally compensates for the fiber transmission loss of a given fiber stage (span). After each span, the signals are amplified by an optical line amplifier (e.g., Erbium doped fiber amplifier), or repeater. Since transmission fiber is a dispersive medium, implying that pulses spread as they travel through the fiber, some form of dispersion compensation is applied at each repeater stage. At the receiving end of the link, the WDM optical signal is de-multiplexed. Each channel is optically pre-amplified and then detected by an optical-to-electrical (O/E) converter (e.g., a photodiode). A decision circuit identifies the “1’s” and “0’s” in the signal. An optical filter can be inserted before the O/E converter to filter out amplifier noise.

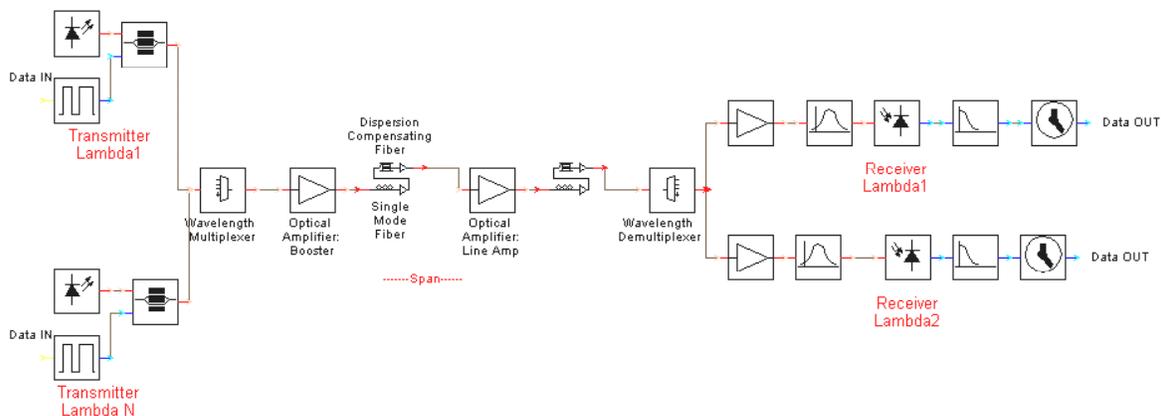


Figure 1: A typical long-haul wavelength division multiplexed optical system

In this paper, we will focus on the modulation scheme for long-haul systems, i.e., the format used to create the optical pulses. The simplest modulation scheme is a non-return-to-zero (NRZ) format, where the pulse is on for the entire bit period. Alternatively, a return-to-zero (RZ) format can be used where the pulse is on for

only a portion of the bit period. The choice of duty cycle will impact other system design parameters such as transmission at a higher bit-rate, closer channel spacing, dispersion management, and polarization mode dispersion (PMD). These issues will be discussed in the following sections.

The duty cycle of a pulse is $\rho = T_{on}/(T_{on} + T_{off})$. The eye diagram and frequency spectrum of a 10 Gb/s NRZ pulse and an RZ pulse with a 50% duty cycle are shown in Figure 2. Observe that the RZ spectrum has a wider bandwidth than the NRZ spectrum. The spectrum of an NRZ signal at 20 Gb/s is the same as that of an RZ signal except for the tones at 10 and 30 GHz.

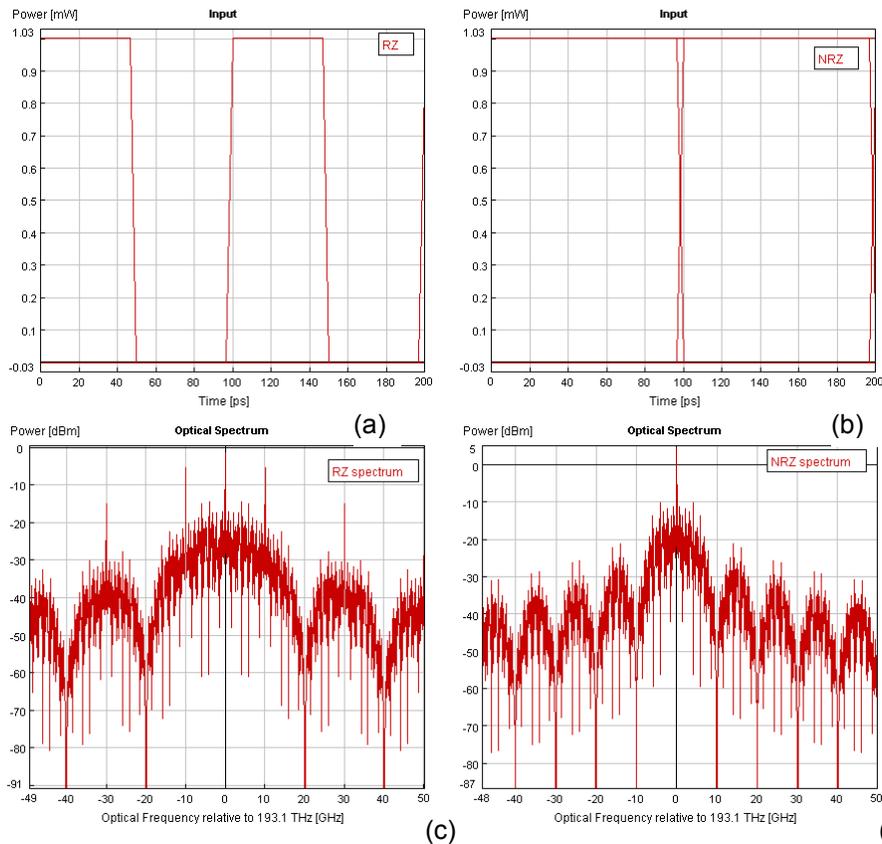


Figure 2: (a) and (b) Eye diagrams of RZ and NRZ signals. (c) and (d) Optical spectrum of RZ and NRZ signals

2. Receiver considerations for RZ and NRZ systems

A typical receiver is described in Figure 1. An impartial comparison between RZ and NRZ signals requires that the electrical bandwidth of the receiver be appropriately set since the optimum bandwidth depends on the pulse width. It has been documented¹ that the optimum electrical bandwidth for a 10-Gbps system with an optically preamplified receiver is about approximately 0.7 times the data rate, and is independent of the duty cycle.

Receiver sensitivity is defined as the received optical power required in order to achieve a certain bit error rate (BER). In Figure 3, the back-to-back sensitivity of

a typical optical system is plotted as a function of duty cycle. A matched filter was used in the receiver, and shot noise (detection noise due to the discrete nature of photons) was included. Note the improvement in receiver sensitivity as the duty cycle is reduced. The reason for this is as follows: If the average optical power launched into the fiber is kept constant, an optical RZ pulse with a 50% duty cycle will have twice the peak power of an NRZ pulse. This increase in power occurs because optical amplifiers are run in the saturation mode, resulting in a gain that scales with average input power. The photodiode is a square-law detector, i.e., the photocurrent is proportional to optical power. Hence the received electrical power (proportional to the square of the photocurrent) is proportional to the square of the optical power. Therefore, the electrical power of an RZ pulse with a 50% duty cycle will be twice that of an NRZ pulse. There will thus be a 3 dB improvement in receiver sensitivity for a 50% duty cycle pulse due to the higher electrical energy per bit. The shot noise will be higher for a pulse with larger amplitude; hence an RZ pulse will be more affected by shot noise, reducing its advantage to approximately 2.5 dB.

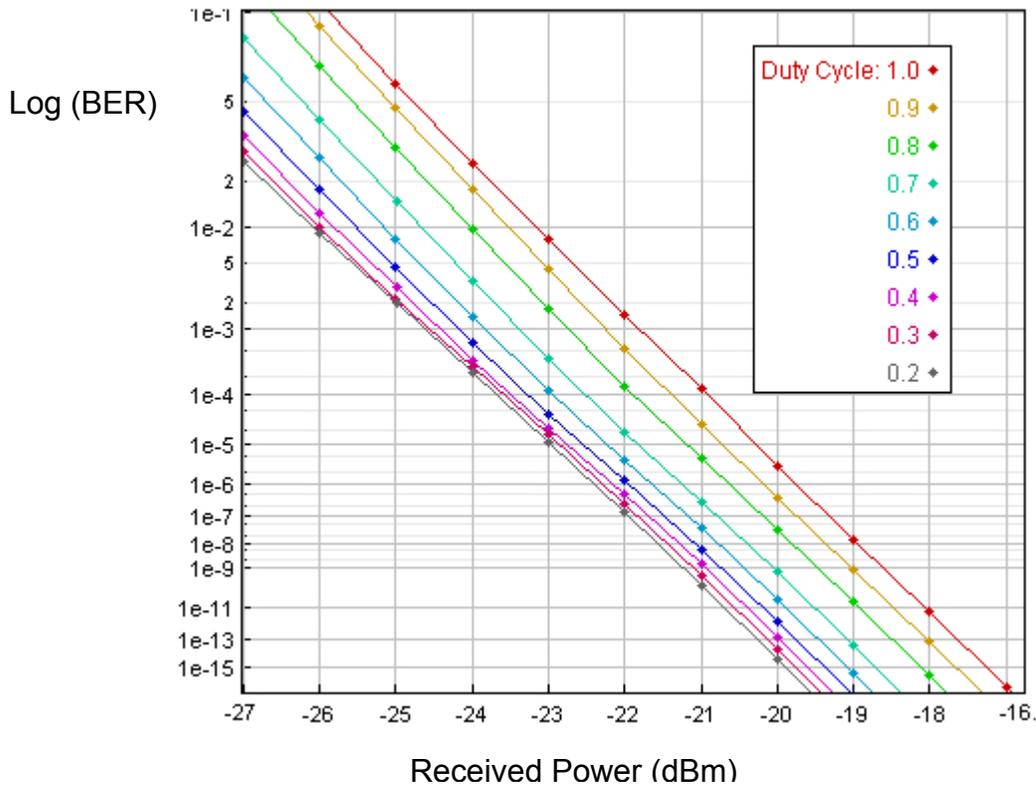


Figure 3: Bit error rate vs. received optical power at different duty cycles for a “back-to-back” system (no optical fiber).

We mentioned in Section 1 that in addition to introducing loss, the optical fiber distorts the signal. In the following sections we will discuss how these impairments influence both formats and examine whether the sensitivity advantage of the RZ format is maintained in the presence of dispersion and non-linear effects.

3. Fiber impairments

3.1. Dispersion

The refractive index of glass is a function of wavelength, which results in the spectral components of a pulse traveling at different group velocities along the fiber. Hence chromatic (material) dispersion broadens optical pulses beyond their time slot, leading to intersymbol interference (ISI). A second component of dispersion in optical fibers is known as waveguide dispersion. This component arises because the proportion of light traveling in the fiber core versus cladding is a function of wavelength. The dispersion coefficient of a fiber is defined as $D = d(1/v_g)/d\lambda$. The typical dispersion coefficient of single mode fiber (SMF) is 16 ps/nm.km. Non-zero dispersion-shifted fibers (NZDSF) such as LEAF™¹ and TrueWave-RS™² have lower dispersion coefficients than SMF. The dispersion coefficient of a fiber is also a function of wavelength, otherwise known as dispersion slope.

Chromatic dispersion in a fiber can be compensated by specially designed fiber with a refractive index profile (core composition) that leads to negative waveguide dispersion characteristics. Another approach is zero dispersion-shifted fibers, designed such that the dispersion coefficient at the loss minimum (1550 nm) is zero. Dispersion compensation schemes must compensate not only for dispersion but also for dispersion slope. In dense WDM systems, it is a challenge to compensate for the dispersion and its slope for each channel over the entire optical spectrum.

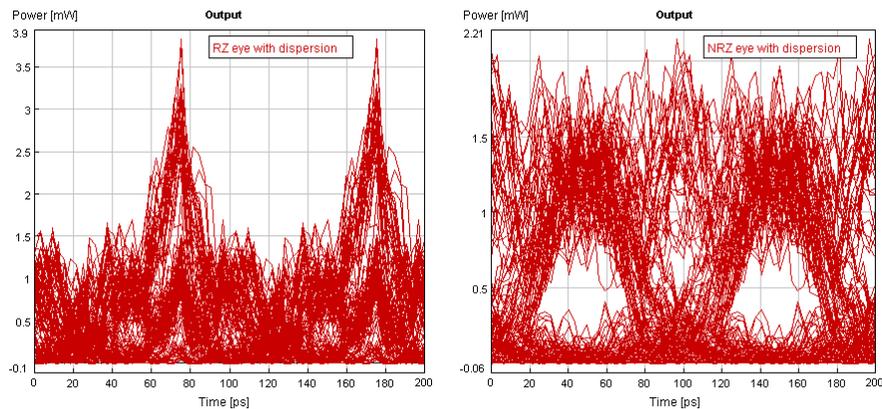


Figure 4: (a) RZ eye of signal through 80km of SMF with a dispersion of 16 ps/nm.km. (b) NRZ eye of signal through the same fiber. Input eyes are shown in Figure 2.

Since an RZ pulse has a wider optical bandwidth than an NRZ pulse, it is more affected by dispersion, as can be seen from the eye diagrams in Figure 4. For the same reason, slope compensation for an RZ signal is also more difficult. RZ transmission through dispersion-shifted fiber would still require the appropriate slope compensation.

¹ LEAF is a registered trademark of Corning.

² True-Wave-RS is a registered trademark of Lucent Technologies.

3.2. Non-linearities

High optical densities in the fiber core lead to two types of non-linear effects, based on scattering and on the non-linear refractive index. Scattering processes such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) manifest themselves as intensity-dependent gain or loss. Figure 5 shows the input and output spectra of a 100-channel system. The total input power is 16 dBm, traveling through 100 km of single mode fiber. Note the Raman tilt due to SRS in the output spectrum. Energy from the shorter wavelength channels is transferred to the longer wavelength channels.

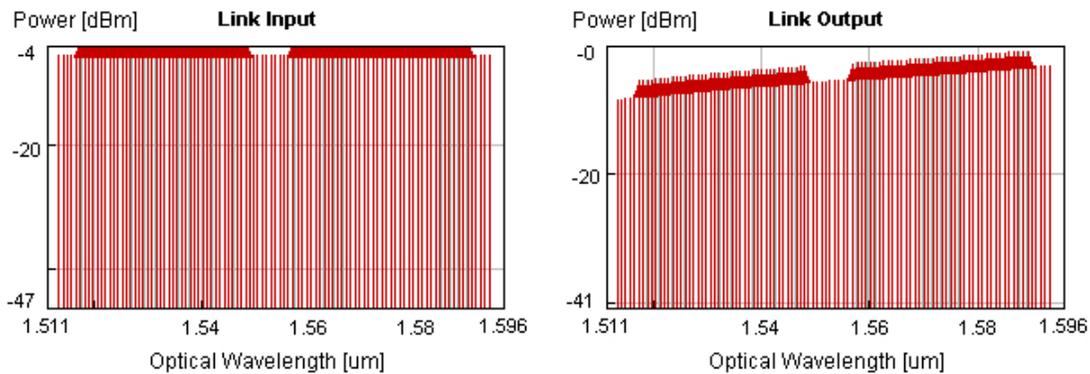


Figure 5: Optical spectrum of 100 channels before (a) and after (b) transmission through 100 km of optical fiber with a Raman coefficient of 0.4

The refractive index n of glass is a weak function of optical intensity, i.e., $n = n_0 + n_2 \cdot P/A_e$, where n_0 is the term independent of power, P is the optical power and A_e is the effective area of the core. The coefficient n_2 for silica fibers is approximately $2.6 \times 10^{-20} \text{ m}^2/\text{W}$. The non-linear contribution to the refractive index results in an intensity-dependent phase change for light propagating in a fiber of

$$\phi_{nl} = \gamma \cdot P \cdot L_e, \text{ where } \gamma = 2 \cdot \pi \cdot n_2 / (\pi \cdot A_e) \text{ and } L_e \text{ is the effective interaction length.}$$

The intensity dependent refractive index gives rise to three effects: fluctuations in the phase of the signal on the channel, known as self-phase modulation (SPM), fluctuations in the phase of signals in other channels, known as cross phase modulation (XPM), and four-wave mixing (FWM), where the beating between two channels leads to tones and sidebands.

Both SRS and SBS depend only on average power and are therefore independent of the modulation format in a dispersion limited system. However, because of the improved receiver sensitivity of an RZ system, lower average power can be launched into the fiber. SPM, XPM, and FWM depend on peak power and the interaction time between channels. NRZ pulses have lower peak power but longer interaction times. RZ pulses have larger peak power and as such are more susceptible to FWM, SPM, and XPM. In the presence of SPM, however, these pulses can undergo compression (solitons) and perform better

than NRZ pulses. The best modulation format in the presence of non-linearities depends on the dispersion management scheme in effect since dispersion causes the energy of a pulse to be dispersed in time. Dispersion management schemes are the subject of much discussion in literature.^{2,3}

4. Span length and link length

The modulation format impacts the design of a given link; each stage of optical amplification introduces noise due to the amplified spontaneous emission of optical amplifiers. As a result, the optical signal to noise ratio (OSNR) degrades along the link. An empirical expression for OSNR is given by the following equation:

$$\text{OSNR (dB)} = 58 - 10 \cdot \log(N) - \text{NF} - 10 \log(L) + P_{\text{out}} - 10 \cdot \log(M) - \kappa,$$

where M = number of channels, N = number of amplifiers, L = loss/span, NF = noise figure of amplifier, P_{out} = amplifier output power, and κ = other factors.

Since the RZ scheme has a better baseline receiver sensitivity than the NRZ scheme, the span length may be increased (received optical power decreased) for a given launch power and receiver sensitivity. Several authors have shown experimentally that longer link lengths can be achieved with the RZ format.⁴

5. Bit rate

Higher bit-rate systems are limited by dispersion. The RZ format would be beneficial for systems with few channels but would require NRZ as the number of channels increase.⁵ Dispersion compensation based on chirped Fiber-Bragg gratings (FBG) to compensate for the residual dispersion of dispersion compensation fibers (DCFs) is under development. The effectiveness of FBG modules in mitigating residual dispersion effects at 40 Gb/s over the multiple channels of the transmission spectrum is being explored.

6. Channel spacing

For 10 Gb/s systems with 100 GHz spacing between the channels, either the RZ or NRZ formats can be used without interchannel cross-talk. Because of its higher optical bandwidth, however, the RZ format would require greater spacing at 40Gb/s, unless special filtering techniques are employed in the multiplexer and demultiplexer.

7. Polarization mode dispersion (PMD)

PMD is caused by the two polarizations traveling at different speeds along the fiber. PMD is a statistical phenomenon and results in pulse broadening. The RZ format is more resilient to PMD than the NRZ format because the energy is confined to the center of the bit period. Therefore, a higher differential group-delay is required before the energy leaks out of the bit period to result in ISI.⁶

8. Summary

In this paper we have discussed that the RZ format has better baseline receiver sensitivity when the average power into the fiber is kept constant. RZ is more affected by dispersion and dispersion slope. For 10-20 Gb/s systems, where dispersion and its slope are well compensated, RZ will perform better than NRZ in most cases. The exception is the zero dispersion regime in zero dispersion shifted fiber,¹ where non-linearities will dominate. Because 40 Gb/s systems are limited by dispersion and dispersion slope, NRZ may be a better choice for a system with a large number of channels,

Implementing the RZ modulation scheme requires a higher bandwidth driver on the transmit end. This scheme can also be implemented using two optical modulators.⁷ This solution may be expensive, however, since a higher bandwidth driver may be more cost effective than two optical modulators. At the receiver end, we have shown that the optimal filter bandwidth for an RZ system may be the same as that of an NRZ system.

9. References

1. "Comparison between NRZ and RZ signal formats for In-line Amplifier Transmission in the zero-dispersion regime," T. Matsuda, A. Naka and S. Saito, *Journal of Lightwave Technology*, Vol. 16, No. 3, March 1998.
2. "RZ Versus NRZ in Nonlinear WDM systems," F. Forggieri, P.R. Prucnal, R. W. Tkach and A. R. Chraplyvy, *IEEE Photonics Technology Letter*, Vol. 9, No.7, July 1997.
3. "Four-photon mixing and high-speed WDM systems," R. W. Tkach, A. R. Chraplyvy, F. Forghieri, A. H. Gnauck and R. M Derosier, *Journal of Lightwave Technology*, Vol.13, pp.841-849, May 1995.
4. "RZ Versus NRZ Modulation Format for Dispersion Compensated SMF-Based 10Gb/s Transmission with more than 100-km Amplifier spacing," C. Caspar, H. M. Foisel, A. Gladisch, N. Hanik, F. Kuppers, R. Ludwig, A. Mattheus, W. Pieper, B. Strebel, and H. G. Weber, *IEEE Photonics Technology Letters*, Vol. 11, No. 4, April 1999.
5. "NRZ Versus RZ in 10-40-Gb/s Dispersion-Managed WDM Transmission Systems," M. I Hayee, and A. E. Willner, *IEEE Photonics Tech. Lett*, Vol.11, No. 8, August 1999.
6. "A Comparison between NRZ and RZ Data Formats with respect to PMD-Induced System Degradation," H. Sunnerud, M. Karlsson and P.A. Andrekson, *IEEE Photonics Technology Letters*, Vol. 13, No.5, May 2001.

7. “Enabling Technologies for 40 Gb/s Long Haul DWDM Transport”, B. Mikkelsen, P. Mamyshev, C. Rasmussen, C. Ketchian, NFOEC, 2000

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