Design and simulation of modified duobinary modulated 40 Gbps 32 channel DWDM optical link for improved non-linear performance

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Abstract: The paper presents a comprehensive analysis of a 40 Gbps Dense Wavelength Division Multiplexing system with 32 channels, spaced at 50 GHz. The design has been optimized for a long haul optical link for Modified Duobinary Return-to-Zero modulation format to establish its superiority over the conventional Duobinary Return-to-Zero format using OptiSystem simulator. The proposed system is designed and tested under perfect dispersion compensation for dispersion management and also with some residual dispersion in the link to mitigate the existing non-linearities. This paper also outlines the superiority of duobinary coding over the conventional non-return to zero modulation with the integration of unequal channel spacing to minimize the Four-Wave Mixing effect. The proposed system has been optimized for a maximum propagation length using different dispersion compensation methods by evaluating the link performance using $Q$ value.

Subjects: Laser & Optical Engineering; Electrical & Electronic Engineering; Electromagnetics & Communication

Keywords: DWDM; modulation formats; DRZ; MDRZ; dispersion compensation; FWM; residual dispersion

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PUBLIC INTEREST STATEMENT

Virtually every digital activity performed on our computers/personal devices gets converted into photons which travel through high capacity optical communication links or networks. At present more than hundred million people enjoy fiber to home facility, exploiting its huge bandwidth at a reliable and lower cost per bit of information transfer. These optical networks not only connect to a cluster of wireless network hubs but also interconnects Internet Protocols, packet switched multi label protocol routers connected with optical client interfaces to support data rate even beyond 100 Gbps. Interestingly this advancement is attributed to increase in the modulation speed by implementing multilevel modulation and multiplexing schemes exploiting optical parallelism at the encoding end along with coherent light wave detection schemes at the receiving end. The fast growing research and developments in this area enables the optical link to form back bone of the new generation global long haul and distribution communication networks.
1. Introduction

The transport capacity of the existing optical networks has grown explosively over the last few decades due to the phenomenal upsurge of high speed and bandwidth intensive internet services (Agrawal, 2002; Charlet, 2006). This in turn led to the migration from the existing 10–40 Gbps systems and much denser wavelength spacing, typically 50 GHz, claiming a higher spectral efficiency (SE). A cost-effective method to support this shift is to upgrade/modify the transmitters and receivers at either end of the long-haul optical communication links while using the existing fiber infrastructure. However, at such narrow channel spacing, the link performance is severely limited due to nonlinear phenomena and chromatic dispersion as they interact and accumulate along the link. Several approaches have been proposed to achieve overall bandwidth efficiency such as channel coding, advanced modulation formats, proper management of polarization mode dispersion (PMD) and chromatic dispersion (CD). Usage of wideband optical amplifiers such as Erbium Doped Fiber Amplifiers (EDFA’s), and improved Dense Wavelength Division Multiplexing (DWDM) multiplexers and de-multiplexers have further boosted the capacity of such links (Agrawal, 2001; Winzer & Essiambre, 2006). These developments thus require an accurate system model which considers both dispersive and non-linear effects in DWDM environment to analyze the impact of these effects at high data speeds.

As compared to the 10 Gbps transmission systems, operation at 40 Gbps is more challenging due to the increased susceptibility to both linear and non-linear effects. The 40 Gbps transmission needs a higher launch power over the 10 Gbps systems to achieve a similar optical signal-to-noise ratio, and this further enhances the impact of nonlinear effects especially in case of multichannel transmission. Four Wave Mixing (FWM) effect is also a major concern on account of its relatively low threshold power and it deteriorates the performance severely with the addition of more channels. A proven way to reduce the FWM crosstalk generation efficiency is to increase the channel separation (Birk & Mikkelson, 2005); however increase in frequency separation precludes DWDM systems. Another method which efficiently mitigates the crosstalk induced due to FWM is to use unequal spacing between channels (Al-Mamun & Islam, 2011), but it leads to complex and costly transmitter architecture, while also being impractical in situations where optical filters and grating based routers need equal channel separation.

Hence, a pragmatic approach is followed wherein periodic dispersion management is used to achieve long haul transmission while effectively combating the deleterious effects due to dispersion and non linearity. Several techniques have been proposed like Dispersion Compensating Fiber (DCF), Fiber Bragg Grating, Optical Phase Conjugation and electrical equalizer to effectively compensate dispersion (Hayee & Willner, 1999; Hodzic, Konrad, & Petermann, 2002). We have used DCF owing to its superiority over other methods (Hoshida et al., 2002) to design a dispersion managed system employing alternating fiber segments with positive or negative dispersion slope. This maintains a much smaller value of average dispersion as compared to that of local dispersion in either fiber segment and thus avoids FWM in general.

Advanced modulation formats are a promising technique to achieve enhanced bandwidth utilization while maintaining quality transmission. Proper choice of signal format is of great importance to maintain a low channel crosstalk penalty as the modulation used, bandwidth of the specified format and channel spacing are closely interrelated. The desire for narrow (≤100 GHz) optical modulation bandwidth in future optical transport networks with transmission rates as high as 100 Gbps can be achieved by implementing forward error correction (FEC). Considering numerable parameters like power margin, spectral efficiency, resilience against group velocity dispersion (GVD) and nonlinear effects, several modulation formats such as carrier-suppressed return-to-zero (Hodzic et al., 2002; Hoshida et al., 2002; Sharan & Chaubey, 2012a), single-sideband RZ (SSB-RZ) (Hodzic et al., 2002; Hoshida et al., 2002; Shtyrina, Fedoruk, & Turitsyn, 2007), Optical Duobinary (ODB) (Sharan & Chaubey, 2012b; Sheetal, Sharma, & Kaler, 2010; Sikdar, Chaubey, Tiwari, & Chaubey, 2012; Yonenaga, 1997), Differential Phase Shift Keying (DPSK) and Differential Quadrature Phase Shift Keying (DQPSK) (Linlin, Jianming, Li, & Xuecheng, 2011; Tan & Pincemin, 2009) have been proposed as an alternative to non-return to zero (NRZ) and RZ. Choosing a modulation scheme which best fits all requirements is thus a technological challenge.
Based on literature study, the formats suitable for ultra DWDM systems are ODB and DQPSK due to their narrower spectrum and higher tolerance to both the line dispersion and non linear effects (Tan & Pincemin, 2009). However, DQPSK modulation scheme owing to its relatively complex transmitter design and the need for Mach-Zehnder interferometric demodulator as well as balanced detector for detection of the DQPSK signal (Sharan & Chaubey, 2012a; Sheetal et al., 2010) is not a cost effective solution. However, duobinary scheme offers the flexibility of decoding the ODB signals into binary signal by usage of a simple direct detection optical receiver (Yonenaga & Kuwano, 1997). Moreover, it shows a better tolerance to CD and achieves acceptable signal transmission over longer distances.

In this paper, the challenges in design of a high spectrally efficient 40 Gbps system are addressed by exploring DRZ and Modified Duobinary Return-to-Zero (MDRZ) modulation format, also known as Optical Carrier Suppressed Scheme. While the discrete frequency tones of RZ signal spectrum are effectively suppressed by both Duobinary Return-to-Zero (DRZ) and MDRZ, the latter provides the advantage of smaller timing jitter and amplitude distortion. Moreover when compared to RZ, both DRZ and MDRZ signals provide smooth operation even at relatively higher average channel powers. These formats have been studied for their suitability in DWDM systems either for a limited number of channels (8 or 16) (Hodzic et al., 2002; Sheetal et al., 2010), or for a typical data rate lesser than 40 Gbps (Sikdar et al., 2012; Tan & Pincemin, 2009). In the present simulation study a 40 Gbps MDRZ modulated system has been attempted and its transmission performance under typical physical impairments has been evaluated and compared with the conventional duobinary transmission. These formats are also investigated to analyze the influence of various dispersion management methods such as pre, post and symmetric schemes. These schemes are studied with both perfect dispersion compensation and over compensation of dispersion under varying input signal power, to evaluate the $Q$ value and eye opening at the receiver end. The study further explores the potency of the integration of unequal channel spacing for suppression of FWM in such optical links.

The organization of paper is as follows. Section 2 describes the design architecture of modulators for NRZ, DRZ and MDRZ format. In Section 3, the methodology and the various assumptions used in the transmitter, optical link and receiver structures are outlined. Section 4 reports the simulative results obtained using different dispersion compensation methods for DRZ and MDRZ formats for comparative analysis and, finally Section 5 concludes the findings.

2. Transmitter architectures

2.1. Non Return-to-Zero format

In the currently deployed systems, NRZ format has been used extensively due to its simple setup as shown in Figure 1. Continuous-wave (CW) laser generates the optical signal which is on-off keyed by the Mach–Zehnder intensity modulator (MZM) driven by 40-GHz NRZ data stream.

2.2. Duo-binary Return-to-Zero format

It owes its superiority over NRZ as it has a lower spectral bandwidth and provides better tolerance against residual CD (Sheetal et al., 2010; Sikdar et al., 2012; Yonenaga, 1997), thus alleviating the requirement of an integrated tunable dispersion compensation (DCM) module in the receiver side. Moreover, its compact spectrum makes duobinary format compatible with 50 GHz ITU grid, further conforming the 40 Gbps system to the existing 10 Gbps WDM long-haul transport infrastructures (Xu, Wang, Chowdhury, Yu, & Chang, 2006; Yonenaga & Kuwano, 1997) and permits an easier upgrade to 40 Gbps network by just interchanging the transmitters without making significant changes in the receiver and transmission line design. It has 3-levels which are generated by the usage of differential precoding and electrical or optical filtering. The incorporation of both phase modulation and amplitude modulation reduces the pulse overlap, resulting in a lesser sensitivity to CD and intra-channel nonlinear effects when compared to NRZ. A phase shift of $\pi$ occurs between two groups of “1”s whenever the number of “0”s in between is odd.
The configuration of a 40 Gbps duobinary transmitter is shown in Figure 2(a). The first step is to generate a NRZ duobinary signal and is achieved by combining a duobinary precoder, NRZ generator and a duobinary pulse generator (Sheetal et al., 2010). The signal from this part drives the initial MZM, whose output is concatenated with a second MZM which is pulsed by an electrical sinusoidal signal having 40 GHz frequency and phase as −90°. Usage of precoder is inherent for duobinary coding to avoid error propagation and additional hardware complexity at the receiver and makes it possible to use a conventional (binary) optical receiver based on IMDD. A straightforward implementation of such a precoder is shown in Figure 2(b) which combines an EXOR logic-gate with a one bit delay feedback tap. But this feedback tap is hard to implement at high data rates. The DRZ format has half the optical modulation bandwidth over NRZ as shown in Figure 2(c).

2.3. Modified Duo-binary Return-to-Zero format

MDRZ format has a much narrower optical bandwidth over the DRZ leading to greater dispersion tolerance and higher fiber non linearity tolerance (Miyamoto et al., 2001; Xu et al., 2006). In this format, the phases of two groups of “ones” that wrap an isolated “zero” are flipped, leading to reduced ghost pulse generation caused by intra-channel four-wave mixing. However, it requires two
optical modulators to obtain this signal; one to generate NRZ duo-binary signal and the other to carve the NRZ data to RZ signal and this increases the transmitter cost.

Figure 3(a) outlines the design of the 40 Gbps modified duobinary transmitter. It is similar to DRZ as the first step is to generate a NRZ duobinary signal, but here a delay-and subtract circuit is used instead of the delay-and-add circuit. The output of this block signals the first MZM, whose output is concatenated with a second modulator which is driven by a sinusoidal electrical signal with 40 GHz frequency and phase $\sim$90°. In duobinary signal case, we change the phase of bits “1” only after a bit “0” appears, but in the MDRZ case we alternate the phase between 0 and $\pi$ for the bits “1”. That is, while keeping the phase of all the “zero” bits constant, a 180° phase variation is introduced between all the consecutive “ones” which leads to suppression of carrier of the duobinary signal as shown in Figure 3(b).

3. Simulation setup

The simulation study has been done using OptiSytem 10.0 simulator which closely realizes a fiber-optic transmission system. The simulation results are derived by solving the nonlinear Schrodinger equation analytically using the split-step Fourier method. The parameters used in simulation are highlighted in Table 1. The proposed DWDM link consists of 32 data modulated transmitters, a fiber section and 32 optical receivers as shown in Figure 4. To analyze the performance of the proposed setup factors such as BER, $Q$-factor and eye opening are considered. The acceptable BER value for an optical link is $10^{-9}$ to $10^{-15}$ and can be obtained in terms of $Q$-factor using

$$Q(dB) = 20 \log(2 \frac{1}{2} \text{erfc}^{-1}(2\text{BER})) \quad (1)$$

The Forward Error Communication (FEC) threshold sets the minimum value of $Q$-factor as 6 or 15.6 dB for error free optical communication (Sikdar et al., 2012). So, throughout this paper $Q$-factor of 15.6 dB has been considered as reference and the performances of various parameters are evaluated.
3.1. Transmitter section
The DWDM transmitter setup comprises a PRBS generators, DRZ and MDRZ modulators for the respective cases, CW lasers, filters and the optical multiplexer and demultiplexer. Pseudo random bit sequence (PRBS) is generated by the PRBS generator at 40 Gbps data rate with $2^9 - 1$ bits. The CW lasers emit equally spaced frequencies between 193.1 and 194.65 THz with 50 GHz channel spacing. MZM’s with extinction ratio of 30 dB are used. CW laser is driven by a data modulator shown in Figures 2(a) and 3(a) for DRZ and MDRZ respectively to generate the modulated optical signal which acts as the input for the 32 input ports of an optical multiplexer. Crosstalk between the adjacent channels is avoided by optical filtering each channel using a second order Gaussian filter with a bandwidth of 56 GHz in the multiplexer.

### Table 1. Simulation parameters

| Parameter                              | Value                  |
|----------------------------------------|------------------------|
| Bit rate                               | 40 Gbps                |
| Sequence length                        | 128                    |
| Samples/bit                            | 64                     |
| DWDM channel spacing                   | 50 GHz                 |
| Central frequency of the 1st channel   | 193.1 THz              |
| Capacity                               | 32-channel 40 Gbps     |
| Distance                               | 60 km × N Spans        |
| Input power                            | −1 dBm                 |

Figure 4. Schematic of simulation setups: (a) pre-compensation scheme, (b) post-compensation scheme and (c) symmetrical-compensation scheme.
3.2. Fiber section
The multiplexed optical signal is then launched over the Single Mode Fiber (SMF). Table 2 enlists the fiber parameters used. The fiber model considers attenuation, Kerr non-linearities, unidirectional signal flow, dispersion effects and both stimulated as well as spontaneous Raman scattering. To suppress the deleterious effects of dispersion over the link DCF is used. We have considered the three possible placement strategies of DCF in the link (i) before the SMF called as pre-compensation scheme (ii) after the SMF referred as post compensation scheme and (iii) symmetrical compensation scheme in which DCF is set between split SMF's as shown in Figure 4. All the configurations have been explored and the best one is used in analysis of results. The length of the DCF is set such that the dispersion accumulated in SMF is cancelled out. Negation of PMD is done by considering the scalar model of both the fibers.

Figure 4(a) outlines the pre-compensation scheme where dispersion and the nonlinearities are compensated by using 10 km DCF before the 50 km SMF. The gain of EDFA’s is set to overcome the attenuation encountered as signal propagates over both the fibers and is 5 dB and 10 dB, respectively. Figure 4(b) shows the model used for post-compensation scheme wherein a 10 km DCF is used after a 50 km SMF to combat the accumulated dispersion. Symmetrical-compensation scheme uses a 10 km DCF between the SMF of 50 km as shown in Figure 4(c). It uses three in-line-EDFA’s each with 5 dB gain, to compensate for losses and a noise figure of 4 dB. The combined signal is then launched over N spans of 60 km each.

3.3. Receiver section
The complete receiver realization involves the demultiplexer, PIN detector, filters and 3R regenerator. At each of the 32 output ports of the optical de-multiplexer 2nd order Gaussian band pass filters having 3 dB cut off frequency as 40 GHz, and depth of 100 dB are used to filter out the individual channels. The filter parameters also have been optimized and various orders and cut-off frequencies were explored to arrive at the best possible value practically. This filtered optical signal passes through individual PIN photodiodes with responsivity \([\text{A/W}]\) of 1 and dark current of 0.1 nA, corresponding to incoming reference frequency range i.e. 193.1–194.65 THz respectively. The electrical signal from PIN photodiode then passes through a 4th order electrical low pass Bessel filter whose cut-off frequency depends on the modulation format used and is optimized at 32 GHz. Thereafter, a 3R regenerator is connected to the BER analyzer which generates graphs and results such as eye diagrams, BER, \(Q\) value, eye opening etc.

4. Results and discussions
The performance of both DRZ and MDRZ formats was first investigated for all the three schemes i.e. pre, post and symmetrical dispersion compensation in terms of the received maximum \(Q\) value and eye opening. For system analysis, the results of the 1st channel were studied to correlate and infer the results of other adjacent channels. For both DRZ and MDRZ formats, the optimum performance was observed for the case of symmetrical dispersion compensation case which is in close agreement to the results reported in literature (Hodzic et al., 2002; Hoshida et al., 2002), and hence this scheme was used throughout the paper. After finalizing on the symmetric scheme, we ran the simulations for two cases: (1) Perfect compensation of GVD and (2) Residual Dispersion compensation of GVD.

| Fiber | Attenuation (dB/km) | Dispersion (ps/km-nm) | Dispersion slope (ps/km-nm²) | Effective core area (μm²) | Non linear refractive index (n₂) |
|-------|---------------------|----------------------|----------------------------|--------------------------|-------------------------------|
| SMF   | 0.2                 | 17                   | 0.08                       | 80                       | 2.6                           |
| DCF   | 0.5                 | -85                  | -0.45                      | 30                       | 2.6                           |
For perfect dispersion compensation case, the parameters of DCF and SMF are chosen with an objective to compensate the first-order dispersion exactly. However, to maintain a residual dispersion-per-span (RDS) (Bertaina & Biga, 1998) in each map, we varied the compensation ratio (CR) between 95 and 105% to find the optimum DCF length. This enables us to visualize the effects of both under compensation and over-compensation which further mitigates the influence of FWM and XPM. The optimum length of DCF was found to be 10.044 km which corresponds to the case of over compensation. It was readily seen that the performance of the link was improved substantially for MDRZ format by using over-compensation over both perfect and undercompensated case. Thus, overcompensation method has been used to design the proposed 32 channel long haul DWDM link. The present study also considers different power levels and varied combinations of the channel spacing to visualize the impact of non-linearity on the overall performance of the system.

Figure 5(a)–(c) outline the performance of both DRZ and MDRZ format graphically for the over compensated case in terms of the Q value as a function of transmission distance. To support high data rate DWDM system, the input launch power must as low as possible to prevent the excitation of non-linear effects. Hence, we varied the input power from −5 dBm to 10 dBm. It is clearly seen from Figure 5(a) that that at low launch power of −5 dBm DRZ scheme performs better than MDRZ in terms of satisfactory performance distance which is 1,200 km for DRZ as compared to just 700 km for MDRZ after which the Q value drops below 15 dB threshold. It is observed that Q value for MDRZ is greater for a shorter distance but with a relatively higher slope of attenuation degradation with length. This may be attributed due to the absence of high power carrier component in the MDRZ format. However as the signal propagates, the accumulated scattering induced non-linearity adds up and degrades the performance and Q value. Obviously channel impairments owing to non-linearity become more challenging for a multi-channel high power DWDM system design. This led to the evaluation of the performance of such systems for various power levels. Similar analysis made for 0 dBm of launch power is presented in Figure 5(b) which shows nearly same qualitative behavior with a quantitative difference. DRZ here achieves a distance of 2,700 km while MDRZ manages around 2,000 km which again is an improvement over the −5 dBm case.

As the launch power was further increased it is seen that, the DRZ format does not shows significant improvement in the maximum achievable distance but MDRZ still performs better up to 2,700 km. Another important inference can be made when we further increase the launch power to 5 dBm as shown in Figure 5(c) where MDRZ format performs better than DRZ accomplishing a total distance of 2,100 km while for DRZ the distance decreases to 1,600 km. Though the distance has decreased for both the formats at higher launch power due to the evolution of non-linearities, but even at this power satisfactory performance is achieved with MDRZ format up to 2,000 km.

Though most of the designed systems don’t work satisfactorily at a power level higher greater than 5 dBm, but our system works smoothly even at 10 dBm power with MDRZ format consistently performing better than DRZ as shown in Figure 5(d). While for DRZ, Q falls off at around 500 km, MDRZ manages transmission over 500 km. This observation reinstates our affirmation that both DRZ and MDRZ formats are suitable for systems operating at high power levels, with MDRZ showing good performance even at 10 dBm. Thus we can infer that for high-speed optical transmission systems, duobinary coding significantly increases system dispersion tolerance while at the same time reducing the sensitivity to non linear effects while providing higher spectral efficiency.

Owing to the superiority of the MDRZ format over DRZ, this format was analyzed for unequal channel spacing, for 16 and 32 channels to observe the impact of FWM cross products on such systems using reported algorithm (ElRazak, Saleh, & Aly, 2011). The study has also been extended for equal channel separation of 100 GHz for 32 channels under perfect compensation scheme requiring a total bandwidth of 3.1 THz. For the unequally spaced case, a minimum channel spacing of 50 GHz is considered and the channel separations are, respectively, 125, 100, 75 and 50 GHz and vice versa resulting in the total unequal bandwidth of 2.675 THz. Figure 6(a) and (b) shows the comparison of equal vs. unequal channel spacing for 16 channels and 32 channels respectively. It is inferred that in both
cases the unequal channel spaced network performs better than the equal one. The maximum distance for 32 unequally spaced channels at 0 dBm launch power is around 600 km as compared to 450 km for the equal channel case. Moreover, there is an added advantage of bandwidth saving.
when using unequal channel separation which saves around for ~225 GHz for the 16 channel case, and approximately ~425 GHz for 32 channel case which is considerable bandwidth saving.

The received eye diagrams of the first channel for MDRZ format is shown in Figure 7 for a launch power of 5 dBm. Figure 7(a) depicts the wide eye at a distance of 60 km while Figure 7(b) shows the eye diagram after signal propagates through 30 spans i.e. 1,800 km. The eye has become considerably distorted as a result of the FWM crosstalk arising due to the interference between the
transmitted channels and the FWM products generated at the channel frequency. Thus, it is concluded that for DWDM systems MDRZ format performs better as compared to the conventional NRZ/RZ owing to its higher tolerance to inherent noise, inter-channel cross-talk, FWM spurious products along with improved receiver sensitivity at higher power levels.

5. Conclusion

This paper demonstrates the design of a 32 channel DRZ and MDRZ modulated optical link operating with 50 GHz channel separation up to 2,700 km using overcompensation technique. The simulated design has been investigated to evaluate optimum long haul distance by using different dispersion compensation schemes for varying input signal power. The simulation predicts that the symmetrical compensation scheme is a superior choice compared to pre and post schemes. It is also inferred that over compensation of the residual dispersion per span makes DRZ and MDRZ superior for long haul applications. MDRZ scheme performs substantially better than DRZ at higher launch powers by suppressing the discrete frequency tones. The proposed design strategy for non-linear effect mitigation with superior dispersion management makes an efficient DWDM system with a compromise of slightly complex transmitter architecture.

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