Upgrading Legacy Long-Haul WDM Systems through Unbalancing the Proportion of 1s and 0s in the Transmitted Data

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ABSTRACT

We present experimental results for wavelength-division multiplexed (WDM) transmission performance using unbalanced proportions of 1s and 0s in pseudo-random bit sequence (PRBS) data. This investigation simulates the effect of local, in time, data unbalancing which occurs in some coding systems such as forward error correction when extra bits are added to the WDM data stream. We show that such local unbalancing, which would practically give a time-dependent error-rate, can be employed to improve the legacy long-haul WDM system performance if the system is allowed to operate in the nonlinear power region. We use a recirculating loop to simulate a long-haul fibre system.

Keywords:
Long-haul undersea systems, optical fibre networks, submarine cable networks, WDM systems.

1. INTRODUCTION

From information theoretic perspectives, the transmitted data are simply a combination of 1s and 0s. This implies that if the bit sequence has all 1s or all 0s, there is no information being transmitted. Therefore, the maximum information can be achieved when the bit sequence has half 1s and half 0s. This, in fact, can be the ideal proportion of the 1s and 0s in transmission [1]. However, it has already been shown that in some systems, particular bit sequences can result in a worse performance than others due to some effects such as inter-symbol interference (ISI) and nonlinearities [2]. Theoretically, the use of 50% 1s and 0s can be the ideal selection for systems which operate in the linear regime, assuming that the system performance is dominated by noise in the electrical receiver which simply adds equally to the 1s and 0s. Thus, the probability of errors in the received 1 and 0 bits is almost the same, which indeed makes the receiver design simple as the threshold can be set at half the average power. In optically amplified transmission systems, the noise contributions for the 1 and 0 bits are different since the 1 is dominated by signal-spontaneous beat noise while the 0 is dominated by the spontaneous-spontaneous beat noise [3]-[4]. The signal-spontaneous beat noise that is induced on the 1-bit has a larger contribution than the spontaneous-spontaneous beat noise of the 0-bit. Thus, the probability of errors in the 1 is apparently larger than that of the 0, and therefore, the bit-error-rate (BER) for the received data is expected to be affected by the proportion of 1s. Nevertheless, this situation is simply avoided in practice as the receiver threshold can be biased such that the error-rate for the 1s is equal to the error-rate for the 0s. Figure 1 shows an example of two systems; the first assumes equal error probability distributions of the 1s and 0s where the threshold can be set in the midpoint between the 1 and 0 amplitudes. The second assumes a wider error probability distribution for the 1s; thus, the threshold must be set below 1/2 so that errors in the received 1s are reduced.

Let us now consider systems that operate in the nonlinear regime. Actually, these systems are often limited by nonlinear interactions, where the noise effect can be neglected. Since the nonlinear effect is induced only on the 1-bit, where there is a pulse (assuming return-to-zero (RZ) modulation), the probability of errors for the 1-bit is much larger than that of the 0-bit. Thus, the BER performance of the system can be a function of the proportion of 1s. This actually can be understood as in real systems, where all amplifiers operate at saturation, the amplifiers' output powers are always constant meaning that despite changing the number of 1s at the transmitter, the average power will be constant at the input of each fibre section. Therefore, the individual pulse energy launched into the fibre will change which will consequently affect the whole system performance. For instance, if the number of 1s increases, the pulse energy decreases which in turn can reduce impairments induced by nonlinearity, with the net effect being an improvement in the performance. This enables reliable communication at reduced energy levels, where this margin in power can be spent to improve the bit-rate distance product [5]. This is of course assuming that the system allows for high nonlinearity where the power is far higher than the optimum power of the system.

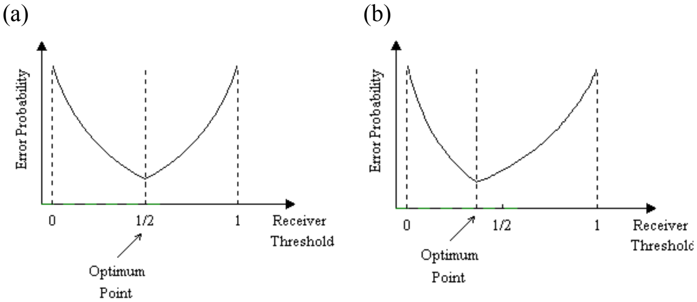

Figure 1: Receiver threshold bias for: (a) System with equal error probabilities for the 1s and 0s; (b) System with unequal error probabilities.

The above argument leads to carefully investigating the effect of unbalancing the fractions of 1s and 0s in both linear and nonlinear WDM systems. Such an effect has already been considered in [6] where a novel pulse position modulation scheme was proposed to encode the data signal such that the probability of 1s is changed before transmission. This, in practice, would require a complex coding/decoding system, which in turn complicates the transmitter and receiver design. In this paper, we aim to study the unbalancing effect such that it can be applied to upgrade the installed systems that already use conventional coding schemes while simultaneously reducing the complexity of the transmitter and receiver. Therefore, advanced modulation schemes such as orthogonal frequency-division multiplexing (OFDM) are not considered in this study, where their performance comes at the cost of significantly enhanced complexity in the receiver.

Since the receiver in the linear system can be biased to equalize the probabilities of the received 1s and 0s, the unbalancing effect is not expected to be as strong as that for the nonlinear system, in which the total BER is a more complicated function of the 1s proportion. Therefore, this paper focuses on the effect induced when the system operates in its nonlinear power region. Any practical improvement being achieved here can be exploited for upgrading traditional systems employing forward error correction (FEC) as discussed below.

2. FORWARD ERROR CORRECTING CODES

In general, studying the effect of different fractions of 1s and 0s in the transmitted data can be useful for some applications related to coding. In specific, FEC codes are good examples to consider in this study. Recall that in FEC, redundant information is transmitted along with the data that can be exploited by the receiver to correct errors incurred during transmission [7]-[9]. Since new bits are added to the original bit stream, which are referred to as *overhead*, the bit-rate of the data will increase after the FEC encoder. However, if the data are originally balanced, i.e. has 50% 1s and 0s on average, the data at the output of the FEC encoder are not necessarily balanced depending on the ratio of the 1s in the overhead. In practice, the FEC encoder is conventionally followed by a scrambler to rebalance the data and ensure an average proportion of 50% before transmission [10]. This is traditionally based on the assumption that the system operates in the linear regime and the error probability for the 1s and 0s is almost equal. In contrast, if the system is allowed to operate in the nonlinear regime, its performance is expected to be affected by the proportion of 1s in the overhead.

Figure 2 shows a simple example of a balanced 10 Gbit/s data stream being encoded by the ITU G.975 Reed-Solomon code with 7% overhead. If the overhead has a higher proportion of 1s, the resulting 10.7 Gbit/s data stream is no longer balanced where its overall fraction of 1s exceeds 50%. This fraction will be rebalanced by the scrambler. However, we believe it is essential to perform an experimental comparison between the balanced and unbalanced 10.7 Gbit/s data signals over a long-haul system working in the nonlinear regime. If a considerable BER improvement is practically achieved with more 1s, as theoretically expected, thus conventional FEC systems are recommended to be operated without requiring an electronic scrambler/descrambler pair, where good performance is simply achieved by operating at high power. This is also valid with more 0s in the data, where the inverse of the bit sequence can be transmitted and then inverted back at the receiver.

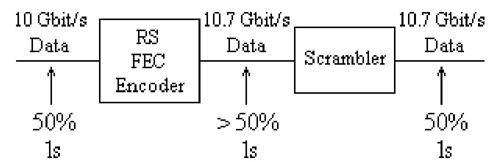

Figure 2: Example of an FEC encoding system with 7% overhead.

3. EXPERIMENTAL SETUP

Figure 3 shows the experimental configuration used. At the transmitter, five WDM wavelengths are modulated via two $LiNbO_3$ modulators being driven by a pattern generator with 10.7 GHz clock and 2^{31}-1 PRBS data pattern. The resulting 5 × 10.7 Gbit/s WDM signals with RZ modulation format are then amplified to the required launch power and enter a 195 km recirculating loop. The wavelengths used are 1553.9-1557.1 nm with 100 GHz spacing.

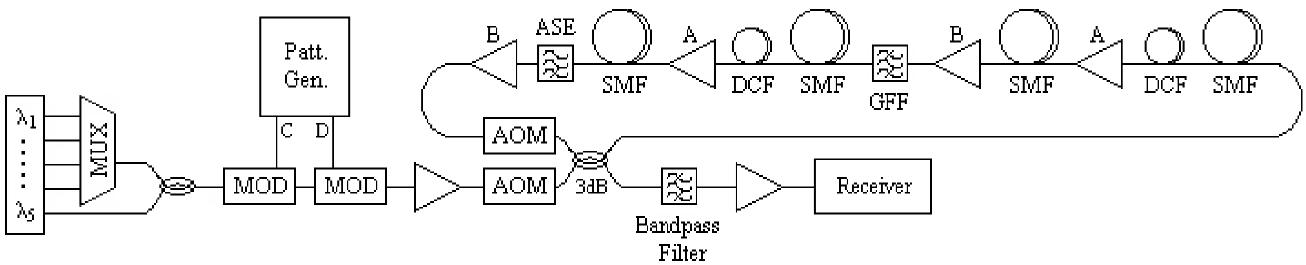

Figure 3: Experimental setup.

The recirculating loop consists of two fibre sections using a symmetric dispersion map in each section so that the accumulated dispersion over the fibre is minimized [11]. Therefore, the first section has 40.7 km single-mode fibre (SMF), 16.5 km dispersion compensating fibre (DCF) with -1383 ps/nm dispersion, and then another 41.8 km SMF. In the second section, it has 42.9 km SMF, 15.2 km DCF with -1387 ps/nm dispersion, and then 38 km SMF. The attenuation coefficients of the SMFs and the DCFs are 0.2 dB/km and 0.5 dB/km, respectively. These losses are compensated by using two C-band erbium-doped fibre amplifiers (EDFAs) in each section. The EDFA denoted A in Figure 3 has a 30 dB maximum small signal gain and ~13 dBm maximum output saturation power; while the EDFA denoted B has a 40 dB maximum small signal gain and ~15 dBm maximum output saturation power. The gain of the EDFAs is set to operate in saturation where each EDFA is followed by a variable optical attenuator (VOA) to adjust the power into the next fibre span. All EDFAs have a noise figure of approximately 5 dB. A gain-flattening filter (GFF) with 2 dB insertion loss is used within the loop to provide in line compensation of the spectral gain profile of the cascaded amplifiers over long distance. It restores all wavelengths to approximately the same intensity hence the same optical signal-to-noise ratio (OSNR) characteristics. An amplified spontaneous emission (ASE) filter with an insertion loss of 3 dB is also used to remove the accumulated ASE gain peak at 1530 nm. The loss of each filter is compensated by the previous EDFA so that the power into each fibre is constant.

At the receiver, a narrowband optical band-pass filter with 0.24 nm bandwidth and 7 dB insertion loss is used to demultiplex the WDM channels. The individual channels are then pre-amplified and detected by a bit-error-rate tester (BERT).

4. RESULTS AND ANALYSIS

4.1 Optimum Power Measurement

The optimum power for the system described earlier can be gleaned from Figure 4. It shows the BER measurements for the central channel (1555.5 nm) versus the total power of the entire WDM signal after 23 recirculations, i.e. ~4500 km. Since there are five channels, the approximate power per channel is 7 dB lower than the total power. This is valid in our case as the extinction of the GFF is set at maximum and centred in the middle of the data wavelengths; thus, the majority of the total average power exists within the data signals band. From Figure 4, it is shown that the optimum total power is around 8 dBm (or ~1 dBm per channel). Ideally, systems are intended to operate at optimum power where the BER is at a minimum. However, here we shall work in the nonlinear regime (> 8 dBm) in order to benefit from the nonlinearity upon changing the number of 1s and 0s in the data as mentioned earlier. Before running the experiment in the nonlinear regime, it is essential to present the recirculating loop performance at the optimum power to determine the distance limitation of the system.

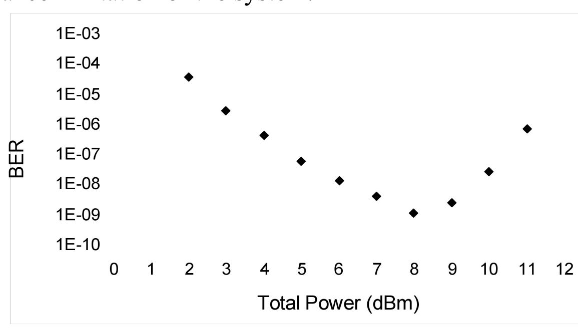

Figure 4: BER (measured for the central channel) versus total power after 4500 km.

4.2 Recirculating loop performance

Figure 5 shows the OSNR measurements for the central channel versus transmission distance using optimum power. It can be seen that the signal can propagate over ~6000 km with an acceptable OSNR. Nevertheless, the performance may be limited further by nonlinear effects. To check this, it is useful to present the BER performance as a function of transmission distance as shown in Figure 6. The curve shows that the maximum distance achieved with BER = 10^{-9} is around 4600 km for most of the channels using 1 dBm per channel. Longer distances are sufficient to induce nonlinear interactions in our system because we periodically use amplifiers at the chirp-free points (i.e. EDFAs denoted B in Figure 3) where the dispersion is fully compensated and thus the peak power is at a maximum. This makes the nonlinear interactions considerable beyond 4600 km thus the BER increases dramatically with distance.

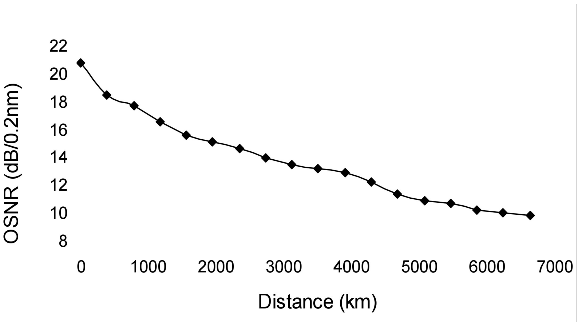

Figure 5: OSNR versus transmission distance for the central channel using 0.2 nm OSA resolution bandwidth.

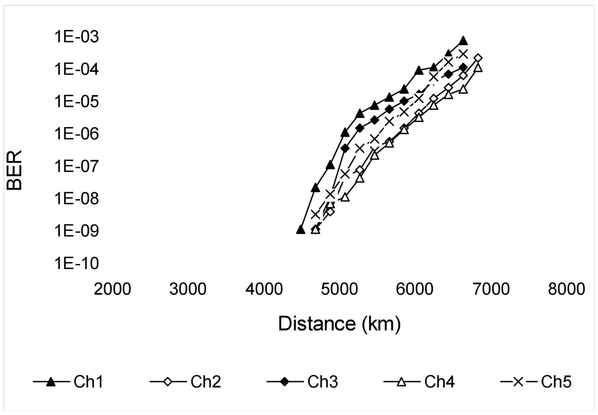

Figure 6: BER versus transmission distance for all WDM signals using optimum power. (Ch1: 1553.9 nm, Ch2: 1554.7 nm, Ch3: 1555.5 nm, Ch4: 1556.3 nm and Ch5: 1557.1 nm).

4.3 Extreme Unbalancing Results

If the system is allowed to operate at optimum power, unbalancing the fraction of the 1s and 0s will degrade the system performance. This is basically because the optimum power corresponds to the optimum pulse energy of the 1-bits. This implies that the ideal fraction of the 1s and 0s in optical transmission is 50% for systems that work near the optimum power. If the system operates in the nonlinear power region, the nonlinear penalty is proportional to the pulse energy; thus, the error-free distance is shorter than that obtained with optimum power. This can be understood as the nonlinear length is reduced according to the following formula:

$$L_{NL}=\frac{1}{\gamma P_0} \qquad (1)$$

where L_{NL} is the maximum distance limited by nonlinearity (called nonlinear length), P_0 is the peak power (related to pulse energy) and γ is the nonlinear coefficient [12] that is inversely proportional to the fibre effective area, which is 80 μm^2 in the SMFs of this experiment. Theoretically, the nonlinear length L_{NL} can be increased by reducing the pulse energy, which is planned to be achieved here through increasing the fraction of the 1s in the data. Based on this, we start by investigating the effect of extreme unbalancing in nonlinear operation, where the fraction of the 1s and 0s are unbalanced by ±25%. This is done to observe the impact in a wide scale and also to set extreme boundaries for the system performance. The total launch power used here is 3 dB higher than the optimum power (i.e. 11 dBm in total or 4 dBm per channel) to ensure high nonlinearities.

Figure 7 shows the back-to-back pulse shape for the central channel with 25%, 50% and 75% 1s, respectively. (Note that all signals are equally attenuated before being displayed to avoid photodiode saturation or damage.) It is clearly seen that the pulse energy decreases as the proportion of 1s increases as expected.

(a) (b) (c)

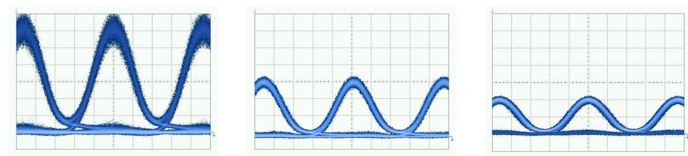

Figure 7: Back-to-back eye diagram for (a) 25%; (b) 50%; (c) 75% 1s in the data. (Time scale: 20ps/div).

The BER results as a function of transmission distance for all five channels are shown in Figure 8. In Figure 8 (a), when the data comprise of 50% 1s, the maximum transmission distance achieved with 10^{-9} BER is around 3500 km. This distance can be compared to that obtained with optimum power, showing that the nonlinear length has reduced considerably with larger pulse energy. In Figure 8 (b), when the fraction of 1s is reduced to 25%, the pulse energy increased in the 1-bits, introducing greater nonlinear interaction, thus the whole performance degraded. In this case, the maximum distance with 10^{-9} BER is shifted down by nearly five recirculations, i.e. 1000 km. In Figure 8 (c), when the fraction of 1s is increased up to 75%, the pulse energy is reduced; hence the nonlinear interaction is decreased and the overall performance improved. A propagation distance of ~4000 km with BER of 10^{-9} is attained in this case. Obviously, the performance of the system is limited by the nonlinear impairment rather than noise. Since the loop has fibers with high local dispersion, e.g. SMF (D ~ 17 ps/km/nm at 1550 nm), and relatively large channel separation, both cross-phase modulation (XPM) and four-wave mixing (FWM) would not be expected to have a large contribution to the overall nonlinear impairment. This is because the bits of different signals have different group velocities when they propagate through the fiber. Thus, they will pass through each other, which reduces the interaction between them during transmission. However, since we use amplifiers at the chirp-free points as stated before, the nonlinear interaction caused by XPM and FWM is enhanced and thus the overall nonlinear impairment can be a combination of XPM, FWM and self-phase modulation (SPM), although SPM has the largest contribution.

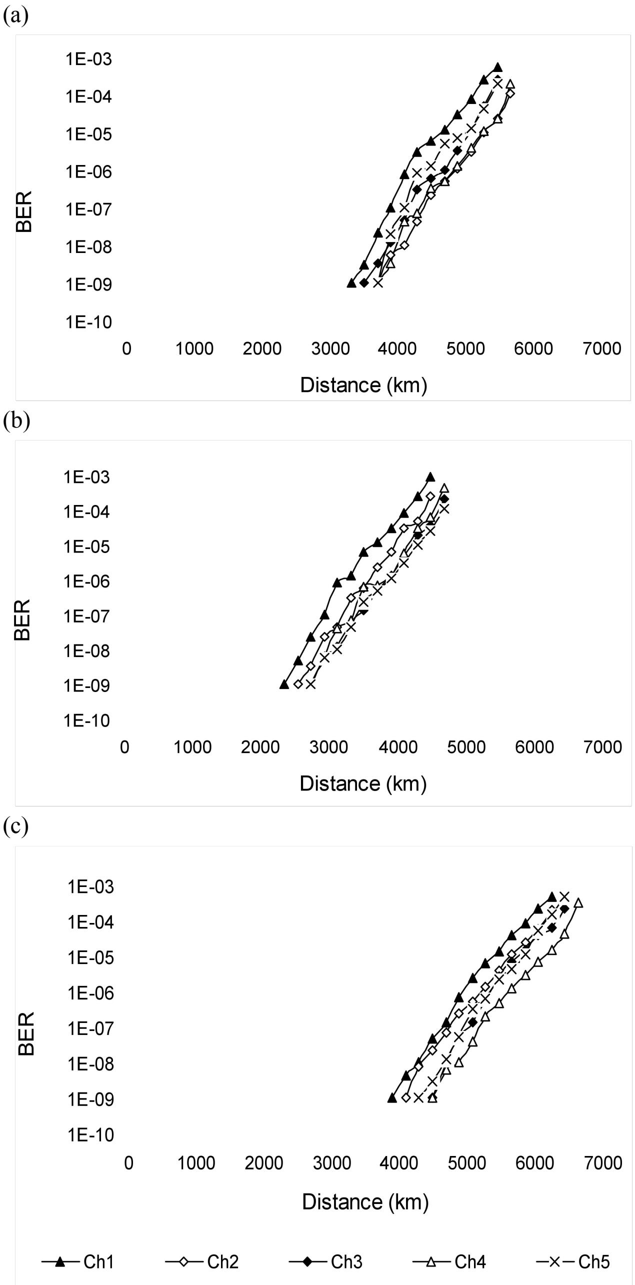

Figure 8: BER versus transmission distance for all WDM signals using: (a) 50% 1s; (b) 25% 1s; (c) 75% 1s. (Ch1: 1553.9 nm, Ch2: 1554.7 nm, Ch3: 1555.5 nm, Ch4: 1556.3 nm and Ch5: 1557.1 nm).

In fact, the propagation distance achieved with 75% 1s (Figure 8 (c)) is interesting as it is shorter by 600 km than the maximum distance of our system when we used optimum conditions (i.e. optimum power and 50% fraction). In principle, this penalty can be compensated by adjusting the launch power, hence the pulse energy of the 1-bit assuming that we have to maintain the fraction of the 1s. The required adjustment can be determined if the pulse energy is determined using the following equation:

$$E = \frac{P_{ch}}{v \times fraction} \tag{2}$$

where P_{ch} is the channel power in W and v is the frequency which is 10.7 GHz here. From Equation (2), the pulse energy for 75% using 4 dBm/ch is 3.13×10^{-13} J, while it is 2.35×10^{-13} J for 50% using the optimum power (1 dBm/ch). This implies that the pulse energy for the 75% must be reduced to 2.35×10^{-13} J to achieve 4600 km distance. This in fact can be attained by reducing the power of the channel, where the exact power can be calculated by fixing the pulse energy in Equation (2) which gives 2.8 dBm/ch. This means that the system can work in the nonlinear regime using 75% 1s and 2.8 dBm/ch rather than 4 dBm/ch to achieve a similar performance to that obtained with the optimum power for 50% 1s.

However, the results of 75% 1s can clearly show the effect of unbalancing and the trends that are expected. Now we look at the case of small deviations from 50%.

4.4 Small Unbalancing Results

To simulate the unbalancing effect caused by the FEC codes, we use a small variation in the fraction, e.g. ±3%. Having performed the experiments as discussed in the previous section, the results for the new fractions are shown in Figure 9 for the central channel when all channels use 4 dBm power. Although we are here most interested in the results of variations ≤ 3%, the large variation results have been included just for comparison where a full-scale picture can be seen.

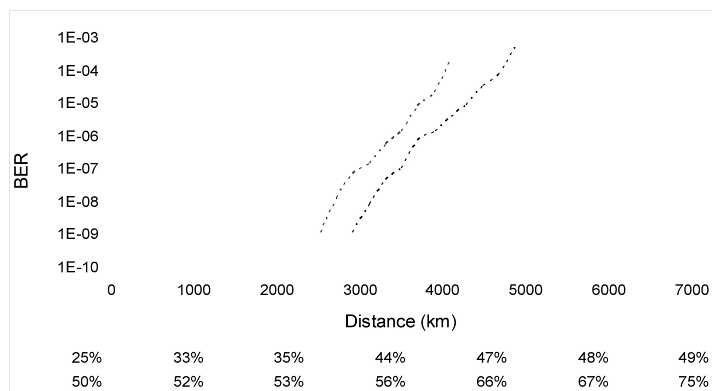

Figure 9: BER versus transmission distance for the central channel using different fractions of 1s.

Again, it is obvious that the propagation distance around the balanced fraction 50% is improved by increasing the fraction of the 1s even with a small variation. Figure 10 shows the eye diagram of the central channel in WDM operation after 22 recirculations (~4200 km) for different fractions. It shows that the nonlinear effects distort the signal with a lower fraction due to the higher pulse energy. Working backward from 75%, the signal starts to have considerable distortion at 56% (in Figure 10 (e)), thus the receiver counts considerable number of errors as shown before in the BER curve of Figure 9. This kind of distortion commonly causes an induced spectral broadening in the signal. Figure 11 shows the spectral shape of the central channel after 22 recirculations for selected fractions. It can be seen that more 1s in the data results in a narrower spectrum due to less nonlinear impairment caused by SPM and other nonlinear interactions. (Note that the spectrum is asymmetric which is caused by modulation at the transmitter.)

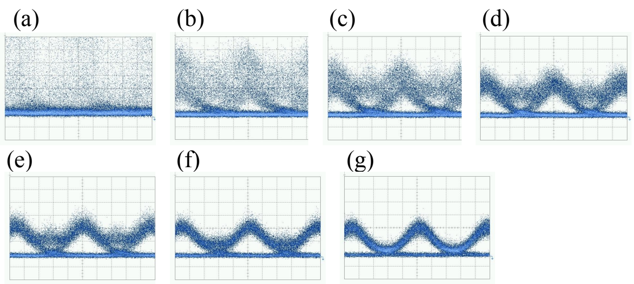

Figure 10: Eye diagram for the central channel after 22 recirculations (~4200 km) using fractions: (a) 25%; (b) 35%; (c) 44%; (d) 50%; (e) 56%; (f) 65%; (g) 75%. (Time scale: 20 ps/div).

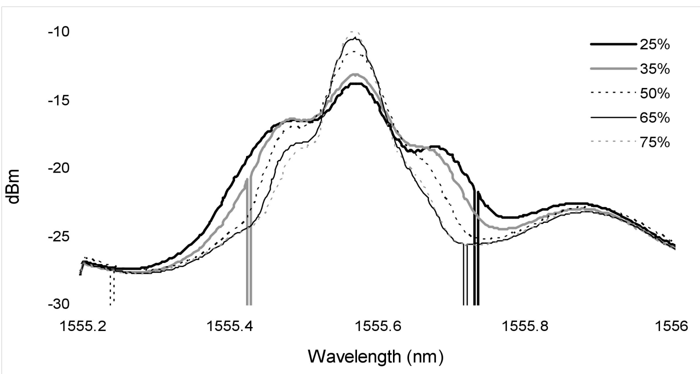

Figure 11: Spectral shape of the central channel after 22 recirculations (~4200 km) for different fractions, using 0.07 nm RBW.

To further quantify the results of Figure 9, it is useful to work out the pulse energy of the 1-bits using Equation (2). For instance, the pulse energy for 56% fraction is 4.19×10^{-13}J using 4 dBm/ch power. Remember that the optimum pulse energy for 50% is 2.35×10^{-13}J using the optimum power (1 dBm/ch). This implies that the pulse energy at 56% must be reduced to 2.35×10^{-13} to achieve optimum performance in this system. Therefore, the power required for 56% to attain such pulse energy is 1.49 dBm/ch from Equation (2). This means that the system can reach the optimum distance if it works in the nonlinear regime and uses 1.49 dBm/ch (or 8.49 dBm in total) in case that the encoder output has about 56% 1s. Again, this gives the ability of saving the additional electronics required in FEC. Repeating the above calculations for other fractions, the power per channel that is required to achieve the optimum pulse energy in the 1-bits and hence the maximum transmission distance is shown in Table 1.

For fractions less than 50% 1s, in which the pulse energy is higher hence nonlinear interaction, it is possible to improve the performance by decreasing the launch power where the power required to achieve the optimal pulse energy can be worked out in the same way used in Table 1. For instance, the power required per channel for fraction 44% to achieve 2.35×10^{-13} J is 0.44 dBm. This power can theoretically be used if the encoder's output is around 44% so that the system can still propagate for long distance. However, it is important to bear in mind that the OSNR will reduce in this case, because the system will work in the linear power region (below optimum power), where the performance will be dominated by noise and thus cannot be similar to that of the optimum case. Therefore, if the encoder output has less than 50% 1s, it is preferable to transmit the inverse of the bit sequence and then re-invert the data at the receiver.

Table 1: Power required per channel for different fractions of 1s to achieve optimum pulse energy in the 1-bits

Fraction (%)	Power (dBm/ch)
50	1.00
52	1.16
53	1.25
56	1.49
65	2.13
75	2.76

In general, if the output fraction of a specific code is known, the operation power can be chosen such that it corresponds to the optimum pulse energy of the system as shown earlier. This would require adjusting the EDFAs gains or their associated VOAs to provide the desired power level at the input of each fibre section.

5. CONCLUSION

This paper demonstrates experimental results for improving legacy long-haul WDM transmission system using an increased proportion of 1s in PRBS data. We initially demonstrate the principle of a considerable distance improvement caused by increasing the proportion of 1s dramatically from 50% to 75%. Since the system operates in the nonlinear power region, the improvement happens due to a significant drop in the pulse energy of the 1-bit and hence the nonlinear effects. We then demonstrate transmission results for smaller proportions of 1s (e.g. 53%, 56%, etc) to better simulate the effect that may occur when an FEC encoder adds more 1s to the data stream. The signal shapes and spectra are presented over long distances for different fractions of 1s, showing better performance with more 1s. As a result, we conclude that the scrambler (and associated descrambler) which conventionally follows the FEC encoder to rebalance the data can be saved if the encoder adds more 1s to the data and the system operates at high power. If the encoder adds more 0s, the inverse of the data can be transmitted and then inverted back to its original sequence at the receiver.

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