SUBMARINE SYSTEM UPGRADES WITH 25 GHZ CHANNEL SPACING USING DRZ AND RZ-DPSK MODULATION FORMATS

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Abstract: The exponential growth of network-traffic is driving demand for greater capacity. High spectral efficiency and reduced repeater count employed in 10-Gb/s optical transmission systems are key to cost-effective capacity expansion. This paper experimentally and numerically evaluates the feasibility of 5000~6000km system upgrades using differential return-to-zero (DRZ) and demonstrates the potential of >9000km system transmission using differential-phase-shift-keying (RZ-DPSK), each system with 128-channels spaced by 25-GHz. Our results show that all channels can operate with 3dB performance margin above the forward error correction (FEC) threshold. Furthermore, we investigate the impact of simultaneous transmission of DRZ and DPSK on the DPSK-channels.

1. INTRODUCTION

The explosive bandwidth requirement brought about by the rapid increase of global broadband access is driving demand for greater system transmission capacity on long-haul backbone networks. Increasing spectral efficiency (SE) and reducing repeater number are two effective solutions to achieve cost-effective capacity expansion, the main focus of the telecommunications industry. Upgrading 10G to 40G/100G is one of the most promising means to achieve high SE. This potential has been demonstrated in some 40-Gb/s transmission experiments performed in both laboratories and field trials. However, large scale commercialization of 40G/100G systems is limited by the maturity of 40G technology and the establishment of a standard and cost-reduced product. From this perspective, 10G will still remain very efficient in comparison to 40G for a relatively long time. Another effective solution to achieve high SE is to densely populate more and more channels in a single fiber, which necessitates the decrease of channel spacing in a given bandwidth. Similarly, increasing the repeater spacing and thus reducing the number of repeaters also requires an improvement in the received optical-signal-to-noise-ratio (OSNR) sensitivity in order to obtain a specified BER. These two solutions pose big challenges to the pulse modulation technology.

Optical differential return-to-zero (DRZ) is an advanced on-off-keying (OOK) modulation technology, invented particularly for high-capacity long-haul transmission with 25GHz channel spacing. It inherits and builds upon some of the advanced features of both carrier-suppressed return-to-zero (CSRZ) and differential phase-shift keying (DPSK) modulation formats. In comparison to CSRZ signals, which have alternating pi-phase shifts between adjacent bits, DRZ signals have differential pi-phase shifts between adjacent marks. Hence, every mark in DRZ signals has a 180-degree phase shift from its nearest mark. This feature significantly reduces inter-symbol interference and thus overcomes the elevation of an isolated zero level occurring in CSRZ signals, providing better dispersion tolerance than the CSRZ format. In addition, complete carrier-suppression together with additional suppression of side peaks in the spectra makes DRZ signals more resilient to nonlinear effects than CSRZ signals. Furthermore, only one Mach-Zehnder (MZ) modulator is needed to generate DRZ signals. This not only lowers the cost but also reduces the complexity and improves the reliability of a DRZ transmitter, hence improving performance of an optical fiber communication system. All these advantages make DRZ one of the most cost-effective solutions for high-capacity long-haul transmission.

The RZ-DPSK modulation format together with balanced detection has been a key technology to achieve trans-oceanic DWDM transmission. With approximately 3-dB of OSNR sensitivity improvement, the repeater spacing can be increased from a conventional 45~50km for OOK systems to 75~80km, greatly reducing the number of repeaters and consequently the cost. Most successful high-capacity trans-oceanic transmission systems deploy 10-Gb/s-DPSK channels at 33.3GHz or 37.5GHz channel spacing [1-2]. However, whether narrower channel spacing such as 25GHz can be used to support trans-oceanic transmission still remains an open question. In addition, RZ-DPSK can be used in the upgrade of OSNR-limited OOK systems to provide more channels.

In this paper, we experimentally and numerically evaluate the feasibility of 5000~6000km system upgrades using cost-effective DRZ and demonstrate the potential of ultra-long-haul transmission using RZ-DPSK, each system with 128-channels spaced 25-GHz apart. Our results show that, all channels can achieve >3dB performance margin above the forward error correction (FEC) threshold. Furthermore, we studied the impact of simultaneous transmission of DRZ and DPSK in a system on the DPSK-channels.

2. EXPERIMENTAL SETUP

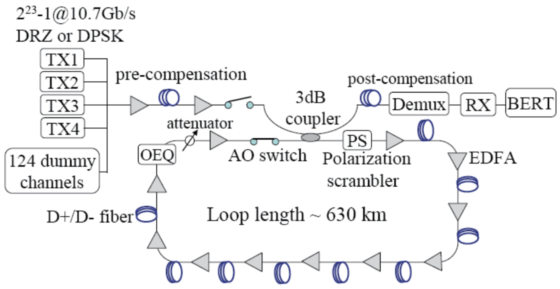

Figure 1: Experimental Setup

To investigate the transmission performance of DRZ and DPSK modulation formats in long-haul and ultra-long-haul systems, we carried out re-circulating loop transmission experiments. Although these experiments cannot clone the installed systems, they provide a relatively inexpensive way to accurately evaluate accumulated signal impairments such as chromatic dispersion, nonlinear effects, ASE noise etc. The schematic diagram of our loop system is shown in Fig.1. At the transmitter, four randomly polarized, evenly spaced DRZ or DPSK channels and 124 ASE dummy channels were multiplexed and launched into a transmission path. The operating bandwidth ranged from 1535nm to 1561nm. The four 10.7-Gb/s signal channels employed patented DRZ or commercialized DPSK transponders with 25GHz channel spacing and 7% FEC overhead. They were modulated by a 2^{23}-1 pseudo-random-bit-stream (PRBS). Their wavelengths are tunable, which allows for experimental studies in the blue, central and red bands within the full C-band.

The loop consisted of nine spans of dispersion-managed fibers, which combined dispersion slope matched large effective area positive dispersion fiber (+D type) and negative dispersion fiber (-D type) in each single span. The dispersion coefficients of +D type and –D type fibers at 1550nm were +20ps/nm/km and -44ps/nm/km, respectively. By adjusting the ratio of the two types of fibers, the average dispersion of the dispersion-managed spans was controlled at about -3ps/nm/km. The average span loss was about 14 dB, which was equivalent to a span length of ~70 km. The loop length per round trip was ~630km. The average loop chromatic dispersion and dispersion slope were about -0.4ps/nm/km and -0.003ps/nm^2/km, respectively. An optical gain equalizer was used in the loop to provide in-line compensation of the uneven spectral gain profiles of the EDFAs. To emulate a straight-line system, we used a loop polarization scrambler to randomly rotate the states of polarization of the signals. Eleven EDFAs were used in the loop to compensate for the fiber- and component-loss. The average EDFA output power and noise figure were 14dBm and 4.8dB, respectively. At the receiver, after dispersion post-compensation and optical de-multiplexing, the signals were detected and the bit-error-ratio (BER) measured.

3. SYSTEM SIMULATOR

We developed a powerful in-house system simulation tool with a user-friendly graphical user interface (GUI) for fast and accurate performance prediction and validation in both repeated and unrepeatered optical transmission systems. By numerical simulations, one can theoretically evaluate different transmission penalties caused by ASE noise, chromatic dispersion, nonlinear effects, polarization effects etc., thus optimizing system design and providing sufficient performance margins for all channels. Most experimental results presented here are compared with those obtained with our system simulator.

4. RESULTS AND DISCUSSION

A. 10-Gb/s DRZ TRANSMISSION

In the 128 × 10Gb/s DRZ transmission experiment, we measured the transmission performance of four sample signal channels, spaced 25GHz apart, over 5040km in the blue, central and red bands respectively. Power pre-emphasis was applied at the transmitter to equalize the OSNR of all channels to within 1dB at the receiver. Fig.2 shows measured and simulated OSNRs and *Q*-factors after transmission. It also shows the minimum required *Q*-factor for error-free transmission using 7% FEC overhead with a dashed line (*Q*=9.2dB). The measured average and minimum channel *Q*-factors were about 12.6dB and 12.2dB respectively. This corresponds to an average and minimum system margin of 3.4dB and 3dB respectively. The corresponding simulated values were 12.8dB and 12.3dB respectively. They are in good agreement with the experimental results.

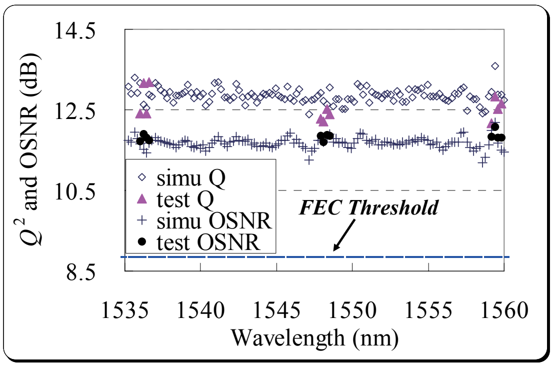

Figure 2: Q^2 and OSNR vs. wavelength for 128×10Gb/s DRZ transmission

We also investigated the residual dispersion and power tolerance in DRZ transmission. Fig.3 shows the 10-Gb/s DRZ residual dispersion tolerance for dispersion-slope-matched fiber. After 5040km of propagation, the chromatic dispersion window corresponding to 1dB dispersion-penalty is approximate 1000ps/nm, exhibiting quite a large dispersion tolerance. To avoid the limitation of channel transmission performance induced by the repeater output power, we also carried out a pre-emphasis experiment to find the *Q* penalty induced by non-optimal channel power. We simultaneously increased and decreased the launch powers of three channels in the central band, spaced 25GHz apart, with the measurement channel (Ch64) in the middle. By normalizing the channel power with respect to the optimum launch power and defining the *Q*-penalty as the difference between received *Q*'s at non-optimal and the optimum launch powers, we obtained the channel power tolerance for DRZ transmission with slope-matched fibers, as shown in Fig. 4.

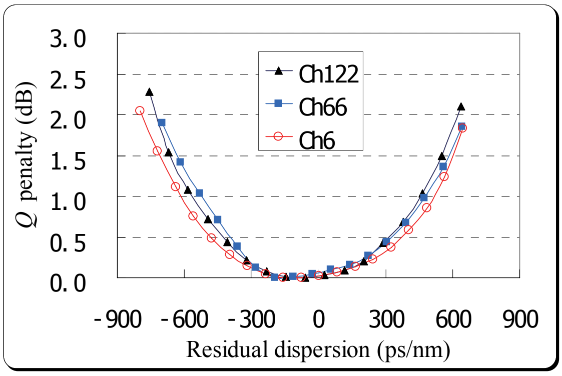

Figure 3: Residual dispersion tolerance for DRZ transmission

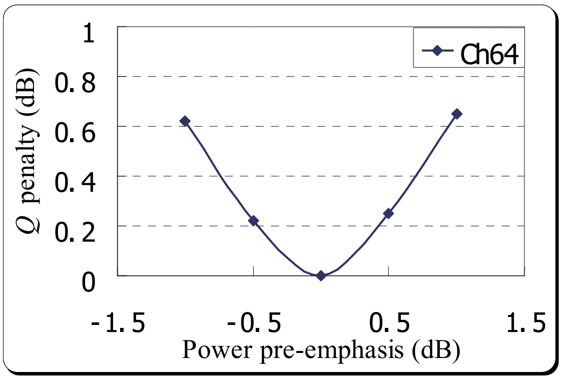

Figure 4: Channel power tolerance for DRZ transmission

In addition to the laboratory loop experiment, we also successfully upgraded an installed trans-Atlantic system to 90× 10Gb/s by using the DRZ format. The whole segment was over 6000km in length, built with conventional non-slope-matched submarine fibers. The repeater spacing was about 50km. The output power of the repeater was 12.5dBm. Fig.5 shows the measured *Q*-factors for all channels. The average and the minimum *Q* values were 13.4dB and 12.3dB, respectively, providing >3dB system margin for all channels to support trans-Atlantic traffic.

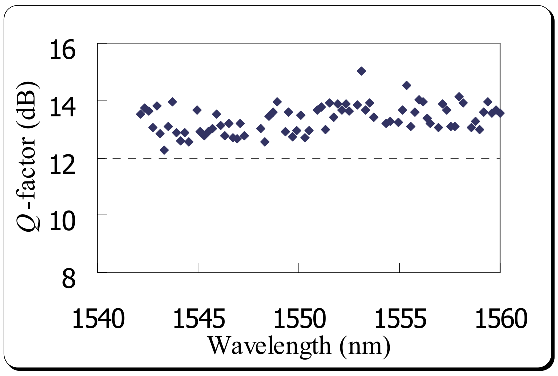

Figure 5: Received *Q*-factor vs. channel wavelength in field trial.

B. 10-Gb/s DPSK TRANSMISSION

With almost the same loop configuration, we carried out a 128 × 10Gb/s DPSK transmission experiment over 9450km. We measured the resulting *Q*-factor of four DPSK sample channels, spaced 25GHz apart, in the blue, central, and red bands respectively. Fig.6 shows the comparison of measured and simulated *Q* values. The measured average and minimum channel *Q*-factors were about 12.6dB and 12.3dB respectively. This corresponds to an average and minimum system margin of 3.4dB and 3.1dB respectively. The differences in channel *Q*-factors were caused mainly by non-optimal channel pre-emphasis at the transmitter.

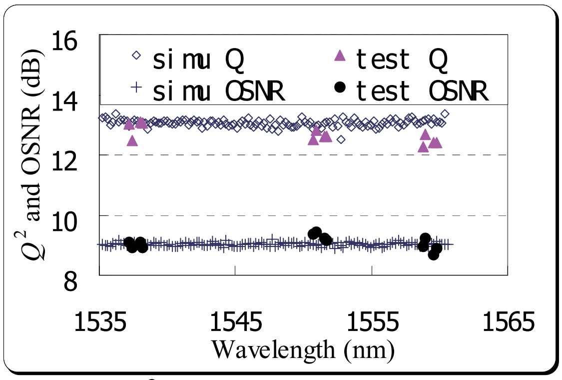

Figure 6: Q^2 and OSNR vs. wavelength for 128×10Gb/s DPSK transmission.

Fig. 7 and Fig. 8 show the residual dispersion and launch power tolerance after 9450km. The measured dispersion window corresponding to 1-dB dispersion penalty transmission was approximately 1070ps/nm/km, slightly larger than the DRZ transmission tolerance over 5040km transmission shown in Fig.3. As one can see in Fig.8, the *Q*-factor at the optimum channel power was close to 13.5dB, which means that all sample channels in 128-channel transmission were not operated at the optimum launch power due to the low output power of the repeaters. This shortened the maximum transmission distance.

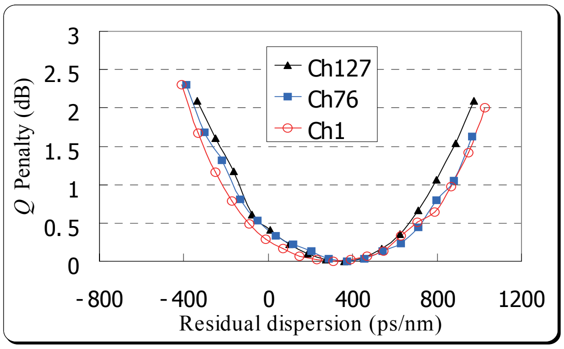

Figure 7: Residual dispersion tolerance for 128×10Gb/s DPSK transmission

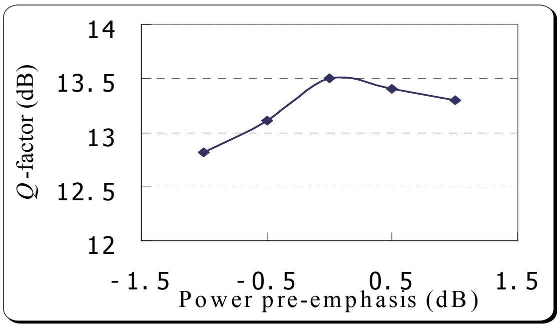

Figure 8: Channel power tolerance for DPSK transmission

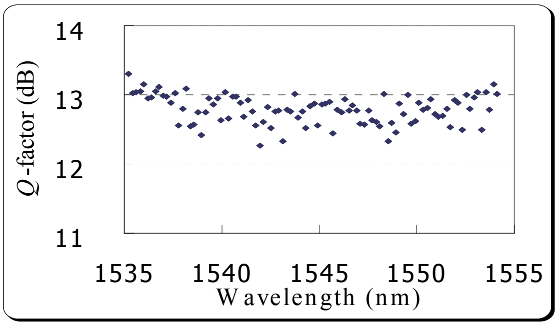

Figure 9: *Q* vs. wavelength for 96×10Gb/s DPSK transmission over 11340km.

To maximize the transmission distance, we performed a 96×10Gb/s DPSK simulation using the experimental configuration to increase the channel power. All channels are spaced 25GHz apart. Fig. 9 shows the received *Q*-factor after 11340km of propagation. One can see that all channels can achieve >3dB system margin, greatly extending the transmission distance.

C. SIMULTANEOUS TRANSMISSION OF DRZ AND DPSK

In some OOK systems whose channel count is limited by OSNR, we can replace some OOK channels with more DPSK channels to increase the number of channels. Our experimental study shows that the impact of OOK signals on DPSK signals after 5000km transmission can be neglected even when their channel spacing is 25GHz. We also carried out a 5670km transmission experiment by replacing some DRZ channels with DPSK channels and at the same time decreased the DPSK channel power by 1.2dB and increased the DRZ channel power by the same amount. With the replacement, all 128 DRZ/DPSK channels achieved 3dB margin in comparison to 2.1dB margin when all channels adopted DRZ formats.

5. CONCLUSIONS

This paper presents WDM transmission experiments and simulations in which 128 10-Gb/s DRZ and DPSK channels were successfully transmitted over 5040km and 9450km, respectively.

6. REFERENCES

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[2] Laurent du Mouza, L.; Dupont, S.; Marmier, P.; Bollaert, P.; Jaouen, M.; Vareille, G.; Letellier, V., "124 x 10 Gbit/s RZ-DPSK transmission over 12380 km without channelized chromatic dispersion management", OFC 2007, San Diego, USA, Paper OThS3.

