RZ-DPSK 10GB/S SLTE AND ITS TRANSMISSION PERFORMANCE ASSESSMENTFOR APPLICATION TO TRANS-PACIFIC SUBMARINE CABLE SYSTEMS

Yoshihisa Inada(1), Ken-ichi Nomura(1) and Takaaki Ogata(1), Keisuke Watanabe(2), Katsuya Satoh(2)

y-inada@ak.jp.nec.com

(1) Submarine Networks Division, NEC Corporation

(2) 2nd Network Platform Development Division, NEC Communication Systems Ltd.

34-6, Shiba 5-chome, Minato-Ku, Tokyo, 108-0014, Japan

Abstract : This paper describes RZ-DPSK 10Gb/s SLTE for commercial use, which can detects 10Gb/s signal with 2.5dB improved performance in terms of optical noise loading under back-to-back measurement. The effectiveness of the equipment has been assessed through very long distance transmission experiment over trans-Pacific reaches. The improvement factor of 2.5dB with RZ-DPSK transponder is kept even under very long distance transmission up to 11,300km.

1 INTRODUCTION

The 10 Gb/s dense WDM systems have been implemented in the last several years as an infrastructure for international communication and global network. Most of the submarine line terminal equipment (SLTE) used in those systems adopted Chirped Return-Zero (CRZ) and advanced forward error correction (A-FEC) algorism, together with other common DWDM technologies such as narrow channel optical multiplexing/de-multiplexing, pre-emphasis and dispersion compensation functions. Further performance improvement in SLTE has attracted much attention, and it has already been reported by many laboratory experimental reports that advanced modulation format of DPSK (Differential Phase Shift Keying) can contribute to achieve a higher capacity and longer distance DWDM systems[1-4].

This paper describes RZ-DPSK 10Gb/s SLTE for commercial use, and its transmission performance assessment for application to extremely long-reach trans-Pacific submarine cable systems.

The SLTE basically consists of two equipments. One is a transponder and the other is a optical multiplexing/de-multiplexing part. The newly developed RZ-DPSK transponder configures a family of our 10 Gb/s DWDM products, and supervised by element management system. It includes a set of transmitting and receiving functions with RZ-DPSK modulation format and BCH error correcting codec. The evaluation of developed equipment has shown that it can detect 10Gb/s signal with 2.5dB improved performance in terms of optical noise loading under back-to-back measurement.

The effectiveness of the equipment has been assessed through very long distance transmission experiment over trans-Pacific reaches. In the experiments, loop configuration has been used with chained amplifier repeaters and representative submarine transmission fibers, namely Non-Zero Dispersion Shifted Fiber (NZ-DSF) and Dispersion Managed Fiber (DMF). It has been confirmed that the propagation penalty is comparable or less than that for CRZ under optimized dispersion mapping, and the improvement factor of 2.5 dB is held true even under very long distance transmission of up to 11,000 km. The impact to system performance has also been confirmed to be much better than the face value due to less influence of optical noise and fiber nonlinearity, both thanks to less number of amplifier spans.

2 10GB/S RZ-DPSK SLTE DEVELOPMENT

2.1 Equipment Functions and Signal Processing

The developed RZ-DPSK SLTE fully complies with the industry specifications for DWDM application. The RZ-DPSK transponder is developed based on common architecture of our current version of SLTE except for specific to RZ-DPSK, other part of SLTE such as optical multiplexing and de-multiplexing parts can be commonly applied as well as the mixed use of different types of transponders.

The transponder incorporates a set of both transmitting and receiving functions with RZ-DPSK modulation format and advanced FEC codes, in which a concatenated BCH codes are applied.

Figure 1 shows the simplified block diagram of RZ-DPSK transponder. In the transmitting side, an O/E portion receives an STM-64/OC-192 optical signal and converts it to an electrical signal. The 10Gb/s electrical signal is de-multiplexed and transmitted to the FEC LSI, which carries out the advanced FEC encoding, overhead data insertion and SDH/SONET performance monitor and then generates the 10.7Gb/s signals. Finally, an E/O portion produces 10.7Gb/s wavelength stabilized optical RZ-DPSK signal through two stage process. The first one is for DPSK modulation driven by DPSK-encoded 10.7Gb/s electrical signal and the second one is for RZ modulation driven by a 10.7GHz sinusoidal wave. In the receiver side, after optical pre-amplification, an O/E portion receives a 10.7Gb/s optical RZ-DPSK signal by DPSK receiver, which consists of DPSK demodulator and balanced photo receiver. The received 10.7Gb/s electrical signal is de-multiplexed and transmitted to the FEC LSI, which carries out the advanced FEC decoding, overhead data termination and FEC section performance monitor and then outputs parallel data signals. These data are multiplexed into a 9.95Gb/s signal and an E/O portion finally converts to an SDH/SONET 10Gb/s optical signal.

This transponder can support the wavelength of the ITU-T grid with 50GHz or 33GHz grid, and optionally can be customized to other requirements. Its wavelength stability is confirmed to be as good as +/-0.01nm.

Twelve systems of the transponder can be accommodated in a V400 Rack.

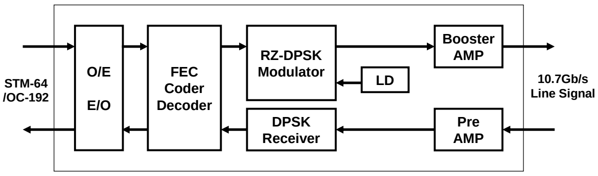


Fig. 1. Block Diagram of RZ-DPSK Transponder

2.2 RZ-DPSK Modulation Format

RZ-DPSK modulation format is one of the candidates.

for further expanding the transmission distance taking advantage of its improved receiving sensitivity and superior tolerance for nonlinear effect.

Figure 2 shows a typical configuration of RZ-DPSK transmitter and receiver. In the transmitter, pre-coded 10Gb/s electrical signal is converted into optical DPSK signals and then RZ modulated. In the receiver side, RZ-DPSK Signal is demodulated by Mach-Zehnder interferometer with one bit delay circuit and detected by the balanced photo-receiver. The RZ-DPSK modulation achieves higher receiving sensitivity, thanks to this peculiar receiving configuration of balanced detection, that can double the eye amplitude of received signals.

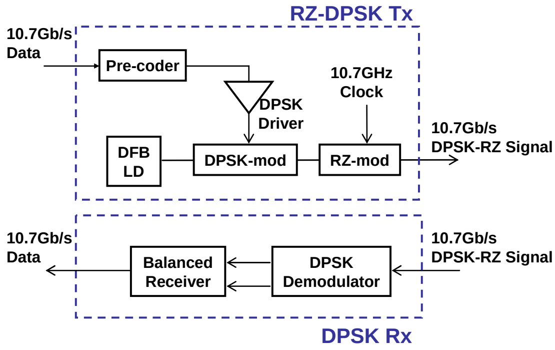


Fig. 2. Block Diagram of RZ-DPSK Tx/Rx

Figure 3 shows the experimental comparison of Q performance for RZ-DPSK signal and conventional RZ signal in back-to-back condition. As shown in this figure, optical SNR tolerance by RZ-DPSK signal is improved by 2.5dB compared to RZ signal. This optical SNR tolerance improvement of RZ-DPSK signal can benefit trans-oceanic submarine cable systems in two ways. One is to increase the ultimate system capacity beyond the original capacity designed with the conventional signal format, such as NRZ or RZ, by increasing the number of wavelengths. The other is to increase repeater spacing, which reduces the number of repeaters, saving the capital expense of submarine cable systems.

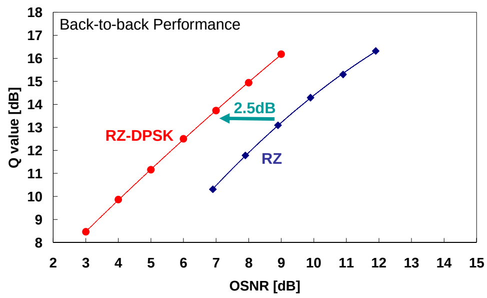


Fig. 3. Optical SNR Tolerance

2.3 Error Correction Performance

The FEC scheme applied in the RZ-DPSK transponder uses the concatenated BCH codes[5], which utilizes BCH(3860, 3824) as the outer code and BCH(2040, 1930) as the inner code. The BCH(2040,1930) and BCH(3860, 3824) codes can correct up to 10 and 3 bit errors of one codeword, respectively. Furthermore, this FEC scheme applies three times iterative decoding, improving the error correction capability without increasing the coding rate. Interleavers and deinterleavers with a depth of 128 bytes are used between the inner and outer code in order to spread the burst errors. This FEC scheme provides an excellent coding gain with the same redundancy of the standard RS(255,239), resulting transmission signal line rate of 10.7Gb/s after this coding.

Table 1 shows the parameters of the Advanced-FEC LSI developed. Both 10Gb/s throughput encoder and decoder have been achieved in a single chip. The Advanced-FEC codec achieves a low power consumption of 3.15 W. This LSI contributed in reducing the equipment size, as well as power consumption.

Item	Description
Code	BCH(2040, 1930) + BCH(3860, 3824)
Net coding gain	8.5dB(BER 1E-13)
Redundancy	6.69%
Process	0.15 μm CMOS
Supply voltage	1.5V, 1.8 V, 3.3 V
Package	BGA (576 pins)
Power Consumption	Terminal mode: 3.15 W (Typical) Regenerator mode: 2.56 W (Typical)
Throughput	9.96 Gb/s (Client), 10.71 Gb/s (coding)

Table 1. Features of Advanced-FEC Codec

Fig.4 shows the simulation results of error correction performance. For comparison purpose, the correction performance with RS(255,239) scheme is also shown. The Advanced-FEC codec can improve the error rate from 3.25E-3 to 1E-13, which corresponds to a 8.5dB net coding gain. The Advanced-FEC codec gives an additional 2.4 dB coding gain compared with the standard RS(255,239) code.

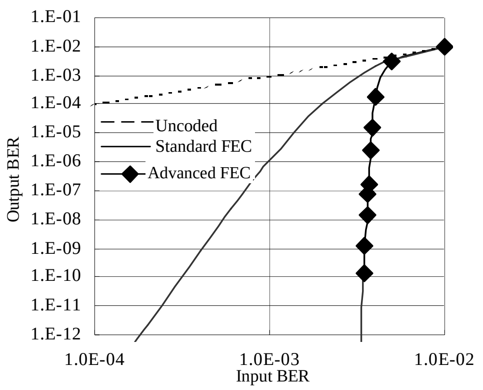


Fig. 4. Error Correction Performance of Advanced-FEC

3 TRANSMISSION PERFORMANCE

3.1 Experimental Setup

To confirm the effectiveness of the 10Gb/s SLTE using RZ-DPSK signal format, we have conducted transmission experiments by using two different types of transmission fibers, such as Dispersion Managed Fiber (DMF) and Non-Zero Dispersion Shifted Fiber (NZ-DSF).

Figure 5 shows our experimental setup for long distance transmission of 66 x 10.7Gb/s RZ-DPSK signals. The transmitter was comprised of 66 DFB-LDs equally spaced at 33 GHz intervals ranging from 1542.1 nm to 1559.5 nm. A total of 3 RZ-DPSK transmitters were used in this evaluation. Even and odd channels were separately modulated into 10.7Gb/s RZ-DPSK signals by two different transmitters. Measurement wavelength was also modulated by another RZ-DPSK transmitter, which is independent from the other two. The even and odd channels were multiplexed by a 3dB coupler and then coupled with the measurement channel. Before transmitting the WDM signals into loop transmission line, appropriate dispersion compensation was applied at the transmitter side.

Two kinds of transmission fiber lines were used as shown in Fig.6. One is NZ-DSF transmission line, which is applied to most of the current submarine cable systems. NZ-DSF span is composed with two types of NZ-DSFs, in which Large Effective core Area Fiber (LEAF) is assigned in first portion to relax the fiber nonlinearity and Low Slope NZ-DSF (LS) is assigned in the second portion to reduce the dispersion slope of transmission fiber. The other transmission line we evaluated was the DMF transmission line[6], which is composed of SMF(D=+20ps/nm/km) and slope-matched DCF (D=-40ps/nm/km). This configuration can achieve excellent dispersion flatness for trans-Pacific distance and greatly reduce the waveform degradation induced by the combined effect of fiber non-linearity and dispersion compared to NZ-DSF. Figure 7 shows the measured dispersion of NZ-DSF transmission line and DMF transmission line used in our experiment. Residual dispersion slope of DMF is less than 0.01ps/nm^2/km, and that of NZ-DSF is about 0.07ps/nm^2/km.

In the receiver, after dispersion compensation, each channel selected by an AWG was detected by a 10.7Gb/s DPSK receiver.

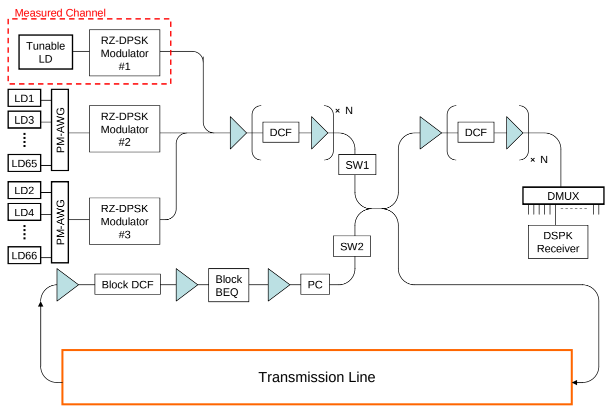
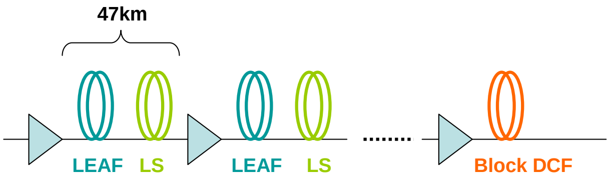
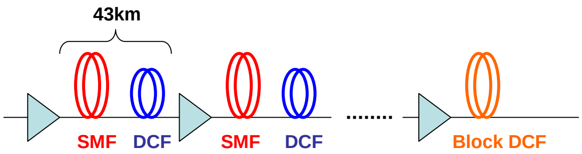


Fig. 5. Experimental Setup



(a) NZ-DSF (loop length: 388km)



(b) DMF (loop length: 872km)

Fig. 6. Transmission Line Configurations

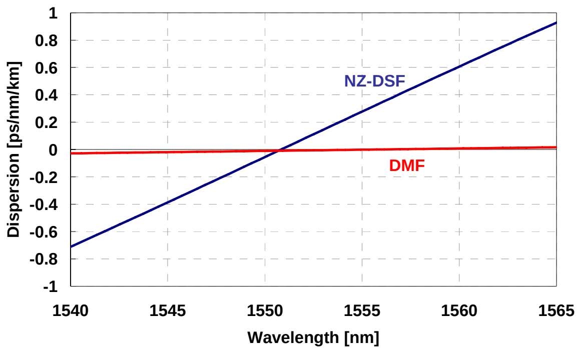


Fig. 7. Dispersion of Two Kinds of Transmission Lines

3.2 9300km Transmission using NZ-DSF

For the NZ-DSF transmission line, the residual dispersion due to the dispersion slope is significantly accumulated at the edge regions of the transmission band as the transmission distance is expanded and induces the waveform distortion by combined effect with fiber non-linearity. To overcome this degradation, Chirped-RZ signal has been used so far. However this signal format can not be applied to the trans-oceanic transmission system of channel spacing of less than 50GHz, because it inherently spreads the signal spectrum causing the overlap of signal spectrum between neighboring channels, and degrading signal performance by a cross talk for narrow channel-spacing WDM systems. To cope with narrow channel spacing of 33GHz in trans-oceanic transmission using NZ-DSF, the RZ-DPSK modulation format is attractive because it has remarkable tolerance against accumulated dispersion, by keeping its signal spectrum sufficiently narrow to fit into the 33GHz channel spacing.

Figure 8 shows the measured Q values and optical spectrum of 66 x 10.7Gb/s RZ-DPSK signals after 9300km transmission of NZ-DSF transmission line. Also shown is detection limit of our advanced-FEC. Received waveforms after balanced detection are shown in Fig.9. In this experiment, span length is 47km and repeater output power is set to +12.3dBm. Measured Q values are 13.1dB on average and 12.4dB at minimum for all measured channels. This result indicates that Q margin is more than 3dB from the FEC detection limit. Experimental Q penalty from the theoretical Q value derived from received optical SNR is 2.1dB on average and 2.8 dB at worst channel, respectively.

As shown in Fig.8, transmission performance at the edge regions of transmission band is pretty good in spite of its large accumulated dispersion due to the dispersion slope. This result clearly indicates the superior tolerance of RZ-DPSK signal against accumulated dispersion. On the other hand, at the center wavelength range around 1551nm that is near net zero dispersion region, Q value degradation was observed compared to other wavelengths. The dominant degradation factor in this region is considered to be the optical phase noise accumulation induced by the combined effect of fiber non-linearity and optical noise accumulation. The RZ-DPSK signal seems to be sensitive to the optical phase noise accumulation, because this signal format uses the optical phase for data modulation.

As is seen from these results, adoption of RZ-DPSF signal into the trans-oceanic submarine cable systems using NZ-DSF is effective compared to other signal formats such as NRZ, RZ and Chirped-RZ, especially at the edge wavelength range, in which residual dispersion is accumulated. RZ-DPSK is also advantageous because of its high receiver sensitivity, accommodation of narrow channel spacing and high tolerance against accumulated dispersion. In order to fully utilize this signal format, further development to suppress the performance degradation around the zero dispersion range is important.

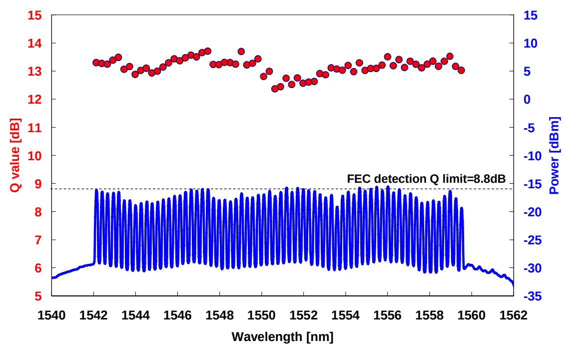
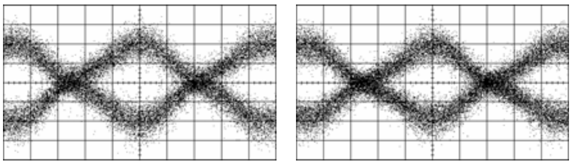


Fig. 8. Q values and Optical Spectrum at 9,300km



(a) 1542.1nm (b) 1550.9nm

Fig. 9. Received Waveforms at 9,300km

3.3 11300km Transmission using DMF

DMF is attractive transmission fiber for trans-oceanic submarine cable systems because of its dispersion flatness and low nonlinearity. However, as described above, RZ-DPSK signal is not suitable for application in the zero dispersion range and there arises concern that RZ-DPSK may not be beneficial to this dispersion flattened DMF transmission line.

To clarify this point, we have conducted long distance transmission experiments by using DMF

Figure 10 shows the measured Q values and optical spectrum of 66 x 10.7Gb/s RZ-DPSK signals after 11,300km transmission. In this experiment, span length is 43km and repeater output power is set to +12.5dBm. To make the best use of DMF transmission line, dispersion map should be optimized according to signal format. In this experiment, average dispersion is adjusted to -0.46ps/nm/km at 1552.5nm in order to avoid the severe optical phase noise accumulation, which is the dominant degradation of RZ-DPSK signal transmission. Measured Q values are 12.7dB on average and 12.4dB at minimum for all measured channels. Q margin is as large as 3.6dB from the FEC detection limit. Experimental Q penalty from the theoretical Q value derived from received optical SNR is 1.4dB on average and 1.7 dB at worst channel, respectively. Figure 11 shows the received waveforms after balanced detection at 11,300km. No significant eye closure induced by the optical phase noise is observed even after 11,300km transmission.

Compared to our previous experiment of 11,300km transmission of 66 x 10.7Gb/s Chirped-RZ signals[5], 0.8dB higher Q value is achieved in this experiment in spite of 1.5dB lower repeater output power condition, thus an improvement factor of 2.5dB with RZ-DPSK signal is almost maintained even under very long distance transmission up to 11,300km.

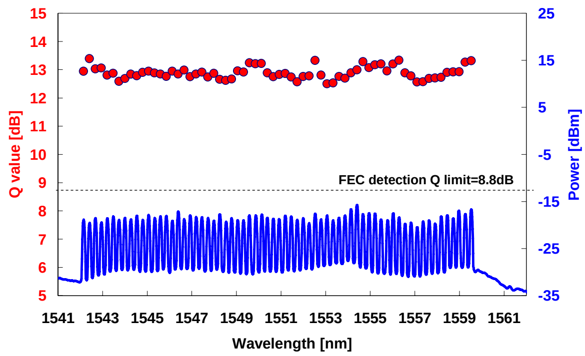
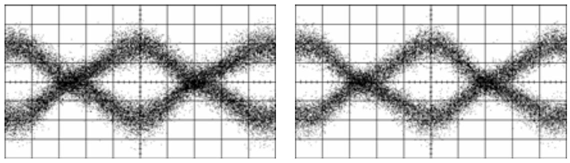


Fig. 10. Q values and Optical Spectrum at 11,300km



(a) 1542.1nm (b) 1552.5nm

Fig. 11. Received Waveforms at 11,300km

4 CONCLUSION

This paper has described RZ-DPSK 10Gb/s SLTE for commercial use and its transmission performance for extremely long distance trans-Pacific submarine cable systems. The developed RZ-DPSK transponder has achieved with 2.5dB performance improvement compared to our conventional RZ transponder. Furthermore, the effectiveness of this equipment has been verified through long distance transmission experiment over trans-Pacific reach and improvement factor of 2.5dB with RZ-DPSK transponder is kept even under very long distance transmission up to 11,300km.

5 REFERENCES

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