Progressive Introduction of ROADM Networks and DPSK Modulation Technology

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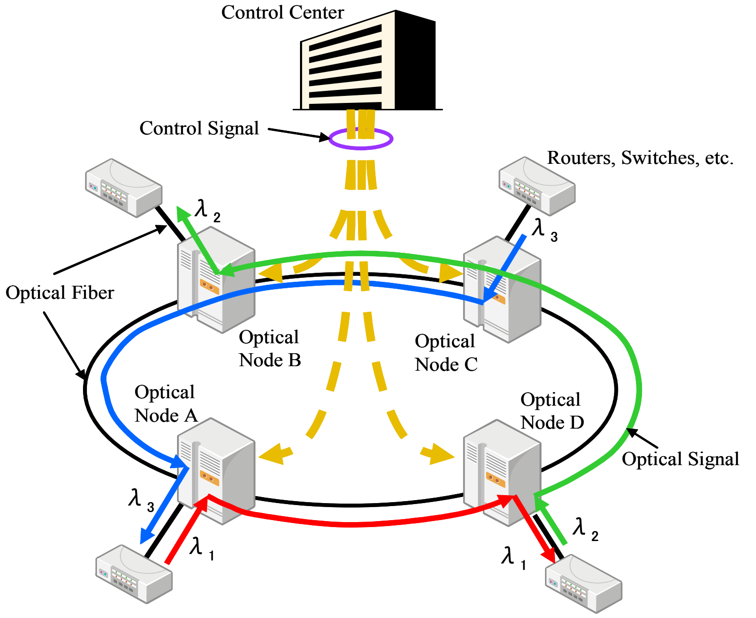
1. Introduction

The continuing annual growth in total traffic on IP networks is leading to demands from subscribers for carriers to offer reasonable data pricing models matching users' needs. The key to achieving this goal is increased investment in lower-cost infrastructure as well as holding down operation costs. ROADM networks and phase modulation technologies are two ways of solving these problems. The two technologies have different objectives but the DPSK modulation method, which is one phase modulation method, is reported as having good affinity with ROADM due to technical progress in DPSK receivers. This white paper outlines ROADM networks and phase modulation technologies and then explains the status of the DPSK receiver for ROADM networks.

2. Progressive Introduction of ROADM Networks

Wavelength Division Multiplexing (WDM) technology greatly increases the amount of data that a fiber can carry. In addition, the flexibility of circuit design is also increased by using Optical Add/Drop Multiplexers (OADM) at optical nodes in the communications path using WDM to split and combine optical signals with specific wavelengths. Networks that can change the Add/Drop wavelengths and which can also be centrally managed from a Control Center are called Reconfigurable OADM (ROADM) networks[1-3]. Figure 2-1 shows a typical example.



Each optical node is connected in a ring configuration. In actual installations, there are clockwise and counterclockwise rings to provide redundancy against faults. In the example shown here, the optical signal moves counterclockwise. An optical signal with wavelength λ_1 is added at Node A and dropped at Node D. Additionally, an optical signal with wavelength λ_2 is added at Node D passes through Node C and is dropped at Node B. In a simple OADM, each optical node Adds and Drops wavelengths according to a fixed plan but in a ROADM system, the Control Center can change wavelengths according to the traffic and demand.

Figure 2-1 ROADM network configuration

There are several methods for configuring the optical nodes used by these ROADM networks[1, 2] as listed below.

(1) Combine multiple 1 x 2 switches with Arrayed-Waveguide Grating (AWG)

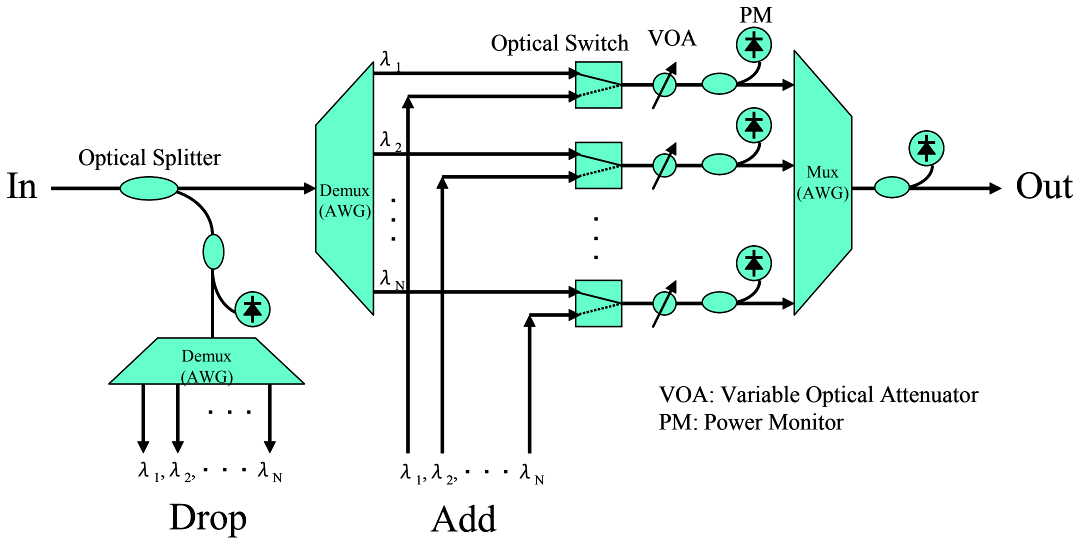
Figure 2-2 shows the configuration[4, 5]. The problems with this arrangement are high insertion loss and high costs.

(2) Combine wavelength blockers with AWG

The insertion loss and costs are improved compared to the previous configuration[1].

(3) Configure design using wavelength selective switches

Advances in Micro-Electro-Mechanical Systems (MEMS) technology have made it possible to create wavelength selective switches (WSS), offering easy system configuration and high-level management functions compared to the previous two methods[1, 2].



Inputting an optical signal creates a Drop signal that is distributed at each wavelength using the Optical Splitter and Demux. Each Add signal is selected by remotely controlled optical switches. A signal from "In" is chosen in the wavelength that was not "Add". A power monitor is inserted at each point to monitor drops in optical signal power. The power at each wavelength is equalized by a Variable Optical Attenuator (VOA) installed in each wavelength channel. In addition, optical amplifiers installed upstream and downstream of these devices compensate the overall loss.

Figure 2-2 Configuration of optical nodes for ROADM[4, 5]

These ROADM networks offer the following advantages and are expected to become more widespread in future.

(a) Remote control of optical path commissioning, decommissioning, and reconfiguration

In systems using OADM and optical-electrical-optical (O-E-O) conversion, onsite work is required at local nodes when establishing a new path or changing a configuration. However, in a ROADM network, the optical path can be set at will because optical nodes can be remotely controlled from the Control Center. As a result, the increased investment in infrastructure as traffic increases as well as the labor costs to repair faults can be held down.

Moreover, Generalized Multi-Protocol Label Switching (GMPLS) can be introduced by ROADM to further increase the network operability. As a result, users' bandwidth requirements can be met promptly, which is a key point of Next Generation Networks (NGN) with assured bandwidth for customers.

(b) Easy changes of bit rates and modulation method

In a ROADM network, the optical signal to nodes is not converted to an electrical signal so transmission to the next node is not dependent on bit rate and modulation method. However, extreme increases in bit rates sometimes experience a drop in signal quality when the occupied bandwidth exceeds the ROADM optical filter bandwidth. This problem is covered in section 4 below.

(c) Reduced power consumption at nodes

In the case of O-E-O conversion at nodes, the power consumption of the O/E and E/O converter and the CPU generally increases, as the bit rate is high. Moreover, total power consumption due to the need for cooling also increases. However, as mentioned previously, ROADM networks do not use O-E-O conversion so power consumption and operation costs can be held down.

3. Modulation Methods for Optical Communications

So far, Non-Return to Zero On-Off Keying (NRZ-OOK) is the main modulation method used by optical communications. However, when using a higher bit rate to support traffic growth, Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) have more impact, causing large decreases in transmission distance. Moreover, further increase in the number of WDM channels is reaching the limit due to increasingly narrower spacing between wavelengths. As a result, various new modulation methods are being researched with the aim of achieving better transport characteristics. The main modulation methods are summarized below[6~9].

(a) NRZ-OOK

Figure 3-1 shows the configuration at the send and receive sides. Since it offers the best cost-performance with simple configuration, this method is being widely adopted for both access and core networks but from the perspectives of ultra-high-speeds and long-distance transport, it suffers from the effects of CD and PMD, and a higher Optical Signal to Noise Ratio (OSNR) is needed to obtain the required Bit Error Rate (BER).

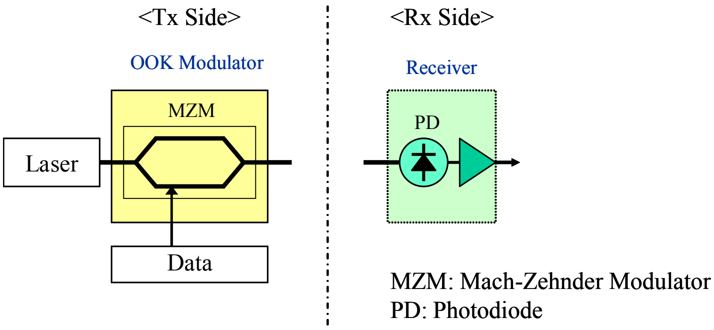


Figure 3-1 NRZ-OOK method configuration

(b) ODB

ODB is the abbreviation for Optical Duo-Binary and is also called PSBT (Phase Shaped Binary Transmission). Figure 3-2 shows an example of the configuration for the send and receive sides. In comparison to the OOK method at the same data rate, the tolerance to CD is high due to the narrow occupied bandwidth in the optical spectrum and there is smaller degradation of a 40-Gbit/s signal even after passage through an optical filter for 10 Gbit/s. However, the OSNR and ability to tolerate optical non-linearity are worse than the other modulation methods described here.

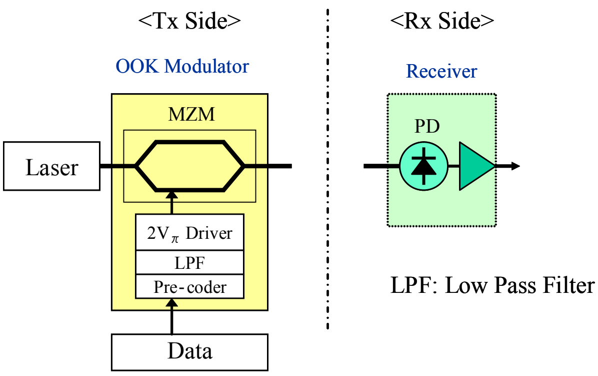


Figure 3-2 ODB method configuration

(C) NRZ-DPSK or RZ-DPSK

DPSK is the abbreviation for Differential Phase Shift Keying. Figure 3-3 shows a configuration example for the send and receive sides. This modulation method uses the difference in the phase of the optical carrier compared to the previous bit when the data bit at the send side is “1” (π[rad]) and “0” (0[rad]). As a result, at the receive side, the difference from the previous bit can be detected by a Delay Line Interferometer (DLI) using an Optical Delay (OD) that sets the delay time T [s] to 1 bit. Although the configuration of this method is more complex than the previous two methods, when a balanced receiver is used, the OSNR needed to obtain the required BER can be improved by 3 dB in theory. The CD tolerance of this method is similar to that of the OOK method.

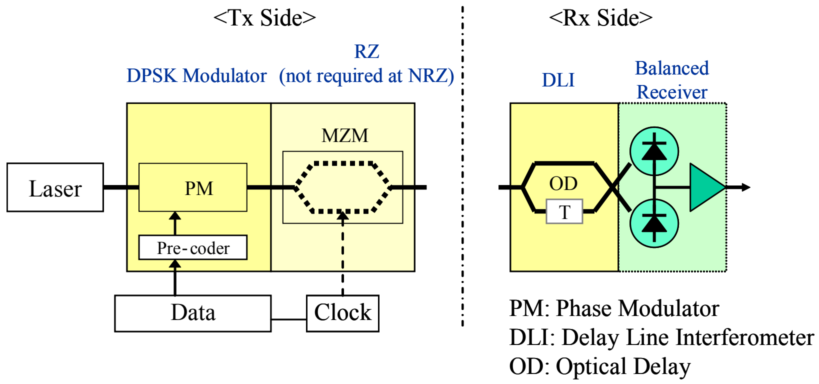


Figure 3-3 NRZ-DPSK and RZ-DPSK method configurations

(d) NRZ-DQPSK or RZ-DQPSK

DQPSK is the abbreviation for Differential Quadrature Phase Shift Keying. Figure 3-4 shows a configuration example for the send and receive sides. The difference between DQPSK and DPSK described above is that the phase shift amount at the send side is π/2 and a 4-value signal (“00”, ”01”, ”11”, ”10”) is sent. In line with this, a pair of delay detection receivers with different phases is used at the receive side. Because the symbol rate is halved compared to the data rate, the tolerance to CD and PMD is increased by this method. In addition, because the bandwidth of the send and receive electronic circuits is halved, the cost is not double that of DPSK.

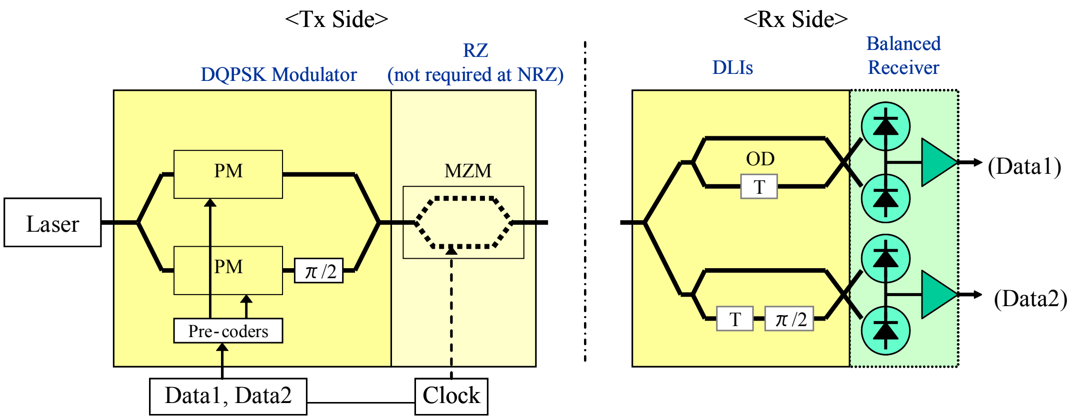


Figure 3-4 NRZ-DQPSK and RZ-DQPSK method configuration

Table 3-1 summarizes the features of the above-described optical modulation methods.

Table 3-1 Comparison of modulation methods[6~13]

Modulation Method	OSNR[10] for BER = 10^{-4}	CD Tolerance [7, 11]	PMD Tolerance* [12]	Optical Non-linearity Tolerance [6, 7, 13]	Configuration and Cost
NRZ-OOK	17.2 dB	Medium	41%	Medium	See Fig. 3-1. Low cost.
ODB	17.6 dB	Good	30%	Poor	See Fig. 3-2. Tx side electronic circuits more complex than OOK.
NRZ-DPSK	14.0 dB	Medium	47%	Good	See Fig. 3-3. Optical circuits more complex than ODB.
RZ-DPSK	13.4 dB	Medium	52%	Good	See Fig. 3-3. In comparison with NRZ-DPSK, requires a modulator for RZ.
RZ-DQPSK	13.9 dB	Good	108%	Good	See Fig. 3-4. Most complex of all methods here and band of electronic circuits halved compared to other methods at same bit rate.

*Compared to 1-bit cycle at BER = 10^{-3} and Penalty = 1.5%

4. Applying DPSK to ROADM Networks

In the ROADM networks described in section 2, the optical signal is Added or Dropped using wavelength filtering at the optical node. Consequently, passage through multiple optical filters and the modulation method for the optical signal used in ROADM networks requires consideration of the following.

(1) Low OSNR needed to obtain required BER

The modulation method used in ROADM networks requires good OSNR characteristics because there is some degree of loss at the optical nodes. In addition, there are usually optical amplifiers in the path and their high output power can cause the optical non-linear phenomenon, so it is often said that it is better to choose a modulation method with high tolerance to this. Considering this point, clearly, the DPSK and DQPSK methods are the best of the modulation methods listed in Table 3-1.

(2) High tolerance to CD and PMD

In a ROADM network where the transport path is switched by command from the Control Center, since the total end-to-end amount of CD and PMD changes according to the path, the chosen modulation method should have high tolerance to CD and PMD. DQPSK modulation is suitable for this and, in addition, ODB modulation is suitable for only CD.

(3) Low signal degradation with passage through ROADM optical filter

Many current designs for ROADM optical nodes are premised on a wavelength spacing (example: 50-GHz spacing) using 10-Gbit/s modulation, but when trying to pass an optical signal that is modulated by a bit rate exceeding 10 Gbit/s, the signal quality is degraded because the sidebands are more attenuated. Consequently, a modulation method with good transfer characteristics for a narrow passband filter is believed to be best. As a result, the ODB and DQPSK modulation methods with narrow occupied bandwidth are best.

From the above explanation, it seems that DQPSK has the best characteristics for ROADM networks but the problem is cost. Conversely, from the cost perspective, DPSK is better than DQPSK and there is ongoing research into technologies for improving Q penalty with a narrowband optical filter and tolerance to CD[14]. As described in section 3, when the bit rate with DPSK is R [Hz], and the DLI delay T is set to 1 bit, or in other words 1/R [s], the Q penalty with an optical narrowband filter can be improved by setting T<1/R. The following sections summarize this principle.

4.1 Relationship between Optical Filter Bandwidth and FSR

The DLI used in DPSK systems has periodic optical frequency characteristics of transmittance depending on the value of T and this period is called the Free Spectral Range (FSR). The relationship between T and FSR is expressed as 1/T = FSR and characteristics are usually analyzed using this FSR. The Q penalty vs FSR or Q value simulation model[15-17] is shown in Figure 4-1.

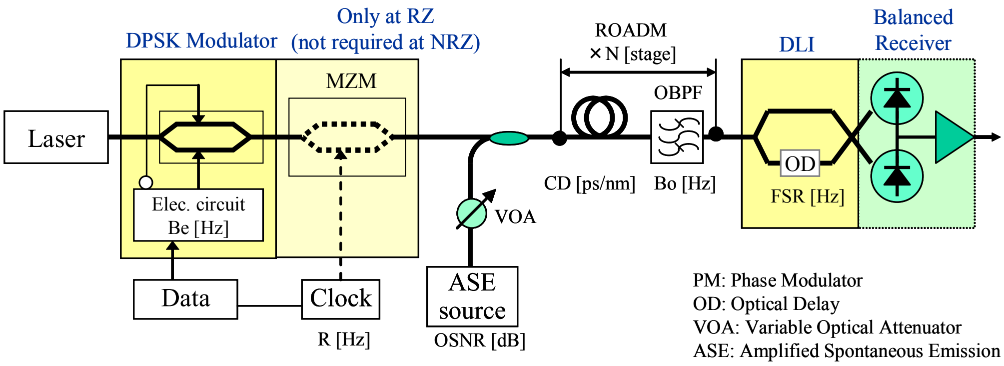


Figure 4-1 Transport characteristics calculation model for DPSK modulation

Studies of the value of FSR vs Q penalty have been reported[15] for the most basic case with one ROADM stage (Fig. 4-1) and chromatic dispersion CD set to 0 with an OSNR value of 16 dB and using the bandwidth of the optical filter (Bo) as a parameter. Figure 4-2 shows part of the results for RZ-DPSK. We can draw the following conclusions from these results.

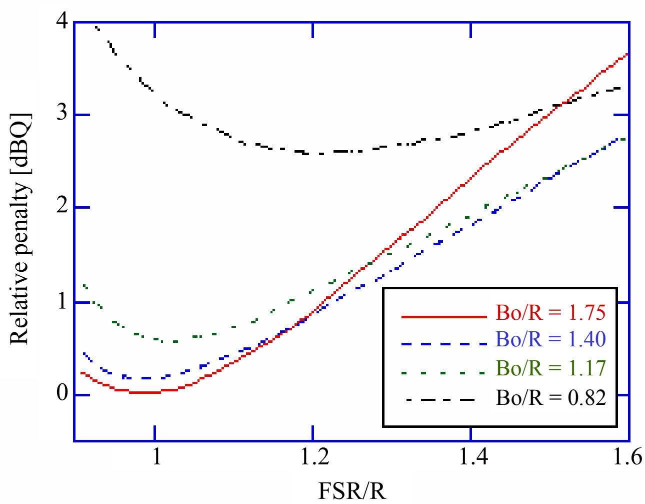
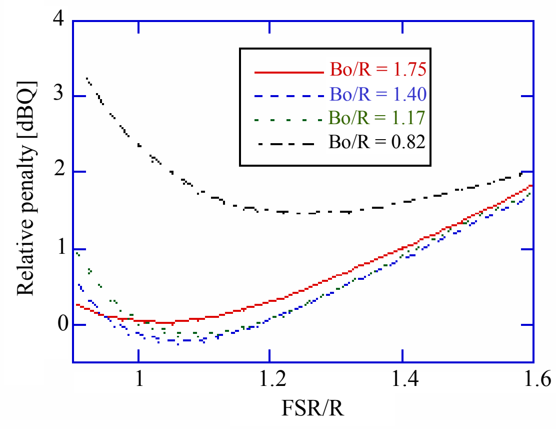


Figure 4-2 Calculation result of FSR vs Q penalty for RZ-DPSK
(partly taken from reference [15] results)

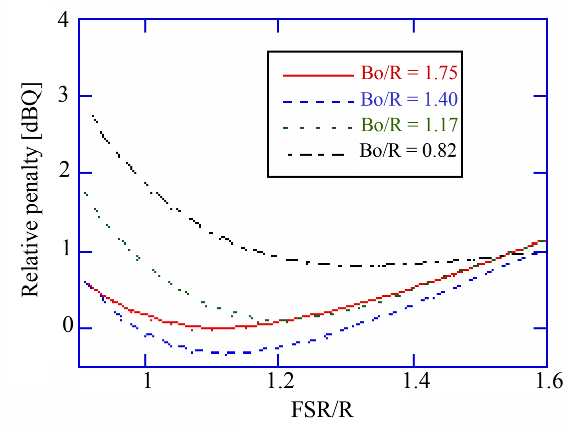
- When a wideband optical filter is inserted so that Bo/R > 1.40 (red and dotted blue lines in Figure 4-2), the ideal FSR = R (perfect 1-bit delay) is achieved.
- As Bo becomes narrower, the minimum value of the Q penalty becomes larger and the value of FSR/R at which the Q penalty becomes smallest increases too. For example, when Bo/R = 0.82 (Figure 4-2 dashed black line), the Q penalty becomes minimum at FSR/R = 1.2.

Figure 4-3 shows part of the results for NRZ-DPSK. In this case, different results are reported for calculation using the bandwidth of the optical modulator driver at the send side (Be). Figure 4-3(a) shows the case when Be = 50 GHz and (b) shows the case when Be = 19 GHz. We can deduce the following from these figures.

- The trend is qualitatively the same as RZ-DPSK. As Bo/R increases, the value of FSR/R at which the Q penalty is smallest approaches 1, but, as Bo/R decreases, FSR/R increases when the Q penalty value becomes minimum.
- When Bo/R = 1.40, the minimum Q penalty becomes negative. This occurs because the Amplified Spontaneous Emission (ASE) is cut by the DLI optical filter itself[15].
- The value of FSR/R when the Q penalty value is minimum also varies with the value of Be. The value becomes minimum at FSR/R = 1.24 when Bo/R = 0.82 and Be = 50 GHz. When Bo/R = 0.82 and Be = 19 GHz, it becomes minimum at FSR/R = 1.34. This means that there is an optimum combination for the transmitter and receiver characteristics.



(a) Be = 50 GHz



(b) Be = 19 GHz

Figure 4-3 Calculation results of FSR vs Q penalty for NRZ-DPSK
(partly taken from reference [15] results)

Figure 4-4 shows the results for FSR/R vs Bo/R when the Q penalty becomes minimum for Figures 4-2 and 4-3. As Bo/R decreases, the optimum FSR/R value rises. For a multistage optical node designed assuming a 50-GHz spacing, when the combined bandwidth is converted to optical frequency and is about 32 GHz, the value of Bo/R becomes 0.74 when passing a 43-GHz signal. For NRZ-DPSK modulation when Be = 19 GHz, from the diagram we can clearly see that FSR/R becomes about 1.53 (FSR = 66 GHz).

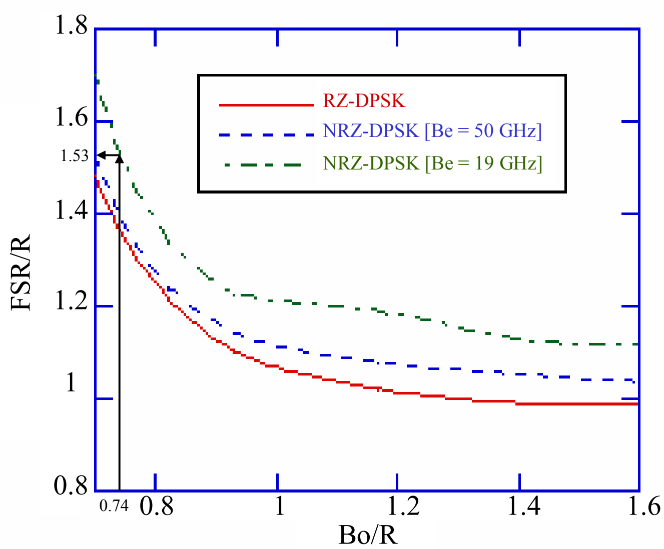


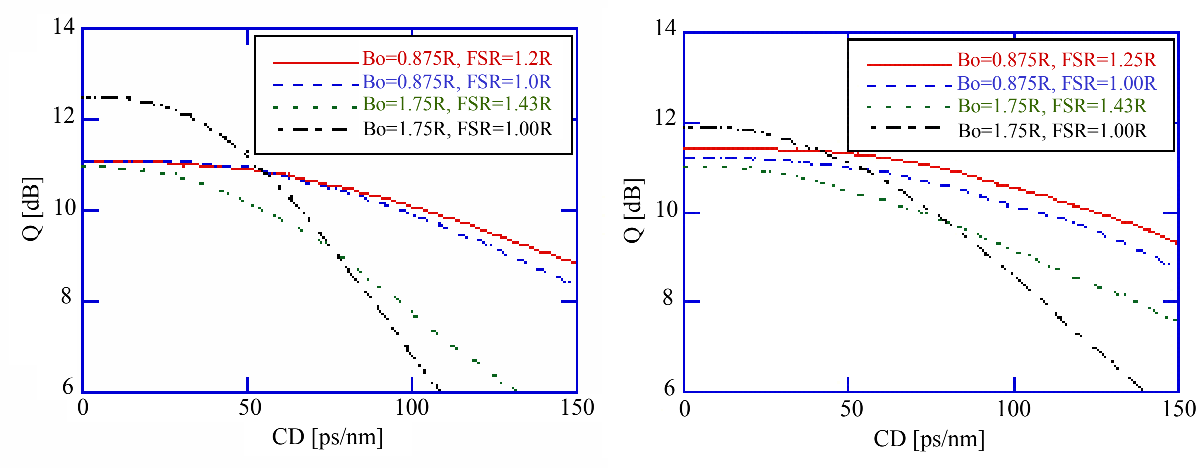
Figure 4-4 Optimum Value of FSR/R vs Bo/R

4.2 Impact of CD

The calculated Q value vs CD when FSR/R > 1 has been reported[16] and Figure 4-5 shows some of the results. This model uses the same parameters (one ROADM stage and OSNR = 16 dB) as in Figure 4-1. Figure 4-5(a) shows the plot for RZ-DPSK. With a wideband optical filter (Bo/R = 1.75) and low CD (<80 ps/nm), as logically expected, a high Q value is obtained when FSR/R = 1. However, at a high CD (>80 ps/nm), a high Q value is obtained when FSR/R = 1.43. Moreover, when inserting an optical filter with a narrower bandwidth than R, such as in ROADM (Bo/R = 0.875), the change in the Q value vs CD becomes smaller, and when FSR/R = 1.2, the Q value can become larger than when FSR/R = 1, especially at high CD.

Next, Figure 4-5(b) shows the calculation for NRZ-DPSK modulation. Even in this case, the trend is broadly the same as RZ-DPSK and with a narrowband filter (Bo/R = 0.875), the Q value becomes extremely high and is higher when FSR/R = 1.25 than when FSR/R = 1.0.

Considering the reduced need for extremely high Q values due to the recent development of error correction technologies in optical communications, these results indicate that stable communications quality can be achieved with residual CD in the optical path when FSR/R is set to more than 1.0, and more when CD fluctuations are anticipated in the path.



(a) RZ-DPSK (b) NRZ-DPSK

Figure 4-5 Calculation results of CD vs Q value

(partly taken from reference [16] results)

4.3 ROADM Network Eye Waveform Simulation

Various simulations have been performed[17] to examine how the eye waveform changes with OOK, RZ-DPSK and NRZ-DPSK when optical filters and optical fibers with CD are coupled in many stages as in a ROADM network. The model assumes that there is no ASE (Figure 4-1) and the optical filter is a second-order Gaussian of 50 GHz 3-dB bandwidth. To perform quantitative evaluation, the following equation[18] was used to measure the Eye Opening Penalty (EOP) (dB)

$$EOP = -10 \log_{10} \left(\frac{B / P_B}{A / P_A} \right)$$

where, A is back-to-back eye opening height, P_A is back-to-back signal power, B is post-transport eye opening height, and P_B is post-transport signal power.

Figure 4-6 shows the results for RZ-OOK and RZ-DPSK when CD of 20 ps/nm in each ROADM stage is assumed. At N = 1, both modulation methods give a higher EOP than NRZ (Figure 4-7) but this is attributed to the wider spectral occupancy of RZ compared to NRZ. Moreover, it is clear that the drop in EOP is smaller for RZ-DPSK than for RZ-OOK. At N ≥ 3, signal degradation becomes smaller in the order of DPSK (FSR/R = 1.4), DPSK (FSR/R = 1.0), and OOK; DPSK at FSR/R > 1 is the clear winner. Although omitted here, this trend becomes quite remarkable as CD increases with each stage. This is due to the smaller variation in the penalty for CD and multiple narrow bandwidth optical filters with DPSK at FSR/R > 1.

Figure 4-7 shows the results for NRZ-OOK and NRZ-DPSK. Although the EOP becomes negative when N = 1 , it means that the amplitude of the eye opening decrease is smaller than the optical power decrease by the filter but it does not mean that the signal quality (Q value) has been improved. At N ≥ 2, as with the RZ waveform, signal degradation decreases in the order of DPSK (FSR/R = 1.4), DPSK (FSR/R = 1.0), and OOK; DPSK with FSR/R>1 is the clear winner again for the same reason as RZ.

When comparing RZ and NRZ waveforms at DPSK (FSR/R = 1.4), the RZ penalty value changes from 2.27 to 3.36 dB as N changes from 1 to 5, but the corresponding change for NRZ is 0.19 to 1.42 dB, showing that RZ has smaller variation due to the number of stages.

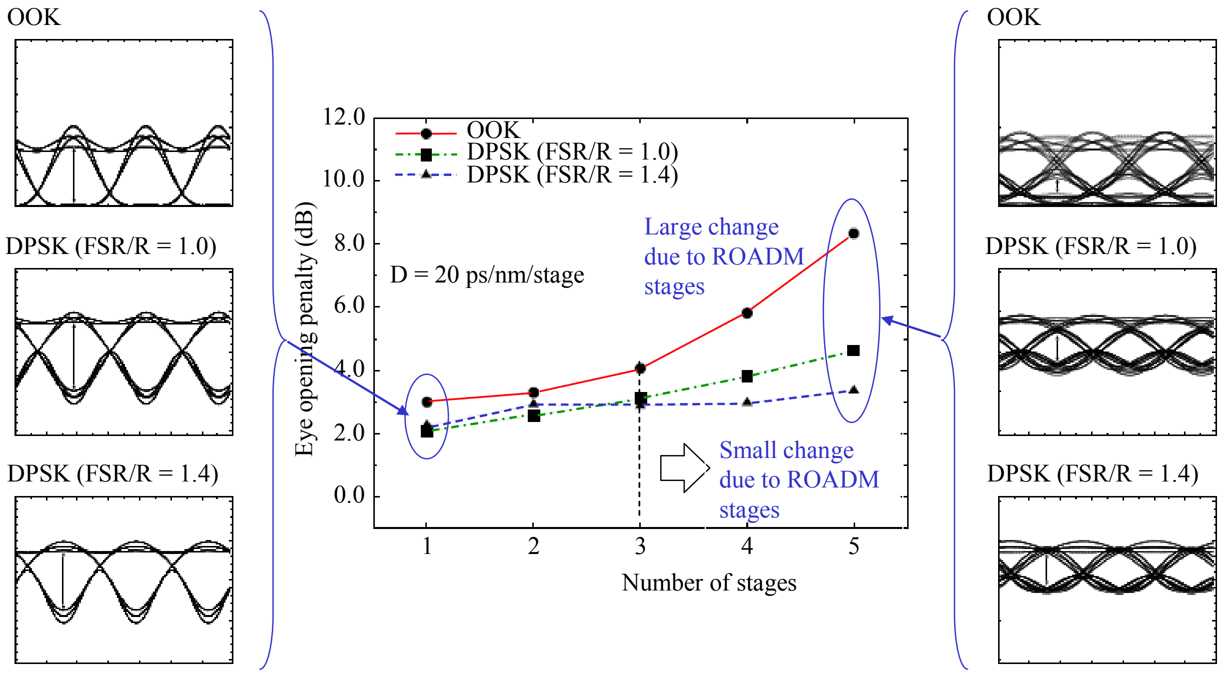


Figure 4-6 Calculated EOP vs number of ROADM stages for RZ-DPSK

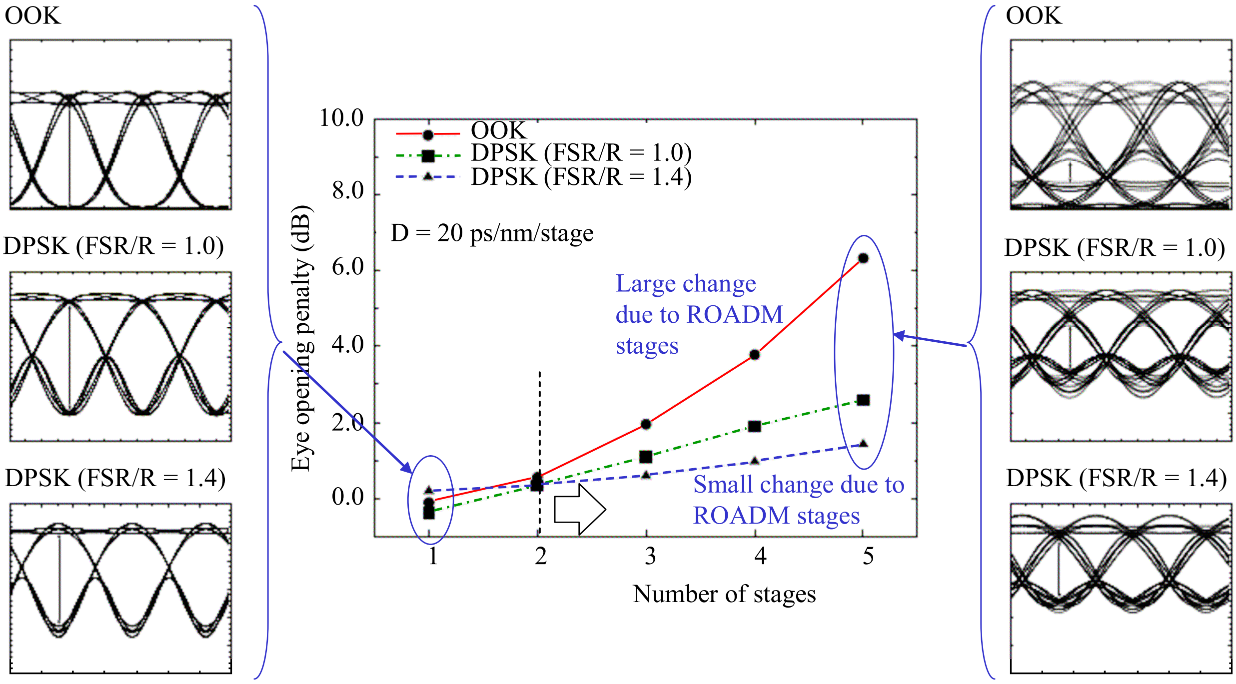


Figure 4-7 Calculated EOP vs number of ROADM stages for NRZ-DPSK

5. Conclusion

ROADM networks seem likely to become widespread in core and metro networks due to their lower investment and running costs. On the other hand, phase modulation technologies are an effective way of increasing capacity of existing optical fiber networks and use of receivers with high FSR for DPSK demodulation will probably stimulate the ROADM rollout. Furthermore, DQPSK seems likely to be the next technology to spread due to the lower cost of optical components and the spread of ROADM networks (meaning increased total dispersion).

Anritsu's MP1595A and MP1800A product families support customers' needs for R&D into high-bit rate modulation technologies and manufacturing.

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