Next-Generation Photonic Transport Network Using Digital Signal Processing

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Coherent optical-fiber transmission technology using digital signal processing is being actively researched and developed for use in transmitting high-speed signals of the 100-Gb/s class over long distances. It is expected that network capacity can be further expanded by operating a flexible photonic network having high spectral efficiency achieved by applying an optimal modulation format and signal processing algorithm depending on the transmission distance and required bit rate between transmit and receive nodes. A system that uses such adaptive modulation technology should be able to assign in real time a transmission path between a transmitter and receiver. Furthermore, in the research and development stage, optical transmission characteristics for each modulation format and signal processing algorithm to be used by the system should be evaluated under emulated quasi-field conditions. We first discuss how the use of transmitters and receivers supporting multiple modulation formats can affect network capacity. We then introduce an evaluation platform consisting of a coherent receiver based on a field programmable gate array (FPGA) and polarization mode dispersion/polarization dependent loss (PMD/PDL) emulators with a recirculating-loop experimental system. Finally, we report the results of using this platform to evaluate the transmission characteristics of 112-Gb/s dual-polarization, quadrature phase shift keying (DP-QPSK) signals by emulating the factors that degrade signal transmission in a real environment.

1. Introduction

In the field of optical communications using digital signal processing, research and development of long-haul transmission technology using high-speed signals of the 100-Gb/s class such as 100-Gbit Ethernet has been quite active.[1] In the future, transmission speeds in optical communications systems will need to reach the 400-Gb/s level and eventually 1 Tb/s to cope with the trend toward higher input/output (I/O) bit rates in the servers and network devices making up data centers. Thus, a major issue of a next-generation optical communications system is how to extend the transmission distance of high-speed signals while also achieving high spectral efficiency so that the amplification bandwidth of optical amplifiers—which is becoming a limiting factor in system capacity—can be efficiently used. One means offered for resolving this issue is adaptive modulation technology that applies the most appropriate modulation format and signal-processing algorithm for current conditions such as the transmission distance between transmit and receive nodes and the required bit rate. Adaptive modulation technology has already come to be partially used in wireless communications, but when it is applied to optical communications systems, the transmission path and frequency slots between transmit and receive nodes should be set in accordance with whatever modulation format has been selected as optimal given the optical transmission characteristics at the time of operation. In this regard, a system parameter is needed to judge whether transmission is feasible between certain transmit/receive nodes for each modulation format. Moreover, the parameter should be carefully designed to ensure that transmission quality is guaranteed when adaptive modulation is applied. The optical transmission characteristics should be evaluated for a variety of transmission-path states while emulating signal-degradation factors under conditions approximating an actual environment.

Aiming for a large-capacity, flexible photonic network, we simulated the use of adaptive modulation in optical transmitters and receivers to evaluate its effectiveness for expanding system capacity and to test the effectiveness of adaptive modulation technology on a photonic network. We developed a transmission evaluation platform[2)] with a digital coherent receiver[3)] that is based on a field programmable gate array (FPGA). It enables a variety of modulation formats and signal processing algorithms to be loaded and evaluated. We evaluated the transmission characteristics of 112-Gb/s dual-polarization, quadrature phase shift keying (DP-QPSK) on a recirculating-loop experimental system that emulates transmission-degradation factors.[4)]

2. Photonic networks using digital signal processing

Optical communications systems using wavelength division multiplexing (WDM) are widely used in current networks. These systems feature an equipment configuration that multiplexes optical signals transmitted under a specific modulation format and bit rate against a frequency grid arranged with either 50- or 100-GHz spacing as defined by ITU-T Recommendation G.694.1. The main reason the modulation format and bit rate are fixed is that the characteristics of optical components used in the optical transmitters and receivers are optimal for a specific modulation format and bit rate.

An optical communications system using digital signal processing presents a different scenario. At the transmitter, the system drives an optical modulator using a digital to analog converter (DAC). At the receiver, the system uses an analog to digital converter (ADC) to convert the analog-based optical-electric-field information obtained from the optical signal and a local oscillator into a digital signal and to then perform signal processing and demodulation. This means that optical signal generation and reproduction can be performed with respect to any modulation format by changing the signal processing algorithms and parameters stored in the transmitter's and receiver's digital signal processors without having to replace the optical components used in those devices.

Figure 1 compares the configuration used for existing photonic networks with that of a photonic network using an adaptive modulation format. The former is based on a fixed bit rate and fixed modulation format while the latter is capable of varying the modulation format in accordance with the transmission distance and transmission requirements. Adaptive modulation is an effective technique for efficiently accommodating high-speed signals (above 100 Gb/s). The system can select the appropriate modulation format and the associated signal processing algorithm that is optimal for communication between the transmitter and receiver in accordance with the transmission distance and required bit rate and then vary channel arrangement accordingly. With adaptive modulation, the use of a modulation format having a high bit/symbol ratio on relatively short transmission paths raises spectral efficiency, while the use of a format with a low bit/symbol ratio on relatively long transmission paths can connect transmit and receive nodes without having to use a regenerative repeater. In short, adaptive modulation enables flexible photonic network operation that can cope with different optical fiber transmission paths and equipment

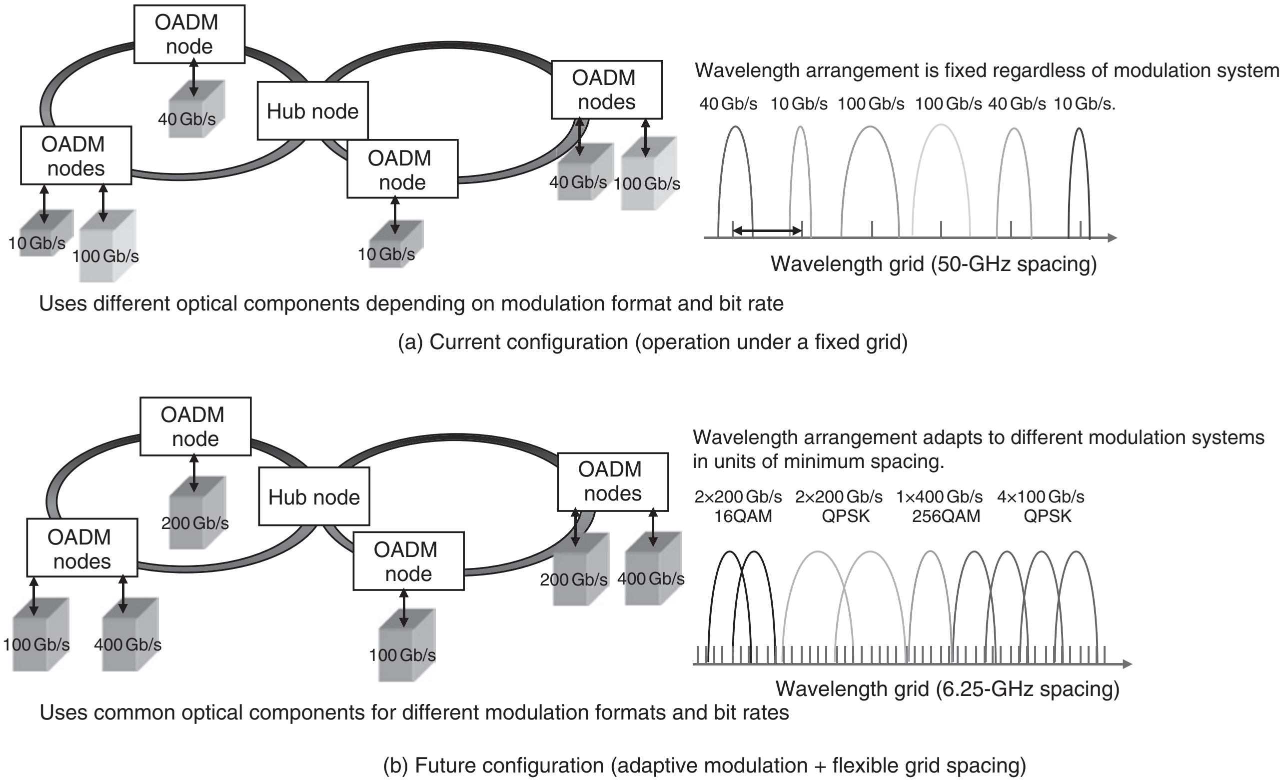


Figure 1
Photonic network architecture using digital signal processing.

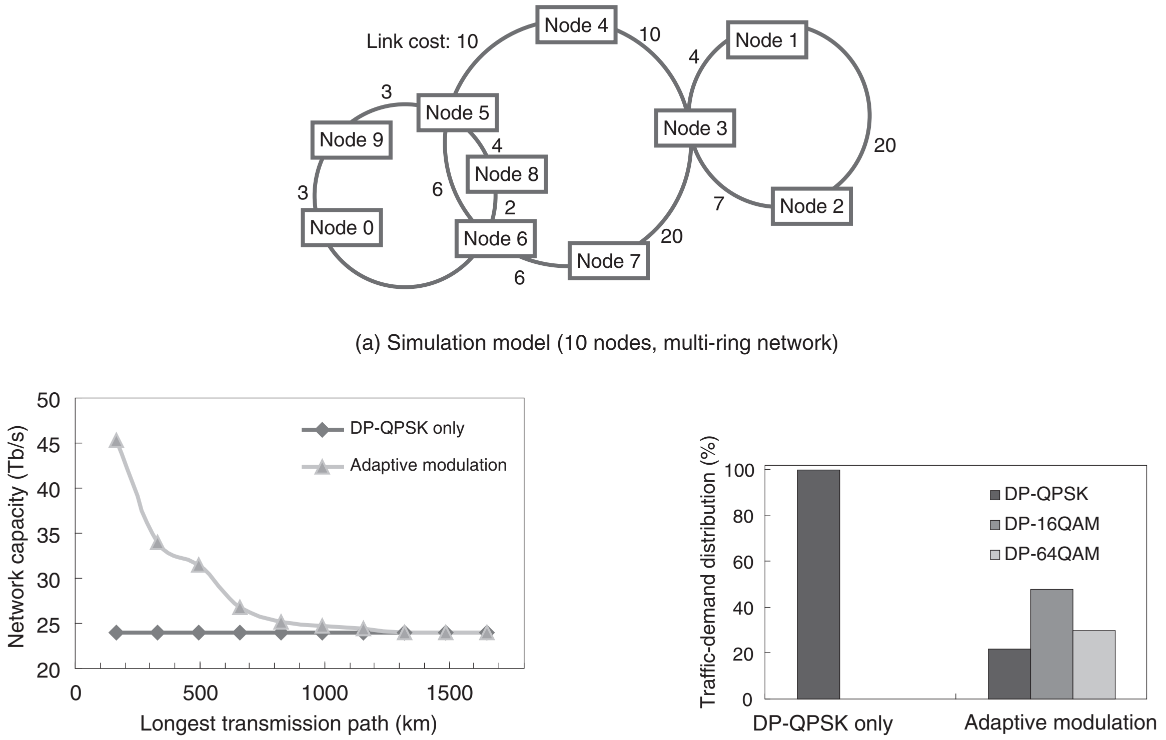
layouts.

3. Capacity enhancement in a photonic network by adaptive modulation

We evaluated the effectiveness of a photonic network using adaptive modulation by conducting a simulation experiment.

1) Experimental configuration and conditions

For this simulation, we examined a multi-ring network consisting of ten nodes, as shown in **Figure 2 (a)**. Traffic demand between nodes had a mesh pattern, and the distance between adjacent nodes was defined in terms of link cost, as indicated in the figure. We assumed a fixed bit rate of 100 Gb/s and used DP-QPSK, dual-polarization 16 quadrature-amplitude modulation (DP-16QAM), and DP-64QAM as the formats for adaptive modulation. For each modulation format, the optical signal to noise ratio (OSNR) deemed necessary at reception with respect to that format's maximum transmission distance was used as an index for deciding whether to select that format. Spectrum slots were assigned to the transmission path between transmit and receive nodes on the basis of the frequency slots required for each modulation format given its symbol rate (DP-QPSK: 25 Gbaud; DP-16QAM: 12.5 Gbaud; DP-64QAM: 8.3 Gbaud). A transmission path was assigned by an algorithm that first determined whether 64QAM—which has the highest spectral efficiency—could be used to transmit signals between transmit and receive nodes without a re-shaping, re-timing, and re-amplification (3R) regenerative repeater. Then, if it could not be used, the algorithm determined in succession the viability of using 16QAM and QPSK, and finally unused spectrum slots were assigned for the modulation format.



(a) Simulation model (10 nodes, multi-ring network)

(b) Network capacity versus longest transmission path in network model

(c) Distribution of traffic demand by modulation format for a maximum transmission distance of 600 km

Figure 2
Characteristics of photonic network system using adaptive modulation technology.

2) Results

Taking the link cost shown in Figure 2 (a) to be a value related to inter-node distance, we plotted the relationship between network capacity and the longest transmission path in the network, as shown in **Figure 2 (b)**. For comparison purposes, two sets of results are presented: that when using only the DP-QPSK modulation format and that when selecting for each path an optimal modulation format from among the three formats. Network capacity on the vertical axis represents the fixed data-transfer rate of 100 Gb/s multiplied by the number of transmission paths that can be set in response to traffic demand between all transmit and receive nodes. These results show that using the adaptive-modulation algorithm to set paths and allocate frequency slots can greatly improve network capacity by 50–90% in a metro network of several 100 km, which is a relatively small-scale network conducive to the use of 64QAM having a high bit/symbol ratio. The percentage of traffic handled by each modulation format for a maximum transmission distance of 600 km is shown by the bar chart in **Figure 2 (c)**, which shows the percentage of traffic allocated to each modulation format with respect to total traffic demand generated among transmit/receive nodes. In contrast to the conventional approach of using QPSK to transmit signals regardless of the inter-node distance, selecting an optimal modulation format from among the three used here increased network capacity by about 11% for a network having a maximum transmission distance of 600 km. In short, applying adaptive modulation technology to a photonic network has the effect of increasing network capacity.

4. FPGA-based digital coherent receiver

The transmission performance of each modulation format when applying adaptive modulation should be accurately determined to enable effective switching between those formats during network operation. Specifically, the digital signal processing algorithms corresponding to these modulation formats and the transmission characteristics of a network system using those algorithms should be evaluated under conditions approximating an actual environment. This evaluation should examine 1) tolerance to signal degradation caused by polarization mode dispersion (PMD) and polarization dependent loss (PDL), which depend on the randomly changing state of polarization along the transmission path, 2) signal degradation due to nonlinear effects along the transmission path, and 3) the composite effect on transmission characteristics caused by a combination of PMD, PDL, and nonlinear effects. The algorithms used for digital signal processing would normally be tested by offline processing using a personal computer (PC) after the optical signal had been received and subjected to analog-to-digital conversion by a digital storage oscilloscope (DSO). In such an evaluation environment, however, time constraints make it difficult to test for all envisioned polarization states with respect to randomly changing parameters like PMD and PDL along the transmission path.

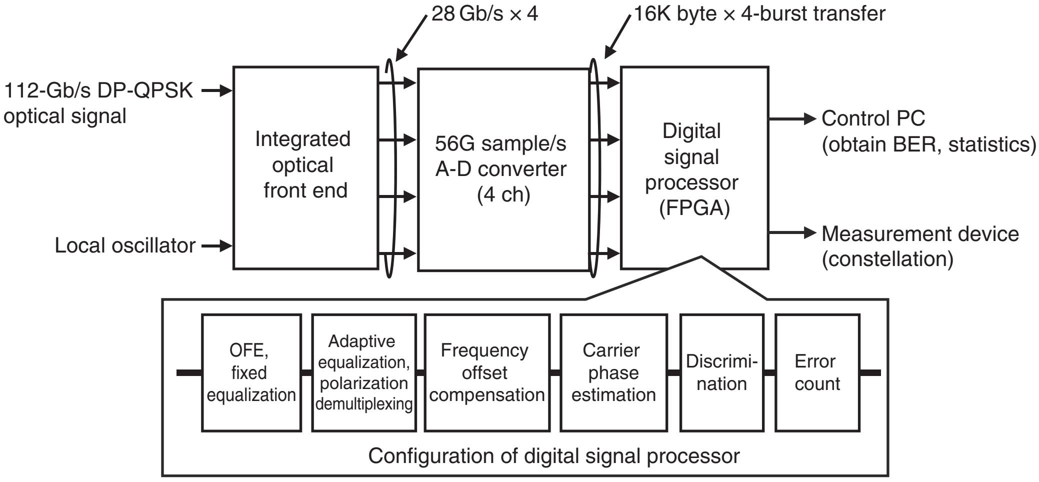
In response to this problem, we have developed an FPGA-based digital coherent receiver as an evaluation tool that accelerates such testing. This receiver has been designed to enable data input and signal processing to be performed in bursts so as to maintain compatibility with recirculating-loop experimental systems that are widely used in evaluating transmission characteristics. The configuration and appearance of this prototype optical receiver are shown in **Figure 3**. It consists of three main components.

1) Optical front end (OFE) integrating a polarization beam splitter, 90° hybrid mixers, photodiodes, and transimpedance amplifiers (TIAs)
2) ADC having a sampling speed of 56G sample/s[5)]
3) Digital signal processor loaded on an FPGA

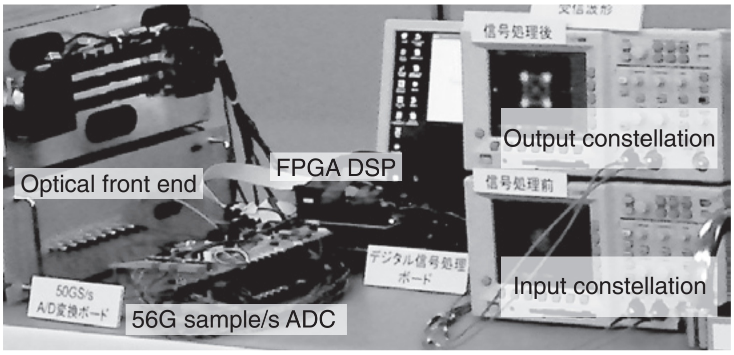
A variety of modulation formats can be evaluated on the same platform by loading the FPGA with the signal processing algorithm corresponding to the modulation format to be evaluated. The digital signal processor used to perform the 112-Gb/s DP-QPSK signal processing described later was configured to perform a variety of functions. These include compensation for variation in OFE characteristics between ports and for waveform distortion occurring along the transmission path, plus polarization demultiplexing, compensation for frequency offset between the input optical signal and the local oscillator, and phase estimation, and, after restoring the signal constellation, differential decoding, discrimination, and error counting. To perform burst-like signal processing in conjunction with a recirculating-loop experimental system, the digital signal processor sends out a get-data trigger signal to the ADC. This signal is used as a basis to successively perform A/D conversion of the 112-Gb/s DP-QPSK signal (against four channels: X polarized wave, Y polarized wave, I, and Q), data transfer from memory (16K bytes × 4 ch) mounted on the ADC board, and signal processing on the digital signal processor.

5. Evaluation of transmission characteristics on evaluation platform

To assess signal degradation caused by PMD, PDL, and nonlinear optical effects and degradation in transmission characteristics caused by their combination, we evaluated transmission characteristics using the FPGA-based digital coherent receiver in a recirculating-



(a) Configuration of coherent receiver and signal processor



(b) Appearance of coherent receiver

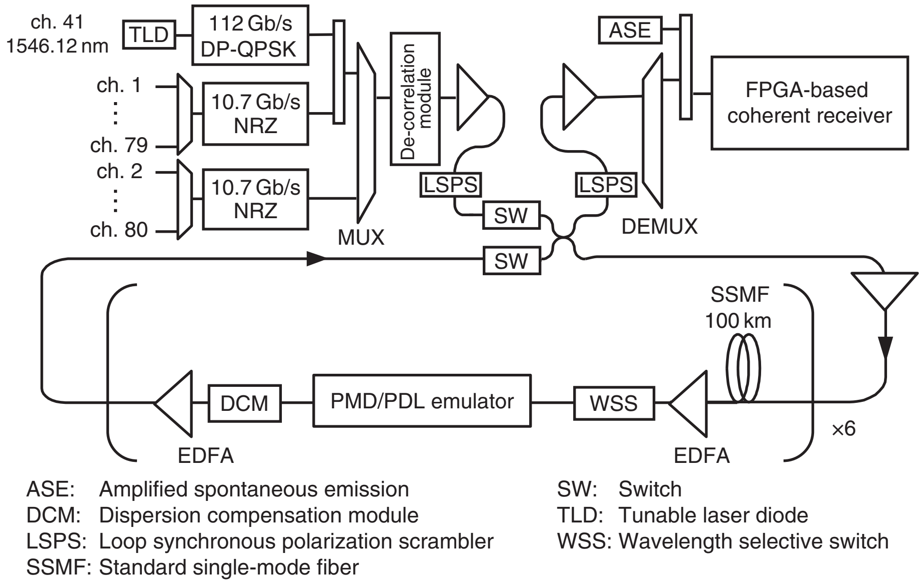
Figure 3
FPGA-based digital coherent receiver.

loop experimental system emulating an actual network environment.

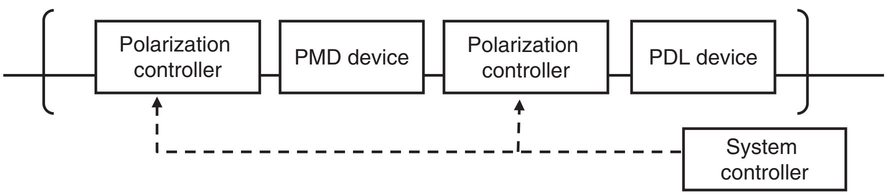
1) Experimental system

The experimental setup is shown in **Figure 4 (a)**. This transmission system mixed a 112-Gb/s DP-QPSK modulation signal with 10.7-Gb/s non-return to zero (NRZ) signals. Eighty wavelengths (channels) of optical sources were set up with a frequency spacing of 50 GHz in the C band (1530.33–1561.83 nm). The channel corresponding to the center wavelength (1546.12 nm) was modulated by the DP-QPSK system while the remaining 79 channels were divided into even- and odd-number channels that were independently modulated using the 10.7-Gb/s NRZ format. The transmission path was a 600-km recirculating loop consisting of six spans of single-mode fiber (SMF), each with a length of 100 km and a loss of ~20 dB. Each node was equipped with an erbium-doped fiber amplifier (EDFA) and a wavelength selective switch (WSS) for emulating reconfigurable optical add-drop multiplexing (ROADM). A PMD/PDL emulator was inserted after the WSS to emulate high-order PMD and PDL.

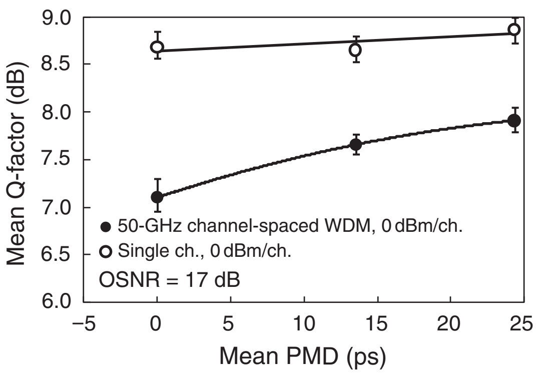
As shown in **Figure 4 (b)**, this PMD/PDL emulator consists of two synchronous polarization controllers, a PMD device, and a PDL device. The polarization controller positioned between the PMD and PDL devices operates synchronously with a trigger for the recirculating loop, and the FPGA-based digital



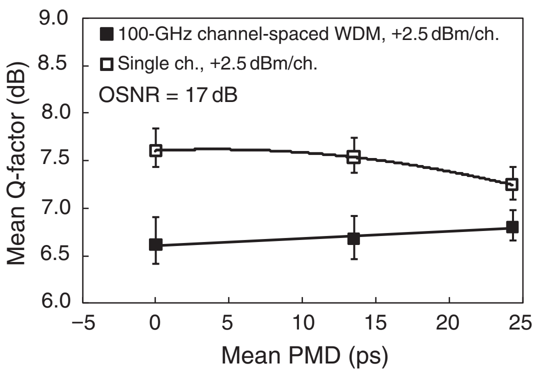
(a) Experimental system



(b) PMD/PDL emulator



(c) Mean Q-factor vs. mean PMD for single-channel transmission and WDM transmission with 50-GHz spacing (0 dBm/ch)



(d) Mean Q-factor vs. mean PMD for single-channel transmission and WDM transmission with 100-GHz spacing (+2.5 dBm/ch)

Figure 4
Experimental set-up for evaluating 112-Gb/s DP-QPSK signal and transmission characteristics.

coherent receiver receives and processes signals in synchronization with that timing. This scheme enables transmission characteristics to be evaluated under a variety of polarization-mode-coupling states. In this experiment, we inserted a device having a PDL value of 0.5 dB, resulting in a mean PDL of approximately 2 dB after transmission over 12 spans. We also used three different PMD devices resulting in mean PMD values of 0, 14, and 24 ps after transmission over 12 spans. Finally, we added amplified spontaneous emission (ASE) noise to the optical signal after transmission over 12 spans and input the resulting signal into the FPGA-based digital coherent receiver. The OSNR was fixed at 17 dB.

2) Experimental results

We measured the bit error ratio (BER) at 100 points under different polarization-mode-coupling states and evaluated signal characteristics on the basis of the Q-factor, which averages out those BER values. **Figure 4 (c)** shows the mean Q-factor versus the mean PMD for single-channel transmission and WDM transmission with 50-GHz spacing (0 dBm/ch). The vertical error bars on the data points represent a distribution of ±30% about the mean Q-factor. Examining the results for single-channel transmission (indicated by the white circles), we see that the Q-factor was nearly constant and independent of the mean PMD, which indicates that the digital coherent receiver can perform PMD compensation without penalty up to a mean PMD value of 24 ps. This result also suggests that no interaction occurs between PMD and nonlinearity in that channel. In contrast, the results for WDM transmission (black circles) show that the Q-factor improved as the mean PMD increased and achieved an improvement of 0.8 dB at a mean PMD value of 24 ps. We consider that this improvement occurred because depolarization of the 10.7-Gb/s NRZ signal by PMD reduced the inter-channel nonlinearity penalties.

Next, **Figure 4 (d)** shows the results for single-channel transmission and WDM transmission with 100-GHz spacing (+2.5 dBm/ch). For single-channel transmission (indicated by the white squares), we see that the Q-factor, though constant up to a mean PMD value of 14 ps, degraded by 0.4 dB at a mean PMD value of 24 ps. We consider that this degradation was caused by interaction between PMD-related waveform distortion and nonlinearity in that channel. For WDM transmission (black squares), we see that the Q-factor was nearly constant with respect to the mean PMD. In other words, there was no improvement in the Q-factor like that observed for WDM transmission with 50-GHz spacing (0 dBm/ch). We consider that the PMD-related decrease in inter-channel nonlinearity penalties cancelled out the performance degradation due to interaction between PMD and nonlinearity in the channel, with the result that no PMD dependency could be observed.

The above results demonstrate that interaction between PMD and intra-channel nonlinearity and that between PMD and inter-channel nonlinearity can either improve or degrade performance depending on the channel spacing and fiber input power.

6. Conclusion

We showed by simulation that adaptive modulation is an effective technique for improving the capacity of a photonic network using digital signal processing. Using an evaluation platform that we developed for testing a variety of modulation formats and signal processing algorithms, we evaluated the characteristics of 112-Gb/s DP-QPSK signals in under emulated quasi-field conditions and clarified how polarization mode dispersion, polarization dependent loss, and nonlinear effects produce a composite effect on transmission characteristics.

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