Transmission Performance Comparison of Direction Detection-Based 100-Gb/s Modulation Formats for Metro Area Optical Networks

Hwan Seok Chung, Sun Hyok Chang, Jonghyun Lee, and Kwangjoon Kim

Transmission performances of direct detection-based 100-Gb/s modulation formats are investigated and compared for metro area optical networks. The effects of optical signal-to-noise ratio sensitivity, chromatic dispersion, cross-channel nonlinearity, and transmission distance on the performance of differential 8-ary phase-shift keying (D8PSK), differential phase-shift keying plus three-level amplitude-shift keying (DPSK+3ASK), and dual-carrier differential quaternary phase-shift keying (DC-DQPSK) are evaluated. The performance of coherent dual-polarization quadrature phase-shift keying (DP-QPSK) with block phase estimation and coherent DP-QPSK with digital differential detection are also presented for reference. According to our analysis, all three direct detection modulation formats could transmit a 100-Gb/s signal over several hundred kilometers of a single-mode fiber link. The results also show that DC-DQPSK outperforms D8PSK and DPSK+3ASK, and the performance of DC-DQPSK is comparable to that of coherent DP-QPSK with digital differential detection. The maximum transmission distance of DC-DQPSK is over 1,000 km, which is enough distance for metro applications.

Keywords: 100 G, modulation format, metro network.

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I. Introduction

Increasing data traffic requires a continuous expansion in network capacity, and modulation format plays a critical role in moving to 100-Gb/s transmission. Modulation formats used for 10-G transmission and 40-G transmission simply cannot perform in 100 Gb/s due to the limited optoelectronic bandwidth and optical signal-to-noise ratio (OSNR). Thus, there have been extensive works on searching modulation formats for 100 Gb/s [1]-[12]. For short distance transmission of a 100-Gb/s signal up to 40 km, IEEE 802.3ba defines 4 lanes × 25 Gb/s operating in the 1,310 nm window [1]. Each lane is modulated by a non-return-to-zero (NRZ) format and multiplexed with 800-GHz spacing. For long-haul transmission of a 100-Gb/s signal over 1,000-km transmission, dual-polarization quadrature phase-shift keying (DP-QPSK) with coherent detection appears to be the most promising technology due to its high tolerance against signal distortions, particularly in chromatic dispersion and polarization-mode dispersion limited links [1]-[4]. With the help of digital signal processing (DSP) on the receiver side, the coherent detection scheme, in principle, could mitigate most of the linear impairments generated from the transmission link. One of the crucial issues for coherent detection in metro networks or medium reach applications less than 1,000 km would be high electric power consumption and complex electronics, such as high-speed analog-to-digital converters and DSP. Recently, direct detection-based modulation formats, such as differential 8-ary phase-shift keying (D8PSK), differential phase-shift keying plus three-level amplitude-shift keying (DPSK+3ASK), dual-polarization differential quaternary phase-shift keying (DP-DQPSK) with optical polarization tracking, and dual-carrier differential quaternary phase-shift keying (DC-DQPSK) have been continuously investigated for metro network and data center interconnection [5]-[12]. These modulation formats could be easily implemented by off-the-shelf components with low electric power consumption.

In this paper, to investigate the feasibility of direct detection modulation formats for metro area optical networks, we evaluate and compare performances of directed detection-based 100-Gb/s modulation formats implemented by DPSK+3ASK, DC-DQPSK, and D8PSK. The effects of OSNR sensitivity, chromatic dispersion, cross-channel nonlinearity, and transmission distance on the performance of D8PSK, DPSK+3ASK, and DC-DQPSK are evaluated. The performance of coherent DP-QPSK with block phase estimation (BPE) and coherent DP-QPSK with digital differential detection (DD) is also presented as a reference. The estimated transmission reach of DPSK+3ASK and D8PSK is less than a few hundred kilometers due to the low extinction ratio of the intensity signal or short symbol distance, whereas that of the DC-DQPSK is over 1,000 km due to good OSNR sensitivity. The transmission performance of DC-DQPSK is comparable to coherent DP-QPSK with digital DD while the spectral efficiency of DC-DQPSK is half of DP-QPSK.

II. Direct Detection-Based 100-Gb/s Modulation Formats

Figure 1 shows a schematic diagram of a direct detection modulation format for a 100-Gb/s modulation. In this analysis, the performance comparisons are restricted to D8PSK, DPSK+3ASK, and DC-DQPSK since polarization demultiplexing is not required in these modulation formats. The three modulation formats utilize several physical properties of a light wave, such as intensity, phase, or frequency. As a result, multilevel modulation with a low symbol rate is achieved for the implementation of a 100-Gb/s transmission. The spectral efficiency of the three modulation formats is 1 b/s/Hz. The D8PSK format accommodates a three-bit transmission within one symbol, and the phase difference of each symbol is 45 degrees, as shown in Fig. 1(b) [8], [9]. Thus, the symbol rate becomes 33.3 Gbaud. One of the typical implementations of the D8PSK transmitter is a combination of an optical IQ modulator and a consecutive phase modulator. The IQ modulator driven by two 33.3-Gb/s binary data streams (D1 and D2) provides a 33.3-Gbaud DQPSK signal at the output. The following phase modulator is driven by the third 33.3-Gb/s binary data stream creating a $\pi/4$ phase-shift to generate a D8PSK signal. At the receiver, a delay line

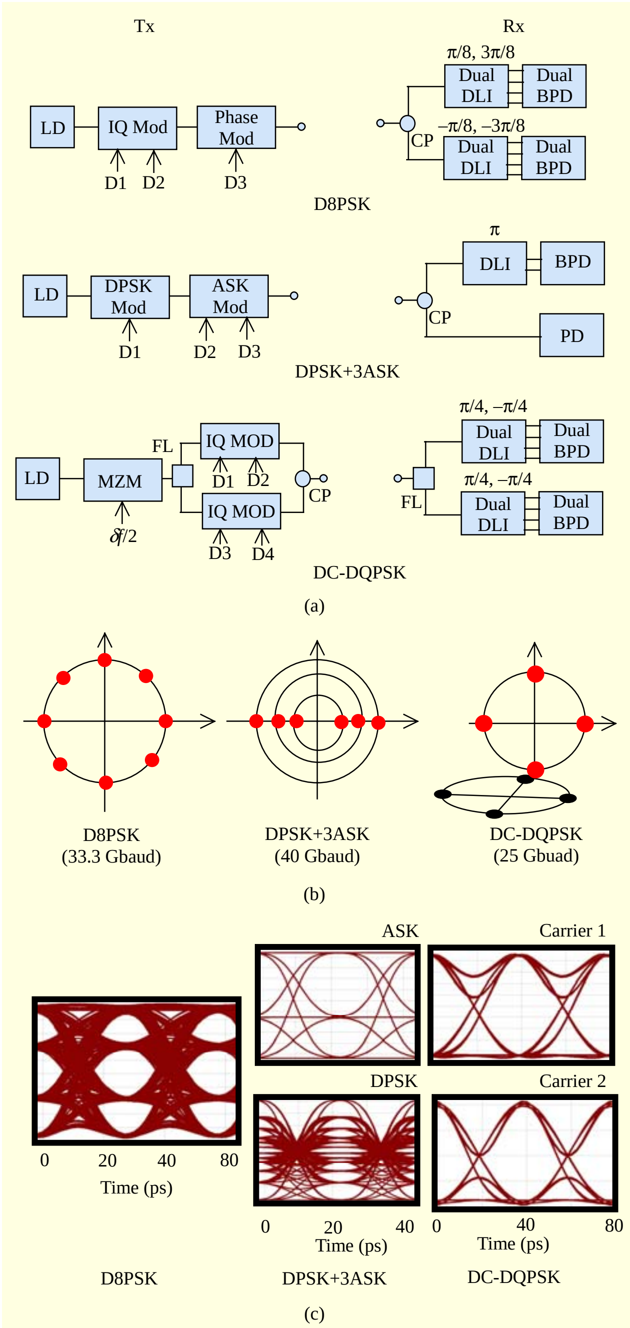

Fig. 1. Direct detection-based 100-Gb/s modulation formats D8PSK, DPSK+3ASK, and DC-DQPSK: (a) schematic diagrams of transmitters and receivers (filter [FL]; coupler [CP]), (b) constellations, and (c) received eye diagrams.

interferometer (DLI) with a free spectral range of 33.3 GHz performs differential demodulation with each DLI operating at the four different optical phase thresholds. The demodulated signals are detected by balanced photodetectors (BPDs), and the resulting electrical signals have four specific levels, as shown in Fig. 1(c). The received signals are treated as bi-level signals, and they are then processed with a single threshold in their respective clock and data recovery module. The DPSK+3ASK format is a combination of an intensity modulation and a phase modulation. The five bits are encoded into two consecutive symbols, which leads to a 40-Gbaud symbol rate to make a 100-Gb/s data rate [10], [11]. The commercially available components for a 40-Gb/s system can be used. The two phases of a DPSK signal are amplitude modulated to create the three symbols per phase, as shown in Fig. 1(b). For the signal detection, the DPSK+3ASK signal is split into a conventional photodetector (PD) for ASK reception and a DLI for DPSK reception. The DC-DQPSK format is composed of two optical frequency carriers, and each carrier is modulated with an optical phase [12]. It is possible to create two carriers by a conventional modulator driven by a $\delta f/2$-GHz clock signal, as shown in Fig. 1(a), in which δf represents carrier spacing. Each optical carrier is modulated into DQPSK and then combined by an optical coupler or an optical filter. At the receiver, an optical filter separates the two DQPSK modulated signals, and each phase-modulated DQPSK signal is converted into an intensity-modulated on-off keying signal by the DLI, as shown in Fig. 1(c). The baud rate of the DC-DQPSK format is 25 Gbaud. Any two different wavelengths can be selected for the dual carriers when the wavelength channels are available in the transmission link. The carrier spacing between carriers is typically set to be 50 GHz.

Regarding implementation complexity, DPSK+3ASK requires less optical components than do D8PSK and DC-DQPSK, whereas DPSK+3ASK and D8PSK require additional level decoding logic while DC-DQPSK can use DQPSK precoding logic at the commercially available gearbox. To reduce the footprint of a direct detection-based optical transceiver, integration of optical devices, such as delay interferometer and PD, are required.

III. Back-to-Back Performances

To evaluate the performances of each modulation format, we use Monte Carlo simulation. The 100-Gb/s signal generation, channel simulation, and detection are done by the commercially available numerical simulation software VPI TransmissionMaker, and the decoding of the received signal is done by Matlab code. The coherently detected 100-Gb/s format with DP-QPSK is shown in Fig. 2 for reference. The carrier phase of the coherently detected signal is estimated by either digital DD or BPE. The rotation of the constellation point due to the laser phase noise is compensated for by measuring the phase difference of two consecutive symbols in the DP-QPSK (DD), whereas, in the BPE (that is, DP-QPSK), it is compensated for by averaging the phase over a number of

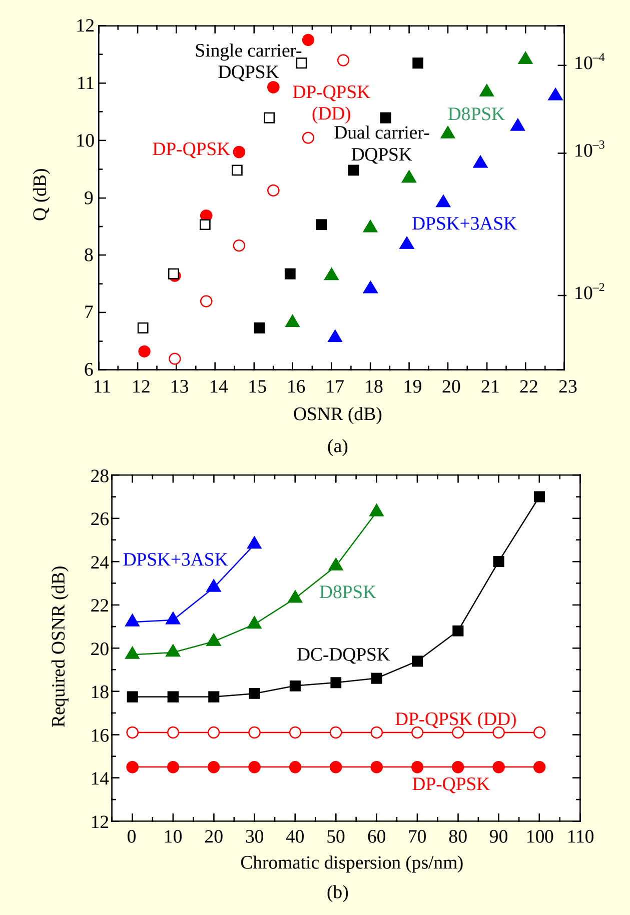

Fig. 2. OSNR sensitivities and dispersion tolerance: (a) OSNR sensitivities and (b) effects of chromatic dispersion on required OSNR to obtain BER of 10^{-3}.

consecutive symbols. The block size of the BPE is optimized to obtain the best performance. The optimum block size is 16 and 8 at linear and nonlinear transmission regimes, respectively. The modulation level of DPSK+3ASK is optimized to improve transmission performance [11]. The shape of the optical filter for the receiver is a second-order Gaussian filter, and its bandwidth is optimized for each modulation format. The Q-factor is calculated from the bit error rate (BER), and the BER is obtained by direct error counting. A total of 51,120 symbols are used for the BER measurement.

Figure 2(a) shows the OSNR sensitivity of each modulation format operating at 100 Gb/s. The OSNR sensitivity for DC-DQPSK, D8PSK, and DPSK+3ASK measured at a BER of 10^{-3} is 17.8 dB, 19.7 dB, and 21 dB, respectively. On the other hand, the OSNR sensitivity of DP-QPSK and DP-QPSK (DD) is 14.6 dB and 16 dB, respectively. Since the DC-DQPSK effectively uses the benefits of the dual-carrier scheme, the OSNR sensitivity of a single carrier that determines the transmission performance when the performance is limited by the OSNR at the linear regime is 14.8 dB. Thus, we can expect that the performance of DC-DQPSK at low input power would be better than that of DP-QPSK (DD) at the linear regime. Figure 2(b) shows the effects of chromatic dispersion on the required OSNR to obtain the BER of 10^{-3}. With the help of DSP at the receiver, in principle, DP-QPSK and DP-QPSK (DD)-based coherent detection could mitigate infinite chromatic dispersion. On the other hand, the chromatic dispersion tolerance value at a 2-dB OSNR penalty for DC-DQPSK, D8PSK, and DPSK+3ASK is 75 ps/nm, 35 ps/nm, and 20 ps/nm, respectively. The dispersion tolerance of the direct detection format is mostly determined by the symbol rate of the signal.

IV. Transmission Setup

To analyze the transmission performance of the direct detection modulation format, we use the system configurations shown in Fig. 3. Seven wavelength division multiplexing (WDM) channels spaced at 50 GHz or 100 GHz are propagated over $N \times 80$ km of single-mode fiber (SMF), where N is the number of spans. The carrier spacing of the DC-DQPSK is fixed to 50 GHz, regardless of adjacent channel spacing. The center channel (channel 4) is operating at 100 Gb/s, and the six adjacent channels are modulated by a

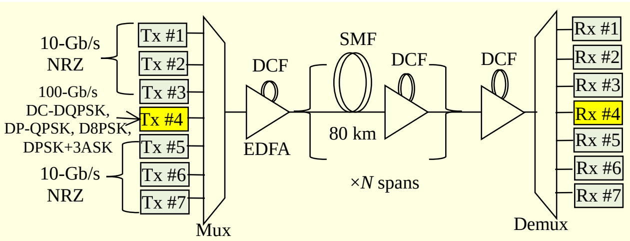

Fig. 3. Analysis setup for evaluation of transmission performances of direct detection formats. Coherent DP-QPSK is included for reference.

Table 1. Evaluation parameters.

Fiber	SMF
Dispersion	16 ps/nm/km
Effective area	80 μm^2
Loss	0.25 dB/km
Transmission distance	N×80 km
NF of EDFA	6 dB
Channel spacing	50 or 100 GHz
Neighboring channels	10-Gb/s NRZ

10-Gb/s NRZ format. We separately verify that increasing the number of channels does not cause significant variations in performance. The modulation format of 100 Gb/s is DC-DQPSK, D8PSK, DPSK+3ASK, or DP-QPSK. The coherent DP-QPSK is included for reference. The multirate 10-G signal and multirate 100-G signal are transmitted over a dispersion compensated SMF link (D=16 ps/nm/km). Dispersion is compensated for at every span, and the dispersion slope is fully compensated for on the receiver side. Our numerical investigations are performed with VPITransmissionMaker and Matlab. The BER is obtained by direct bit counting. Other numerical investigation parameters are summarized in Table 1.

V. Results and Discussions

First, we investigated the tolerance of the direct detection-based 100-Gb/s modulation format to fiber nonlinearity. Since each modulation format has a different OSNR sensitivity, the amplified spontaneous emission (ASE) noise was added after transmission. Thus, the ASE noise was not generated at each erbium-doped fiber amplifier (EDFA). The OSNR of DC-DQPSK was set to be 19.3 dB, whereas that of D8PSK and DPSK+3ASK was 22.3 dB. The transmission distance was set to be 1,040 km. Figure 4 shows the measured Q-factor and Q-penalty. The Q-penalty shown in Fig. 4(b) was obtained from the results of Fig. 4(a) by calculating the Q-factor difference from a single channel performance of –10-dBm/ch input power. In the case of the single channel transmission, the DC-DQPSK format showed the best self-phase modulation tolerance, due to the wide eye-opening of the received signal. On the other hand, when the 100-Gb/s signal was copropagated with 10-Gb/s NRZ neighboring channels, DPSK+3ASK was the most robust modulation format to cross-phase modulation (XPM). This can be induced by the higher phase margin and shorter walk-off length of DPSK+3ASK compared to those of DC-DQPSK and D8PSK. The results show that D8PSK exhibits the worst performance in a single channel as well as a multichannel with NRZ transmission even though the OSNR sensitivity of D8PSK is better than that of DPSK+3ASK in back-to-back configuration.

The effects of fiber input power when a 100-Gb/s signal is copropagated with 10-Gb/s NRZ signals are shown in Fig. 5. In this case, the ASE noise was generated at each EDFA, and the noise figure (NF) of each EDFA was set to be 6 dB. Since there is a higher OSNR requirement for D8PSK and DPSK+3ASK than for DC-DQPSK, the transmission distance for investigation was separated into 480 km and 1,040 km. After the 480-km transmission, the DPSK+3ASK format showed better performance than did the D8PSK format. For example, the maximum Q-factor for DPSK+3ASK and

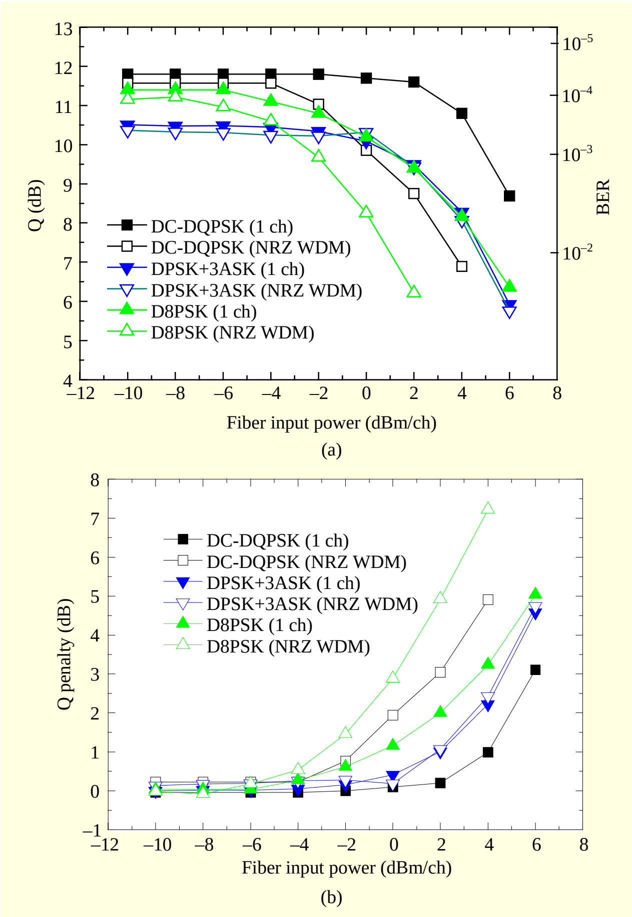

Fig. 4. Effects of 10-Gb/s neighboring channels on 100-G channel after 1,040 km of dispersion compensated SMF link. ASE noise is added after transmission of 1,040 km. OSNR of DC-DQPSK is 19.3 dB, whereas that of DPSK+3ASK and D8PSK is 22.3 dB: (a) Q-factor and (b) Q penalty.

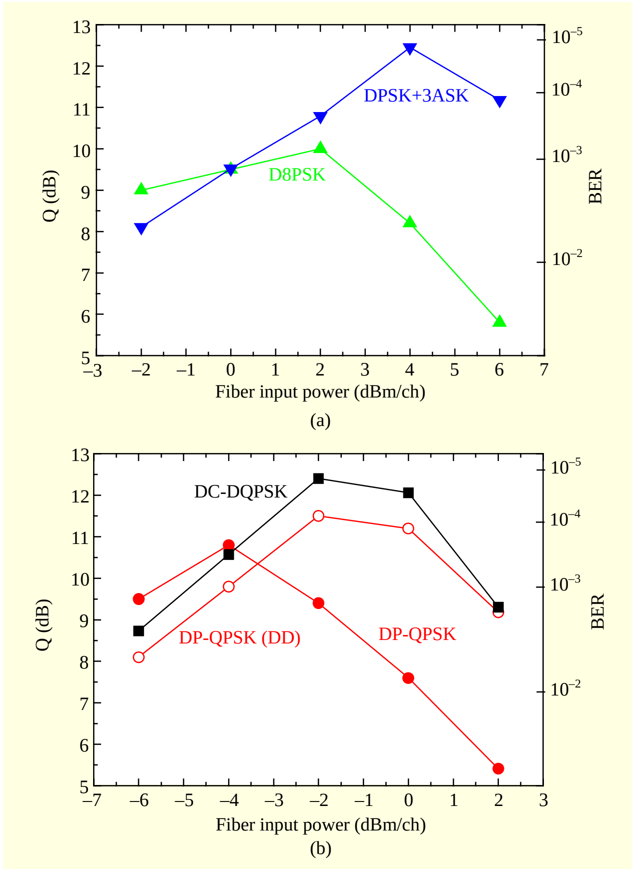

Fig. 5. Effects of fiber input power when 100-Gb/s channel is transmitted with 10-Gb/s NRZ neighboring channels. ASE noise is generated at each EDFA span: (a) Q-factor after 480 km and (b) Q-factor after 1,040 km.

D8PSK was 12.45 dB and 10 dB, respectively. Since the BER of the DC-DQPSK format after 480 km was error-free, the Q-factor could not be obtained. Thus, the transmission distance was increased to 1,040 km, the performance of which is shown in Fig. 5(b). Since the DC-DQPSK effectively uses the benefits of a dual-carrier scheme, the transmission performance of DC-DQPSK is determined by the OSNR requirement of a single carrier. Thus, the performance of DC-DQPSK is better than that of DP-QPSK (DD), whereas the performance of DC-DQPSK is worse than DP-QPSK at a linear regime. As the fiber input power was increased, the DP-QPSK was significantly affected by cross-channel nonlinearities (especially XPM). The Q-factor of DP-QPSK can be enhanced by employing digital DD for phase estimation. Because the nonlinear phase noise due to XPM was highly correlated in adjacent channels, the nonlinear noise could be effectively mitigated by digital DD. This was also applicable to DC-DQPSK, which employs optical DD. Thus, the Q-factor of 10.8 dB in DP-QPSK was increased to 11.5 dB, and the Q-factor of DC-DQPSK was 12.4 dB. The results show that the overall performance of DC-DQPSK is comparable to that of DP-QPSK with digital DD.

Figure 6 shows the measured Q-factor of a 100-Gb/s modulation format as a function of transmission distance. The fiber input power for each modulation format in Fig. 5 was used for this analysis. The fiber input power for D8PSK and DPSK+3ASK was 2 dBm and 4 dBm, respectively. The fiber input power for DP-QPSK (BPE) was –4 dBm, whereas that of DP-QPSK (DD) and DC-DQPSK was –2 dBm. When 10 Gb/s NRZ channels were spaced at 100 GHz, the maximum transmission distance to obtain the BER of 10^{-3} for DC-DQPSK, DPSK+3ASK, and D8PSK was 1,520 km, 560 km, and 400 km, respectively. Even though the OSNR requirement of DPSK+3ASK was higher than that of D8PSK, DPSK+3ASK could transmit a 100-Gb/s signal a longer distance than could D8PSK, due to nonlinear tolerance. With the help of the lower OSNR requirement and the robustness of

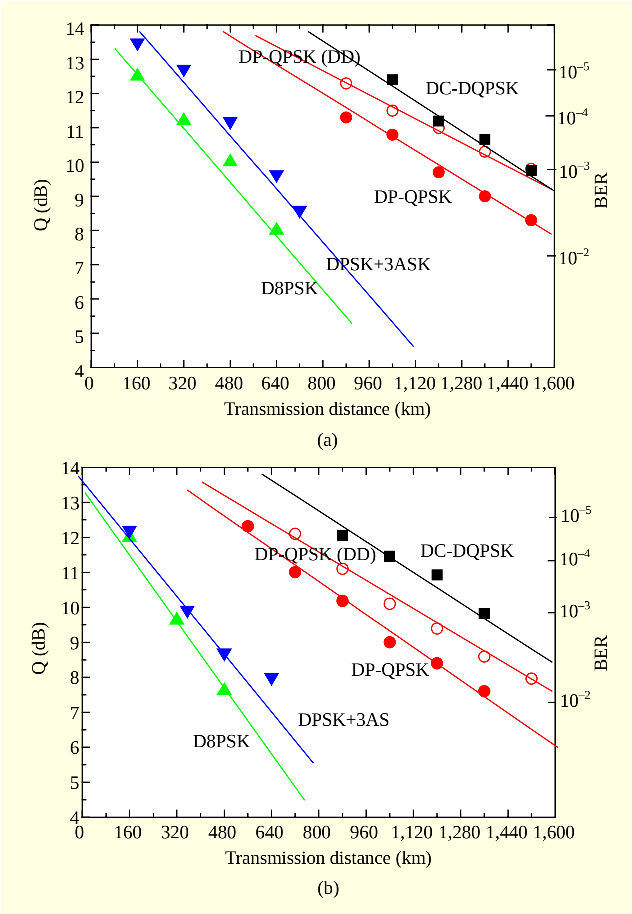

Fig. 6. Transmission performance of 100-Gb/s modulation format when adjacent 10-Gb/s NRZ channels are spaced at (a) 100 GHz and (b) 50 GHz.

cross-channel nonlinearities of the DC-DQPSK format, the transmission distance of DC-DQPSK was comparable to that of DP-QPSK (DD). It should be noted that the spectral efficiency of DP-DQPSK (DD) was two times higher than that of DC-QPSK, even though the maximum transmission distance was similar when 10-Gb/s NRZ channels were copropagated. Figure 6(b) shows the transmission performance when 10-Gb/s NRZ channels were spaced at 50 GHz. The fiber input power for D8PSK and DPSK+3ASK was reduced to 0 dBm and 2 dBm, respectively, whereas the fiber input power for DP-QPSK (BPE), DP-QPSK (DD), and DC-DQPSK was the same as that of the 100 GHz spacing. When the channel spacing of the adjacent channel was changed from 100 GHz to 50 GHz, the performance difference between DC-DQPSK and DP-QPSK (DD) slightly increased. Even when adjacent channel spacing was reduced to 50 GHz, the DC-DQPSK occupied a 100-GHz spectral width due to the 50-GHz carrier spacing. Thus, the adjacent 10-Gb/s NRZ channels would have a slightly higher impact on DP-QPSK (DD) than on DC-DQPSK. The maximum transmission distance for DC-DQPSK, DPSK+3ASK, and D8PSK was reduced to 1,280 km, 320 km, and 240 km, respectively, due to increased cross-channel nonlinearities. However, the results show that the DC-DQPSK format can still accommodate a 100-Gb/s signal over 1,000 km, which is enough transmission distance for metro applications.

VI. Summary

We investigated and compared performances of direct detection-based 100-Gb/s modulation formats for metro area optical networks. The OSNR sensitivity of D8PSK was better than that of DPSK+3ASK in back-to-back configuration, whereas the transmission performance of DPSK+3ASK was better than that of D8PSK since D8PSK was easily affected by cross-channel nonlinearities. The DC-DQPSK format outperformed the D8PSK and DPSK+3ASK formats in terms of OSNR requirement, dispersion tolerance, and transmission distance. When a 100-Gb/s signal was copropagated with 10-Gb/s NRZ neighboring channels spaced at 100 GHz, the maximum transmission distance to obtain the BER of 10^{-3} for DC-DQPSK, DPSK+3ASK, and D8PSK was 1,520 km, 560 km, and 400 km, respectively. The DC-DQPSK format could accommodate a 100-Gb/s signal over 1,000 km in 100 GHz as well as 50 GHz spacing, and the result was comparable to that of coherent DP-QPSK with digital DD.

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