System performance influenced by channel plan for coherent PDM-QPSK/OOK hybrid transmission systems

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The impact of channel occupancies on polarization division multiplexed quadrature phase-shift keying (PDM-QPSK)/on-off keying (OOK) hybrid systems is investigated numerically over a dispersion-managed transmission link. In addition to keep large residual dispersion per span, we find that suitable channel occupancy also help to improve the nonlinear tolerance of such hybrid systems significantly. About 2.4-dBm more nonlinear threshold (NLT) and 75% increase of transmission reach can be obtained under suitable channel plan for 112-Gb/s PDM-QPSK/OOK hybrid systems.

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Upgrading existing 10-Gb/s to 40-Gb/s or higher networks are widely accepted in order to obtain as high transmission capacity as possible. This could be performed preferably by progressively inserting 40-Gb/s channels into wavelength slots originally planned for 10-Gb/s channels with non-return to zero (NRZ) format, i.e. without changing the channel spacing of 50 GHz. Thus, in such an upgrade scenario, the transport system would consist of co-propagating hybrid data rates. To carry 40-Gb/s channels in such dense wavelength division multiplexed (DWDM) systems, advanced modulation formats are needed. Coherently-detected polarization division multiplexed quadrature phase-shift keying (PDM-QPSK) modulation combined with digital signal processing (DSP) and direct detection differential QPSK (DQPSK) have been proved promising solutions for such hybrid system numerically and experimentally[1−4].

One important issue for assessing the suitability of a given 40-Gb/s format is how it coexists with 10-Gb/s on-off keying (OOK) channels. Some experiments and numerical simulations have shown that in such hybrid systems, the performance of the phase modulated channels (i.e. DQPSK or PDM-QPSK) can be highly influenced by the inter-channel cross-phase modulation (XPM) coming from the adjacent OOK channels[5−7]. Therefore, many investigations have been conducted, focusing on what XPM penalties in such hybrid transmission relate to and how to reduce them as much as possible[8−12]. Of these efforts, it should be noted that Ref. [11,12] have proved experimentally and analytically that such XPM penalty in DQPSK/OOK hybrid systems strongly depends on system configurations such as channel plans and dispersion maps.

For non-coherent DQPSK/OOK hybrid transmissions, the impact of channel occupancy has been mentioned before, but no detailed numerical results for coherent PDM-QPSK/OOK systems. In this letter, using numerical simulations, we extend previous work and investigate comprehensively the impact of channel plans on both 40- and 112-Gb/s NRZ-PDM-QPSK/OOK hybrid DWDM systems over a 1 000-km non-zero-dispersion-shifted fibers (NZDSFs) dispersion-managed transmission link. It is found that similar to DQPSK/OOK case, the system performance of coherent PDM-QPSK/OOK systems is also highly influenced by channel plan and this will be more pronounced at higher bit rate.

In this letter, all the simulations are performed using the open-source software Optilux[13]. The system model is shown in Fig. 1. There are seven channels with channel spacing Δf=50 GHz, centered around 1 550 nm. For the transmitter, two independent QPSK signals are generated by using two Mach-Zehnder modulators (MZMs) driven by 2^{11} symbols with NRZ shaped pulses and then polarization multiplexed. An optical multiplexer and a demultiplexer are present at the transmitter and the receiver respectively. In the simulations, they are both modeled as the 2nd order Super-Gaussian filters with 40-GHz bandwidth. Before wavelength multiplexing, the states of polarization (SOPs) of each channel is randomized on the Poincarè sphere. All symbol patterns are purely random sequences and uncorrelated for each WDM channels. The NRZ-OOK transmitter at 10-Gb/s is typical and all channels have the same average power and

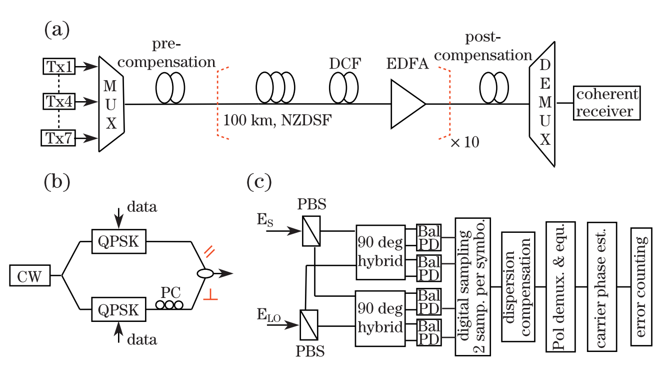

Fig. 1. System configuration in our simulations. (a) Transmission line; (b) block diagram of the PDM-QPSK transmitter; (c) block diagram of the coherent receiver.

are synchronous at the pre-fiber.

The transmission link consists of N=10 identical spans of 100-km-long NZDSF and dispersion-compensating fiber (DCF). The transmission fiber has nonlinear index γ=1.5 $W^{-1}km^{-1}$, attenuation α=0.22 dB/km, and chromatic dispersion D =3.8 ps/(nm·km). The residual dispersion per span (RDPS) is set to D_{in}=30 and 40 ps/nm with the pre-compensation equal to $D_{pre} = -D/\alpha - D_{in}(N-1)/2$[14]. A post-compensation is presented at the end of the link whose value set the overall dispersion to zero. All DCFs are linear and without loss in our simulations. Following the DCF, an erbium-doped fiber amplifier (EDFA) is inserted to compensate for the loss of preceding span. Each fiber is simulated as the concatenation of 50 random birefringent waveplates without polarization mode dispersion (PMD). The propagation is noiseless, while noise is only loaded before the receiver, thus neglecting nonlinear phase noise (NLPN), which is here negligible[15]. We assume flat gain amplifiers with 7-dB noise figure at each span end.

The received signal, after passing through an optical filter and a polarization beam splitter (PBS), is combined with an ideal local oscillator in a 90° hybrid. After the mixer, the four signals are filtered by the 5th order Bessel filter with bandwidth 0.65× baudrate (i.e. 6.5 or 18.2 GHz), sampled at twice the symbol rate, and then digitally processed with: polarization recovery employing the constant modulus algorithm (CMA)[16], Viterbi carrier phase estimation[17] and symbol decision.

The center channel is examined by calculating the bit error rate (BER) through the Monte Carlo algorithm and then converting the estimated BER to Q-factor. The simulations are stopped when the relative estimation errors on BER reach 20% with a Gaussian confidence of 95%, providing in each case at least 100 errors. Each BER is averaged over 20 different runs with different random seeds. Each seed corresponds to different random bit sequences, initial SOPs, and fiber waveplates realizations.

Four different channel occupancies are considered as shown by the optical spectrum in Fig. 2. Figure 2(a) is called C-ADM for a QPSK channel amidst six neighboring OOK channels. Figure 2(b) is called C-INT for hybrid interleaved OOK and QPSK signals. Figure 2(c) is called C-NNN for a C-INT channel plan with the nearest 10-G neighbor channel moving away 50-Hz from the central channel (the nearest OOK channel away from the central QPSK channel 100-GHz). Figure 2(d) is called C-ONE for all the OOK channels located at one side of the QPSK channels.

The transmission performance of mixed 40-Gb/s (or 112-Gb/s) PDM-QPSK and 10-Gb/s NRZ-OOK are given in Fig. 3, which shows the Q-factor versus launch power per channel after 1 000-km transmission for the system under the four channel occupancies. Evidently, the system performance improves with the increase of the RDPS for all the cases. Large RDPS provides large channel walk-off that helps mitigate the XPM penalties coming from the OOK channel, which is the main nonlinear impairment in such hybrid systems. Moreover, the best performance is always obtained with C-NNN channel plan for both 40- and 112-Gb/s QPSK systems. This is not surprising since XPM grows with the walk-off length[19], i.e. with inverse channel spacing. On the other hand, the nonlinear tolerance of C-ADM case is the lowest since it has the worst-case XPM impairments. From Fig. 3(a), we can see that for the 40-Gb/s PDM-QPSK/OOK hybrid transmission, the Q value increases from 6.5 dB under C-ADM plan to 9.8 dB under C-NNN case when the input power is fixed to −3 dBm, yielding a 3.3-dB Q-improvement. Meanwhile, the C-ONE and C-INT have similar performance across the whole input power range, only 0.8 dB difference between Q-factor at input power equals to −3 dBm.

Figure 3 also shows the 112-G PDM-QPSK suffers from a reduced optical signal-to-noise ratio (OSNR) sensitivity due to its higher bit rate (about 3.5-dB decrease in Q-factor at input power=−7 dBm relative to 40-Gb/s QPSK/OOK). However, the nonlinear threshold (NLT, defined as input power per channel at best Q value) is better than 40-G PDM-QPSK because higher baudrate leads to reduced XPM penalties in such systems[8,9]. In addition, as shown by these curves, we can see that compared with 40-Gb/s PDM-QPSK case, the Q-factor has a more clear difference from C-ADM to C-NNN plans, even in linear regime (i.e. ascending region of Q-factor vs. power) at 112 Gb/s. Hence, we can conclude that at higher bit rate, the system performance of such hybrid transmission is more susceptible to the channel plans and this will be verified again in the ensuing measurements.

Figure 4 shows the NLT versus RDPS under the four channel occupancies for 40- and 112-Gb/s hybrid systems. The worst NLT always comes to C-ADM plan and NLT grows linearly for the four channel plans in the order C-ADM, C-INT, C-ONE, and C-NNN for the two bit rates, which is consistent with our results before. For 40-G systems, the NLT increases from −5.7 dBm under C-ADM plan to −4.5 dBm under C-NNN case, while about 2.4 dB increase in NLT can be obtained from C-ADM to C-NNN plan at 112-G QPSK when RDPS equals 50 ps/nm.

In a final test, we measure the maximum achievable distances at BER=3×10^{-3} as functions of input power

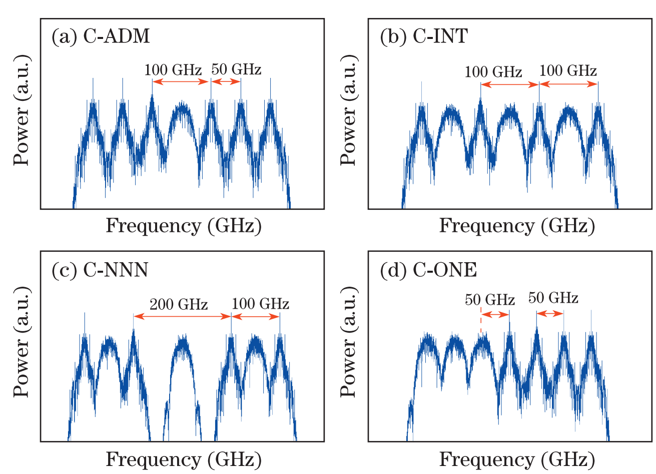

Fig. 2. Four different channel occupancy plans: (a) C-ADM: the central QPSK channel is surrounded by six 10-Gb/s OOK channels; (b) C-INT: QPSK channels and OOK channels are hybrid interleaved; (c) C-NNN: the nearest channels away from the central channel 100 GHz; (d) C-ONE: all the OOK channels located at one side of the QPSK channels.

for the systems under four channel occupancies and the results are shown in Fig. 5. For the lower input powers the transmission performance is limited due to ASE noise; for the higher input powers the performance is mainly limited due to XPM effect. Just as we have observed before, the C-NNN plan has the best nonlinear tolerance and results in an increase in the maximum reach from 1 260 (800) to 1 780 (1 400) km, compared with the C-ADM case at 40(112)-Gb/s. Again, we observe that channel plan has a more significant impact on system performance at higher bit rate, yielding a 75% increase distance at 112 G, but only 40% increase at 40-G PDM-QPSK between the best and worst channel occupancies.

In conclusion, systematic investigation of hybrid 10-Gb/s NRZ-OOK and 40-Gb/s (112-Gb/s) PDM-QPSK transmissions under different channel plans over a typical dispersion-management long-haul link is conducted. It is shown that channel plan has a significant impact on the system performance and this will be more pronounced at higher bit rate. About 2.4-dB increase in NLT and 75% increase of transmission reach can be obtained

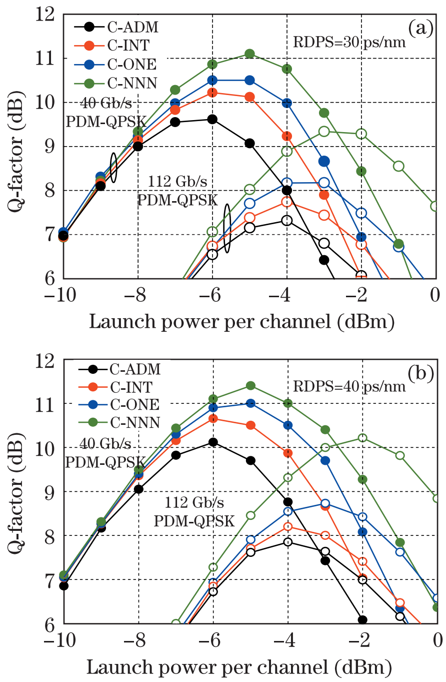

Fig. 3. Q-factor versus input power for 40- and 112-Gb/s PDM-QPSK with 10-Gb/s OOK neighboring channels after 1 000-km transmission. (a) RDPS=30 and (b) 40 ps/nm.

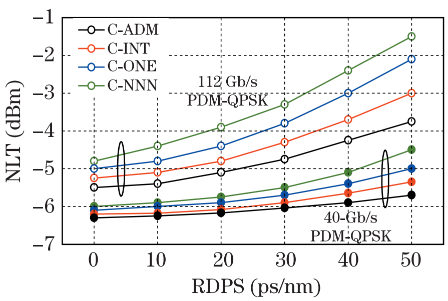

Fig. 4. NLT versus RDPS for the four channel plan at 40- and 112-Gb/s QPSK with 10-Gb/s OOK neighboring channels after 1 000-km transmission.

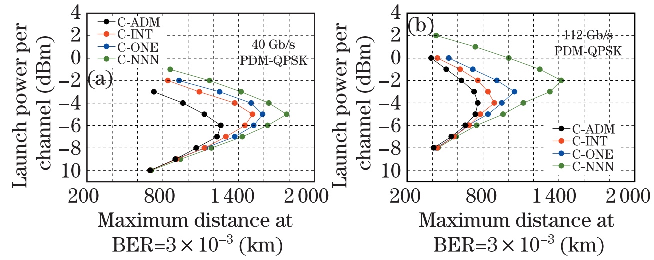

Fig. 5. Maximum distance at BER=3×10^{-3} as a function of the input power for (a) 40- and (b) 112-Gb/s QPSK/OOK hybrid transmission under different channel plans. RDPS=40 ps/nm.

under suitable channel plan at 112-Gb/s systems. Hence, appropriate system designs are needed to ensure hybrid transmission with acceptable nonlinear crosstalk.

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