Evaluation of correlative coding and DP-16QAM n-channel 112Gbit/s coherent transmission: digital non-linear compensation perspective

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Abstract: We numerically report on the complexity reduction of digital backward propagation (DBP) by utilizing correlative encoded transmission (dual-polarization quadrature duobinary) at a bit-rate of 112Gbit/s over 1640km fibre link. The single channel (N=1) and multi-channel (N=10) transmission performances are compared in this paper. In case of multi-channel system, 10 transmitters are multiplexed with 25GHz channel spacing. The fibre link consists of Large A_{eff} Pure-Silica core fibre with 20 spans of 82km each. No in-line optical dispersion compensator is employed in the link. The system performances are evaluated by monitoring the bit-error-ratio and the forward error correction limit corresponds to bit-error-ratio of 3.8×10^{-3} . The DBP algorithm is implemented after the coherent detection and is based on the logarithmic step-size based split-step Fourier method. The results depict that dual-polarization quadrature duobinary can be used to transmit 112Gbit/s signals with an spectral efficiency of 4-b/s/Hz, but at the same time has a higher tolerance to non-linear transmission impairments. By utilizing dual-polarization quadrature duobinary modulation, comparative system performance with respect to dual-polarization 16-quadrature amplitude modulation transmission can be achieved with 60% less computations and with a step-size of 205km.

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1. Introduction

The requirements for bandwidth and capacity in metro and long-haul optical communication systems due to the demands of high-speed data services, internet video services, data centers and higher bandwidth residential broadband connections, are exponentially increasing. Recent advancements in high data-rate optical transmission systems have triggered an intensive investigation in digital signal processing (DSP) algorithms [1–3] as well as in spectrally efficient advanced modulation formats [4, 5]. Coherent optical quadrature phase shift keying (CO-QPSK) is considered as the strongest candidate for implementing 100GbE networks due to its relatively low OSNR requirements and can have spectral efficiency (SE) of 2.2b/s/Hz in case of DP-RZ-QPSK [6]. In order to meet the ever increasing demand of capacity requirements, increase in SE of the transmission system can be a possible solution. Most recently advanced modulation formats, M-quadrature amplitude modulation (QAM) [M=4,16,32,64, 256 and 1024] and orthogonal frequency-division multiplexing (OFDM) have been investigated in order to increase the SE [5, 7–9]. However, this high SE is obtained at the expense of complicated transmitter structures, i.e. OFDM, and dense constellation diagrams, i.e. M-QAM (where M=16,32,64, 128 etc), which collectively make them less robust against fiber transmission impairments i.e. chromatic dispersion (CD) and non-linearities (NL).

Correlative coding (CC) or partial response signalling (PRS) techniques were first introduced [10], in order to increase the spectral efficiency of the transmission systems. It was determined that by considering the correlation or dependencies between the amplitudes of transmitted pulses, we could achieve the symbol rate of $2N$ symbols/s in a bandwidth of N Hz [10]. This signalling method differs from the conventional pulse amplitude modulation (PAM) system in a sense that a controlled amount of inter-symbol interference (ISI) is introduced to attain certain spectral shapes which allows to transmit 2b/s/Hz achieving full theoretical capability. This correlation between successive bits in a binary signal leads the signal spectrum to be more concentrated around the optical carrier [11]. Correlative coding technique is realized by implementing quadrature duobinary (QDB) modulation in recent times [12, 13] to attain high SE without increasing the complexity of the transmitter excessively [14, 15]. The dual-polarization quadrature duobinary (DP-QDB) coding can have the SE of 4b/s/Hz at 100Gbit/s data rate and due to its relatively simple transmitter structure it becomes more attractive than DP-QAM [16].

The transmitter architecture of DP-QDB is relatively similar to DP-RZ-QPSK modulation, as shown in Fig. 1. The four electrical binary data streams driving the modulators are passed through duobinary pre-coders and then passed through a low pass filter (LPF) having the bandwidth of (symbol rate)/4. This LPF functions as delay and add components through the ISI, they induce between adjacent bits [17], as depicted in Fig. 1(a). For example, if the (input) data sequence is $x(nT)=(0, 0, 1, 0, 1, 0, 0, 1, 1, 0)$, we would instead transmit the (output) data sequence $y(nT)=(0, 0, 1, 0, 1, 0, 0, 1, 1, 0) + (*, 0, 0, 1, 0, 1, 0, 0, 1, 1) = (0, 0, 1, 1, 1, 1, 0, 1, 2, 1)$. Here the sign $*$ denotes the initial value ($z(nT)$) of the input sequence, which is

Fig. 1. (a) Equivalent model of filter stage for duobinary encoding, (b) Optical duobinary modulator, (c) Dual-drive MZM, (d) MZM bias and derive conditions for optical DB signal, (e) Quadrature duobinary (QDB) constellation diagram and (f) Eye-diagrams for DB and QDB respectively.

assumed to be zero. Note that while the input sequence is binary and consists of 0s and 1s, the output sequence is a ternary sequence consisting of 0s, 1s, and 2s. Mathematically, DB results in $y(nT) = x(nT) + x(nT - T)$, where T is the bit period and n is the number of bit sequences.

The DB signal can be generated by applying a baseband, three-level electrical DB signal to a dual-drive MZM as shown in Fig. 1(d) that is biased at maximum extinction ratio, as shown in Fig. 1(c). Conceptually, the carrier is a continuous wave signal, a sinusoid denoted by $a \cdot \cos(\omega t)$. The three levels of the ternary signal correspond to $a \cdot \cos(\omega t)$, 0 and $-a \cdot \cos(\omega t)$, which is denoted by -1, 0, and +1. These duobinary signals are then applied to the I-Q modulator, thus producing QDB signal (Fig. 1(b)). The 9-point constellation and eye-diagram of DB signal is shown in Fig. 1(e). The eye-diagram of QDB is also depicted in Fig. 1(f). The independently generated x and y polarized QDB signals are then combined by a polarization beam combiner to have DP-QDB.

Despite of all efforts to get the SE transmission with advanced modulation formats, CD and NL are the main impediments in improved system performance. To solve the issue, transmitter and receiver side digital signal processing (DSP) algorithms, termed as Digital Backward

Propagation (DBP), to compensate chromatic dispersion and intra-channel non-linearities have been investigated in [18–26]. But the complexity of DBP algorithm is extremely high due to ultra-wide bandwidth requirements that it becomes an intrinsic impediment in the real-time implementation of DBP algorithm [27,28]. In order to reduce the complexity of the algorithm, the correlated DBP (CBP) algorithm has been investigated for QPSK transmission systems [29,30] and 80% reduction in the computational efficiency has been reported.

In this paper, we have numerically evaluated and compared the non-linear tolerance of correlated coding in the form of DP-QDB with DP-16QAM over 112Gbit/s transmission over 1640km of large effective area pure-silica-core-fibre (LA-PSCF) link. The performance is evaluated both for single channel as well as 10-channel DWDM transmission with a channel spacing of 25GHz. Furthermore, the comparison of transmission performance of DP-QDB and DP-RZ-QPSK modulation format has also been made at a channel spacing of 50GHz attaining a SE of 2b/s/Hz. The complexity of the DBP algorithm in-terms of step-size (h) is also scrutinized for spectrally efficient modulation formats.

Fig. 2. Simulation setup for 112Gbit/s DP-QDB system, whereas; LD=laser diode, ADC=analog to digital converter, DSP=digital signal processing module, LPF=low pass filter, PBS=polarization beam splitter, PBC=polarization beam combiner.

2. Simulation setup

Figure 2, illustrates the general numerical model to investigate the two modulation formats, i.e. DP-QDB and DP-16QAM, at a bit-rate of 112Gbit/s for N -channels. The data streams consist of $2^{16} - 1$ pseudo-random binary sequence (PRBS). The DP-16QAM transmitter is operated with four electrical binary streams with data rates of 14Gbit/s for each polarization, whereas DP-QDB transmitter is modelled with four duobinary encoded electrical streams with data rates of 28Gbit/s and RZ pulse shaping is also performed on DP-QDB [31]. In order to simulate DP-RZ-QPSK system, RZ pulses with 50% duty cycle are used and MZM is driven with a clock of 28GHz. Single channel ($N=1$) and multi-channel ($N=10$) DWDM transmission performances are compared in this paper. The fiber link consists of Large A_{eff} Pure-Silica core fiber (LA-PSCF) type fiber with 20 spans of 82km each and has the physical parameters of: attenuation $\alpha=0.16$ dB/km, dispersion $D=21$ ps/(nm-km) and non-linear coefficient $\gamma=0.6$ ($\text{km}^{-1} \cdot \text{W}^{-1}$). No in-line optical dispersion compensator is employed in the link. Erbium-doped fiber amplifier (EDFAs) are modelled with 13.12dB of gain and 4dB of noise figure. A phase-diversity homodyne coherent receiver is used to detect the DP-16QAM and DP-QDB [17]. To simplify our numerical analysis, we neglect the effect of polarization mode dispersion (PMD) and laser line width. In order to investigate the transmission performance of DWDM DP-QDB and DP-16QAM at 4b/s/Hz SE, 10 transmitters are multiplexed with 25GHz channel spacing. While for the investigations of 2b/s/Hz SE for DP-RZ-QPSK and DP-QDB transmission, 10 transmitters are multiplexed with 50GHz channel spacing. The system performances are evaluated by monitoring the bit-error-ratio (BER) and the forward error correction (FEC) limit corresponds

to BER of 3.8×10^{-3} . The DBP processing module is used after the coherent detection and is based on the symmetric split-step Fourier method.

3. Results and discussions

3.1. Tolerance to non-linear transmission impairments

Figure 3(a), depicts the transmission performance of DP-16QAM 112Gbit/s transmission over 1640km of fibre. The system performance is compared by digitally compensating the fibre transmission impairments as; (a) chromatic dispersion compensation (CD), i.e. linear equalization (LE) and (b) digital backward propagation (DBP). The DBP algorithm is employed here on the basis of one-step per fibre span (DBP-1S). The single channel transmission shows improvement in system performance in terms of input launch power by a factor of ≈ 2.8 dB and ≈ 2.1 dB in DWDM transmission at BER of 3.8×10^{-3} . This improvement depicts efficient compensation of CD and NL by DBP. Whereas, the reduced improvement in case of DWDM is due to the strong inter-channel non-linear effects.

Fig. 3. BER performance of 112Gbit/s: (a) DP-16QAM and (b) DP-QDB (right) for single channel (1-ch) and multi-channel (DWDM) with 25GHz channel spacing using; (i) linear equalization (LE) and (ii) digital backward propagation (DBP).

The tolerance of non-linear transmission in DP-QDB system is analysed in Fig. 3(b). We have investigated LE and DBP performance in this case for the same link design as our previous investigation. We have seen that the system performance is improved by a factor of ≈ 3.5 dB in single channel and ≈ 2.7 dB in DWDM transmission. Also that the overall non-linear threshold point (NLT) is improved in DP-QDB by 2dB as compared to DP-16QAM. This depicts that DP-QDB is more tolerant to non-linear effects, shows enhanced system performance with DBP and can transmit over longer distances as compared to DP-16QAM system, while both have same spectral efficiency (SE) of 4b/s/Hz. On the other hand another added advantage of DP-QDB modulation is its feasibility of realizing high SE without increasing the complexity of the transmitter excessively.

Furthermore, we have numerically evaluated and compared the transmission performances at different spectral efficiencies. For this investigation a 10 channel DP-QDB transmission system is implemented with 50GHz channel spacing giving a SE of 2b/s/Hz. The performance is compared with DP-RZ-QPSK transmission. The other physical parameters of the transmission set-up are kept constant as previous investigation. The results are depicted in Fig. 4 after implementing the DBP algorithm. It is clear from the results that DP-RZ-QPSK has more non-linear tolerance as compared to DP-QDB at a SE of 2b/s/Hz and the system performance has improved by ≈ 3 dB at BER of 1×10^{-3} . It means that for 50GHz channel spacing, the DP-RZ-

QPSK modulation has more tolerance for non-linear transmission impairments, have the simple transmitter/receiver architectures and less complex signal processing algorithms to detect the received signals, as compared to DP-QDB. But at higher SE, DP-QDB can be used to reduce the channel spacing to 25 GHz in order to obtain an SE of 4-b/s/Hz.

Fig. 4. Non-linear transmission performance of 10-channel DP-QDB vs. DP-16QAM (with 25GHz channel spacing) and DP-QDB vs. DP-RZ-QPSK (with 50GHz channel spacing).

3.2. Complexity of DBP algorithm for spectrally efficient modulation formats

In order to exploit the complexity of the DBP algorithm for both the modulation formats, we have investigated the performance w.r.t different DBP step number per 1640km of fiber link. The 112Gbit/s system is investigated at 4dBm signal launch power and the results are depicted in Fig. 5. The results illustrate a significant decrease in the complexity of the DBP algorithm for single channel DP-QDB encoded transmission. The comparative system performance w.r.t DP-16QAM transmission can be obtained in just 8 DBP steps for 1640km of fiber link (60% reduction in algorithm complexity). This computational effort corresponds to 0.4DBP steps per fiber span and 205km of step-size. Furthermore; for DWDM transmission at the FEC limit (BER of 3.8×10^{-3}), by using DP-QDB encoded transmission, the complexity of the DBP algorithm can be reduced to 0.7 steps per fiber span (30% reduction) w.r.t DP-16QAM transmission. The overall results depict that; (a) DP-QDB transmission has more non-linear tolerance as compared to DP-16QAM and (b) the low-complexity of the DBP algorithm can be achieved by utilizing DP-QDB transmission both in single and multi-channel transmission. Even at the NLT point, DP-QDB is performing efficiently, as shown in Fig. 3(b), compared to DP-16QAM, so we will get the reduced complexity likewise.

Finally, we have focused on the numerical investigation of maximum achievable transmission distance for a BER of 1×10^{-3} employing DBP in the transmission for both the modulation formats. Using the same parameters of transmission i.e. 112Gbit/s, 1640km of fiber and by using DBP-1S, the results are as shown in Fig. 6. By analysing the results we have noticed that DP-QDB encoded transmission has the maximum transmission reach of 5280km and 4900km for single and multi-channel transmission respectively. This actually outperforms the DP-16QAM transmission which has the maximum transmission reach of approximately 4500km and 4200km. We have found from our numerical investigations that we can achieve 15-18% more transmission distance in case of DP-QDB encoded transmission. This shows once again the superior performance of DP-QDB over DP-16QAM.

Fig. 5. BER as a function of number of DBP calculation steps for complete fiber link.

Fig. 6. Optical transmission reach at BER of 1×10^{-3} for DP-QDB and DP-16QAM transmission.

4. Conclusion

In this paper, we have numerically evaluated the transmission performance of 112Gbit/s N-channel Correlative encoded (DP-QDB) and DP-16QAM systems employing DBP over 1640km of fiber with no in-line optical dispersion compensation. The DP-QDB encoded transmission is investigated for single and multi-channel transmission, complexity of DBP algorithm and maximum optical transmission reach. We have also numerically evaluated and compared the transmission performances at different spectral efficiencies i.e. 2b/s/Hz and 4b/s/Hz. While comparing to DP-16QAM with the same data rate and SE, DP-QDB has a transmitter structure similar to DP-QPSK and a better tolerance against non-linearities. In case of DP-QDB transmission; (a) NLT is improved by a factor of 2dB, (b) the complexity of DBP algorithm is reduced by 60% [0.4DBP steps per fiber span, step-size of 205km] and (c) maximum transmission reach is improved by 15-18%. The inclusive results depict promising performance of DP-QDB for reducing the complexity of DBP algorithm.

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