BENEFITS AND LIMITS OF MODULATION FORMATS FOR OPTICAL COMMUNICATIONS

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Abstract. *This paper is focused on benefits and limits of intensity and phase modulation formats used in optical communications. The simulation results are obtained using OptSim software environment, employing Time Domain Split Step method. Non-Return to Zero, Return to Zero, Chirped Return to Zero and Carrier-Suppressed Return to Zero formats are compared in terms of Bit Error Rate and spectral efficiency to find the limits for selected transmission network topologies. It is shown that phase modulation formats offer many advantages compared to intensity formats. Differential Phase-Shift Keying and mainly Differential Quadrature Phase-Shift Keying improve the Bit Error Rate and transmission reach, among others. A promising solution is the application of Polarization Division Multiplexing Quadrature Phase-Shift Keying, which primarily benefits in spectral efficiency, estimated reach, optical signal to noise ratio and chromatic dispersion tolerances.*

Keywords

BER, CRZ, CSRZ, DPSK, DQPSK, Duobinary, eye diagram, modulation formats, NRZ, OptSim, PDM-QPSK, Q-factor, RZ.

1. Introduction

The upgrade of fiber optic telecommunication systems to higher bit rates very often requires solving the impact of polarization mode dispersion and nonlinear effects, such as Four Wave Mixing (FWM), that can significantly affect transmission at 10 Gb·s^{-1} speeds and higher. For transmission rates higher than 40 Gb·s^{-1} per channel, the use of more advanced formats is necessary and the design of new modulations is expected. This requires detailed knowledge on performance efficiency of modulation formats, as well as the clear specification of shortcomings to be solved while proposing new solutions.

This paper investigates modulation formats in OptSim software environment (version 5.2) from the perspective of the Bit Error Rate (BER), Q-factor and physical reach to find their main advantages, and the performance limits. The transmission schemes for high-density optical systems operating at 40 and 100 Gb·s^{-1} wavelength channels can use phase modulation combined with Polarization Division Multiplexing (PDM), coherent detection and digital signal processing [1], [2]. PDM halves the symbol rate, which enables usage of higher bit rates, cheaper components and fitting into a proper channel grid at the cost of an increased transceiver complexity [1], [3]. It has been shown that PDM Quadrature Phase-Shift Keying (PDM-QPSK) format is very promising for high fiber reaches and huge data flows. For this reason, the model of this modulation format has been developed.

2. State of the Art

2.1. Intensity Modulation Formats

This paper, among others, deals with binary intensity formats due to the significant back-to-back receiver sensitivity penalty of multilevel intensity formats [4], [5]. Although a certain combination of Amplitude Shift Keying (ASK) and phase modulations (e.g. RZ-DPSK-3ASK format) [1] have advantages, the limited extinction ratios of the ASK modulated levels limits the Optical Signal-to-Noise Ratio (OSNR) tolerance of the format.

The two most common intensity modulations are Non Return to Zero (NRZ) and Return to Zero (RZ). Conventional NRZ format has been widely implemented, mainly because of its signal bandwidth and its relatively easy generation. We compare and discuss features of these formats together with other binary intensity formats such as: Chirped Return to Zero (CRZ) and the most widespread pseudo-multilevel format: Carrier-Suppressed Return to Zero (CSRZ), which could be an optimal solution for high speed transmission systems [4].

Duobinary (DB) format represents correlative coding, a subclass of which is known as partial-response signaling. The main benefit of the DB format is its high tolerance to Chromatic Dispersion (CD) and narrow-band optical filtering [4]. The main goal of using this format at 10 Gb$\cdot$s^{-1} is to increase the dispersion tolerance, whereas at 40 Gb$\cdot$s^{-1} it is to achieve high spectral efficiency in Wavelength Division Multiplexing (WDM) systems. Nevertheless, the immunity of DB to nonlinear effects at 40 Gb$\cdot$s^{-1} does not differ much from similar duty cycle On/Off Keying (OOK). In section 3.3, we compare DB to OOK to find which of the formats performs better for a selected network topology. A further discussion and comparison of DB and Phase-Shaped Binary Transmission with respect to transmission impairments at 40 Gb$\cdot$s^{-1} can be found in reference [6].

2.2. Phase Modulation Formats

Phase-based modulation formats provide higher spectral efficiency and better OSNR tolerances meanwhile increasing the complexity of a transceiver. The main advantage of Differential Binary Phase-Shift Keying (DBPSK or simply DPSK) over OOK is a 3 dB receiver sensitivity improvement [4]. Although the resistance of DPSK and CSRZ formats to fiber nonlinearities may be similar, the improved sensitivity of DPSK receivers generally results in a better overall system performance. Detectors for DPSK signals are also more complex as they must convert the phase difference into an intensity signal which can be converted into an electrical signal by photo detectors. In section 3.4, we compare the NRZ and RZ variants of DPSK to find which of them offers better results in terms of BER and Q-factor for a selected topology.

Knowing how to eliminate shortcomings of two-level formats, it is suitable to investigate models of multilevel formats. Differential Quadrature Phase-Shift Keying (DQPSK) is a multilevel format that has received appreciable attention. Leaving aside aspects of the transceiver design, DQPSK is an appropriate solution to achieve narrow signal spectra. At the same bit rate, DQPSK is more robust to Polarization Mode Dispersion due to its longer symbol duration, while comparing it with binary formats [4]. Its spectrum shape is similar to that of DPSK; however its compression in frequency enabled DQPSK to achieve higher spectral efficiency and increased tolerance to CD [4]. Similarly as for DPSK, we compare the NRZ and RZ variants of DQPSK, again in terms of BER and Q-factor.

2.3. Advanced Modulation Formats

PDM-QPSK has been widely differently denoted either by polarization division multiplexing, polarization multiplexing, dual polarization or orthogonal polarization [1]. Its transmitter is the same as in PDM-DQPSK. Innovation in PDM-QPSK stands for the employment of a coherent receiver. The use of digital signal processing simplifies the receiver design although a large number of components is required, as well as low-linewidth lasers [7]. Despite the fact that other formats have been designed and some of them are already commercially available, such as PM-OFDM-QPSK; PDM-QPSK proves to perform better at 100 Gb$\cdot$s^{-1} and at greater reaches, with respect to estimated reach, spectral efficiency, OSNR, CD and differential group delay tolerances [1].

In PDM, two optical signals are coupled to two orthogonal polarizations being mutually delayed by a symbol period to improve OSNR. The two delayed lines: a coupled resonator and a photonic crystal waveguide are compared by using PDM transmission in the study by F. Morichetti et al [8]. PDM can also double transmission capacity of other modulation formats. The PDM has been applied experimentally by L. Cheng et al. to increase 8 DQPSK channels with 200 GHz DWDM grid from 100 Gb$\cdot$s^{-1} to 200 Gb$\cdot$s^{-1} [9]. Data were transmitted through a 1200 km long link with completely compensated chromatic dispersion. However, in their experiment, an automatic polarization control was not implemented and proper polarization should be set every ten minutes manually. In section 3.5, we investigate this modulation format at 100 Gb$\cdot$s^{-1} in a 2400 km long transmission system.

3. Methods

Simulations are performed in OptSim environment using the Time Domain Split Step (TDSS) method. Simulation results are performed on the created models of modulation formats, incorporated into a model of an optical transmission system, with respect to the eye diagram, BER, OSNR and Q-factor.

3.1. Time Domain Split Step Method

OptSim employs the TDSS method to realize the signal distribution equation in a fiber. The method is based on the following formula [10]:

$$\frac{\partial A(t,z)}{\partial z} = (L+N)\cdot A(t,z), \tag{1}$$

where A(t,z) is the complex envelope, L is the operator which describes linear effects and N describes the impact of non-linear phenomena on the signal propagation. The Split-Step algorithm applies L and N operators to calculate $A(t,z)$ over small fiber spans ∂z separately. The TDSS algorithm calculates L in the time domain by applying convolution in sampled time [10]:

$$TDSS \rightarrow AL\left[n\right] = A\left[n\right] * h\left[n\right] = \\ = \sum_{k=-\infty}^{\infty} A\left[k\right] \cdot h\left[n-k\right], \tag{2}$$

where h is the impulse response of a linear operator L.

3.2. Monitors

1) Eye Diagram

The eye diagram is a graphical representation of signals, in which many cycles of the signal are superimposed on top of each other. The amount of noise, jitter and inter-symbol interference (ISI) of an optical signal can be judged from its appearance [11], as illustrated in Fig. 1. Less noise makes the eye diagram look “smoother”, since there is less distortion of a signal. The larger the size of the eye opening is, the lower the error rate will be [12].

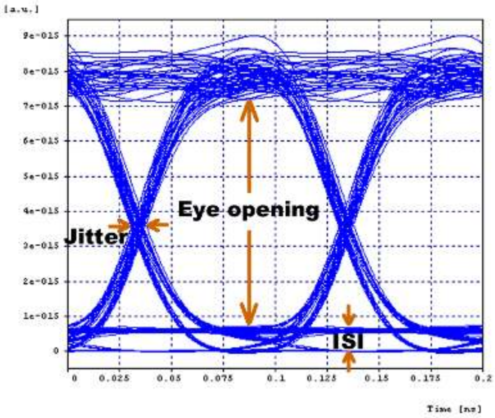

Fig. 1: Sample eye diagram showing jitter and representing error rate by its opening.

2) Bit Error Rate

BER specifies the ratio of bit errors to the total number of transmitted bits. Therefore, a lower BER indicates a better performance. BER is affected by attenuation, noise, dispersion, crosstalk between adjacent channels, nonlinear phenomena, jitter or by bit synchronization problems. Its performance may be improved by launching a strong signal into a transmission system unless this causes cross-talk and more errors; by choosing a robust modulation format, or finally by applying channel coding schemes, among others.

3) Optical Signal to Noise Ratio and Q Factor

OSNR is obtained as the ratio of the net signal power to the net noise power. The predominant source for its degradation is noise inserted by optical amplifiers. Q-factor is another important parameter, which is used in this paper for the evaluation of simulations. It can be expressed, as follows [12]:

$$Q\left[-\right] = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}, \tag{3}$$

where μ_0, μ_1 are the mean log.0, log.1 level values, and σ_0, σ_1 are the corresponding standard deviations. Q-factor specifies the minimum required OSNR to obtain a certain value of BER. The mathematical relation between Q-factor and BER is given by the following equation [12]:

$$BER\left[-\right] = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right). \tag{4}$$

In general, the BER decreases as the Q-factor increases. For a Q-factor ranging from 6 to 7, the BER is obtained as of 10^{-9} up to 10^{-12}.

3.3. Intensity Modulation Formats Models

1) Non Return to Zero, Return to Zero, Chirped and Carrier-Suppressed Return to Zero

In the following simulation scheme, we compare NRZ, RZ, CRZ and CSRZ formats in a selected 10 Gb·s^{-1} transmission system. We assume a possible tree topology solution of a Passive Optical Network (PON), shown in Fig. 2.

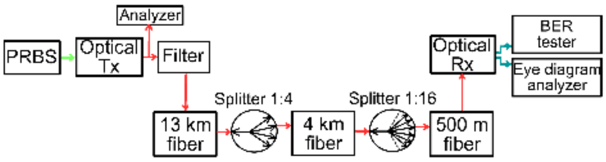

Fig. 2: Topology used for modeled modulation formats.

In the optical distribution network, we use three standard single-mode fibers (SSMF) with the lengths of 13 km, 4 km and 500 m respectively, each with 0.25 dB·km^{-1} loss. SSMFs are separated by two splitters with ratio 1:4 and 1:16. The output power level of the transmitters is set to 0 dBm. For filtering purposes, theraised cosine filter with a 2 dB loss and the center wavelength at the operating wavelength of this system (i.e. 1550 nm) is placed after the transmitter. In CRZ, a chirp is added to the RZ optical signal by applying a phase modulation. In the case of CSRZ, the RZ optical signal enters to a phase modulator, driven by a sine wave generator at frequency half of the bit rate. As a result, any two adjacent bits will have a π phase shift and the central peak at the carrier frequency is suppressed. The results from simulations are discussed in section 4.1.

2) Duobinary Modulation Format

The aim of the next simulation scheme is to compare DB with OOK. For this purpose, a 10 Gb·s^{-1} passive optical network is implemented as illustrated in Fig. 3.

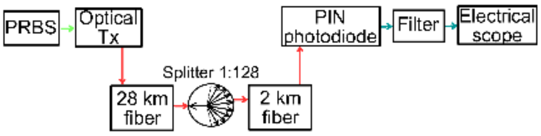

Fig. 3: Simulation scheme for DB modulation.

We consider another possible tree topology solution of a PON. The power level of lasers in each transmitter is set to -3 dBm. Modulated signals are launched over a 28 km long SSMF with 0.25 dB·km^{-1} loss, which is followed by a splitter with splitting ratio 1:128, and another SSMF with the length of 2 km. The receiver consists of a PIN photodiode, an electrical filter and electrical scope for measurement purposes. In this scenario, we compare DB's error performance with that of NRZ and CSRZ, which were chosen based on the results from the simulation described in the previous section. The DB transmitter is realized by driving an amplitude dual-arm Mach Zehnder (MZ) modulator with opposite phase signals [13]. The achieved simulation results are discussed in section 4.2.

3.4. Phase Modulation Formats Models

1) Non Return to Zero Differential Phase-Shift Keying and Return to Zero Differential Phase-Shift Keying modulation formats

Other investigated formats are NRZ-DPSK and RZ-DPSK, both evaluated in terms of BER and Q-factor for another 10 Gb·s^{-1} selected PON topology with physical reach 20 km and 32 subscribers, as illustrated in Fig. 4. The essential difference between DPSK and RZ-DPSK simulations stands in the transmitter's configuration. RZ-DPSK modulated pulses can also be created by using an MZ modulator instead of a phase modulator as done in our assumed scenario [4]. Modulated optical signals travel through a 19 km SSMF with 0.25 dB·km^{-1} loss and optical splitter 1:32, followed by a second SSMF of length 1 km. Signals are demodulated by the Mach-Zehnder Delay Interferometer (MZDI) (block I in Fig. 4) [13] whose differential time delay is set to the bit duration, i.e. 100 ps. Both output interfaces of the MZDI, i.e. the "constructive", (in which there is no phase change between adjacent bits), and "destructive" port (phase change is π), are connected to a balanced receiver (block II in Fig. 4), which primarily consists of two receivers for these two signal parts. The electrical signal from one of the receivers is inverted and subsequently both electrical signals are added together as shown in Fig. 4. The results are presented in section 4.3.

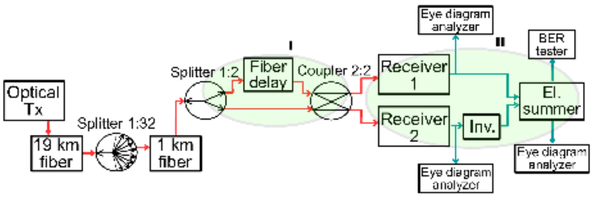

Fig. 4: Simulation scheme for the DPSK modulation format.

2) Non Return to Zero Differential Quadrature Phase-Shift Keying and Return to Zero Differential Quadrature Phase-Shift Keying

Similarly as for DPSK (previous section), in the following simulation schemes we investigate the NRZ-DQPSK and RZ-DQPSK formats in terms of the error performance for a 10 Gb·s^{-1} transmission system. In orded to simplify, a 150 km long SSMF with 0.2 dB·km^{-1} loss is used. Two 5 Gb·s^{-1} data sources are encoded to generate appropriate in-phase (I) and quadrature (Q) modulation signals, as shown in Fig. 5.

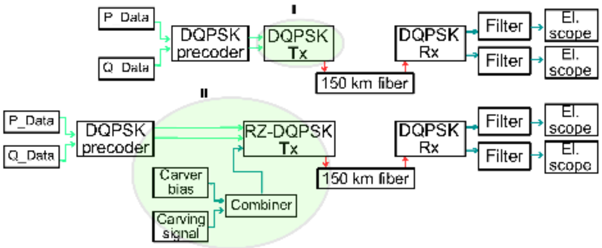

Fig. 5: NRZ-DQPSK and RZ-DPQSK simulation schemes.

The power level of lasers in each transmitter is set to -10 dBm. In RZ-DQPSK, the carving signal varies in the range [V_{off} : $V_{off} + V_{\pi}$] (Fig. 5, block II). The receiver in both schemes is implemented in an explicit form by applying two 2DPSK receivers to obtain both I and Q components [13]. The results are given in section 4.4.

3.5. Polarization Division Multiplexing Quadrature Phase-Shift Keying

PDM-QPSK is a very promising modulation format especially in networks operating at 100 Gb·s^{-1} wavelength channels. For this purpose, we investigate the limit of the PDM-QPSK format in terms of error performance for a 100 Gb·s^{-1} transmission system operating at 193 THz, including a 7 % of Forward Error Correction (FEC) overhead. Four data sources are used to generating a single PDM-QPSK signal. The PDM-QPSK modulated signals travel through a 2400 km transmission system, composed of twenty-four non-zero dispersion shifted fibers (e.g. LEAF) with the loss of 0.2 dB·km^{-1} and chromatic dispersion being around 4 ps·nm^{-1}·km^{-1} at the considered band, as schematically shown in Fig. 6. Each of the fiber spans is 100 km long and is separated from one another by inline optical amplifiers (OA) with the fixed gain of 20 dB.

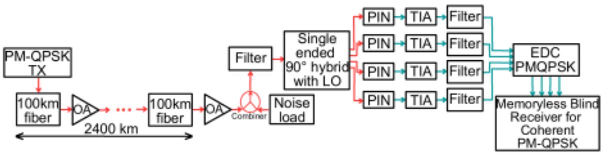

Fig. 6: PDM-QPSK simulation scheme.

Signals are noise loaded to extract the received BER as a function of OSNR [3]. At the receiver, a single ended 90 ° hybrid with the local oscillator and four PIN photodiodes in its four output interfaces enable the coherent detection. Signals further travel through trans-impedance amplifiers, electrical filters and subsequently through an ideal electronic dispersion compensator, which applies the same compensation on all signals. The final component in the PDM-QPSK receiver consists of a memoryless "blind" receiver, which separates orthogonal polarizations as well as in-phase and quadrature signals by applying the Constant Modulus and Viterbi & Viterbi algorithms [13]. The simulation results are given in section 4.5.

4. Results

4.1. Comparison of Non Return to Zero, Return to Zero, Chirped and Carrier-Suppressed Return to Zero

In this section, we discuss the simulation results referring to the scheme shown in Fig. 2 (section 3.3, part 1). The optical spectra of NRZ, RZ, CRZ and CSRZ formats are presented in Fig. 7.

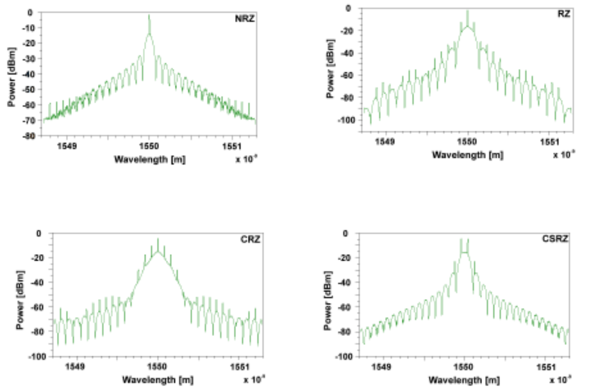

Fig. 7: Transmitter's optical spectra for the modulations: NRZ (top left), RZ (top right), CRZ (bottom left), and CSRZ (bottom right).

In NRZ, the local maxima of power can be observed at multiples of the bit rate [14]. The format exhibits a narrower main lobe than other investigated formats. However, this feature doesn't mean NRZ is more resistant to Cross-Phase Modulation (XPM) and FWM in Dense WDM systems, making it not the best choice for high-capacity optical systems [15]. In CRZ, phase varies within the time span of each pulse and its spectrum gets significantly broader (Fig. 7). Although the chirp can be used to suppress dispersion, it generally increases cross-talk penalty and deteriorate the overall performance. CSRZ's carrier suppression helps to reduce the interference between adjacent pulses and thus to improve the overall signal quality [14], resulting in a less distorted eye diagram (Fig. 8).

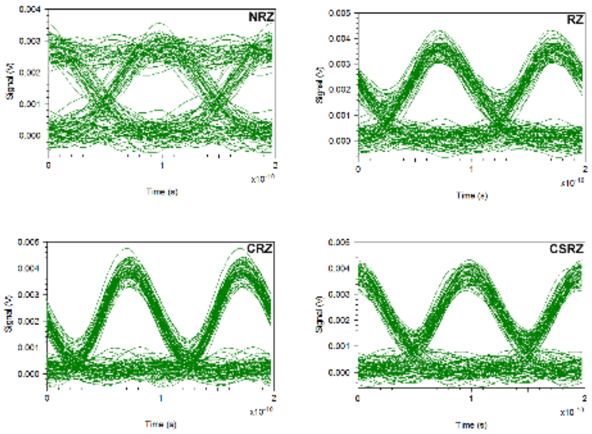

Fig. 8: Eye diagrams for NRZ, RZ, CRZ and CSRZ.

Table 1 summarizes the numerical results from this simulation. The obtained BER values and their corresponding Q-factors give a better performance characterization of these formats.

The results showed that CSRZ offers the lowest BER, mainly due to its carrier suppression. It can also

Tab. 1: Simulation results for NRZ, RZ, CRZ and CSRZ.

Modulation format	BER [-]	Q [-]
NRZ	$1.12{\cdot}10^{-6}$	4.73
RZ	$2.80{\cdot}10^{-9}$	5.83
CRZ	$6.10{\cdot}10^{-11}$	6.44
CSRZ	$4.02{\cdot}10^{-11}$	6.50

be concluded that conventional NRZ offers the worst BER and Q-factor.

4.2. Comparison of Non Return to Zero, Carrier-Suppressed Return to Zero and Duobinary modulation formats

The simulation results in section 4.1 show that CSRZ offers the lowest BER for the modeled PON topology, meanwhile NRZ the highest one. For such a reason, these two formats were chosen in the simulation scheme described in section 3.3 part 2 for comparison purpose with the DB format. The numerical results are presented in the following table.

Tab. 2: Simulation results for NRZ, CSRZ and DB.

Modulation format	BER [-]	Q [-]
NRZ	$1.29{\cdot}10^{-11}$	6.65
CSRZ	$3.27{\cdot}10^{-21}$	9.39
DB	$1.46{\cdot}10^{-16}$	8.37

The eye diagram of NRZ was found to be again the most distorted compared to CSRZ and DB. This results in a higher error rate in receiver's side as can be seen from BER and Q-factor values of NRZ, given in Tab. 2. According to these results, it can also be concluded that CSRZ offers the lowest BER value again.

4.3. Non Return to Zero Differential Phase-Shift Keying and Return to Zero Differential Phase-Shift Keying

The following results concern comparison of NRZ-DPSK and RZ-DPSK formats (section 3.4, part 1). The aim of the simulation is to figure out which of these two modulation formats performs better in terms of BER and Q-factor. Tab. 3 summarizes the obtained numerical results.

Tab. 3: Comparison of BER and Q-factor in NRZ-DPSK and RZ-DPSK.

Modulation format	BER [-]	Q [-]
NRZ-DPSK	$3.81{\cdot}10^{-7}$	4.95
RZ-DPSK	$9.65{\cdot}10^{-13}$	7.04

The eye diagram of RZ-DPSK was found to be less distorted than for NRZ-DPSK. The BER value we obtained from NRZ-DPSK is high, making it not a proper solution for the assumed scenario. On the other hand, RZ-DPSK enables a transmission with a lower BER.

4.4. Non Return to Zero Differential Quadrature Phase-Shift Keying and Return to Zero Differential Quadrature Phase-Shift Keying

Simulation schemes for comparison of NRZ-DQPSK and RZ-DQPSK in terms of BER and Q-factor were described in section 3.4 part 2. Eye diagrams for both formats are measured at the receiver by using electrical scopes for both in-phase and quadrature components. The following table summarizes the obtained results.

Tab. 4: Comparison of BER and Q-factor in NRZ-DQPSK and RZ-DQPSK.

Modulation format		BER [-]	Q [-]
NRZ-DQPSK	In-phase	$3.12{\cdot}10^{-11}$	6.67
	Quadrature	$2.81{\cdot}10^{-11}$	6.65
RZ-DQPSK	In-phase	$2.09{\cdot}10^{-28}$	11.30
	Quadrature	$1.39{\cdot}10^{-31}$	11.74

It can be noticed from Tab. 4 that RZ-DQPSK offers a much lower BER, and higher Q-factor respectively. As a result, this format can enable a longer physical reach for a certain BER value compared to NRZ-DQPSK.

4.5. Polarization Division Multiplexing Quadrature Phase-Shift Keying

The following numerical results concern simulation of PDM-QPSK, described in section 3.5. Table 5 shows that the resulting pre-FEC BER value measured by the PDM-QPSK receiver is on the order of 10–5. This proves the suitability of this modulation format for such a long-distance transmission system.

Tab. 5: Simulation results for PDM-QPSK.

PDM-QPSK	Signal 1	Signal 2	Signal 3	Signal 4	Total
pre-FEC BER ($\cdot 10^{-5}$ [-])	3.05	3.05	1.53	15.26	5.72

The advantage of polarization formats has its source in slower accumulation of attenuation and dispersion influence because on the contrary to multilevel phase modulations, the performance is not increased by adding new states being closer and closer to each other, but by considering another polarization.

5. Conclusion

The CSRZ format proves to perform better than other investigated intensity modulation formats, mainly due to its carrier suppression that reduces the interference between adjacent pulses. On the other hand, it was shown that phase-based modulation formats, especially RZ-DQPSK due to its narrower optical spectrum, enable longer reaches among others. The most promising modulation is PDM-QPSK, which is developed for advanced transmission systems operating at 100 Gb·s^{-1} per channel. This format benefits from the combination of phase modulation with PDM, coherent detection and digital signal processing. PDM-QPSK was successfully simulated for a 2400 km long transmission system, operating at 100 Gb·s^{-1}. Significant improvements in terms of optical reach have been depicted, which was the main reason of gradually increasing the fiber length, or the splitting ratio respectively. The comparison is interesting especially when getting closer to the performance limits of the modulation formats. Frequency modulations show their benefits when increasing the bit rate per channel, as well as the overall transmission capacity, on the other hand, PDM-QPSK shows a huge progress when increasing the reach, while at short reaches it doesn't perform much better that the other formats. A future research would be focused on other advanced modulation formats and for higher transmission rates, since they open a large space for further improvements and proposals of new modulation formats.

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