Chapter 2
DQPSK Optical Networks Impaired by Multi Line Rates and Mixed Modulation Formats Interferers

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Abstract Future metropolitan optical networks face the challenge of having signals with different modulation formats and different bit rates coexisting in the network. The interference between those signals, and mainly from signals at the same wavelength, named in-band crosstalk, may lead to severe network performance degradation. In this work, the performance of 40 Gb/s DQPSK optical receivers impaired by in-band crosstalk due to mixed modulation formats and multiple line rates is assessed. It is shown that the most severe performance degradation due to in-band crosstalk is caused by 10 Gb/s interferers, being the OOK interferer the most detrimental to the network performance. We show also that the reduction of the duty-cycle of the interferers increases the DQPSK optical receiver tolerance to in-band crosstalk.

2.1 Introduction

Nowadays, optical networks have the capability of transporting signals with multiple modulation formats and a multitude of bit rates, in order to support the growing traffic capacity demands. The actual trend is to further increase the number

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of different formats and bit rates that coexist in the network [9, 15]. The main reason for this increase is the widespread use of coherent technology and the flexibilisation of the 50 GHz optical grid—the so called flexgrid [11]. Nevertheless, this technology, that allows the use of advanced modulation formats with greater spectral efficiency and increased signal bit rate, is mostly used in long-haul networks [14]. On the other hand, optical metropolitan area networks (MANs) are still based in intensity modulation direct detection systems, because of their simplicity and low power consumption characteristics. The typical signals coexisting in these metro networks are the 10 Gb/s OOK (On-Off Keying) and DPSK (Differential Phase-Shift Keying) signals, and the 40 Gb/s DPSK and DQPSK (Differential Quadrature Phase-Shift Keying) signals.

The physical constraints of optical MANs are an important issue in network planning and performance evaluation. In particular, in-band crosstalk is considered an important physical limitation [8]. The impact of this phenomenon has been intensively studied in direct detection systems. In the majority of these studies, it is assumed that the crosstalk signals have the same bit rate and modulation format than the selected signal. Examples of these studies for OOK, DPSK and DQPSK signals are, respectively, given in [1, 2, 10]. There are also a few studies which consider that the selected signal has a different bit rate and modulation format than the crosstalk signals [3, 5]. In [3], an analytical formalism is used to evaluate the impact of a single OOK interferer in a DPSK system, and in [5] the impact of a single OOK/DPSK/DQPSK interferer in a DPSK system is evaluated in an experimental and simulation setup.

In this work, we extend these studies and evaluate the impact of in-band crosstalk due to 10/40 Gb/s OOK/DPSK/DQPSK multiple interferers on the performance of 40 Gb/s DQPSK optical receivers. The crosstalk impact is evaluated by Monte Carlo (MC) simulation, and an analytical formalism based on the moment generating function [2] is used to validate the MC simulation for the single interferer scenario. The impact of the extinction ratio of OOK signals and the impact of the crosstalk signal duty cycle on the receiver performance are also assessed.

This paper is structured as follows. Section 2.2 describes the simulation model to assess the impact of multi-format interferers in a DQPSK receiver. Numerical results are discussed in Sect. 2.3 and conclusions are presented in Sect. 2.4.

2.2 System Description

In this section, the model used to characterise the DQPSK optical receiver is described. The implementation of the MC simulator used to assess the performance of the optical receiver when impaired by in-band crosstalk is also presented.

2.2.1 Optical DQPSK Receiver

The structure of a typical differential direct detection DQPSK receiver is depicted in Fig. 2.1, [6]. It consists of an optical pre-amplifier with a constant power gain G over the amplifier bandwidth; an optical filter with −3 dB bandwidth B_o; and a −3 dB coupler to split the signal between the two branches of the optical receiver. Each branch of the optical receiver consists of a delay line interferometer with a differential delay equal to the symbol period T_s; a balanced photodetector; and a post-detection electrical filter with −3 dB bandwidth B_e. In the lower branch (Q), the arms of the interferometer have a phase difference of π/4, while in the upper branch (I), the interferometers arms phase difference is −π/4 [6]. Throughout this work, the possible imperfections of the optical DQPSK receiver are neglected.

The electrical field at the optical filter output, $\vec{E}(t)$, can be expressed as [2]

$$\vec{E}(t) = \left[\sqrt{G}\cdot\vec{E}_s(t) + \sqrt{G}\cdot\sum_{i=1}^{M}\vec{E}_{c,i}(t) + \vec{E}_{ASE}(t)\right] * h_o(t) \qquad (2.1)$$

where * stands for convolution and $h_o(t)$ is the impulse response of the optical filter. The first term of (2.1), $\vec{E}_s(t)$, corresponds to the electrical field of the incoming DQPSK signal, named selected signal and is described as $\vec{E}_s(t) = \sqrt{P_s}\ \exp[j\theta_s(t)]\vec{e}_s$, where P_s is the average signal power at the optical pre-amplifier input; $\theta_s(t)$ is the signal phase that carries the DQPSK symbol information, with possible values $\{\pi/4, 3\pi/4, -3\pi/4, -\pi/4\}$; and $\vec{e}_s$ is the signal polarization unit vector.

The second term of (2.1), $\sum_{i=1}^{M}\vec{E}_{c,i}(t)$, corresponds to the electrical field of the in-band crosstalk, with M possible interferers. The complex envelope of the ith crosstalk signal field can be represented as

$$\vec{E}_{c,i}(t) = \sqrt{P_{c,i}}A_{c,i}\left(t+\Delta\tau_{c,i}\right)\cdot\exp\left[j\left(\theta_{c,i}(t+\Delta\tau_{c,i})+\Delta\phi_{c,i}\right)\right]\vec{e}_c \qquad (2.2)$$

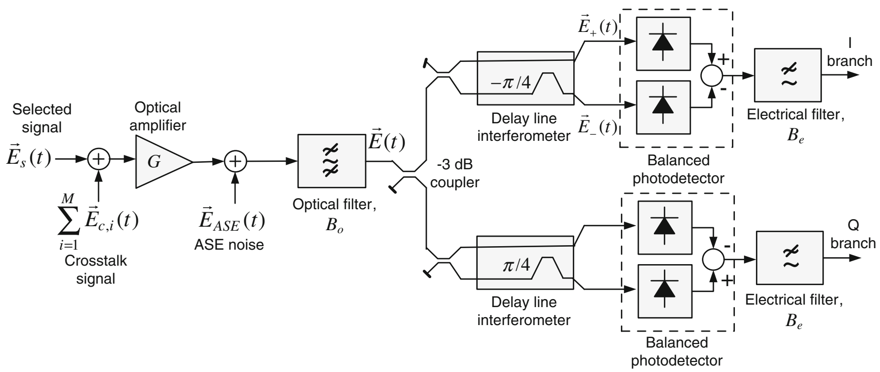

Fig. 2.1 Block diagram of the DQPSK optical receiver

where $P_{c,i}$ is the crosstalk power. The crosstalk level of the ith interferer is defined as the ratio between the crosstalk power, $P_{c,i}$, and the signal power, P_s. The total crosstalk level is the sum of the crosstalk levels of the M interferers. In (2.2), $\Delta\tau_{c,i}$ is a random time shift within one symbol period, which is modelled considering a uniform distribution over that period [13]; $\Delta\phi_{c,i}$ is a random phase difference with respect to the selected signal, which is modelled considering a uniform distribution over the interval [0, 2π[[13]; $\vec{e}_c$ is the crosstalk signal polarisation unit vector, which as a worst-case assumption is assumed co-polarised with the selected signal, $\vec{e}_s = \vec{e}_c$; $A_{c,i}(t)$ and $\theta_{c,i}(t)$ are, respectively, the envelope and the phase of the crosstalk signal, which define the modulation format of the ith interferer. The modulation formats and bit rates of the crosstalk signal considered in this work are 10 Gb/s OOK, 10 Gb/s DPSK, 40 Gb/s OOK, 40 Gb/s DPSK and 40 Gb/s DQPSK. The extinction ratio of the OOK crosstalk signals is defined as $r = P_1/P_0$, with P_1 defining the average power of the bits '1' and P_0 the average power of the bits '0'. The duty-cycle of RZ (Return-to-Zero) pulses, D, is defined as the fraction of time that a rectangular pulse lasts within a symbol period, before it returns to zero.

The third term of (2.1), $\vec{E}_{ASE}(t)$, corresponds to the complex envelope of the electrical field of the amplified spontaneous emission (ASE) noise originated at the optical pre-amplifier. The ASE noise is assumed as a zero mean white stationary Gaussian noise with single-sided power spectral density in each polarisation described by $N_o = h\nu_s GF/2$, where $h\nu_s$ is the photon energy at the signal wavelength, and F is the pre-amplifier noise figure.

The −3 dB couplers and delay interferometers are modelled as in [12]. For the I branch, the electrical fields $\vec{E}_+(t)$ and $\vec{E}_-(t)$ are described by

$$\begin{bmatrix} \vec{E}_+(t) \\ \vec{E}_-(t) \end{bmatrix} = \frac{1}{2\sqrt{2}} \begin{bmatrix} j\vec{E}(t) + j\vec{E}(t - T_s) \cdot \exp(-j\pi/4) \\ -\vec{E}(t) + \vec{E}(t - T_s) \cdot \exp(-j\pi/4) \end{bmatrix} \tag{2.3}$$

Using the same model described in [12], the electrical fields after the delay line interferometer of the Q-branch of the optical receiver can be readily calculated. The photodetectors are modelled as ideal square-law detectors.

2.2.2 Monte Carlo Simulation

In the MC simulation, a sequence of bits of length N_b corresponding to the information carried by the DQPSK selected signal is generated using deBruijn sequences [7]. The differential encoding and conversion to quaternary symbols with Gray coding follows [4, 6]. Then, the sequence of symbols is discretized in N_a samples per symbol, which allows considering the signal waveform within a symbol period [for example, non-RZ (NRZ) or RZ pulses]. Hence, the effect of intersymbol interference on the performance of the DQPSK optical receiver can be rigorously evaluated on the MC simulation.

In the simulator, the ASE noise is generated using a random number generator, which follows a Gaussian distribution with zero mean and variance of $N_o \cdot B_{sim}$, where B_{sim} is the bandwidth used in the MC simulation. In each iteration of the simulation, a sample function of the ASE noise is generated [7].

At that same iteration, a sample function of the crosstalk signal is also constructed. Each ith crosstalk signal is generated considering a random sequence of bits, which are, then modulated. The same modulation format is considered for all ith crosstalk signals.

After the generation of selected signal, crosstalk signal and ASE noise sample functions, the electrical field given in (2.1) is obtained and is propagated through the DQPSK optical receiver depicted in Fig. 2.1. The current at the output of the I branch and Q branch is, then, determined and sampled at the time instants corresponding to the maximum eye-opening obtained without noise and crosstalk. After sampling, each received bit in its respective branch, which is corrupted by noise and crosstalk, is compared to the corresponding transmitted bit to find out if an error has occurred. The bit error probability (BEP) is, then, calculated from [4]

$$BEP = \frac{BEP_I + BEP_Q}{2} \tag{2.4}$$

where BEP_I and BEP_Q are the bit error probabilities, respectively, of the I and Q branches, which are estimated through direct error counting using

$$BEP_I = \frac{N_{E,I}}{N_{it} \cdot N_b/2} \tag{2.5}$$

$$BEP_Q = \frac{N_{E,Q}}{N_{it} \cdot N_b/2} \tag{2.6}$$

where N_{it} is the number of iterations of the MC simulation, which is equivalent to the number of simulated sample functions and $N_{E,I}$ and $N_{E,Q}$ are the number of counted errors, respectively, in the I and Q branches of the receiver. A specific number of counted errors is set as a stopping criterion of the MC simulation.

2.3 Numerical Results

In this section, the impact of multi-format and multi-rate crosstalk signals on the performance of 40 Gb/s DQPSK pre-amplified optical receivers is evaluated using MC simulation. The duty-cycle variation of the crosstalk signals, the extinction ratio variation of OOK crosstalk signals and single and multiple interference are considered in these studies.

Throughout this section, the amplifier noise figure, F, is 5 dB, the pre-amplifier gain, G, is 30 dB, and both ASE noise polarisations are considered. The optical filter is a Gaussian filter with normalized −3 dB bandwidth given by $B_o T_s = 5$. The electrical filter is a Gaussian filter with normalized −3 dB bandwidth given by $B_e T_s = 0.7$. The optical signal-to-noise ratio (OSNR) is measured in the reference bandwidth of 0.1 nm at λ_s = 1550 nm. The total crosstalk level considered for the interferers is −13 dB, for all data rates and modulation formats. This means that the power corresponding to the sum of powers of each individual interferer is −13 dB below the original DQPSK signal power. We also assume that the power is equally distributed by the interferers. The modulation formats of the crosstalk signal considered are 10 Gb/s OOK, 10 Gb/s DPSK, 40 Gb/s OOK, 40 Gb/s DPSK and 40 Gb/s DQPSK. The bit rate of the selected DQPSK signal is 40 Gb/s. The number of simulated bits is $N_b = 2^7$, N_a = 128 samples per symbol and B_{sim} = 5.1 THz are used. The BEP is estimated using MC simulation considering at least $N_{E,I}$ = 1000 or $N_{E,Q}$ = 1000 counted errors. This high number of counted errors, in comparison with the typical 100 errors used in MC simulation [7], has been set to obtain BEP curves with a very smooth behavior.

2.3.1 *Single and Multiple Interference in Multi-rate and Multi-format Scenarios*

In this subsection, the impact of multi-rate and multi-format crosstalk signals on the selected DQPSK signal is evaluated. The pulse shape of all modulation formats is NRZ and the extinction ratio of the OOK interferers is ideal, $r = \infty$. The influence of the random time shift $\Delta\tau_{c,i}$ is neglected, since it has been verified that its influence on the receiver performance is minor, when considering NRZ pulse shapes.

Figure 2.2 shows the BEP as a function of the OSNR, for a single interferer, M = 1, with different modulation formats and bit rates on the crosstalk signal. The BEP obtained without crosstalk is also depicted in Fig. 2.2 for comparison purposes. To check the MC simulation results, the BEP is also computed using the analytical formalism (A) proposed in [2], considering the absence of crosstalk and a 40 Gb/s DQPSK crosstalk signal. This analytical formalism is capable of assessing in a rigorous way the impact of in-band crosstalk in DQPSK receivers independently of the optical and electrical filter shapes, considering the isolated DQPSK symbol scenario. This formulation was first developed in [10] for analysing the impact of in-band crosstalk in DPSK receivers and uses an eigenfunction expansion technique to decompose signal, crosstalk, and ASE noise, at the optical filter input, in a series of orthogonal functions and relies on the moment generating function to

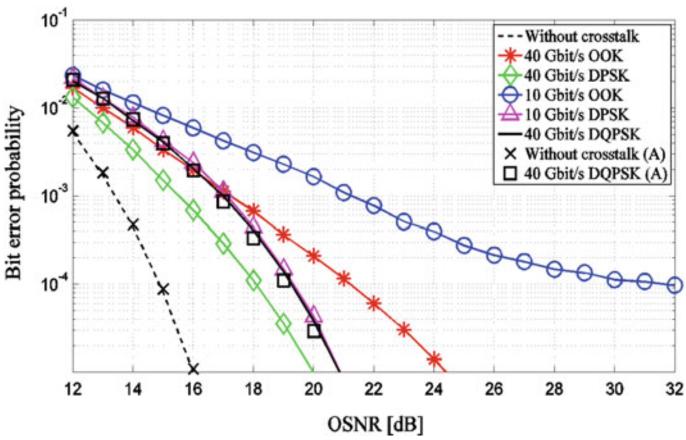

Fig. 2.2 BEP as a function of the OSNR for a single interferer, M = 1 and different modulation formats and bit rates on the crosstalk signal

describe the decision variable statistics. From Fig. 2.2, a good agreement between simulation and analytical results is observed.

Figure 2.2 shows that the 10 Gb/s OOK crosstalk signal leads to the most severe interference on the 40 Gb/s DQPSK optical receiver. For very high OSNR, the BEP is reaching a floor. The 40 Gb/s OOK interferer leads to the second worst BEP degradation, especially for OSNRs above 17 dB, where the signal-crosstalk beating power is becoming significant. The 40 Gbs DQPSK and 10 Gb/s DPSK crosstalk signals provide similar performances, while the less harmful interferer is the 40 Gb/s DPSK. As a main conclusion, the interference of amplitude modulated signals leads to higher BEP degradation than phase-modulated signals interference. This conclusion is in agreement with the results presented in [5] for a single interferer and considering a 40 Gb/s DPSK signal as the selected signal. This conclusion is similar to the one found in the presence of cross-phase modulation (XPM) [11]. Amplitude modulated signals at 10 Gb/s induce a higher XPM on coexisting phase modulated signals at higher bit rates, and as a result, lead to higher performance degradation.

It is still an open issue if this scenario is kept for $M > 1$. Figures 2.3 and 2.4 depict the BEP as a function of the OSNR for, respectively, M = 4 and M = 8 interferers, considering different modulation formats and bit rates on the crosstalk signals. It should be pointed out that, we have considered that, all M interferers have the same modulation format and bit rate.

Figure 2.3 shows that, for M = 4, the BEP reaches a floor for high OSNRs for all crosstalk signals, except for the 40 Gb/s DPSK interferer case. For such high OSNRs, the beating between signal and crosstalk is dominating the optical receiver performance, and the power increase of the selected signal gives no longer any performance improvement. The higher BEP degradation occurs also for the 10 Gb/s interferer. However, in comparison with M = 1, the 10 Gb/s DPSK interferer leads

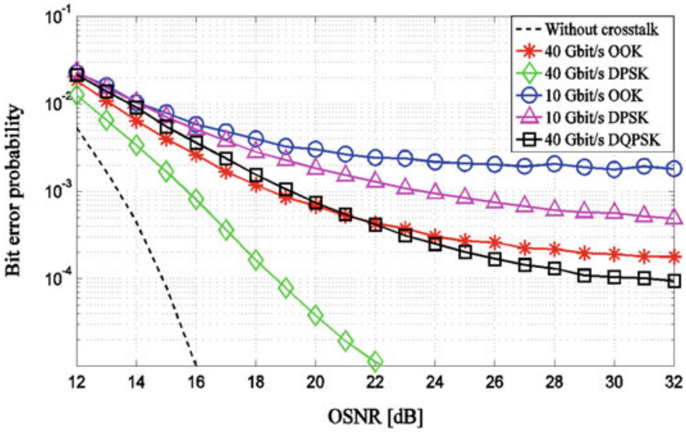

Fig. 2.3 BEP as a function of the OSNR for $M = 4$ interferers and different modulation formats and bit rates on the crosstalk signal

to a higher BEP degradation than 40 Gb/s OOK and DQPSK signals, which exhibit a similar performance.

Figure 2.4 shows the enhancement of the behaviours observed in Fig. 2.3, with the increase of the interferers number. The 40 Gb/s OOK and 40 Gb/s DQPSK crosstalk signals lead practically to the same receiver performance. The BEP with the 10 Gb/s DPSK crosstalk signal is becoming similar with the 10 Gb/s OOK crosstalk signal. Notice that between Figs. 2.3 and 2.4, the increase on the number of interferers had no particular influence on the BEP, when considering the 10 Gb/s

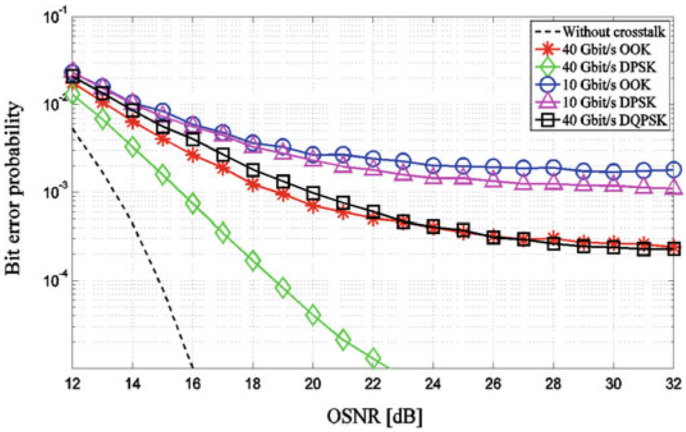

Fig. 2.4 BEP as a function of the OSNR for $M = 8$ interferers and different modulation formats and bit rates on the crosstalk signal

OOK signal. This means that the superposition of the symbol patterns of the interferers is not contributing for further degradations of the receiver performance. For the 40 Gb/s DPSK crosstalk signal, the increase of the number of interferers practically does not influence the BEP.

As a main conclusion, we have seen that with the increase on the number of interferers, the slower bit rate signals, 10 Gb/s, are the ones that lead to a higher BEP degradation. As the bit rate is smaller, when there is a combination of symbols on the crosstalk signals that impairs significantly the receiver performance, it affects at least four times the same number of symbols on the selected 40 Gb/s DQPSK signal.

2.3.2 Duty-Cycle Variation

In this subsection, the influence of the duty-cycle of the crosstalk signals on the receiver performance is investigated. All results are obtained considering a 40 Gb/s DQPSK NRZ signal and M = 4 interferers. In these studies, the influence of a random time shift $\Delta\tau_{c,i}$ inside the symbol period is taken into account in the BEP estimation. Although the main qualitative conclusions are not changed, the values of the BEP may differ noticeably, when neglecting this random time shift for interferers with RZ pulse shape.

Figures 2.5, 2.6 and 2.7 show the BEP as a function of the OSNR for, respectively, 10 Gb/s OOK, 10 Gb/s DPSK and 40 Gb/s DQPSK crosstalk signals, for several duty-cycles. The extinction ratio of the OOK interferers is assumed ideal, $r = \infty$.

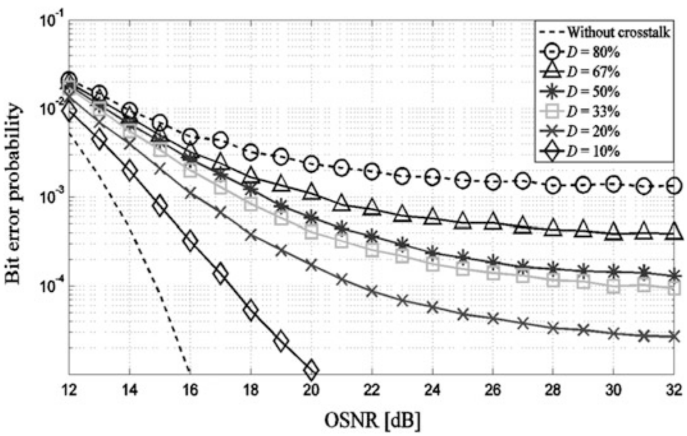

Fig. 2.5 BEP as a function of the OSNR for 10 Gb/s OOK crosstalk signal with M = 4 and different duty-cycles

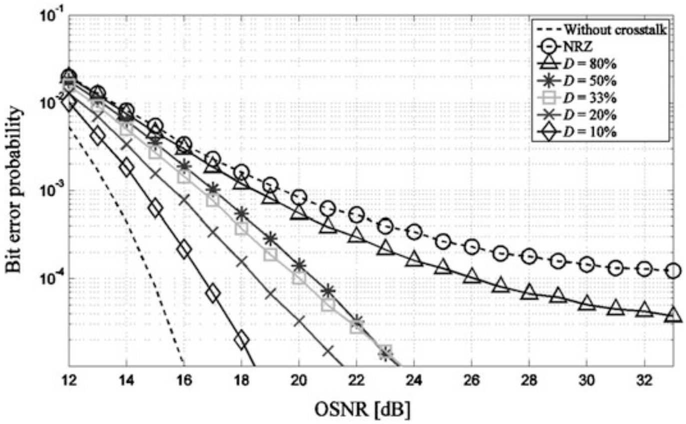

Fig. 2.6 BEP as a function of the OSNR for 10 Gb/s DPSK crosstalk signal with M = 4 and different duty-cycles

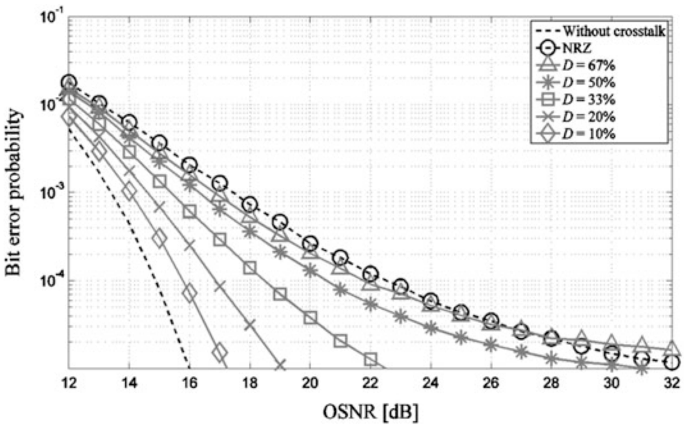

Fig. 2.7 BEP as a function of the OSNR for 40 Gb/s DQPSK crosstalk signal with M = 4 and different duty-cycles

Figures 2.5, 2.6 and 2.7 show that the reduction of the duty-cycle of the interferers reduces the crosstalk impact on the receiver performance. For very low duty-cycles (below 20 %), the BEP estimated in the presence of crosstalk becomes very close to the BEP estimated in its absence. With the duty-cycle reduction, the fraction of time of the pulse that is interfering with one pulse of the selected signal is becoming smaller, and the crosstalk impact on the receiver performance is decreased, although the total crosstalk power is the same.

Similar conclusions to those taken from Figs. 2.5, 2.6 and 2.7 have been drawn when considering 40 Gb/s OOK and 40 Gb/s DPSK crosstalk signals.

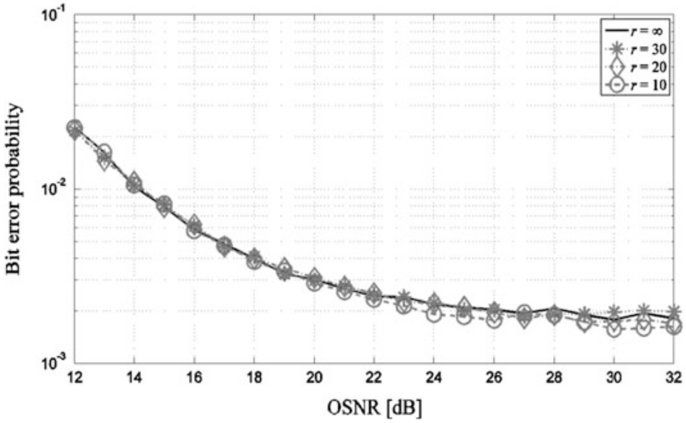

Fig. 2.8 BEP as a function of the OSNR for 10 Gb/s OOK NRZ crosstalk signal with $M = 4$ and different extinction ratios

2.3.3 Extinction Ratio Variation

In this subsection, the influence of the extinction ratio of 10 and 40 Gb/s OOK interferers on the 40 Gb/s DQPSK receiver performance is investigated.

Figure 2.8 depicts the BEP as a function of the OSNR for 10 Gb/s OOK NRZ crosstalk signals, with the extinction ratio as a parameter. Figure 2.8 shows that the 40 Gb/s DQPSK optical receiver performance is practically independent of the extinction ratio of the interferer. The same conclusion has been found for the 40 Gb/s OOK interferer and is in agreement with the results presented in [3] for DPSK optical receivers.

2.4 Conclusions

In this work, the impact of in-band crosstalk due to multi-rate and multi-format interferers on the performance of 40 Gb/s DQPSK optical receivers has been assessed using MC simulation.

It has been shown that the 10 Gb/s OOK interferer, which is the traditional modulation format of optical communication systems, is the one that leads to the highest performance degradation of the 40 Gb/s DQPSK receiver. For a high number of interferers, slower bit rates, i.e., 10 Gb/s, on the crosstalk signals are the most detrimental to the receiver performance. The crosstalk induced by 40 Gb/s DPSK signals is the less harmful and is practically independent of the number of interferers.

It has been shown that the reduction of the duty-cycle of the interferers decreases the crosstalk impact on the receiver performance and that the influence of the OOK interferer extinction ratio on the DQPSK receiver performance is practically negligible.

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