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Implications of in-band crosstalk on DQPSK signals in ROADM-based metropolitan optical networks

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ABSTRACT

Metropolitan optical networks can be designed to transport a multitude of signals with different bit rates and modulations formats. In this way, in-band crosstalk signals, originated from imperfect isolation inside ROADM (Reconfigurable Optical Add and Drop Multiplexer)-based optical nodes, will potentially have a different modulation format than the primary signal. In this paper, the origin of in-band crosstalk in a typical ROADM is analysed and its impact on differential quadrature phase-shift keying (DQPSK) signals is assessed through an analytical formalism based on the moment generating function (MGF) of the receiver decision variable. Various scenarios are analysed including the case of multiple interfering terms with different modulation formats, namely the on-off keying (OOK). It is concluded that the OOK interferer is more detrimental than the DQPSK interferer for DQPSK systems, or than the differential phase-shift keying (DPSK) interferer for DPSK systems.

1. Introduction

In order to support the growing capacity demands and the growing need for dynamic optical connections, metropolitan optical transport networks have been facing some new challenges [1]. In particular, the traffic growth requires the usage of higher bit rates and at the same time the application of modulation formats with higher spectral efficiency than the traditional on-off keying (OOK), such as the differential quadrature phase-shift keying (DQPSK) [2]. This format is particularly appropriate for direct detection based metropolitan networks, since it can guarantee a lower latency and a lower power consumption than the ones used on coherent detection based long-haul or backbone networks, such as the dual polarisation quaternary phase-shift keying (DP-QPSK) format [3]. On the other hand, metropolitan optical networks must evolve from the quasi-static paradigms of today so they can be able to provide more dynamic and agile connectivity [1].

The ROADM (Reconfigurable Optical Add and Drop Multiplexer) is an essential element of today's optical transport networks. It has the advantage of allowing express optical channels that do not require local processing, to pass through the nodes without optoelectronic conversions and at the same time permits to reconfigure the node by software adding dynamism at the optical layer. There has been an intense investigation on the

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development of ROADMs technology and architectures during the past decade [4]. Nowadays, multidegree ROADMs that exhibit colourless, directionless and contentionless (CDC) add and drop features are commercially available [5]. While in today metro context fixed ROADM, in both metro-access and metro-core, or at most colourless ROADM, in metro-core, are the standard case, the CDC ROADMs will be appropriate in next future for the most challenging scenarios, but only for metro-core contexts, whereas for metro-access, where cost will still be an important issue and the full flexibility will be not required, the colourless and directionless ROADM will be the most suitable option [1]. A key optical device in a ROADM is the wavelength selective switch (WSS) that is used to implement the wavelength routing function [5]. Ideally, these devices should have a perfect isolation for the add and drop operations, but in practice some leakage occurs due to imperfect isolation inside the WSSs. These leakage signals, usually known as crosstalk signals, interfere with the primary data signal at the optical receiver, contributing to degrade the signal quality [6].

The impact of these crosstalk signals, especially when the crosstalk has the same nominal wavelength as the primary signal – the in-band crosstalk –, has been the focus of widespread attention over the years, but mainly in the context of systems based on OOK [7], and differential phase-shift keying (DPSK) schemes [8]. The implications of this impairment on other modulation formats, like for example DQPSK with direct detection and QPSK with coherent detection, have been less investigated and require further studies. In [9], the authors quantify experimentally the impact of in-band crosstalk on a 10 Gbit/s DQPSK signal due to a single DQPSK interferer, while in [10], it is developed an analytical formalism, and also a simulation tool, to deal with the influence of the same impairment on that scheme, but, once again, only a single interferer with the same modulation format of the primary signal has been considered. Furthermore, there is also some work published on this topic for QPSK signals (see for example [11]).

Metropolitan optical networks can be designed to support optical signals with mixed line rates, and multiple modulation formats, like OOK, DPSK and DQPSK, in order to minimize network cost [12]. In addition, the same problem of coexistence of mixed line rates exists in a long-haul network which was designed and deployed in the past to carry OOK (10 Gbit/s) and where the introduction of DQPSK (40 Gbit/s) was necessary because it was not possible, for technical or economic reasons, to build a new network suitable with coherent transponders. In this way, the problem of having interferers with modulation formats different from the one of the desired signal will require particular attention. This problem has been less analysed in the literature, however there is a simulation and experimental work [13], and also an analytical work [14] that considers DPSK primary signals. In what concerns DQPSK primary signals there is also a simulation study and an analytical treatment for the single interferer scenario [14].

In this paper, we start by analysing the origin of in-band crosstalk in a simple four-node network based on broadcast and select ROADMs. Then, we present an analytical formulation to analyse the performance of DQPSK signals in the presence of in-band crosstalk due to ROADMs, by extending our previous work, [14], in order to include the influence of an arbitrary number of interferers with different modulation formats from the primary signal. In particular, we focus our attention on the impact of OOK interferers in DQPSK signals, since OOK is still one of the most used formats in optical networks. A comparison study between the impact of OOK interferers in DPSK and DQPSK receivers is also one of the goals of this work, as well as a comparison between the impact of OOK and DQPSK interferers in a DQPSK receiver. A stochastic Monte Carlo simulator is also developed to validate the analytical formalism.

This paper is organized as follows. In Section 2, the origin of in-band crosstalk generated inside a ROADM is explained. The analytical formulation developed to analyse the impact of in-band crosstalk in DQPSK receivers is presented in Section 3. In particular, the decision variable modelling is explained and the statistical characterisation of this variable, based on the moment generating function (MGF), is done. The numerical results are presented in Section 4, where the impact of multi-format in-band crosstalk in DQPSK receivers is quantified and compared with the one obtained in DPSK receivers. Finally, the conclusions are outlined in Section 5.

2. Origin of in-band crosstalk in ROADMs

In order to understand the origin of in-band crosstalk in ROADM-based optical networks let's consider the four-node

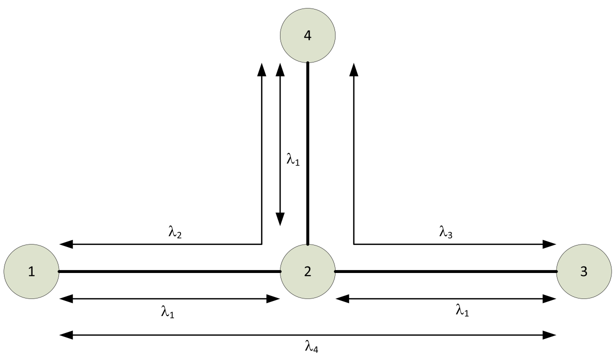

Fig. 1. Four-node star network with the wavelength assignment that allows a full-mesh logical topology.

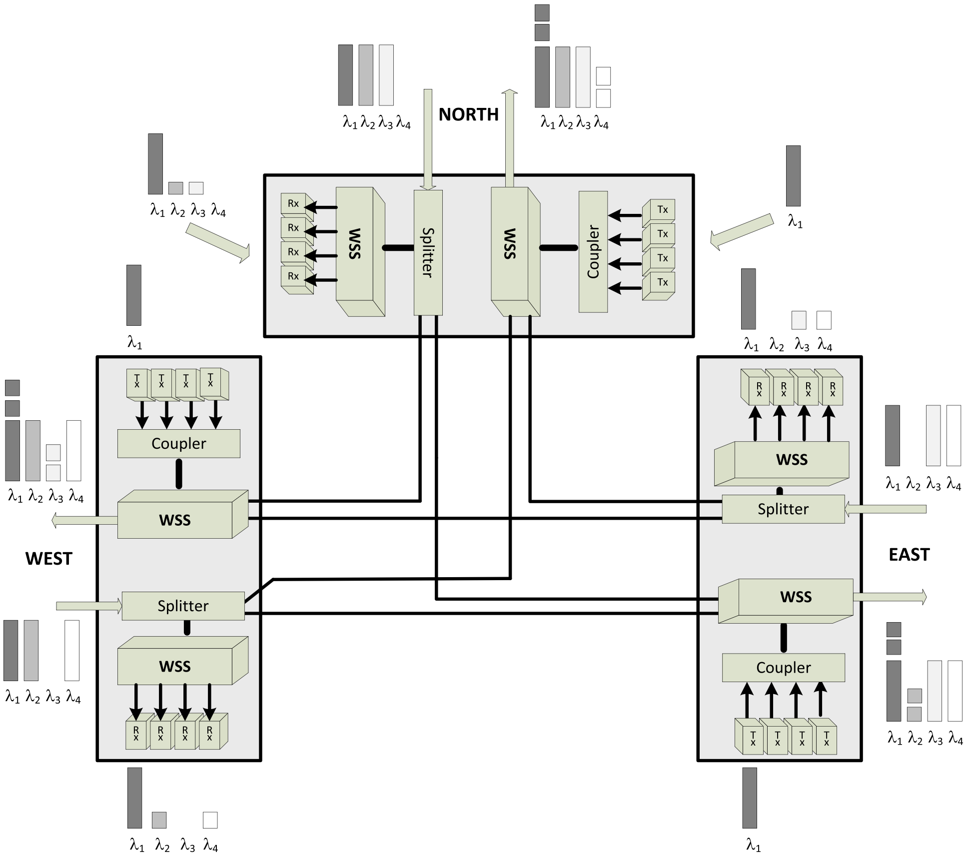

Fig. 2. A possible architecture based on a 3-degree colourless broadcast and select ROADM [15], for node 2 of the network shown in Fig. 1, with the crosstalk generation inside this node, both in-band and out-band.

network shown in Fig. 1. This network has a star physical topology and a full-mesh logical topology which is implemented using the wavelength assignment described in the referred figure. From this figure we can observe that, for example, λ_1 is assigned to the bidirectional connection between nodes 1 and 2 and λ_4 to the connection between nodes 1 and 3. Furthermore, the central node must be capable of dealing with bidirectional connections with WDM (Wavelength-Division Multiplexing) signals with four wavelengths.

Fig. 2 shows the structure of the ROADM used in node 2 [15]. This is a 3–degree colourless broadcast and select architecture, where we can identify three line ports (West, East, and North) that connect to other nodes using a pair of optical fibres and three local ports, for add/drop functions, that connect to local transceivers. This figure also shows the wavelengths that are used at the different ports according to the wavelength assignment considered. As seen, only the wavelength λ_1 is locally added/dropped. All others wavelengths (λ_2, λ_3, and λ_4) are express wavelengths and as a consequence pass through the node transparently. A central piece of the ROADM is the N:1 WSS, where N is the node degree. It is required one of these WSSs per degree. Furthermore, the colourless architecture requires an additional WSS per degree in order to drop the adequate wavelengths to the local ports.

Due to its central role in optical networks, it is expected that the WSS properties (parameters, characteristics) will impact the overall network performance. The imperfect port isolation is one of the critical parameters and is responsible for generating leakage signals at the WSS output in the wavelengths that are blocked by the switch.

Both in-band and out-band crosstalk components will be present in the ROADM output ports due to leakage. The out-band crosstalk is the result of incomplete supressed wavelengths at the local drop ports, or at the line ports when these wavelengths are not used to carry data. For example, in Fig. 2 the primary signal at wavelength λ_1 dropped at the West local port suffers out-band crosstalk from λ_2 and λ_4, while the WDM signal at the East line port also suffers from out-band crosstalk from λ_2. In the in-band crosstalk case, the primary signal and the interference have the same nominal wavelength. Referring again to Fig. 2 the signal added to the local port of the West direction will experience in-band crosstalk from the incompletely blocked signals at wavelength λ_1 that come from the other two directions.

The in-band crosstalk is much more detrimental to network performance than out-band crosstalk, because contrary to the last one it cannot be removed by filtering. As a consequence in our analysis we will deal only with in-band crosstalk.

The observations from the previous paragraphs, for a 3-degree colourless ROADM, can be generalized for an N-degree colourless ROADM. Consequently, for an N-degree colourless ROADM the maximum number of in-band crosstalk signals generated is $N-1$ if the primary signal is processed inside the ROADM (i.e. the signal is dropped and then added) and $N-2$ if the primary signal is an express signal. This number can be considerably large if we consider a practical scenario where the primary signal path cross multiple ROADMs until it reaches its final destination. Hence, the total number of in-band interferers depends on the number of ROADMs crossed, on their dimension (i.e. degree), as well as, on the wavelength assignment used in the network.

3. Analytical formulation

In order to evaluate the impact of in-band crosstalk, originated in a ROADM-based optical network like the one depicted in Fig. 2, and considering that the primary signal at a specific wavelength is a DQPSK signal, we develop in Section 3.1, an analytical model to evaluate the impact of this impairment on the performance of those networks. This model is capable of dealing with crosstalk signals with modulation formats different from the one of the primary signal, a possible scenario in metropolitan ROADM-based optical networks. In particular, we focus our attention on OOK and DQPSK crosstalk signals. Finally, in Section 3.2 we characterize statistically the decision variable by obtaining its MGF, which is then used to derive an expression for bit error probability (BEP).

3.1. Receiver decision variable model

The block diagram of a typical direct detection DQPSK receiver using balanced detection is depicted in Fig. 3 [16]. It consists of an optical pre-amplifier with a power gain G, an optical filter characterised by an arbitrary low-pass equivalent impulse response $h_o(t)$ and a -3 dB optical bandwidth B_o, a -3 dB coupler and two branches, the in-phase (I) – branch and the quadrature (Q) – branch. The -3 dB coupler splits the signal between the I – and Q – branches of the optical receiver and in each branch, there is a delay line interferometer (DLI), a balanced photodetector and an electrical post-detection filter. The phase difference between the two arms of the DLI in the I-branch is set to $-\pi/4$, whereas in the Q-branch DLI is set to $\pi/4$. The post-detection filter is described by an impulse response $h_e(t)$ and by a -3 dB electrical bandwidth B_e. It is worth noting that the structure of QPSK receivers based on coherent detection is more complex than the one described for DQPSK, requiring, for example, the use of lasers with very narrow linewidth, to act as local oscillators, and the employment of sophisticated electronics such as high speed analogue-to-digital converters (ADC) and digital signal processing (DSP) circuits [3]. This leads to higher costs and higher electrical power consumption, which are critical issues for metropolitan networks.

We assume that at the input of the DQPSK receiver, we have an incoming DQPSK signal, named primary signal, corrupted by in-band crosstalk due to M interfering signals that can have a modulation format different from the primary signal and can be originated due to the imperfect port isolation of the multi-degree ROADMs that the primary signal must cross in an optical network environment.

The electrical field at the receiver optical filter output, $\vec{E}(t)$, can be expressed as [17]

$$\vec{E}(t) = \left[\sqrt{G}\vec{E}_s(t) + \sqrt{G}\sum_{i=1}^{M}\vec{E}_{x,i}(t) + \vec{E}_n(t)\right] * h_o(t), \quad (1)$$

where * denotes convolution. In the first term of (1), the electrical field $\vec{E}_s(t)$ corresponds to the primary signal; the second term of (1), $\sum_{i=1}^{M}\vec{E}_{x,i}(t)$, corresponds to the in-band crosstalk signal; and, finally, the third term, $\vec{E}_n(t)$, corresponds to the amplified spontaneous emission (ASE) noise originated from the optical pre-amplifier, which is considered to be a zero mean white stationary Gaussian noise with single-sided power spectral density in each polarisation described by N_o, and with the same polarisation as the primary signal.

The complex envelope of the primary data field can be represented as

$$\vec{E}_s(t) = \sqrt{2P_s}u(t)\exp\left[j\theta_s(t)\right]\vec{e}_s, \quad (2)$$

where P_s is the average signal power at the optical pre-amplifier input, $u(t)$ is a rectangular pulse of unitary amplitude within the time interval $[0, T]$ (T is the symbol period), $\vec{e}_s$ is the signal polarisation unit vector, and $\theta_s(t)$ is the signal phase that carries the DQPSK symbol sequence

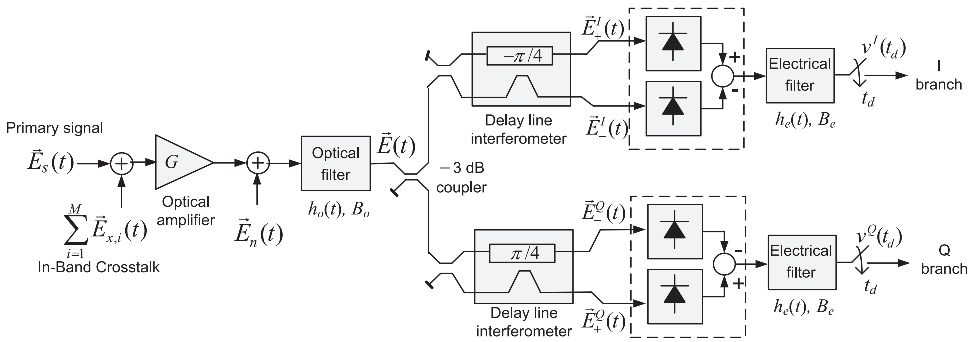

Fig. 3. Block diagram of the direct detection DQPSK optical receiver.

of the primary data signal and can take one of the four values $\{\pi/4, 3\pi/4, -3\pi/4, -\pi/4\}$.

The i-th crosstalk signal field in (1) can be also represented by the complex envelope as

$$\vec{E}_{x,i}(t) = \sqrt{2P_{x,i}a_{x,i}(t)}u(t)\exp\left[j\theta_{x,i}(t)+j\phi_{x,i}\right]\vec{e}_{x,i}, \quad (3)$$

where $P_{x,i}$ is the average crosstalk power at the optical preamplifier input, $\vec{e}_{x,i}$ is the crosstalk polarisation unit vector, $a_{x,i}(t)$ and $\theta_{x,i}(t)$ are, respectively, the envelope and phase of the i-th interferer that define the modulation format of the crosstalk signal. In this work, the crosstalk signal can be a DQPSK or an OOK signal. In the first case, $a_{x,i}(t)=1$ and $\theta_{x,i}(t)$ can take one of the four values $\{\pi/4, 3\pi/4, -3\pi/4, -\pi/4\}$. In the second case, the OOK format, $\theta_{x,i}(t)=0$ and $a_{x,i}=1$ for a bit "one" and $a_{x,i}=r$ $(0 \le r < 1)$ for a bit "zero" (r is the ratio between the average optical power level of a bit "one" and the average optical power level of a bit "zero"). The random phase $\phi_{x,i}$ describes the phase noise difference between the primary signal and the i-th crosstalk signal, which is assumed constant over the symbol period and is statistically modelled considering a uniform distribution over the interval $[-\pi,\pi]$ [8]. Throughout this paper, it is assumed a worst case interference scenario, i.e., all the interfering signals are assumed to be co-polarised and temporally aligned with the primary signal [8]. The crosstalk level of the i-th interferer, ε_i, is defined as the ratio between the crosstalk power and the primary signal power ($\varepsilon_i = P_{x,i}/P_s$), whereas the total crosstalk level is given by $\varepsilon_T = \sum_{i=1}^{M}\varepsilon_i$.

Assuming that the DQPSK receiver has no imperfections [16], the two branches of the receiver (see Fig. 3), the in-phase (I) – branch and the quadrature (Q) – branch, are symmetrical, so we proceed by analysing only the Q-branch. Also, as pointed out in [16], the analysis of the DQPSK receiver is equivalent to analysing a DPSK receiver with a phase error of $\pi/4$ in the DLI [17]. Hence, the electrical fields at the DLI outputs of the Q-branch are, respectively, $\vec{E}^{Q}_{+}(t) = [\vec{E}(t)+\vec{E}(t-T)e^{j\pi/4}]/(2\sqrt{2})$ and $\vec{E}^{Q}_{-}(t) = [\vec{E}(t)-\vec{E}(t-T)e^{j\pi/4}]/(2\sqrt{2})$ for the constructive port and for the destructive port [16]. These fields are assumed to be detected using a pair of identical photodiodes with unitary responsivities and the resulting currents are subtracted and filtered by an electrical filter. The decision variable of the Q-branch, $v^Q(t_d)$, at the electrical filter output (see Fig. 3), defined at the decision time t_d, can then be written as the difference between the random variable $v^Q_+(t_d)$, resulting from the constructive port, and the random variable $v^Q_-(t_d)$, resulting from the destructive port,

$$v^Q(t_d) = v^Q_+(t_d) - v^Q_-(t_d). \quad (4)$$

Note that in this branch, only one of the two bits of the DQPSK transmitted symbol is detected; the other bit is obtained from the I-branch of the receiver [18].

Next, the decision variables $v^Q(t_d)$ and $v^I(t_d)$ can be written as a sum of independent random variables. To achieve that goal an eigenfunction expansion technique to decompose the signal, the crosstalk, and the amplified ASE noise at the optical filter input, in a series of orthogonal functions is employed [8].

3.2. Statistical characterization of the decision variable

The MGF of the receiver decision variable is used to characterize the decision variable statistics and its evaluation follows the approach described with more detail in [8], where the impact of in-band crosstalk is assessed in a DPSK system. Here, the MGF is modified in order to accommodate the in-band crosstalk impact on the DQPSK receiver performance.

Hence, the MGF of the decision variable of the Q-branch of the receiver, $v^Q(t_d)$, can be given by [8]

$$M_{v^Q}(s) = M_{v^Q_+}(s)M_{v^Q_-}(-s), \quad (5)$$

where the MGF of $M_{v^Q_+}(s)$ and $M_{v^Q_-}(s)$ can be expressed as [8],

$$M_{v^Q_+}(s) = \frac{1}{\prod_{k=0}^{\infty}[1-s\lambda_k N_o/2]^2} M_{y_+}\left[\sum_{k=0}^{\infty}\frac{s\lambda_k T\xi_k}{(1-s\lambda_k N_o/2)}\right] \quad (6a)$$

$$M_{v^Q_-}(s) = \frac{1}{\prod_{k=0}^{\infty}[1-s\lambda_k N_o/2]^2} M_{y_-}\left[\sum_{k=0}^{\infty}\frac{s\lambda_k T\xi_k}{(1-s\lambda_k N_o/2)}\right]. \quad (6b)$$

In (6a) and (6b), $\xi_k = u_k^2/T$ with $u_k = \int_{-T/2}^{T/2}\varphi_k(\tau)d\tau$, where $\varphi_k(t)$ are the eigenfunctions used in the series expansion of the signal, crosstalk and ASE noise at the optical filter input and λ_k are its respective eigenvalues [8]. Also, in (6a) and (6b),

$$M_{y^+}(s) = \exp[sGP_s\alpha_s^+] \times \prod_{i=1}^{M}\{\exp[sGP_s\varepsilon[(\alpha_{x,i}^+)^2+(\beta_{x,i})^2]] \times I_0[s2GP_s\sqrt{\varepsilon}(\beta_s\alpha_{x,i}^+ - \beta_{x,i}\alpha_s^+)]I_0[s2GP_s\sqrt{\varepsilon}(\alpha_s^+\alpha_{x,i}^+ + \beta_s\beta_{x,i})]\} \quad (7a)$$

$$M_{y^-}(s) = \exp[sGP_s\alpha_s^-] \times \prod_{i=1}^{M}\{\exp[sGP_s\varepsilon[(\alpha_{x,i}^-)^2+(\beta_{x,i})^2]] \times I_0[s2GP_s\sqrt{\varepsilon}(\beta_{x,i}\alpha_s^- - \beta_s\alpha_{x,i}^-)]I_0[s2GP_s\sqrt{\varepsilon}(\alpha_s^-\alpha_{x,i}^- + \beta_s\beta_{x,i})]\} \quad (7b)$$

where $I_0(.)$ denotes the modified Bessel function of the first kind of order zero, $\alpha_s^{\pm} = (1 \pm a_s/\sqrt{2})/2$, $\beta_s = a_s/(2\sqrt{2})$, $\alpha_{x,i}^{\pm} = (1 \pm a_{x,i}/\sqrt{2})/2$, $\beta_{x,i} = a_{x,i}/(2\sqrt{2})$ and $\Delta\theta_i = \theta_{x,i}(T) - \theta_s(T) + \phi_{x,i}$ when the modulation format of the primary signal and interferers is the DQPSK format. When the OOK is considered for the interferers $\alpha_{x,i}^{\pm} = [\sqrt{a_{x,i}} \pm \sqrt{a_{x,i}(T)/2}]/2$, $\beta_{x,i} = \sqrt{a_{x,i}(T)/8}$ and $\Delta\theta_i = \phi_{x,i} - \theta_s(T)$, with $a_{x,i}(T)$ the transmitted OOK symbol in the previous time interval relatively to $[0,T]$. For the sake of simplicity, we neglect the crosstalk-crosstalk beating terms in the above equations, since the performance in practical situations is not affected by those terms [8]. This general formalism can be used to evaluate other scenarios, in particular, it can be used to study the impact of multi-format in-band crosstalk in DPSK systems. This study has already been done in [8], where it was assumed that the interferer has a DPSK format, and in [14], where the interferer is an OOK signal.

Having derived the MGF of the decision variable, we are now in conditions to assess the system performance. This performance is typically quantified by assessing the BEP

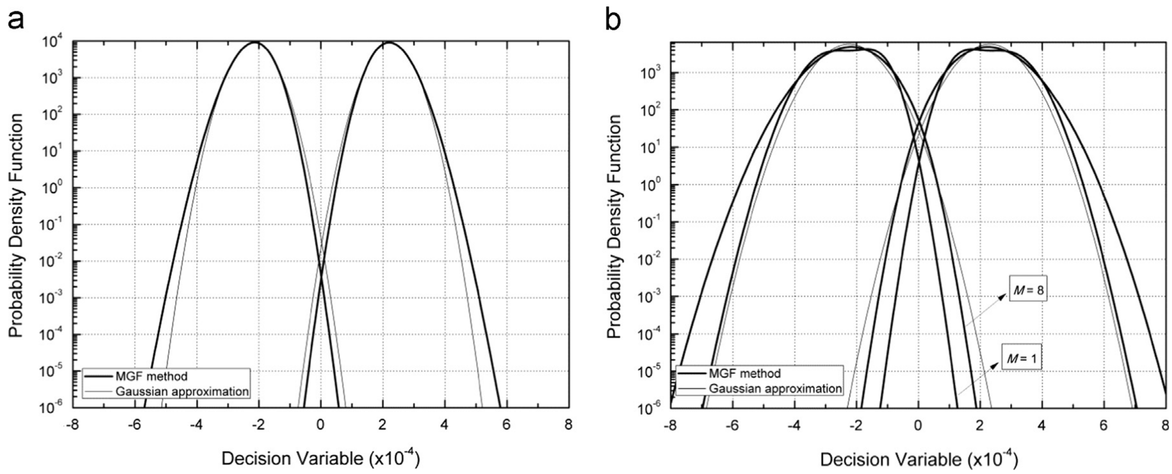

Fig. 4. PDF of the decision variable of the Q-branch: (a) ignoring in-band crosstalk; and (b) considering a total crosstalk level of −15 dB distributed by a single and eight DQPSK interferers.

and the optical signal to noise ratio (OSNR). Having in mind the equivalence between the DQPSK receiver and the DPSK receiver with a phase error of $\pi/4$ in the DLI [16], the average BEP in the Q-branch is evaluated with the saddlepoint approximation method [8], that uses the MGF presented in (5). In this BEP computation, we apply a binomial symbol conditioning on the interfering signals that are assumed to be equally likely [8]. The overall BEP is found by averaging the BEP of the I- and Q-branches. Note that, ideally, when there are no receiver imperfections, the BEP of the I-branch is the same as the BEP of the Q-branch.

4. Numerical results and discussion

In this section, the impact of in-band crosstalk on the performance of 40 Gbit/s DQPSK pre-amplified optical receivers is assessed considering the analytical formalism developed in the previous section. First, in Section 4.1, in order to gain insight into the statistics of the decision random variable, the probability density function (PDF) of the decision variable is evaluated. Next, in Section 4.2, the impact of DQPSK crosstalk signals in a DQPSK receiver is compared with the impact of DPSK crosstalk signals in a DPSK receiver as a function of the number of interfering terms, the crosstalk level and the OSNR, which is measured in the reference bandwidth of 0.1nm at 1550nm. In Section 4.3, we compare the impact of OOK crosstalk signals, in, both, DQPSK and DPSK receivers.

Throughout this section, the amplifier noise figure, F, is 5 dB, the pre-amplifier gain, G, is 30 dB, both ASE noise polarisations are considered and an ideal extinction ratio for the OOK interferer is assumed ($r=0$). The optical and electrical filters are both Gaussian shaped, which is usually known as Gaussian receiver configuration, with, respectively, a −3 dB normalized bandwidth given by $B_oT=5$ and a −3 dB normalized bandwidth given by $B_eT=0.7$. Furthermore, in this section, it is assumed that both DQPSK and DPSK signals have the same bit rate (40 Gbit/s), therefore the receiver bandwidth, defined by B_e, for detecting a DQPSK signal is half the bandwidth used to detect a DPSK signal.

In order to validate the analytical results, we have also developed a Monte Carlo simulator to estimate the BEP of the DQPSK receiver impaired by in-band crosstalk with multi-format interfering terms [14]. This BEP is estimated considering at least 100 counted symbol errors.

4.1. *On the probability density function of the decision variable*

A qualitative impact of the effects of in-band crosstalk in the system performance can be acquired by evaluating the PDF of the decision variable which is done, in this section, by taking the inverse Laplace transform of (5). The resulting integral expression can be evaluated using the saddle point integration method as it is detailed in [8]. A comparison with the PDF obtained with the Gaussian approximation is also performed.

The Gaussian approximation is a simple analytical tool, when compared to the MGF-based formalism developed in Section 3, to evaluate system performance and its simplicity results from considering that the decision variable statistics can be characterized by a Gaussian random variable. Nevertheless, it is well-known that this approximation is very inaccurate for analysing the performance of DPSK signals impaired by in-band crosstalk [8]. In this way, and, as was already referred in section 3 that the analysis of the DQPSK receiver is equivalent to analysing a DPSK receiver with a phase error of $\pi/4$ in the DLI, it is expected that the Gaussian approximation remains inaccurate for evaluating the impact of in-band crosstalk in DQPSK receivers.

In order to check this inaccuracy, Fig. 4 shows the PDFs of the decision variable of the Q-branch obtained from MGF-based formalism of Section 3 and the PDFs predicted by the Gaussian model, considering, in Fig. 4(a), the situation where the in-band crosstalk is ignored, and, in Fig. 4(b), a total crosstalk level of −15 dB distributed by a single and eight DQPSK interferers. In these evaluations, it is assumed that the primary signal and the interferer are in the same symbol state and the average signal power at the pre-amplifier input, P_s, is −35 dBm. Since the optimum

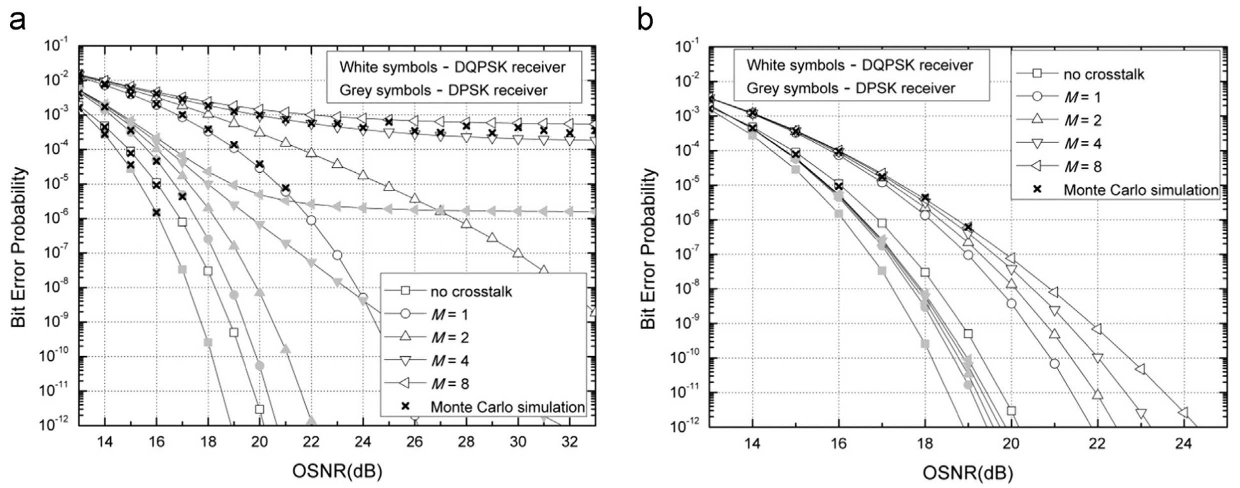

Fig. 5. BEP as a function of the OSNR for 0, 1, 2, 4 and 8 interfering terms for both DQPSK and DPSK receivers, considering (a) total crosstalk level of −13 dB and (b) total crosstalk level of −20 dB.

decision threshold occurs at the crossing point between the PDFs, the focus of our attention will be the inner tails of the PDFs, because it is the area under these tails that determines the BEP. As can be seen in Fig. 4(a) and (b), the Gaussian inner tails are clearly above the tails evaluated with the MGF-based method when the crosstalk is neglected and for the single interferer scenario suggesting that the Gaussian approximation over–estimates the BEP. Nevertheless, for the eight interferer case the Gaussian PDF inner tails and MGF-based ones become more similar suggesting that for a larger number of interfering terms this approximation could be used, a situation that did not occur for DPSK signals [8]. Note that the value of the Gaussian PDF crossing point, in Fig. 4(b), is fixed, because the variance of the Gaussian decision variable is kept constant independent of number of interferers [8].

4.2. Impact of DQPSK crosstalk signals

In this section, we quantify the impact of in-band crosstalk due to DQPSK interferers in DQPSK receivers and compare it with the impact of in-band crosstalk due to DPSK interferers in DPSK receivers.

In Fig. 5, the BEP is plotted as a function of the OSNR, with the number of interfering terms as a parameter for both DQPSK and DPSK receivers, considering in Fig. 5(a), a total crosstalk level of $\varepsilon_T = -13$ dB and in Fig. 5(b), a total crosstalk level of $\varepsilon_T = -20$ dB. For validation of the analytical method, several curves obtained by Monte Carlo simulation are also plotted in Fig. 5.

In the first place, we can observe from this figure that in the absence of crosstalk and at a good BEP (e. g., 10^{-12}) DQPSK requires about 1 dB higher OSNR than DPSK, in contrast with scenarios with the same symbol rate where the difference is about 4 dB [10], due to the fact of using a narrower receiver bandwidth, as referred before. From Fig. 5 it is also clear that despite the total crosstalk level remaining constant, −13 dB in Fig. 5(a) and −20 dB in Fig. 5(b), the performance deteriorates as the number of interferers increase, a trend that was already observed for DPSK receivers in [8]. Additionally, Fig. 5(a)

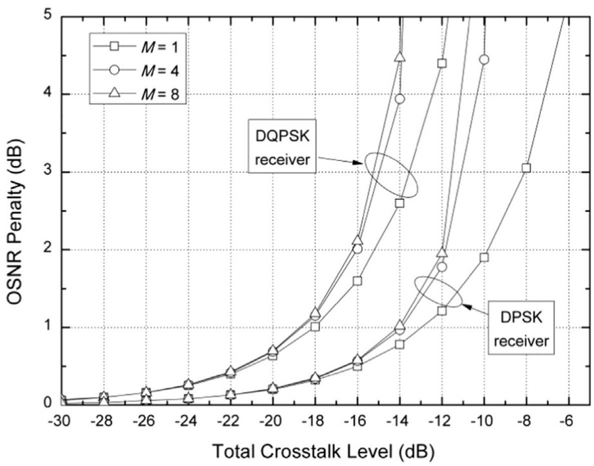

Fig. 6. OSNR penalty as a function of the total crosstalk level for both DQPSK and DPSK receivers with the number of interferers as a parameter. The BEP reference level is at 10^{-3}.

shows the presence of an error floor, which is clearly evident for $M = 8$ for both DQPSK and DPSK receivers and also for $M = 4$ for DQPSK receivers. This floor is due to the dominance on the receiver performance degradation of the noise power originating from the beating between signal and in-band crosstalk over the noise power due to the beating between signal and ASE noise, as already has been shown in [19] for DPSK receivers. Note that in Fig. 5(b), when the total crosstalk level is reduced to −20 dB, the error floor disappears, since the beating term between signal and ASE noise becomes dominant over the beating term between signal and crosstalk.

Moreover, from both Fig. 5(a) and (b), it is clear that DPSK receivers need a much lower OSNR increase than DQPSK receivers, for a fixed BEP, in order to face the impact of in-band crosstalk, revealing the fact that DQPSK receivers are less tolerant to in-band crosstalk than DPSK receivers [10].

Finally, we can also check, from Fig. 5, the similarity between the analytical and Monte Carlo simulation results,

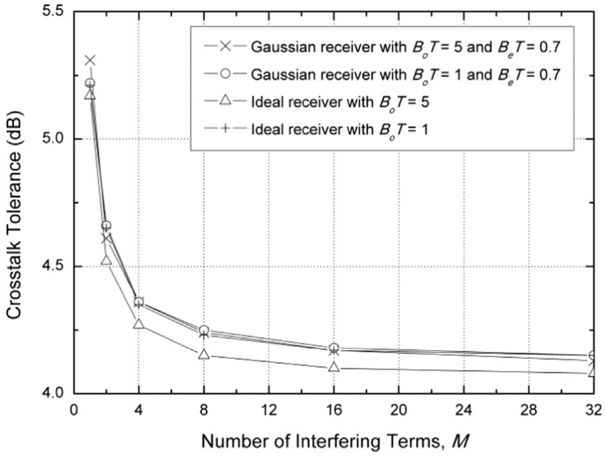

Fig. 7. Crosstalk tolerance of DPSK receivers relatively to DQPSK receivers as a function of the number of interfering terms considering a 2 dB OSNR penalty for two receiver configurations: Gaussian receiver configuration with B_eT=0.7, for B_oT=1 and B_oT=5, and ideal receiver configuration with B_oT=1 and B_oT=5.

which contributes to the validation of the analytical formalism. In Fig. 5(a), we represent the Monte Carlo simulation curves for $M=0,1$ for the DPSK receiver and $M=0,1,8$ for the DQPSK receiver, whereas, in Fig. 5(b), we represent these curves, only, for $M=8$ for both DQPSK and DPSK receivers.

Next, in Fig. 6, the OSNR penalty due to in-band crosstalk as a function of the total crosstalk level, for both DQPSK and DPSK receivers, is depicted. The OSNR penalty is a widely used metric to quantify the crosstalk impact and is defined as the increment in decibels in the OSNR, required to maintain the error probability at 10^{-3} in the presence of in-band crosstalk. These results show that for a 2 dB OSNR penalty and a single interferer, the DPSK receiver has a gain of 5.3 dB over the DQPSK receiver in terms of crosstalk tolerance, since it tolerates a -9.7 dB crosstalk level, whereas DQPSK receiver only tolerates -15 dB. Although, in this analysis the DQPSK and DPSK comparison has been undertaken at the same bit rate, it is expected that similar results will be got for comparisons at the same symbol rate [10].

The experimental results in [9] report a smaller gain in the crosstalk tolerance, ~3 dB. We believe that this difference can be mainly attributed to the fact that in the experimental set up of [9] the DQPSK signal was demodulated using a single differential detector that was tuned to demodulate either the I or the Q component of the DQPSK signal, instead of using a DQPSK receiver to detect simultaneously the two components, as we have considered in our analysis.

Also, note that this 5.3 dB gain is very close to the tolerance of DPSK receivers relatively to OOK receivers, 5.5 dB, reported by the authors in [8]. So, we can conclude that DPSK has a similar crosstalk tolerance in relation to both DQPSK and OOK receivers, for the single interferer scenario. For the case of four and eight interferers, the crosstalk tolerance is reduced to about ~4.3 dB, showing that the robustness of DPSK receivers towards in-band crosstalk, relatively to DQPSK receivers, diminishes approximately 1 dB for a large number of interferers. In comparison with the ~3 dB tolerance of DPSK receivers in relation to OOK receivers reported in [8], for a large number of interferers, we can conclude that DPSK receivers are slightly less crosstalk tolerant relatively to OOK receivers than relatively to DQPSK receivers, when the number of interfering terms is high.

It is also interesting to see how this OSNR penalty, represented in Fig. 6, for both DQPSK and DPSK receivers is related with the penalty obtained for QPSK receivers, typically used in long-haul and backbone networks. For a 1 dB OSNR penalty the QPSK receiver allows a -15 dB crosstalk level, as reported in [11], whereas the DQPSK and DPSK receivers, respectively, tolerate a -18 dB and -13 dB for the single interferer scenario, as can be seen in Fig. 6. So, from this observation it can be concluded that the DPSK direct detection receiver is the most tolerant to in-band crosstalk.

In Fig. 7, the crosstalk tolerance, for a 2 dB OSNR penalty, of DPSK receivers relatively to DQPSK receivers is represented as a function of the number of interfering terms for two receiver configurations, the Gaussian receiver for $B_oT=5$ and $B_eT=0.7$ and the ideal receiver (based on a rectangular optical filter with $B_oT=5$ and an electrical integrate-and-dump filter). Additionally, the curves for both receivers configurations when $B_oT=1$ are also plotted. As can be observed when the number of interfering terms increases, the crosstalk tolerance decreases until it reaches a constant value. In particular, the crosstalk tolerance has a maximum value of about 5.3 dB for a single interfering term and reaches a constant value of about 4.1 dB for a number of interfering terms superior to 16. Another observation from Fig. 7 is the fact that the crosstalk tolerance for both receiver configurations and the two values of the optical normalized -3 dB bandwidth B_oT is practically the same, as was also concluded in [8] for DPSK receivers.

4.3. Impact of OOK crosstalk signals

In this section, the impact of in-band crosstalk due to OOK interferers in both DQPSK and DPSK 40 Gbit/s receivers is

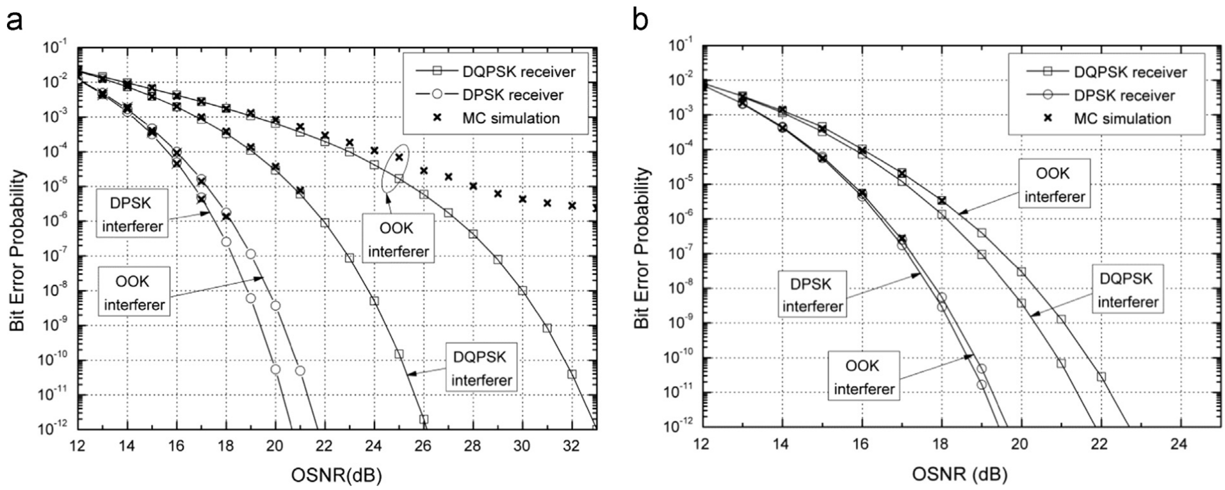

Fig. 8. BEP as a function of the OSNR, for both DQPSK and DPSK receivers, considering a single OOK interferer and (a) a crosstalk level of −13 dB and (b) a crosstalk level of −20 dB. The BEPs for the single DQPSK and DPSK interferers are also depicted.

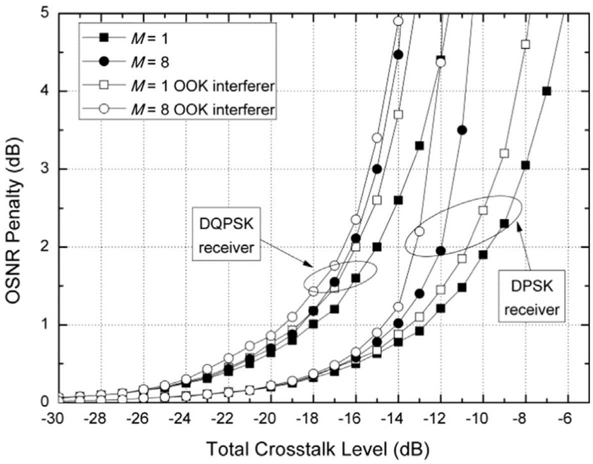

Fig. 9. OSNR penalty as a function of the total crosstalk level for both DQPSK and DPSK receivers for one and eight interferers when the modulation format of the interferer is OOK. The BEP reference level is at 10^{-3}.

analysed. In Fig. 8, the BEP is plotted as a function of the OSNR, for a single OOK interferer scenario, for both DQPSK and DPSK 40 Gbit/s receivers, considering (a) −13 dB crosstalk level and (b) −20 dB crosstalk level. In order to have a similar spectral content in both the primary signal and crosstalk signal, we considered a 40 Gbit/s OOK interferer in the DPSK receiver and a 20 Gbit/s OOK interferer in the DQPSK receiver, since the symbol rate in this receiver is 20 GBaud. The BEPs for the single DQPSK and DPSK interferers are also depicted in Fig. 8 for comparison purposes.

From Fig. 8, it can be concluded that the OOK interferer is more detrimental than the DQPSK or DPSK interferer for DQPSK or DPSK receivers. Moreover, as the crosstalk level increases from −20 dB (Fig. 8 (b)) to −13 dB (Fig. 8(a)) the enhancement of this detrimental behaviour can be observed, since when the OOK interferer is considered, the OSNR for a fixed BEP is further increased in comparison to the case when both DPSK and DQPSK interferers are present. These conclusions are also corroborated by the MC simulation results presented in Fig. 8. Nevertheless, we note that for the OOK interferer scenario in a DQPSK receiver when a −13 dB crosstalk level is considered (see Fig. 8(a)), the MC simulation curve and the analytical curve start to diverge for OSNRs greater than 23 dB, and a BEP floor is reached in the MC simulation curve. This behaviour can be attributed to the fact that the MC simulator uses a sequence of symbols to compute the BEP, whereas the analytical formalism uses only a single symbol.

Finally, in Fig. 9, the OSNR penalty due to a single and eight OOK interferers as a function of the total crosstalk level, for both DQPSK and DPSK receivers is presented. The curves of the OSNR penalty when the interferers have DQPSK and DPSK formats, respectively, for the DQPSK and DPSK receivers are also plotted for comparison purposes. These results show that, for a 2 dB OSNR penalty and a single interferer term, the DPSK receiver and the DQPSK receiver tolerate a crosstalk level $\sim$1 dB lower when the interferer has an OOK modulation format. The same trend is observed for the eight interferer case, but in this scenario, the OOK interferer exhibits lesser restrictions on the crosstalk level in the DQPSK receiver than in the DPSK receiver; 0.4 dB for the DQPSK receiver and 1.2 dB for the DPSK receiver.

5. Conclusion

In this work, the in-band crosstalk generation inside a typical ROADM for metropolitan optical networks is explained and it is concluded that in a ROADM-based network the total number of in-band interferers that impair the primary signal depends on the number of ROADMs crossed, on their dimension (i.e. degree), as well as, on the wavelength assignment used in the network. To quantify in a rigorous way the impact of in-band crosstalk on the performance of DQPSK signals, an analytical formalism based on the MGF of the receiver decision variable is developed. It is shown that this complex formalism is necessary for assessing the impact of this phenomenon since the PDF of the decision variable is clearly not Gaussian for the majority of the scenarios. In this way, the impact of in-band crosstalk on the performance of DQPSK optical receivers is assessed, through the MGF-based formalism, and compared with its impact on DPSK receivers. This impact is further investigated as a function of the number interferers and considering the scenario where the crosstalk signals have the same modulation format as the primary signal, or a different modulation format. In particular, special attention has been given to the OOK interferer. The analytical results are validated using a stochastic Monte Carlo simulation method.

From our analysis, it can be concluded that DQPSK receivers are less tolerant to in-band crosstalk than DPSK receivers. In particular, it was found that, for a 2 dB OSNR penalty, when the crosstalk signals have the same modulation format as the primary signal, the crosstalk tolerance of DPSK receivers relatively to DQPSK receivers has a maximum value of about 5.3 dB for a single interfering term, whereas for multiple interferers, this tolerance decreases and reaches a constant value of about 4.1 dB for a number of interfering terms superior to 16.

When the interferer has an OOK modulation format and considering the single interferer scenario, we concluded that the crosstalk level is $\sim$1 dB lower relatively to the scenario where the interferer has the same format as the primary signal, for both DQPSK and DPSK receivers. For the eight interferer scenario, we found a crosstalk level decrease of 0.4 dB for the DQPSK receiver and 1.2 dB for the DPSK receiver.

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