Analytical Tools for Evaluating the Impact of In-Band Crosstalk in DP-QPSK Signals

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***Abstract*—An analytical tool based on the moment generating function of the receiver decision variable that can evaluate the impact of multiple in-band crosstalk signals in DP-QPSK (Dual-Polarization Quadrature Phase-Shift Keying) signals is presented. It is shown that when the number of interferers increases from 1 to 64 the crosstalk level, that assure a 2dB power penalty, becomes more stringent, -12 dB for the single interferer scenario and -15 dB for 64 interferers. The Gaussian approximation is also used for comparison purposes.**

***Keywords*—in-band crosstalk; Dual Polarization – Quadrature Phase-Shift Keying; ROADM; moment generating function; optical networks**

I. INTRODUCTION

Efficiency is a key issue in today's transport networks [1]. Improving efficiency at the optical network level, in particular at its physical layer, is achieved by using technologies that can increase the transport capacity of the optical fiber [2]. This transport capacity had a huge boost with the use of optical coherent detection technology, which enables to receive optical signals with advanced modulation formats that put more and more bits in a single transmitted symbol – interface cards for 100 Gbps, using the DP-QPSK (Dual-Polarization Quadrature Phase-Shift Keying) format, are commercially available. Besides improving efficiency by increasing fiber capacity, efficiency can also be improved by providing more flexibility to the optical network building blocks, such as ROADMs (Reconfigurable Optical Add and Drop Multiplexers) [3].

There has been an intense investigation on the development of ROADMs architectures during the past decade [4], and we have been witnessing the evolution from the fixed add/drop structure to a colorless (C), next colorless and directionless (CD) and finally colorless, directionless and contentionless (CDC) structure that allow dynamic capacity allocation. Nowadays, there is a great interest from both carriers and equipment suppliers in CDC ROADMs since the contentionless add/drop feature allows to remove much of the complexity associated with allocating and routing wavelengths through the network [5]. However, these structures potentially use large optical switches where there is a large number of paths between any input/output pair [5], which potentially gives rise to a large number of in-band crosstalk signals. Moreover, these CDC ROADMs usually use multicasting for the add/drop operation which also contributes to increase the crosstalk level [6].

So, an important question arises when we design CDC ROADMs: What is the impact of the physical layer limitations, in particular in-band crosstalk, when these structures are used for routing DP-QPSK signals ?

In-band crosstalk, considered the most limiting type of crosstalk, has been deeply analyzed in systems with direct detection [7]-[9]. First, it was studied in the traditional on-off keying (OOK) systems using simple analytical models based on the Gaussian approximation and later using more rigorous models based on the moment generating function (MGF) of the receiver decision variable [7]. Analytical models based on the MGF for differential phase-shift keying (DPSK) systems [8] and differential quadrature phase-shift keying (DQPSK) systems [9] were also developed.

Regarding coherent detection systems there are already some studies that have analyzed the impact of in-band crosstalk. In 2011, K.-P. Ho published an analytical work that evaluates the impact of this impairment on DP-QPSK systems considering a single interferer and an optical matched filter [10]. Furthermore, there are some studies, based on experimental and simulation tools that analyses the influence of in-band crosstalk in DP-M-ary Quadrature Amplitude Modulation (DP-M QAM) systems [11]-[13].

In this paper an analytical formulation based on the MGF of the decision variable that allow us to study the impact of in-band crosstalk due to multiple interfering terms, originated for example in CDC ROADMs, is developed, considering DP-QPSK signals. We will also study the accuracy of the Gaussian approximation. A stochastic simulation based on the Monte-Carlo method will be used to validate or indicate the accuracy of the analytical formalism.

The remainder of this paper is structured as follows. Section II describes the model used to characterize the DP-QPSK optical receiver in presence of in-band crosstalk. In Section III the theory developed to obtain the MGF of the decision variable at the receiver output is presented. The impact of multiple interferers on the receiver performance is assessed and discussed in Section IV. Section V presents a 3–degree CDC ROADM and the in-band crosstalk generation inside this structure. Finally, some concluding remarks are provided in Section VI.

II. DP-QPSK RECEIVER DESCRIPTION

A DP-QPSK receiver consists of two structures identical to the one depicted in Fig. 1 connected with two polarization beam splitters. Since, in this work we assume that these components are ideal, system performance evaluation can be assessed with only the structure of Fig. 1 [14]. The coherent QPSK receiver model has a 2x4 90° hybrid and two balanced photodetectors.

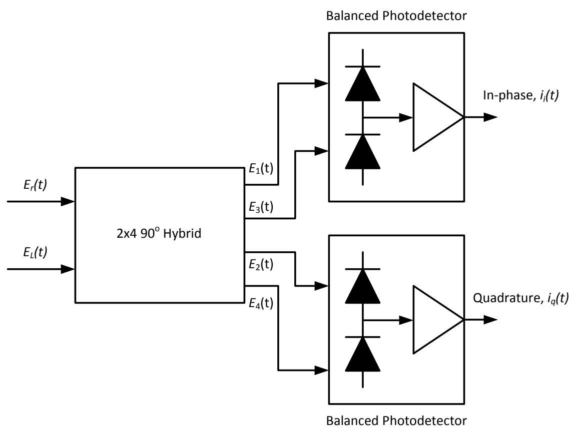


Fig. 1. Structure of a coherent QPSK receiver.

In Fig. 1 $E_r(t)$ and $E_L(t)$ denote the complex envelope of received and local oscillator fields. The 2x4 90º optical hybrid is described by the following input/output relationship [14],

$$\begin{bmatrix} E_1(t) \\ E_2(t) \\ E_3(t) \\ E_4(t) \end{bmatrix} = \frac{1}{2} \cdot \begin{bmatrix} 1 & 1 \\ 1 & j \\ 1 & -1 \\ 1 & -j \end{bmatrix} \cdot \begin{bmatrix} E_r(t) \\ E_L(t) \end{bmatrix} \tag{1}$$

The current at the output of the in-phase and quadrature channels is given, respectively, by $i_i(t) \propto |E_1(t)|^2 - |E_3(t)|^2$ and $i_q(t) \propto |E_2(t)|^2 - |E_4(t)|^2$, which allows us to write,

$$i_i(t) \propto E_r(t) E_L^*(t) + E_r^*(t) E_L(t) \tag{2}$$

$$i_q(t) \propto j\left[E_r(t) E_L^*(t) - E_r^*(t) E_L(t)\right] \tag{3}$$

where $E_L^*(t)$ and $E_r^*(t)$ are, respectively, the complex conjugate of $E_L(t)$ and $E_r(t)$.

In the presence of interference due to N in-band crosstalk signals the received field $E_r(t)$ is given by

$$E_r(t) = \sqrt{GP_s} e^{j\theta_s} + \sum_{i=1}^{N} \sqrt{GP_{xi}} e^{j[\theta_{xi} + \Delta\phi_i(t)]} + E_n(t) \tag{4}$$

where the first term represents the primary signal, the second term the N interfering terms and the third term the amplified spontaneous emission noise (ASE) due to optical amplification. In (4) P_s and P_{xi} represent, respectively, the primary signal optical power and the i-th interferer optical power; θ_s and θ_{xi} represent, respectively, the phase of the QPSK primary signal and the phase of the i-th QPSK interferer taking the values $\pi/4, 3\pi/4, -3\pi/4, -\pi/4$; $\Delta\phi_i(t)$ represent the phase difference between the signal and the i-th interferer and is modelled as a uniformly distributed random variable between 0 and 2π.

In this analysis we are assuming that the primary signal and the interferers are aligned in time as the worst case and aligned in polarization [10]. Furthermore, the ASE noise field $E_n(t)$ is considered to be a zero mean white stationary Gaussian noise that can be expressed in terms of the in-phase and quadrature components as $E_n(t) = n_c(t) + jn_s(t)$ and the local oscillator field E_L can be expressed in terms of its optical power as $E_L = \sqrt{P_L}$.

It can be shown that, for N interfering terms, the in-phase and quadrature currents, respectively, $i_i(t)$ and $i_q(t)$ can be given by,

$$\begin{aligned} i_i(t) \propto\ & 2\sqrt{GP_s P_L} \cos\theta_s + \\ & 2\sum_{i=1}^{N} \sqrt{GP_L P_s \varepsilon_i} \cos(\Delta\phi_i(t)) + 2\sqrt{P_L} n_c(t) \end{aligned} \tag{5}$$

$$\begin{aligned} i_q(t) \propto\ & 2\sqrt{GP_s P_L} \sin\theta_s + \\ & 2\sum_{i=1}^{N} \sqrt{GP_L P_s \varepsilon_i} \sin(\Delta\phi_i(t)) + 2\sqrt{P_L} n_s(t) \end{aligned} \tag{6}$$

where ε_i is the crosstalk level defined by $\varepsilon_i = P_{xi}/P_s$. The total crosstalk level is given by $\varepsilon_T = \sum_{i=1}^{N} \varepsilon_{xi}$. Note that $\Delta\phi_i(t)$ absorbs the crosstalk angle θ_{xi}, in both (5) and (6), since it is modelled as a uniform distribution.

These currents are then electrically filtered by two electrical filters with –3 dB bandwidth B_e and an impulse response $h_e(t)$.

III. ANALYTICAL TOOLS FOR PERFORMANCE EVALUATION

A. *Moment generating function based formulation*

In order to study the impact of in-band crosstalk in a DP-QPSK system the correct characterization of the receiver decision variable is essential. In this work we will use the MGF formulation associated with the wideband optical filtering assumption to describe the statistics of this variable [8]. This assumption implies using an ideal optical filter with a large bandwidth-time product and an integrate-and-dump electrical filter with $h_e(t)=1/T$ (T is the symbol duration) for $t\in[0,T]$ and zero elsewhere. This assumption avoids the problem of solving complicated integral equations by using, for example, complex exponentials as orthogonal functions in the signal and noise expansions [8].

It can be shown that for $\theta_s=\pi/4$ the MGF of (5) is given by

$$M_I(s)=\exp(s\sqrt{GP_sP_L/2})\exp(\frac{1}{2}s^2\sigma_n^2)\prod_{i=1}^{N}I_0(s\sqrt{GP_sP_L\varepsilon_i}) \quad (7)$$

with $I_0(\cdot)$ denoting the modified Bessel function of the first kind of order zero, $\sigma_n^2=P_L<n_c^2>=P_L(S_n/2)B_e$, with $B_e=1/T$ and S_n is the power spectral density of the spontaneous emission noise given by $S_n=h\nu(g-1)F/2$ with $h\nu$ the photon energy at the signal wavelength, and F the noise factor.

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 bit error probability (BEP) and the signal-to-noise ratio (SNR). The average BEP in the in-phase channel is evaluated with the saddlepoint approximation method [9], that uses the MGF presented in (5). In this BEP computation, we assume a worst case scenario where all the interferers are ONES. Assuming that the BEP for the in-phase and quadrature channel are the same, the overall BEP is approximately two times the BEP of the in-phase channel.

B. Gaussian approximation

Besides the use of the MGF we will also use a simpler formulation based on only the first and second order moments of the decision variable - the well-known Gaussian approximation. In this scenario the signal to noise ratio is given by [10],

$$\rho_s=\frac{\rho_{s0}}{1+\varepsilon_T\rho_{s0}} \quad (8)$$

where ρ_{s0} is the signal to noise ratio with only the amplifier noise and is given by $\rho_{s0}=P_s/(h\nu F/2B_e)$ with $B_e=1/T$. So, the overall BEP is given by [10],

$$P_e=\frac{1}{2}\mathrm{erfc}\sqrt{\frac{\rho_s}{2}} \quad (9)$$

where erfc(.) is the complementary error function.

IV. RESULTS

In order to illustrate the application of the formulation developed previously, this section presents some numerical results of the BEP and SNR penalty due to in-band crosstalk in a DP-QPSK signal. Both the single interferer and multiple interferer scenarios will be considered. For comparison purposes, we also used the Gaussian approximation. The ASE noise considered in this section is characterized by $G=30\,\text{dB}$ and $F=3\,\text{dB}$.

A. Single interferer scenario

In Fig. 2 the SNR penalty as a function of the crosstalk level for the single interferer scenario is presented considering the MGF formulation derived in the previous section, the Monte-Carlo simulation reported in [13], the Gaussian approximation and the formalism presented by Ho in [10]. The SNR penalty is a widely used metric to quantify the crosstalk impact and is defined in this work as the increment in decibels in the SNR, required to maintain the error probability fixed at 10^{-3} in the presence of crosstalk.

As can be observed in Fig. 2 our MGF based formulation gives almost the same results as Ho formulation [10]. Also, these results are in agreement with our Monte-Carlo simulation results [13] and with the experimental results reported in [11]. The Gaussian approximation as expected gives a larger penalty, in particular for a crosstalk level of -12 dB the Gaussian approximation predicts a penalty ~ 2 dB greater than the real value.

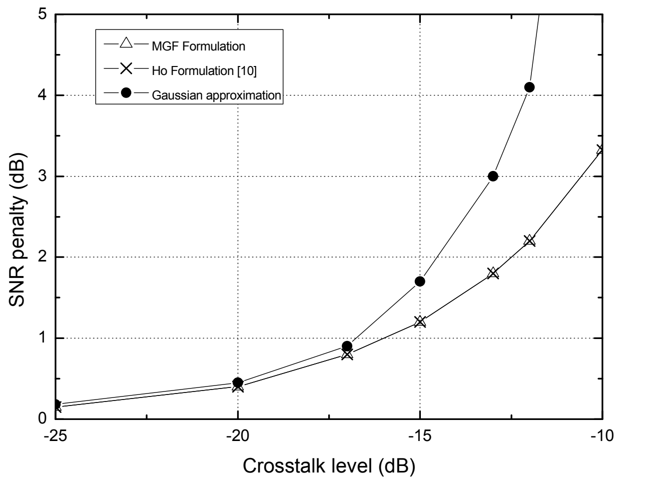


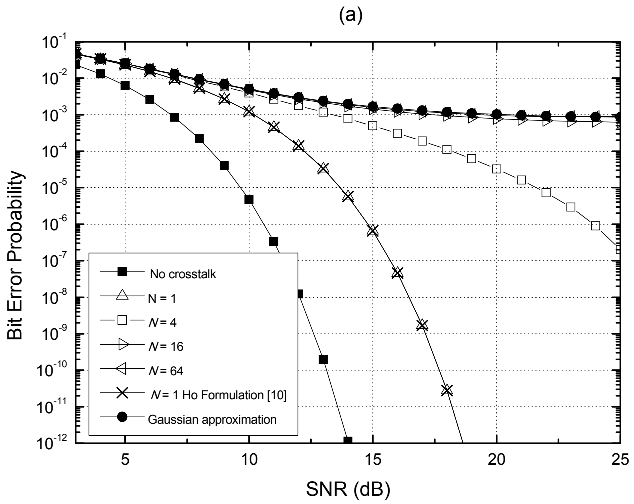
Fig. 2. SNR penalty as a function of crosstalk level for a single interferer scenario.

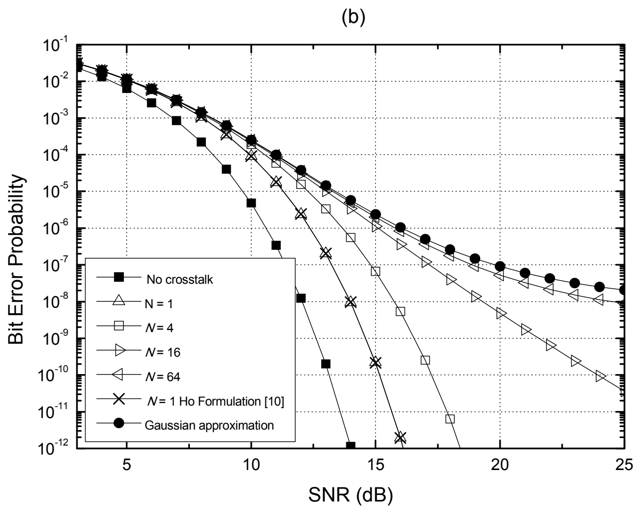
B. Multiple interferer scenario

In this sub-section the impact of in-band crosstalk due to multiple interfering terms is analyzed in terms of the BEP and also in terms of the SNR penalty. In both scenarios the

Gaussian approximation is also represented for comparison purposes.

In Fig. 3 the BEP is represented as a function of the SNR (@ 20 Gbaud) considering a crosstalk level of, Fig. 3(a), -10 dB, Fig. 3(b), -15 dB, and Fig. 3(c), -20 dB, and for four scenarios: single interferer, 4 interferers, 16 interferers and 64 interferers. In these figures the situation with no crosstalk is also represented, as well as the results obtained by Ho formulation [10] and by the Gaussian approximation. As can be observed from Fig. 3 as the crosstalk level increases from -20 dB to -10 dB the BEP for a large number of interferers becomes completely different from the BEP for a single interferer. For the -10 dB crosstalk level scenario for a large number of interferers the BEP even reach a BEP floor. As expected the Gaussian approximation gives very similar results in comparison with the 64 interferers case.





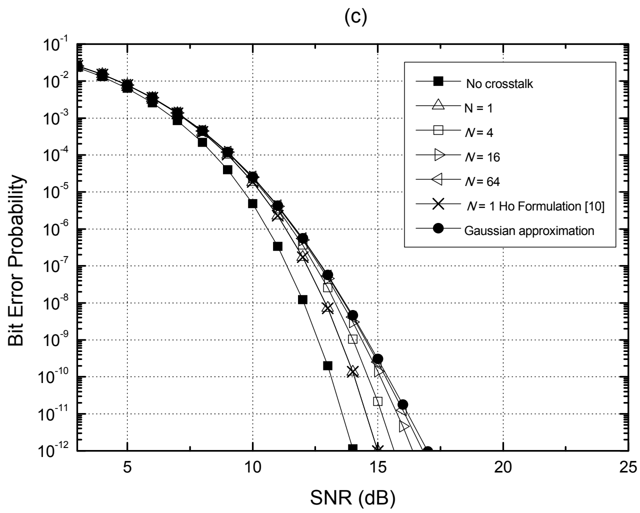


Fig. 3. BEP as a function of the SNR (@ 20 Gbaud) considering a crosstalk level of (a) -10 dB; (b) -15 dB; (c) -20 dB, with the number of interfering terms as a parameter. The situation with no crosstalk is also represented, as well as the Gaussian approximation and the Ho formulation [10] curve ($N = 1$).

In Fig. 4 the SNR penalty as a function of the crosstalk level for multiple interfering terms ($N = 1, 4, 16, 64$) is presented considering the MGF formulation derived in the previous section. For a 2-dB SNR penalty the single interferer scenario is ~2 dB more tolerant than the 64 interferer case.

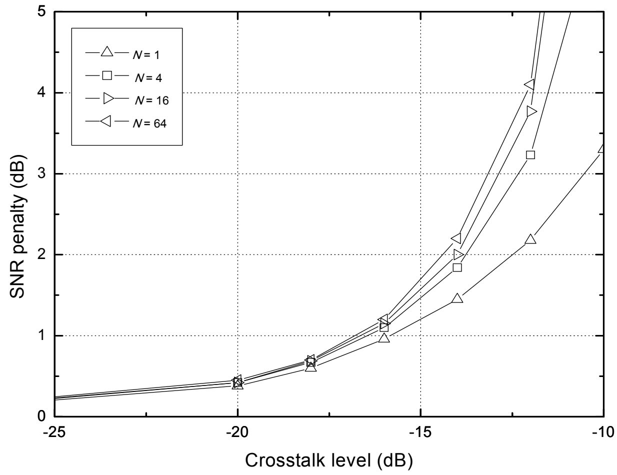


Fig. 4. SNR penalty as a function of crosstalk level for multiple interfering terms: 1, 4, 16 and 64.

V. EXAMPLE OF IN-BAND CROSSTALK GENERATION INSIDE A 3–DEGREE CDC ROADM

In this section the in-band crosstalk generation inside a 3–degree CDC ROADM based on a broadcast and select architecture is analysed [5], [6]. The structure of this ROADM is shown in Fig. 5. We consider that in each input fiber there are four wavelengths, λ_1, λ_2, λ_3 and λ_4. These input signals are split, with a 1×3 splitter, to the other directions outputs and to the drop port. In each fiber output the wavelength is selected by the corresponding wavelength selective switch (WSS 3×1). In the drop port the wavelength is selected by a multicast switch (MCS) – in our example we have a 3×12 MCS. In the add port we have a 12×3 MCS.

In order to quantify the number of interfering terms generated inside the ROADM depicted in Fig. 5 we consider that the red wavelengths, λ_1, in all the three fiber inputs, are dropped and three new signals with wavelength λ_1 are added and directed to the three output fibers. We also assume that the other wavelengths signals, λ_2, λ_3 and λ_4, are express signals. In this worst case scenario each output signal λ_1 is impaired by four in-band interferers, two of them generated by the red signals presented at the other two directions and the other two generated by the two signals λ_1, besides the primary signal, presented at the add port. These crosstalk signals appear, respectively, due to imperfect isolation of the WSS and the MCS. Also, we can observe that at the drop port each signal λ_1 is impaired by two in-band interferers generated by the signals at the other two fiber inputs due to imperfect isolation of the MCS. The out-band crosstalk is also represented in Fig. 5.

The observations from the previous paragraphs, for a 3–degree CDC ROADM, can be generalized for a *N*–degree CDC ROADM. Consequently, for a *N*–degree CDC ROADM based on a broadcast and select architecture the maximum number of in-band crosstalk signals at each fiber output is $2(N-1)$ and at the drop port is $N-1$, assuming that all the signals with wavelength λ_1 are dropped and added.

In a realistic scenario where the primary signal path can cross multiple CDC ROADMs until it reaches the receiver the number of interferers could be considerably larger. So, it can be concluded that the total number of in-band interferers depends on the number of ROADMs crossed, on their degree, as well as, on the wavelength assignment used in the network.

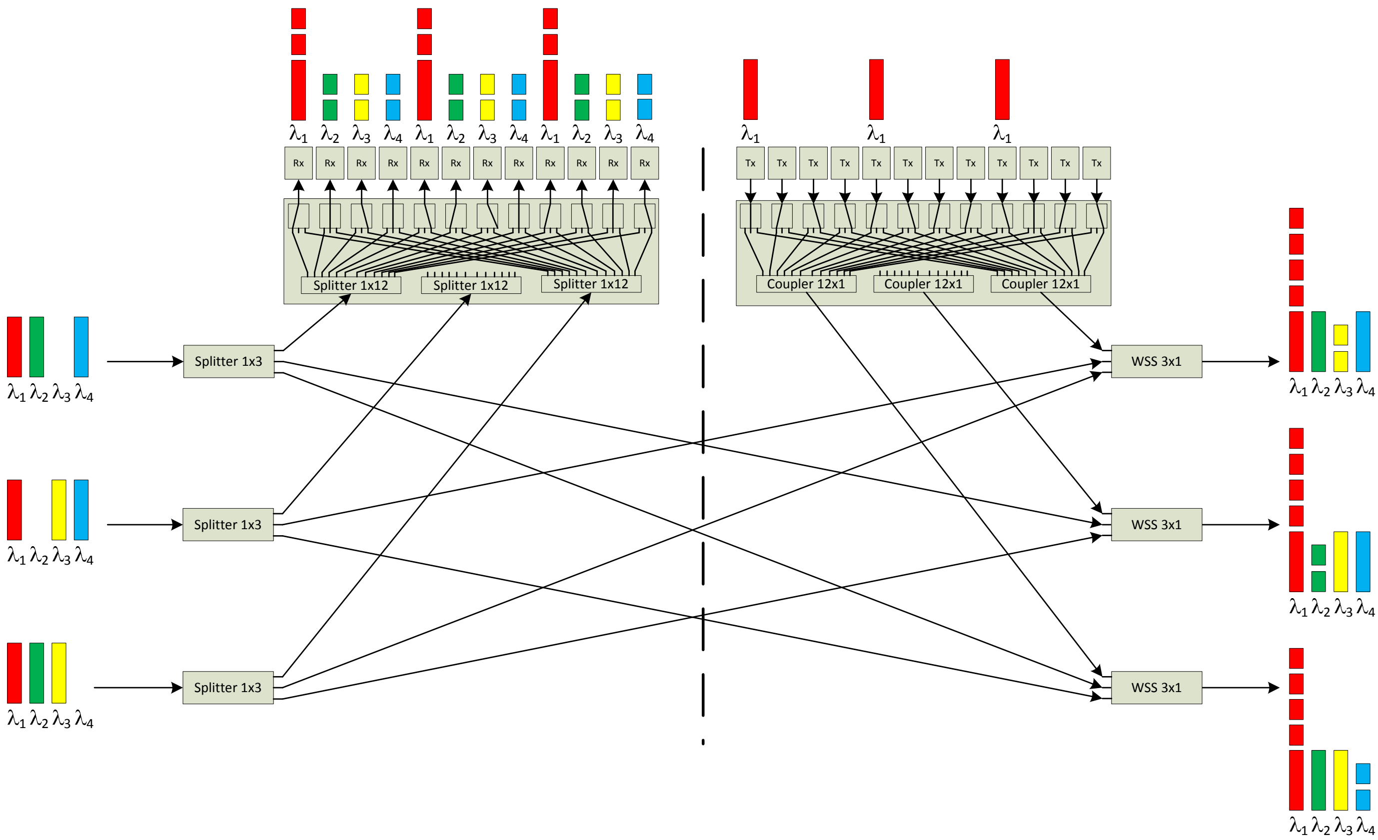


Fig. 5. A 3–degree CDC ROADM based on a broadcast and select architecture with the crosstalk generation inside this structure, both in-band and out-band.

VI. CONCLUSIONS

In this work we quantified the impact of in-band crosstalk due to multiple interferers in DP-QPSK signals. The multiple interferer scenario appears in CDC ROADMs with multicasting on the add & drop ports that are expected to be used in a near future.

We used a MGF based formulation that relies on the wideband optical filtering assumption to evaluate the impact of in-band crosstalk. For comparison purposes the Gaussian approximation was also used. The SNR penalty for a single interferer is in agreement with other works in the literature. The multiple interferer scenarios, as expected, give larger penalties and approximates to the Gaussian approximation for a large number of terms. For a crosstalk level of -12 dB the single interferer case gives a 2.2 dB penalty, whereas the 64 interferer case gives a 4.2 dB penalty.

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