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Power Penalty and Bit Error Rate Investigation due to Crosstalk in Bidirectional Optical Transceiver

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Abstract - **Optical communication is privileged over conventional radio or microwave communication in its immunity against crosstalk interference under specific constraints such as: "good wave length separation, ideal connectors, splices circulators, arrayed wave guide gratings (AWGs) as well as ideal semiconductor components; Otherwise crosstalk will be a disturbing problem that degrades the system performance. This crosstalk is arising from several impairments such as dispersion, multiple access interference (MAI), all forms of noise, nonlinear effects, and due to the detection of undesired signals at the same numerical wavelength. The severe effect of crosstalk will introduce large power penalties and bit-error rate (BER) that restricting the performance of optical networks. The current manuscript; proposes to tackle the effect of cross talk in bidirectional optical transceiver using good wave length separation with ideal components. Also, investigates the effect of crosstalk on power penalty of optical communication receiver due to the contributions of the thermal noise in PIN photodiode and spontaneous beat noise in avalanche photodiode (AVD). Moreover; the BER performance with and without crosstalk has been evaluated. Furthermore; the relation between the crosstalk versus the number of channels and hops will be investigated.**

Key words: Bidirectional, Crosstalk, Power penalty, Thermal noise, Beat noise, and BER.

1. INTRODUCTION

Optical fiber cables are widely used in fiber optic communications to support multimedia such as "LAN, WAN, MAN, Broadcast, and TV services". They permit transmission over longer distances with higher data rates than the other forms of transmission media. High capacity optical telecommunication systems deploy wavelength channels at data rates higher than 10Gbit/s in each channel. Although the potential number of channels in an optical fiber may be large enough to fulfil the required information capacity, it is limited by the bandwidth of optical devices, such as optical amplifiers. As a result, the wavelength channels should be allocated as close as possible to each other within the amplifier band. System impairments will occur when optical wavelength-selective components along the transmission are not able to distinguish the closely- spaced wavelength channels so that, the optical fiber can no longer be treated as a linear medium. As a consequence, optical crosstalk can places constraints on the performance of optical transmission. This crosstalk occurs in multichannel optical transmission system due to signals from one channel arrive in another they become noise in the other channel. This crosstalk has serious effects on the signal-to noise ratio, the error rate and the power penalty of the system.

The main reasons for the occurrence of the crosstalk are due to no good wave lengths separation among channels, not using ideal optical components such as circulators, splices, AWGs and connectors. Moreover, some impairments of optical communications lead to the occurrence of crosstalk such as dispersion, MAI and all forms of noise in addition to nonlinear effects (i.e. Cross-phase modulation, Four-Wave Mixing, Simulated Raman scattering and Simulated Brillouin Scattering). So the work of this manuscript investigates the effect of intra-band crosstalk on the BER and the power penalty of the system. Where; the intra-band crosstalk gives rise to a significant signal degradation and power penalty that leads to an increased bit error probability [1-2]. Network performance will not only limited due to the intra-band crosstalk arises in bidirectional optical cross connect (BOXC), but also due to spontaneous beat noise in AVD and thermal noise in PIN photodiode. So, all these limitations will be considered in this work.

The main goals of this paper are to: 1) tackle the effect of cross talk in bidirectional optical transceiver. 2) Investigate the effect of crosstalk on power penalty of optical communication receiver due to the contributions of thermal noise in PIN photodiode and spontaneous beat noise in avalanche photodiode (AVD). 3) Evaluate the BER performance with and without crosstalk. 4) Investigate the relation between crosstalk with the number of channels and hops.

The paper is organized as follows: Section 2, classifies the different kinds of crosstalk, Section 3, dedicated for the proposed optical transceiver architectures, Section 4, analyses power penalty due to cross talk, Section 5, investigates BER with crosstalk, Section 6, investigates BER without crosstalk, Section 7, dedicated for the simulation results, finally Section 8, will highlight the conclusion tailed by the more relevant references.

2. CROSSTALK CLASSIFICATION

Crosstalk can be broadly classified into linear and non-linear types. Fig. 1 illustrates the different types of optical crosstalk that may arise in wavelength division multiplexing (WDM) networks.

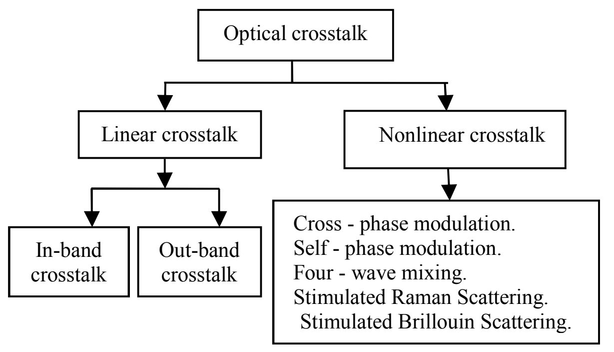


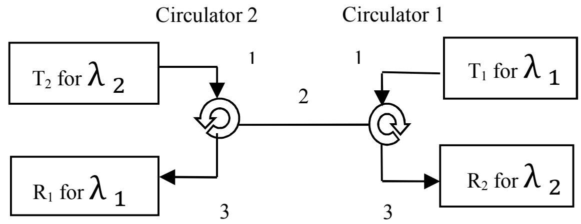
Fig.1: Different types of crosstalk in WDM networks.

The above classification depends on the network topology and the components that used. In metropolitan and long-haul networks, optical fibre characteristics are strongly affected by the power and frequency of propagated WDM channels. Although the power in each channel of the WDM signal may be below that needed to produce fibre non-linearity, the total power summed over all channels can quickly become significant [3]. Nonlinearity causes inter-channel effects such as Self Phase Modulation (SPM) [4], Cross Phase Modulation (XPM) and Four Wave Mixing (FWM) [5]. In local area networks (LANs), which are used to transmit data over short distances, the effect of nonlinearity is less challenging. Linear crosstalk is the dominant type and results from non-ideal performance of WDM nodes. So; this manuscript focuses on this kind of crosstalk which has been categorized into two main kinds. The first kind is called *inter-band* crosstalk which is known by “out of band” crosstalk i.e., the crosstalk and desired signal fall into different wavelength bands. While the second kind is called, *intra-band cross talk which is* known “in band crosstalk” i.e. the crosstalk and desired signal fall within the same wavelength band [6, 7].

It has been reported that [8]; out-of-band crosstalk can be eliminated through the use of a de-multiplexer or narrowband filter. However, such techniques are unable to remove the effects of in-band crosstalk which is too severe to be ignored [6], due to it causes power penalty which in turn increases the bit error rate. The in-band crosstalk will be investigated in two cases. The first case, when the received signal is dominated by thermal noise and the second case, when the received signal is dominated by spontaneous beat noise.

3. PROPOSED ARCHITECTURES for the TRANSCEIVER

In this section; I suggest to implement an ideal optical communication system using appropriate wavelength separation between channels, dense wave length division multiplexing (DWDM) and ideal components such as LASER diodes, single mode fiber (SMF), ideal circulators, connectors, splices, arrayed wave guide gratings (AWGs) and avalanche photodiode (AVD) with full duplex transceiver to increase the capacity. Two architectures based on bidirectional optical transceivers have been addressed. The first architecture is a simple duplexer system as clarified in Fig.2 in which bidirectional transceiver has been used for full duplex to transmit and receive optical signals through one SMF cable. To avoid crosstalk we adopt wavelength separation between each two signals not less than 0.8 nm (i.e approximately 100 GHz). In this architecture; two transmitters, two receivers, two optical signals have been transmitted through one SMF. The circulator plays an important role of controlling the incoming and outgoing signals at the two transceivers since the distance between the two transceivers is constant. Then, the power of the two signals must be the same with different wave lengths.



T_1: Transmitter number one, T_2: Transmitter number two, R_1: Receiver number one, and R_2: Receiver number two.

Fig.2: Full duplex optical transmission

Fig. 3 illustrates the second proposed architecture using dense wavelength division multiplexing (DWDM) for full duplex.

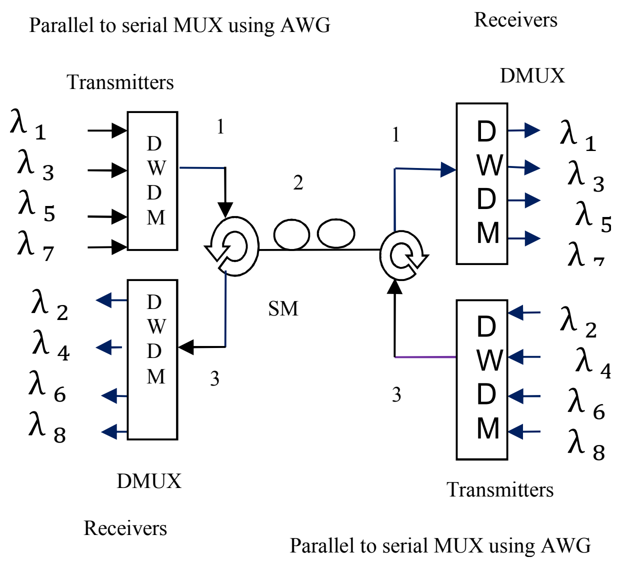


Fig.3 Full duplex Multi - channel DWDM optical transmission

In this architecture more than two optical signals have been transmitted from each transmitter through one SMF simultaneously. In this diagram; AWG is used, and the optical signals have been classified into two categories. The first category classifies the optical signals into two groups, odd signals such as $\lambda_1, \lambda_3, \lambda_5, \lambda_7$ and even signals such as $\lambda_2, \lambda_4, \lambda_6, \lambda_8$. The second category classifies the optical signals into two groups also, upstream such as $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ and downstream such as $\lambda_5, \lambda_6, \lambda_7, \lambda_8$. The transmitted optical signals have the same power but their wavelengths are different to avoid crosstalk.

4. MODELING and ANALYZING POWER PENALTY due to CROSSTALK

Power penalty in optical communication is the tax in optical power that should be paid to compensate the performance degradation of the system due to crosstalk impairment. This crosstalk will effect on the optical photo detector's sensitivity due to the contribution of several impairments [9] such as thermal noise in PIN photodiodes, quantum shot noise in avalanche photodiode (APD), chromatic dispersion and fiber modal noise.

Power penalty is equal to the rate of increasing the signal power to keep the *Q* factor and BER at the same level that would exist if no impairments were present [10]. Thus in the rest of this section, I will discuss and analyze the power penalty for some crosstalk values and will be simulated by mat lab programming. Moreover, a comparison study among different crosstalk values will be performed.

Power penalty due to crosstalk is regarded as the reduction of power level differences between the one and the zero states which is represented by [8]:

$$P_d = \left\{ \frac{p(t_1)\Big|_{d_s(t_1)=1} - p(t_0)\Big|_{d_s(t_0)=0}}{A^2/2} \right\} \quad (1)$$

Where

$[p(t_1)\Big|_{d_s}(t_1) = 1]$ is the optical power in state one,

$[p(t_0)\Big|_{d_s}(t_0) = 0]$ is the optical power in state zero

The power penalty is given by:

$$P_p = -10 \log \{P_d\} \quad (2)$$

Since the spectral emission from the laser diode will be considered a Gaussian distribution, thus the mean and variance for a random variable will be given by:

$$E\,[P_d] = 1 \quad (3)$$

$$\text{var}\,[P_d] = \sum_{1}^{X_n} \delta_c \quad (4)$$

Where

δ_c : is the crosstalk coupling coefficient

In the case of optical receiver, noise is dominated by *thermal noise*; the power penalty to the received optical signal is given by [8]:

$$P_p = -10 \log \left(1 - 6\sqrt{\sum_{i=1}^{X_n} \delta_c} \right) \quad (5)$$

Where

P_p : represents the power penalty of the receiver optical signal

X_n : is the number of crosstalk elements

While in the case of optical receiver noise is dominated by *spontaneous beat noise*, the power penalty in accurate estimation is given by [8]:

$$P_p = -5 \log \left(1 - 6\sqrt{\sum_{i=1}^{X_n} \delta_c} \right) \quad (6)$$

From the previous Equations "(5)" and "(6)" it is clear that; the relationship between the power penalty and the crosstalk must be directly proportional to each other and the relationship between the signal power received and the power penalty is inversely proportional. So from Eq. "(5)" and Eq. "(6)" we can use the Matlab to simulate the power penalty of optical fiber duplexer in case of the optical receiver detects thermal noise and spontaneous beat noise respectively.

5. BER INVESTIGATION with the PRESENCE of CROSSTALK

In this section; the BER performance degradation due to crosstalk is evaluated and discussed for optical cross connect (OXC) parameter and number of wavelengths per fiber. This BER is defined as the number of bit errors which occurs within the space of one second and can be given by [11]:

$$BER = 0.5 \; erfc \; \left(\frac{Q}{\sqrt{2}}\right) \quad (7)$$

Where:

Q: is a function proportional to the receiver signal-to-noise ratio (SNR) and is expressed as:

$$Q = (R_b * P_i)^{\wedge}2 \Big/ \sqrt{(\delta_{ase}{}^{\wedge}2 + \delta_c{}^{\wedge}2} \quad (8)$$

Where:

R_b : Bit rate (bit/s)

P_i = Input power in dbm

δ_c = Crosstalk coupling coefficient

δ_{ase} =Amplified spontaneous emission noise induced by parametric gain and spontaneous Raman scattering in optical fiber Raman amplifier.

$$\delta_{ase} = \sqrt{(G-1) * S_e} * h * f * (B.W) \qquad (9)$$

Where:
G = Gain
S_e = Spontaneous Emission Factor
h = blank's constant = $6.634*10^{-34}$
f = frequency of the signal
c = Speed of light
λ = Wavelength
$B.W$= Band width in hertz.

In case of using different number of channels and hops, thus crosstalk can be calculated using the same input power number by:

$$\delta_c^2 = N_H * R_{spp}^2 * R_d^2 * P_i^2 * (2 * \varepsilon_{adj} + (N_{ch} - 3)\varepsilon_{nonadj} + X_s \qquad (10)$$

Where:
N_H = Number of hops
R_{spp} = Ratio of signal peak power
N_{ch} = Number of channels
R_d = Detector resistance
ε_{adj} = Effective adjacent channel crosstalk
ε_{nonadj} = Effective non adjacent channel crosstalk
X_s = crosstalk value of the optical switch.

6. BER INVESTIGATION without CROSSTALK

Crosstalk can be tackled in optical communication system by implementing ideal system design using, ideal AWGs, circulators, DWDM, and other optical devices in addition to, good wavelength separation among channels. For this case crosstalk δ_c will be considered zero. Thus Eq. "(8)" can be rewritten in the simplified form with $\delta_c = 0$ as:

$$Q = {(R_b * P_s)^{\wedge}2} \big/ {\delta_{ase}} \qquad (11)$$

From Eq. "(11)" in Eq. "(7)"; we can get the BER without crosstalk using different values for the bandwidth such as: $B.W = 2 * R_b$, $B.W = 4 * R_b$, $B.W = 6 * R_b$,... etc .

7. SIMULATION RESULTS

7.1: Simulation results for power penalty due to crosstalk

In the simulation results using Matlab the work will be focused on the more dangerous kind of crosstalk which is the intra-band crosstalk. Where the second kind of inter-band crosstalk can be avoided using small range detector or narrow band filter.

First, when the system is implemented such that each transmitter transmits one optical signal as indicated previously in Fig. 2 of the first proposed architecture. The power penalty versus crosstalk coupling coefficient in dB when the optical receiver detects thermal noise, and spontaneous beat noise using the mathematical model in Eq. "(5)" and Eq."(6)" respectively. I have got the rang of crosstalk coupling coefficient δ_c from -65 dB up to -25 dB to cover all the possibilities of crosstalk values. The simulation result in Fig. 4, illustrates some of the crosstalk values that have been chosen randomly and tabulated in Table 1 below.

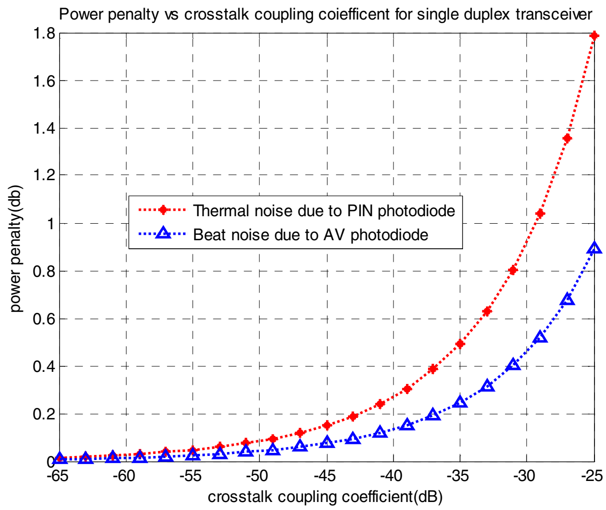


Figure 4: Power penalty versus crosstalk coupling coefficient for the case when each transmitter transmits one signal.

TABLE1: The relation between crosstalk coupling coefficient (δ_c) and power penalty (P_P)

δ_c		PP	
Detection of thermal noise	**Detection of beat noise**	**Detection of thermal noise**	**Detection of beat noise**
-45	-45	0.1491	0.07453
-43	-43	0.09425	0.1885
-41	-41	0.2	0.1193
-39	-39	0.3027	0.1513
-37	-37	0.3846	0.1923
-35	-35	0.49	0.245
-33	-33	0.6264	0.3132
-31	-31	0.8045	0.4023
-29	-29	1.04	0.5198
-27	-27	1.355	0.6775
-25	-25	1.788	0.8938

The number of crosstalk elements in this case is only one due to in this architecture only one optical signal from each transmitter has been sent. The results illustrate that; the power penalty is increasing by increasing the value of crosstalk and hence, cause degradation to the received data transmitted from other transmitter. The upper curve in Fig.4; represents the power penalty when the optical receiver detects *thermal noise*, while the lower curve represents the power penalty when the optical receiver detects *spontaneous beat noise*. So, this result has approved that, the crosstalk which dominated by the thermal noise provides higher power penalty than the spontaneous beat noise.

Second, for DWDM architecture in which more than one optical signal transmitted simultaneously as illustrated previously in Fig.3, in this case the number of crosstalk elements depend on the number optical signals transmitted from the transmitter. Our simulation result in Fig. 5 reveals that; as long as the number of crosstalk elements is small, so the power penalty caused by the intra-band crosstalk would be low and vice versa.

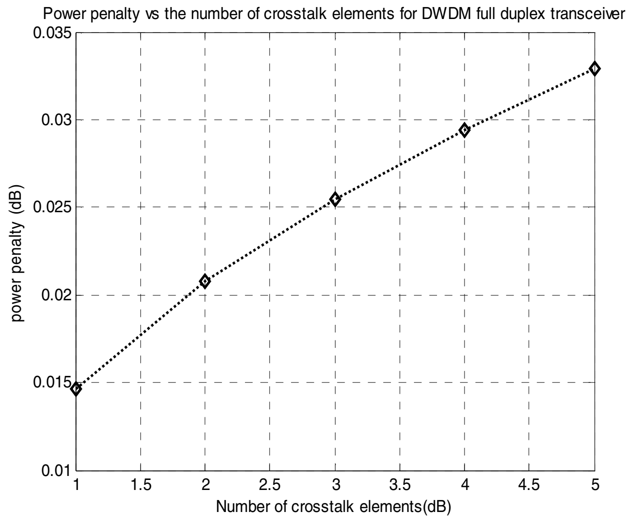


Figure 5: Power penalty versus crosstalk elements for the case when each transmitter transmits more than one signal.

7.2 Simulation results for BER versus input power

7.2.1 BER without crosstalk ($\delta_c = 0$)

From equations “(7)”and “(11)” for ideal system design, so the crosstalk will equal to zero. I have carried-out the simulation results in Fig. 6 using different values of B.W such as $B.W = 2 * R_b$, $B.W = 4 * R_b$, *and* $B.W = 6 * R_b$. The results reveal that; the higher the bandwidth, the higher the BER and vice versa. On the other hand; the larger the amount of input power, the lower the BER.

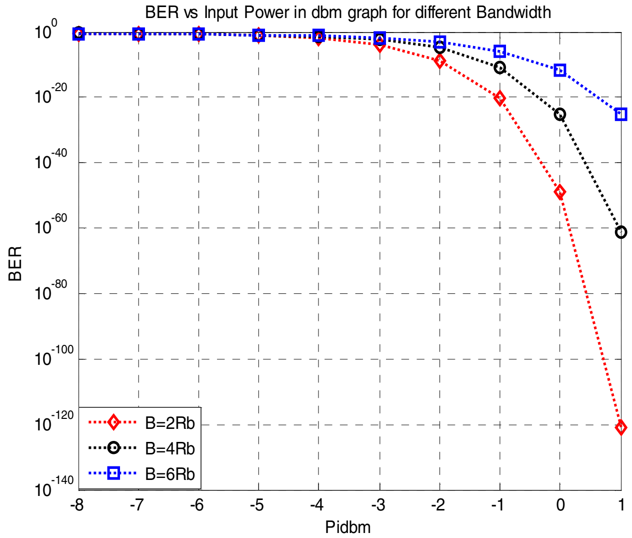


Figure 6: BER vs input power dbm for different Bandwidth.

7.2.2 BER with crosstalk

From Equations “(7, 8 and 9)”, after using the mat lab simulations, the results are given in Fig. 7 below. The input power has taken in the range from -10 dBm up to 15 dBm. The results clarify the relation between BER against the received input power in dBm for fixed band width at B.W= $2R_b$ with different crosstalk values. It is clear that; for ideal components design and good wavelength separation we can get zero crosstalk, and hence we have got the lowest BER with less power as indicated in the lower curve at S_c = 0, and the other curves for different crosstalk values. The power penalty is the difference between two powers; namely input power with a specific crosstalk and input power without crosstalk, so to calculate the power penalty we need to calculate the difference of input power with crosstalk from the power without crosstalk. For example, we have got 10^{-6} BER and calculated the power penalty corresponding to this value. We have got input power -2.5 dBm when the crosstalk is zero. For input power 3.5dBm, the crosstalk is 10^{-4} and the power penalty = 3.5 dBm - (-2.5 dBm) = 6 dBm. For input power 8 dBm, the crosstalk is 10^{-3} and the power penalty equal 10.5 dBm. For input power 11dBm, the crosstalk is 10^{-2} and the power penalty equal 13.5 dBm. For input power 13 dBm, the crosstalk is 10^{-1} and the power penalty equal 15.5 dBm.

Referring to Equations “(7, 8, 9)” and “(10)” the simulation results in Fig. 8; illustrates the relation between crosstalk against the number of the used channels for different hops. It is obvious that; the crosstalk is increasing with increasing the number of channels and the number of hops.

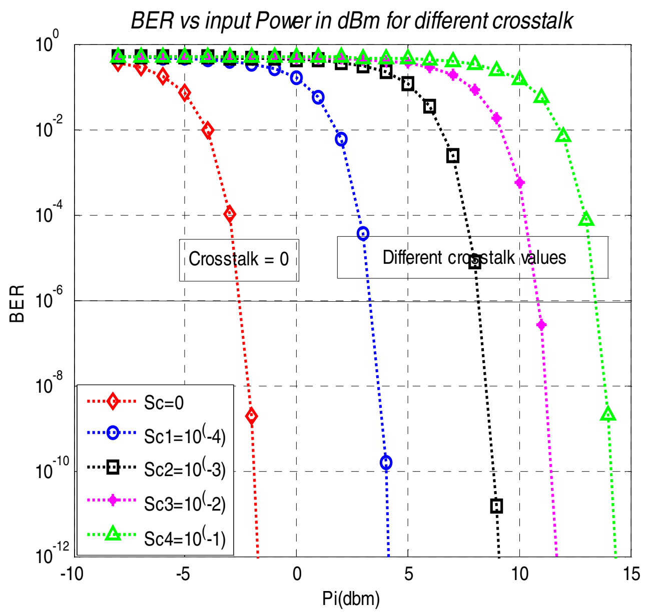


Figure 7: BER vs input power in dbm for different crosstalk.

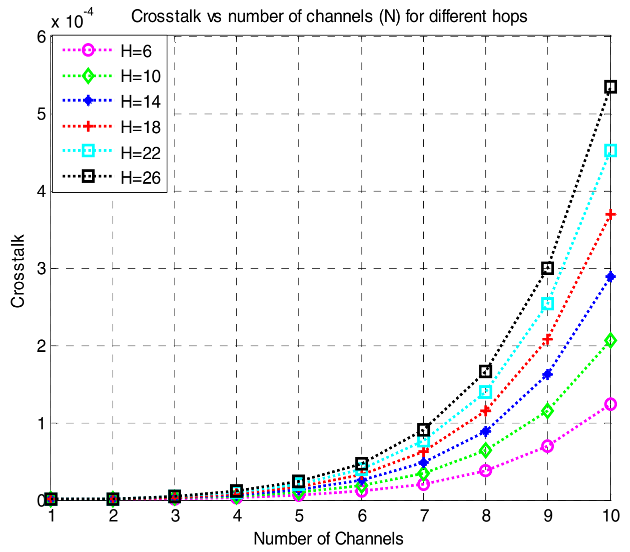


Fig. 8: Crosstalk vs number of channels with different hops

8. CONCLUSIONS

In this Manuscript; bidirectional optical transceiver for full duplex has been addressed to increase the capacity and reduce the cost. In the proposed architecture; the manuscript addressed the physical impairments that cause crosstalk, and they have considered in the system implementation to avoid the crosstalk and hence the power penalty. Also the paper investigated the effect of crosstalk on power penalty of optical communication receiver due to the contributions of the thermal noise in PIN photodiode and spontaneous beat noise in avalanche photodiode (AVD). Moreover; the BER performance with and without crosstalk has been evaluated. Furthermore; the relation between crosstalk versus the number of channels and hops has been investigated. The simulation results revealed that; the power penalty due to the effect of thermal noise in PIN photodiode is more harmful than the effect of spontaneous beat noise in avalanche photodiode, and they approved that; the intra-band crosstalk did not affect the received signal as long as it is less than -25 dB. If we have implemented ideal system design using the addressed procedures, the crosstalk will equal to zero and hence we can get lower BER with lower input power than the case when the crosstalk exists. BER versus input power with and without crosstalk has been carried out in the simulation results, and the power penalty for each crosstalk has been calculated. Finally, the relation between crosstalk against the number of channels with different hops has been investigated, and the results revealed that; increasing the number of channels and the number of hops will increase the crosstalk which in turn increases the power penalty and BER.

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