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Crosstalk Impact and Performance Evaluation of Optical Cross Connects in Different Transparent Wavelength Division Multiplexed Optical Transport Networks

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Abstract— ***This paper has presented different wavelength division multiplexing techniques that have dramatically increased the capacity of optical transmission systems. Its main advantages have made it the current favorite multiplexing technology for optical networks. That is no doubt that Crosstalk is generated when a demultiplexer separates incoming wavelengths onto different output fibers. Optical cross connect (OXC) is a device which is used for switching high speed optical signals. We have deeply investigated the performance analysis to find the dramatic effect of crosstalk in different multiplexed optical networks. Firstly, the performance in coarse wavelength division multiplexing (CWDM) have been investigated and then compared the results with using two multiplexing techniques namely, wavelength division multiplexing (WDM) and dense wavelength division multiplexing (DWDM). Signal to noise ratio (Q) or signal quality factor, bit error rate (BER), and power penalty are the major interesting performance parameters in the current study. System parameters optimization are applied to reduce the effect of crosstalk.***

Index Terms— ***Optical cross connect, Signal to noise ratio, Bit error rate, Crosstalk, Nonlinearity effect, and Power penalty.***

I. INTRODUCTION

Optical wavelength division multiplexing (WDM) networks are very promising due to their large bandwidth, their large flexibility and the possibility to upgrade the existing optical fiber networks to WDM networks. WDM has already been introduced in commercial systems [1]. All optical cross connects (OXCs), however, have not been used for the routing of the signals in any of these commercial systems. Several OXC topologies have been introduced, but their use has so far been limited to field trials, usually with a small number of input–output fibers and wavelength channels. The fact, that in practical systems many signals and wavelength channels could influence each other and cause significant crosstalk in the optical cross connect, has probably prevented the use of OXC's in commercial systems [2]. The crosstalk levels in OXC configurations presented so far are generally so high that they give rise to a significant signal degradation and to an increased bit error probability. Because of the complexity of an OXC, different sources of crosstalk exist, which makes it difficult to optimize the component parameters for minimum total crosstalk [3].

The continuous increase in the demand for broadband services will impose unprecedented demands on the transport optical layer in terms of transmission capacity and routing agility. WDM is widely recognized as the preferred transport mechanism for the next generation of high capacity systems. WDM transmission experiments of 1 Tbit/s have already been reported [4]. An important step towards the implementation of end-to-end optical networks, is the realization of a reliable and simple OXC that is able to scale smoothly in order to cope with this increased transmission capacity. The cross connect throughput is defined as the product given by the number of input/output links times the number of wavelength channels per link times the bit-rate per link. Apparently, OXCs with over 10 Tbit/s throughput will be needed. OXCs in wavelength routed networks are attractive due to their reduced complexity in routing and connection set-up procedures. The cross connection of the various wavelength channels is implemented using space switches with either a crossbar fabric or a bus fabric, something that generates interrelation (crosstalk) between the channels. Large crossbar switches are lossy and their performance is optimum only for one wavelength channel. In this case, the designer is bound to select only one architecture (Scheme 1 in [5]) something that is not desirable due to the attributed crosstalk limitations. Space switches in the form of amplifier gate switch arrays [6] are attractive but again their complexity should be traded with performance [7] and their scalability per node is limited due to amplified spontaneous emission (ASE) accumulation to a switch size of 32 x 32 [8]. For each delivery-and-coupling switch, a power combiner is used with number of ports equal to the number of wavelength channels something that is scaling up the passive losses for a considerable number of channels. This architecture is suitable for a large number of links populated with a small number of wavelength channels something that underutilize the fiber bandwidth. Also, it does not have broadcast capability.

The paper is organized in the following sections. Section II has explained the optical communication transmission systems based on optical cross connects. Section III has presented the basic equations and analysis of the performance parameters of optical cross connects. Section IV has presented the simulation results and performance evaluation of optical cross connects in optical communication networks. Finally, section V has presented the summary of optimization performance parameters to reduce the crosstalk effects.

II. TRANSMISSION SYSTEM BASED ON OXC BLOCK DIAGRAM

A general structure for such WDM Transmission system with optical cross connects are shown in Fig. I. Here, multi nodes of a cross connect are shown in a two sided model with the transmit side on the left and the receive side on the right. As shown in the figure, Data comes from any source. Each transmitted signal carries a number of unique wavelengths which correspond to the destination data, here several channel multiplexed and go optical cross connect [9].

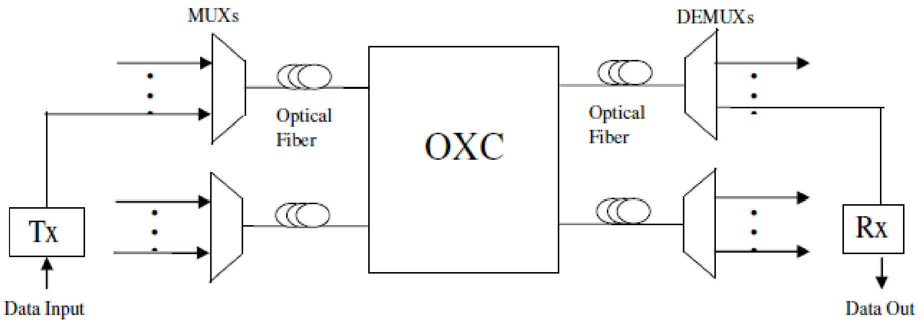

Fig. I. Block diagram of an optical WDM transmission system with an OXC [9].

All the optical signals are wavelength-multiplexed and are transmitted over a single mode fiber to the network hub. At the hub wavelength de multiplexers separate the signals from each incoming fiber. All channels intended for a given destination are passively re arranged, and since they were allocated different wavelength, they can be wavelength multiplexed and sent towards the destination on a single fiber. At the receiver of each node, the different channels are wavelength de multiplexed.

III. OXC MODELING ANALYSIS

For most practical WDM networks, this requirement of BER is 10^{-12}, which means that a maximum one out of every 10^{12} bits can be corrupted during transmission. Therefore, BER is considered an important figure of merit for WDM networks; all designs are based to adhere to that quality. BER in WDM system is calculated by the equation [9]:

$$BER = 0.5\, erfc\left(\frac{Q}{\sqrt{2}}\right) \qquad (1)$$

Where Q is a function proportional to the receiver signal-to-noise ratio (SNR) which can be given by:

$$Q = \frac{\left(P_S\ R_b\right)^2}{\sqrt{\sigma_{ASE}^2 + \sigma_c^2}} \qquad (2)$$

Where R_b is the transmission bit rate, P_s is the signal power in dBm, σ_c is the crosstalk, and σ_{ASE} is the ASE (amplified spontaneous emission) noise induced by parametric gain and spontaneous Raman scattering in optical fiber Ramen amplifier. It is an unwanted noise which can be described by the following equation [3, 5]:

$$\sigma_{ASE} = \sqrt{2\,(G-1)\, n_{sp}\, h\, \frac{c}{\lambda} R_b} \qquad (3)$$

Where G is the gain, n_{sp} is the spontaneous emission factor or population inversion factor, h is the Planck's constant, c is the speed of light, and λ is the operating optical signal wavelength. For the same input power crosstalk can be calculated for different number of channels and hops using the equation [6]:

$$\sigma_c = \sqrt{M\,(b\, R_d\ P_S\ )^2 \left(\left(2\,\varepsilon_{adj} + (N-3)\varepsilon_{nonadj} + X_{switch}\right)\right)} \qquad (4)$$

Where M is the number of hops, b is the ratio of signal peak power, N is the number of channels, R_d is the detector responsivity, ε_{adj} is the effective adjacent channel crosstalk, ε_{nonadj} is the effective non adjacent channel crosstalk, and X_{switch} is the crosstalk value of the optical switch fabric [11]. Where the power penalty can be expressed by:

Power penalty (Pp) = Power with crosstalk - Power without Crosstalk (5)

IV. NUMERICAL SIMULATION AND PERFORMANCE ANALYSIS

In the present study, optical cross connect communication systems have deeply investigated based on different multiplexing techniques and different both transmission bandwidth and optical transmission windows over wide range of the affecting operating parameters as shown in Table 1.

Table 1. List of parameters used in simulation [5, 9, 10, 11].

Parameter	Definition	Value and unit
P_S	Input optical signal power	-15 dBm- 20 dBm
N (CWDM)	Number of transmitted channels	16 Channels
N (WDM)	Number of transmitted channels	60 Channels
N (DWDM)	Number of transmitted channels	400 Channels
λ	Optical signal wavelength	1550 nm
R_b	Bit rate	2.5 Gb/s
n_{sp}	Population inversion Factor	1.8
M	Number of hops	6 Hop
R_d	Detector responsivity	0.85 A/W
G	Gain	20 dB
ε_{adj}	effective adjacent channel crosstalk	0.5 dB

ε_{nonadj}	effective non adjacent channel crosstalk	0.5 dB
X_{switch}	optical switch fabric crosstalk	0.01 dB
b	Signal peak power ratio	1

Based on the model equations analysis, assumed set of the operating parameters, and the set of the series of the Figs. (1-28), the following facts are assured:

i) Fig. (1-a,1-c and 1-e) have shown that input power will increase for increasing number of hops in case of CWDM for bandwidth=2.5 GHz, B=10 GHz and B=40 GHz respectively. This figures assured that for more number of hops we need extra power to obtain the best BER and also if the bandwidth increase, the required input power will increase. Now from these figures, for fixed bit error rate we can calculate and draw the power penalty for three cases. Power penalty is the difference between two powers, input power with crosstalk and the power without crosstalk.so for calculating power penalty, calculate the difference between input power with crosstalk and the power without crosstalk. Here Bit error rate 10^{-12} must be taken for all figures and calculate the power penalty corresponding of this value for B=2.5 GHz, B=10 GHz and B=40 GHz as shown in Table 2 below.

Table 2. List of estimated power penalty of the number of hops for CWDM at different bandwidth.

No. of Hops	Power penalty		
	B=2.5 GHz	B=10 GHz	B=40 GHz
Without Crosstalk	0	0	0
6 Hops	10.14	8.65	7.137
12 Hops	11.65	10.16	8.647
18 Hops	12.52	10.99	9.497
24 Hops	13.21	11.95	10.207

ii) Fig. (1-b, 1-d and 1-f) have assured that power penalty increases with increasing number of hops and will decrease when bandwidth increases because from the definition of power penalty is the difference between input power with crosstalk and the input power without crosstalk and as we see in the case of without crosstalk for B=2.5 GHz as seen in Fig.1 it need input power =-3.55 dBm and for B=10 GHz as seen in Fig. 1-c it need input power =-2.04 dBm and for B=40 GHz as seen in Fig. 1-e it need input power =-0.527, so the input power will increase by increasing the bandwidth by large value. But if we take the case of m=6 as an example to obtain at it the input power with crosstalk so for B=2.5 GHz as seen in Fig.1 it need input power = 6.59 dBm and for B=10 GHz as seen in Fig. 1-c it needs input power =6.60dBm and for B=40 GHz as seen in Fig. 1-e, it needs input power =6.61, so the power will increase by very small value so the power penalty will decrease by increasing bandwidth (notice :Power penalty was plotted from previous table)

iii) Fig.(2-a, 2-c, and 2-e) have shown that input power will increase as the number of hops increased in case of WDM at bandwidth=2.5 GHz, B=10 GHz and B=40 GHz respectively. These figures have assured that for more number of hops we need extra power more than in case of WDM to obtain the best BER and also if the bandwidth increase, the required input power will increase by large value in case of without crosstalk and by small value in case of with crosstalk. Here we have taken Bit error rate 10^{-12} for all figures and calculate the power penalty corresponding of this value for B=2.5 GHz, B=10 GHz and B=40 GHz as shown in Table 3 below.

Table 3. List of estimated power penalty of the number of hops for WDM at different bandwidth.

No. of Hops	Power penalty		
	B=2.5 GHz	B=10 GHz	B=40 GHz
Without Crosstalk	0	0	0
6 Hops	13.13	11.48	10.25
12 Hops	14.66	13.13	11.6
18 Hops	15.46	14.03	12.5
24 Hops	16.16	14.63	13.1

iv) Fig. (2-b, 2-d and 2-f) have indicated that power penalty increase with increasing number of hops at WDM more than the value that was calculated in the last case (CWDM) and will decrease less than the value that was calculated in the last case (CWDM) and this was discussed in the last case.

v) Fig. (3-a, 3-c, and 3-e) have shown that input power will increase as the number of hops increased in case of DWDM for bandwidth=2.5 GHz,10 GHz ,=40 GHz respectively. These figures have assured that for more number of hops we need extra power more than the value in last two cases (CWDM&WDM) to obtain the best BER and also if the bandwidth increases, the required input power will increase by large value in case of without crosstalk and by small value in case of with crosstalk. Here we have taken Bit error rate 10^{-12} for all figures and calculate the power penalty corresponding of this value for B=2.5 GHz, B=10 GHz and B=40 GHz as shown in Table 4 below.

Table 4. List of estimated power penalty of the number of hops for DWDM at different bandwidth.

No. of Hops	Power penalty		
	B=2.5 GHz	B=10 GHz	B=40 GHz
Without Crosstalk	0	0	0
6 Hops	17.3	15.85	14.3
12 Hops	18.7	17.53	15.8
18 Hops	19.6	18.15	16.6
24 Hops	20.2	18.75	17.2

vi) Fig. (3-b, 3-d and 3-f)have demonstrated that power penalty increase with increasing number of hops more than the value that was calculated in the last two cases (CWDM&WDM) and it will decrease with increasing bandwidth because the reason that was discussed in the last case.

vii) Fig. (4-a, 4-c and 4-e) has assured that input power in case of 400 channel will increase more than that in case of 60&16 for increasing number of channels and input power in case of 60 channels will increase more than that in case of 16 channels. These figures assured that for more number of channels we need extra power to obtain the best BER and also if the bandwidth increase, the required input power will increase by large value in case of without crosstalk and by small value in case of with crosstalk. Here we have taken Bit error rate 10^{-12} for all figures and calculate the power penalty corresponding of this value for different signal bandwidth as shown in Table 5.

Table 5. List of estimated power penalty of the number of channels at different bandwidth.

No. of Channels	Power penalty		
	B=2.5 GHz	B=10 GHz	B=40 GHz
Without Crosstalk	0	0	0
16 Channels	10.12	8.73	7.24
60 Channels	13.17	11.73	10.21
400 Channels	17.27	15.78	14.26
600 Channels	18.17	16.78	15.26

viii) Fig. (4-b, 4-d and 4-f) have indicated that power penalty in case of 400 channels (DWDM) will increase more than power penalty in case of 60 channels and 16 channels respectively. But it will decrease with increasing bandwidth.

ix) Fig. 5 has assured that crosstalk will increase as number of channels increased. As well as the number of hops increases, this results in the crosstalk will be increased respectively.

x) Fig. (6-a, 6-b and 6-c) give the relation between quality factor or SNR and input power in case of different multiplexing techniques (CWDM,WDM, and DWDM) respectively. These figures have assured that quality factor or SNR will be increased as the input power increases and the best quality factor will be at the lowest bandwidth.

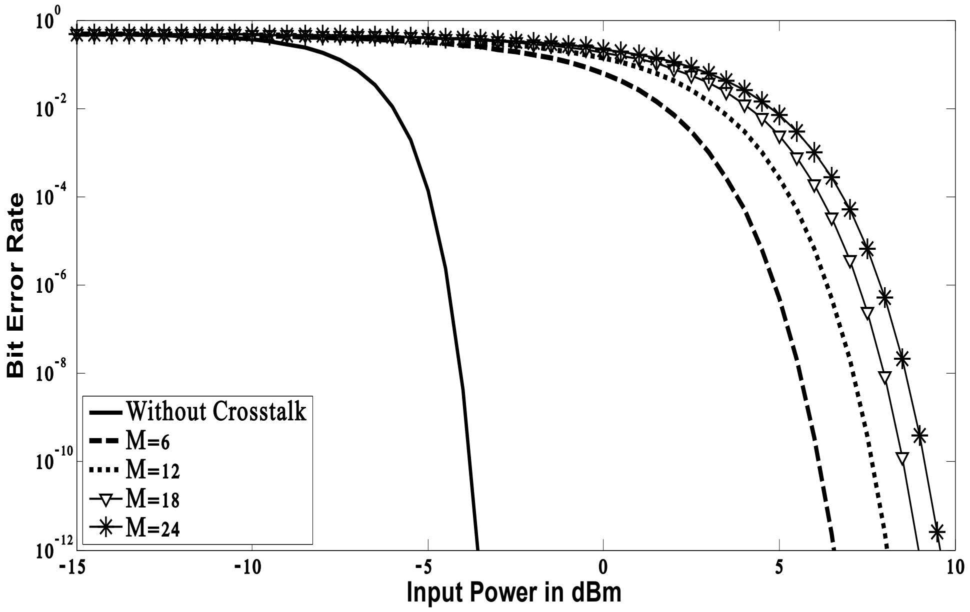

Fig. 1-a. Bit error rate in relation to input signal power at different number of hops for Bandwidth=2.5 GHz at the assumed set of the operating parameters for CWDM. (Take BER=10^{-12} as reference).

Fig. 1-b. Power Penalty in relation to number of hops at bandwidth=2.5 GHz for CWDM.

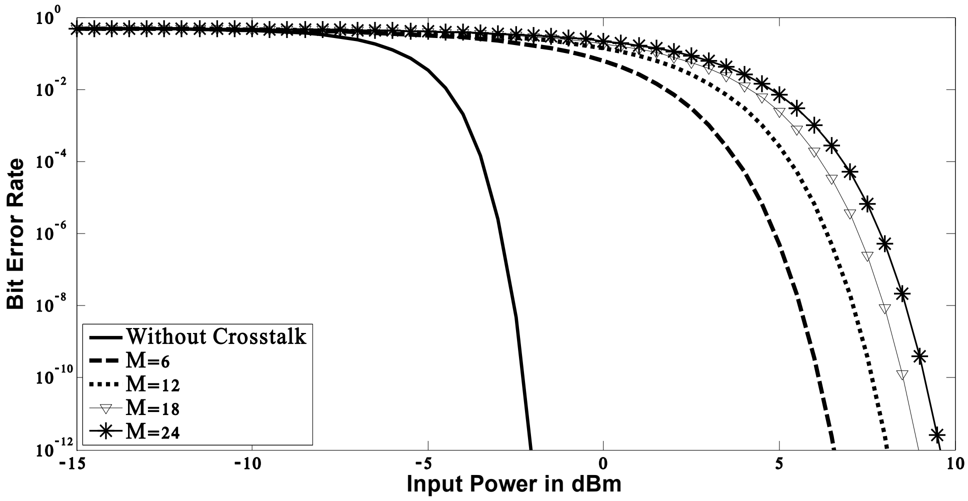

Fig. 1-c. Bit error rate in relation to input signal power at different number of hops for Bandwidth=10 GHz at the assumed set of the operating parameters for CWDM. (Take BER=10^{-12} as reference).

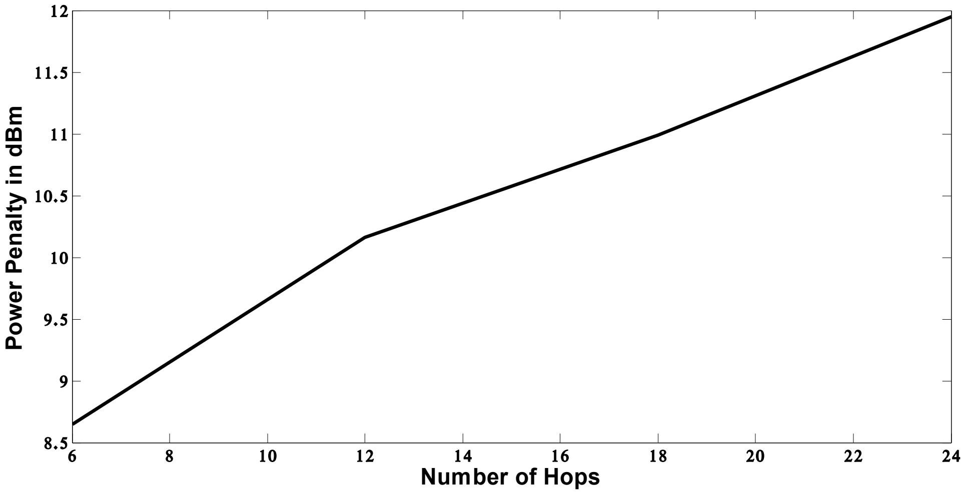

Fig. 1-d. Power Penalty in relation to number of hops at bandwidth =10 GHz for CWDM.

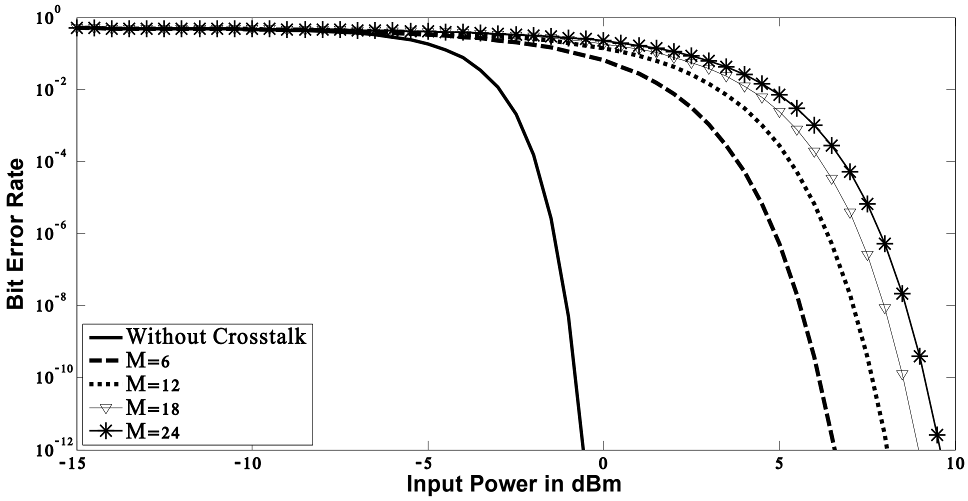

Fig. 1-e. Bit error rate in relation to input signal power at different number of hops for Bandwidth=40 GHz at the assumed set of the operating parameters for CWDM. (Take BER=10^{-12} as reference).

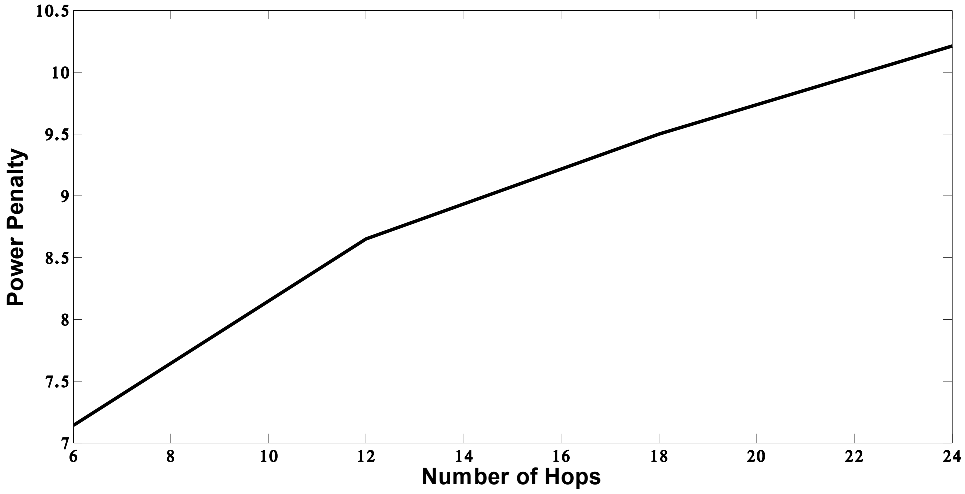

Fig. 1-f. Power Penalty in relation to number of hops at bandwidth =40 GHz for CWDM.

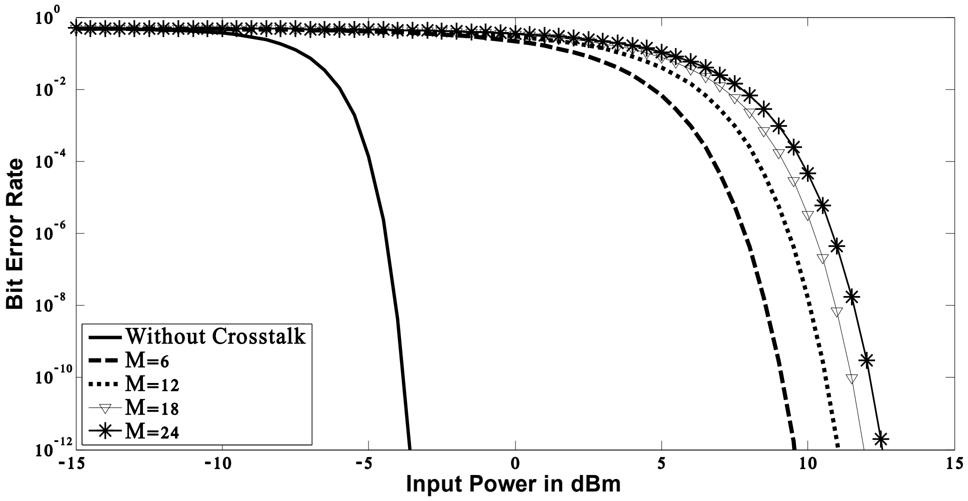

Fig. 2-a. Bit error rate in relation to input signal power at different number of hops for Bandwidth=2.5 GHz at the assumed set of the operating parameters for WDM. (Take BER=10^{-12} as reference).

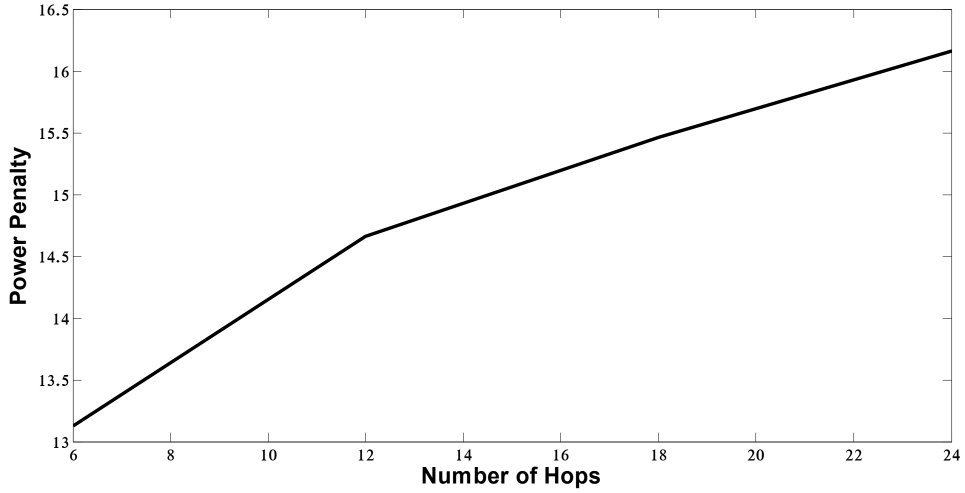

Fig. 2-b. Power Penalty in relation to number of hops at bandwidth =2.5 GHz for WDM.

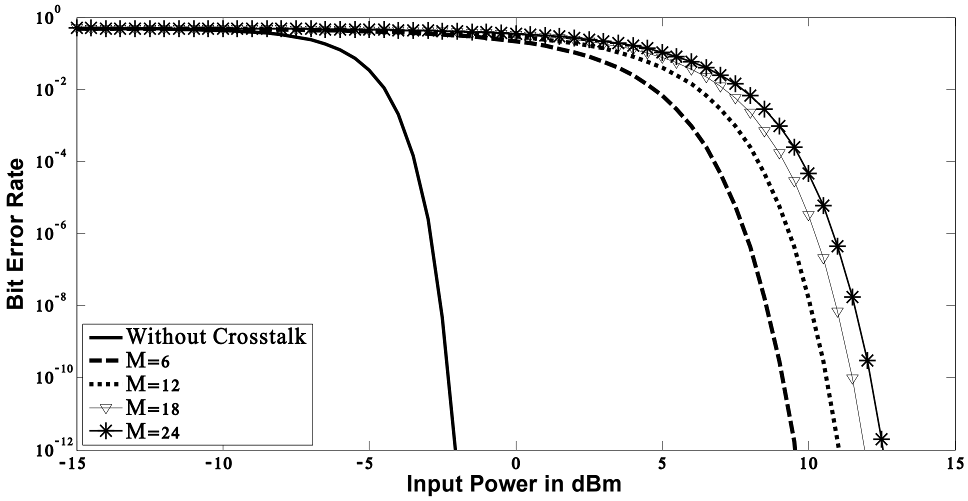

Fig. 2-c. Bit error rate in relation to input signal power at different number of hops for bandwidth =10 GHz at the assumed set of the operating parameters for WDM. (Take BER=10^{-12} as reference).

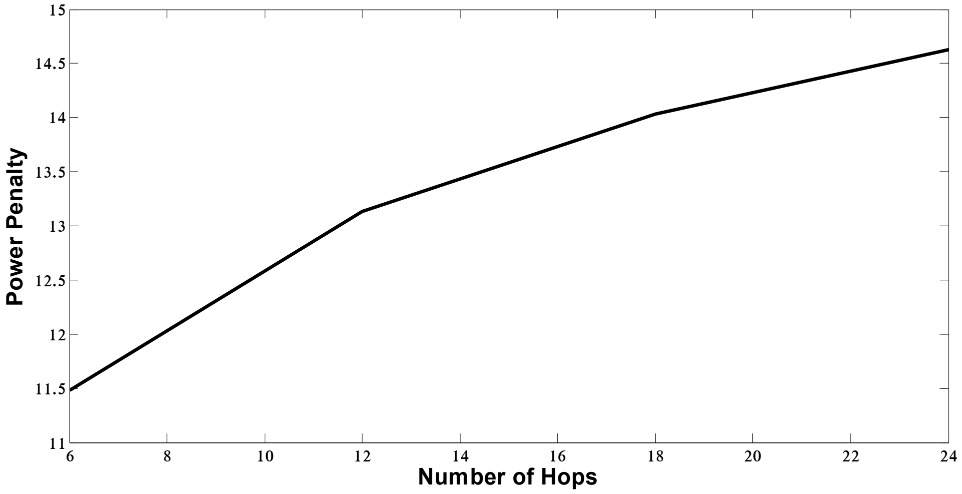

Fig. 2-d. Power Penalty in relation to number of hops at bandwidth =10 GHz for WDM.

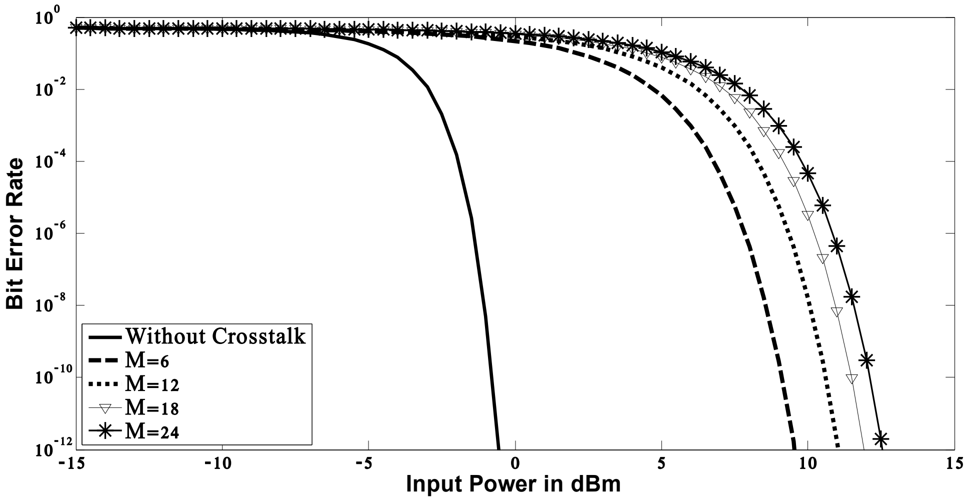

Fig. 2-e. Bit error rate in relation to input signal power at different number of hops for bandwidth =40 GHz at the assumed set of the operating parameters for WDM. (Take BER=10^{-12} as reference).

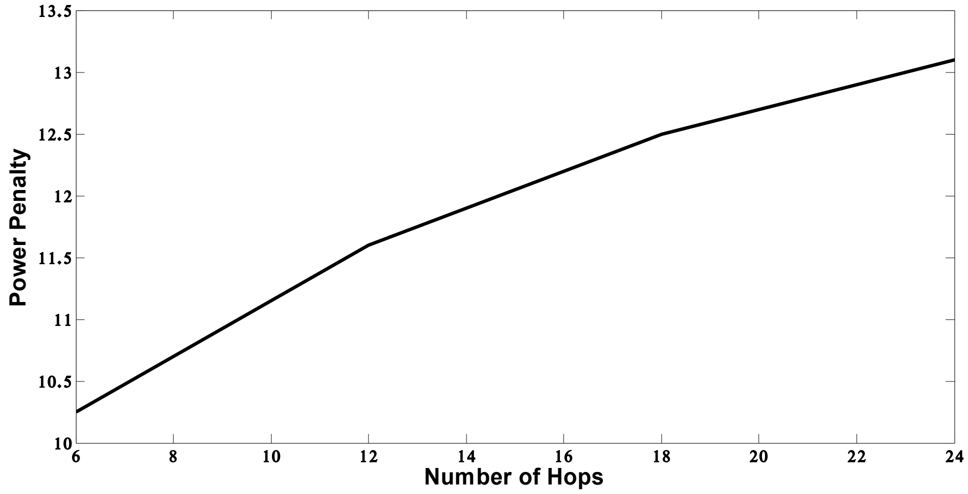

Fig. 2-f. Power Penalty in relation to number of hops at bandwidth =40 GHz for WDM.

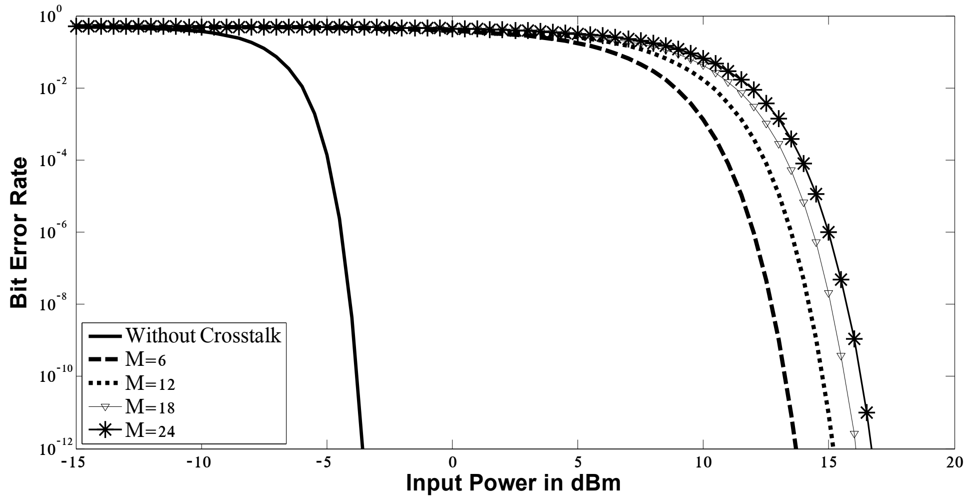

Fig. 3-a. Bit error rate in relation to input signal power at different number of hops for bandwidth =2.5 GHz at the assumed set of the operating parameters for DWDM. (Take BER=10^{-12} as reference).

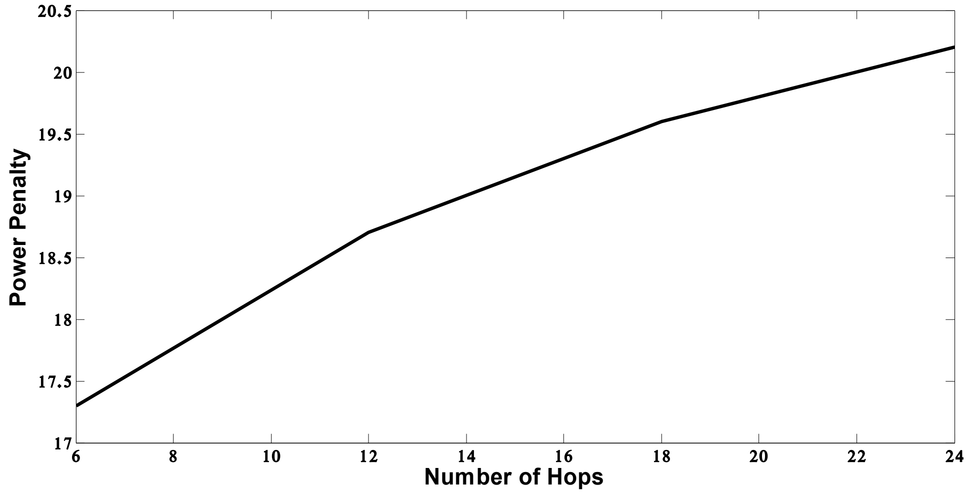

Fig. 3-b. Power Penalty in relation to number of hops at bandwidth =2.5 GHz for DWDM.

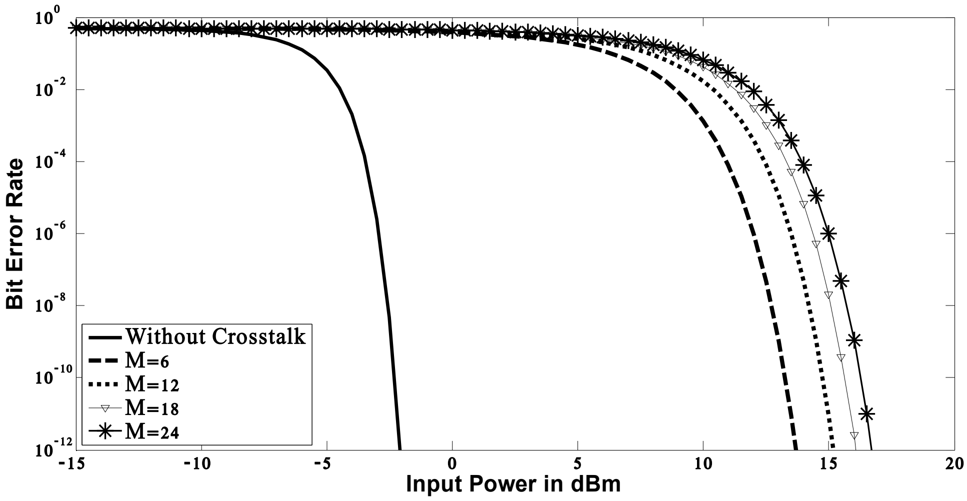

Fig. 3-c. Bit error rate in relation to input signal power at different number of hops for bandwidth =10 GHz at the assumed set of the operating parameters for DWDM. (Take BER=10^{-12} as reference).

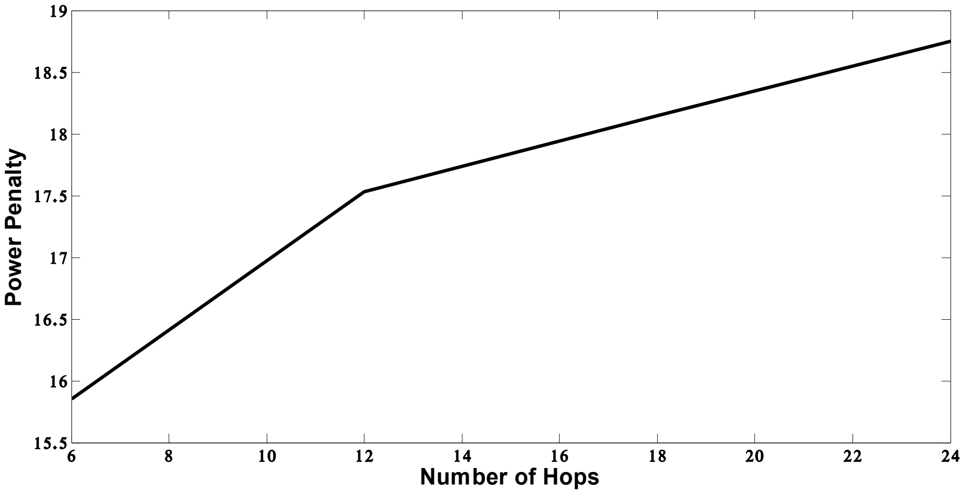

Fig. 3-d. Power Penalty in relation to number of hops at bandwidth =10 GHz for DWDM.

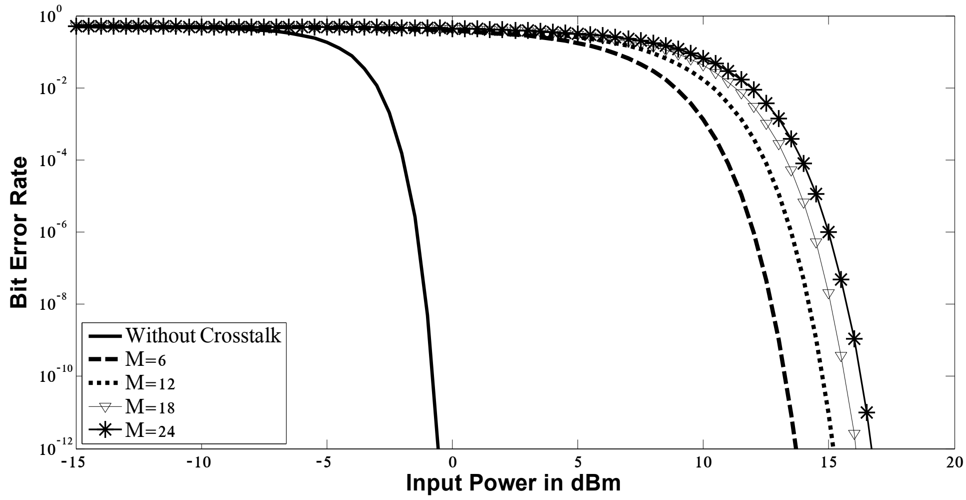

Fig. 3-e. Bit error rate in relation to input signal power at different number of hops for bandwidth =40 GHz at the assumed set of the operating parameters for DWDM. (Take BER=10^{-12} as reference).

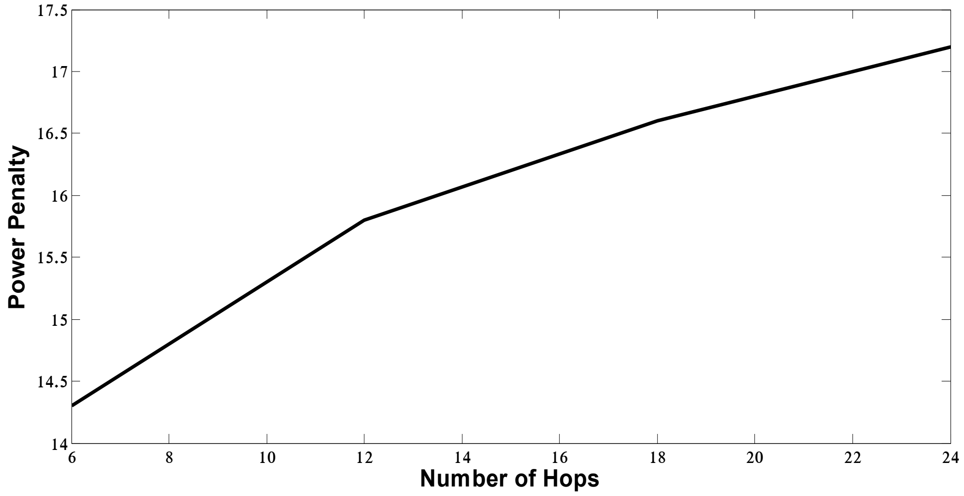

Fig. 3-f. Power Penalty in relation to number of hops at bandwidth =40 GHz for DWDM.

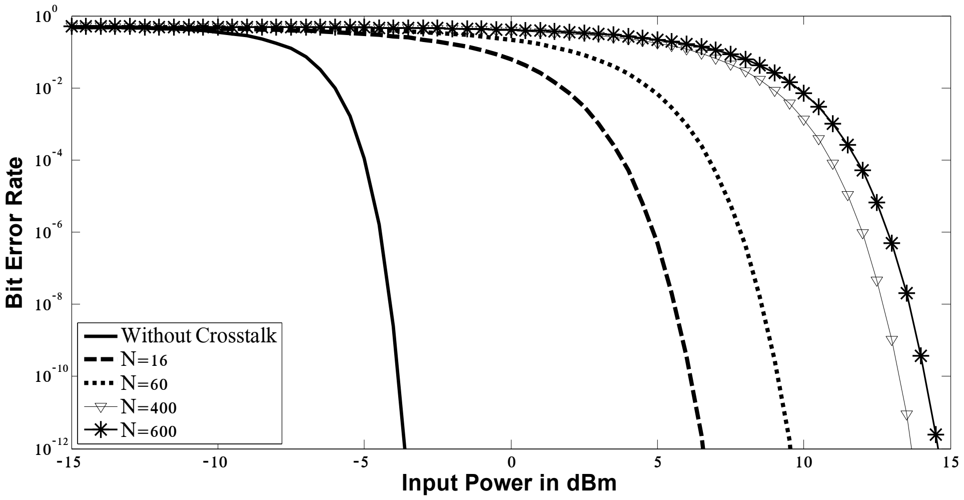

Fig. 4-a. Bit error rate in relation to input signal power at different number of channels for bandwidth =2.5 GHz at the assumed set of the operating parameters. (Take BER=10^{-12} as reference).

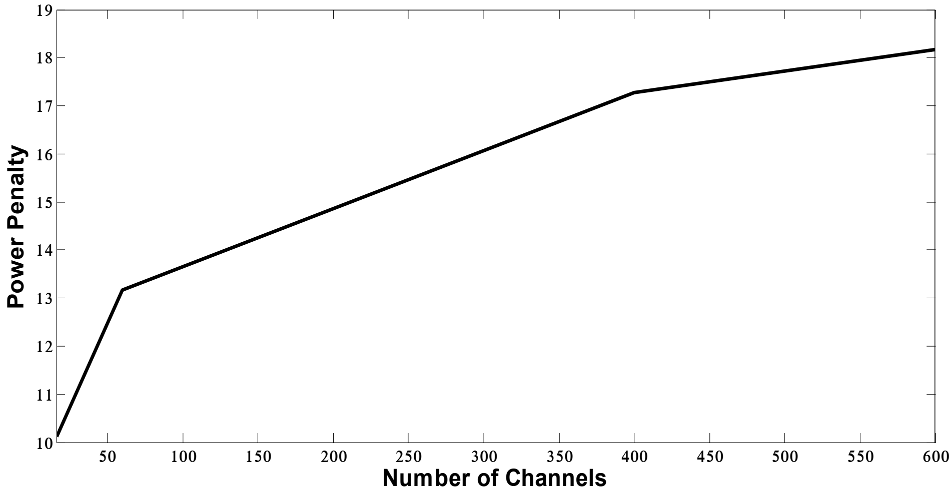

Fig. 4-b. Power Penalty in relation to number of channels at bandwidth =2.5 GHz.

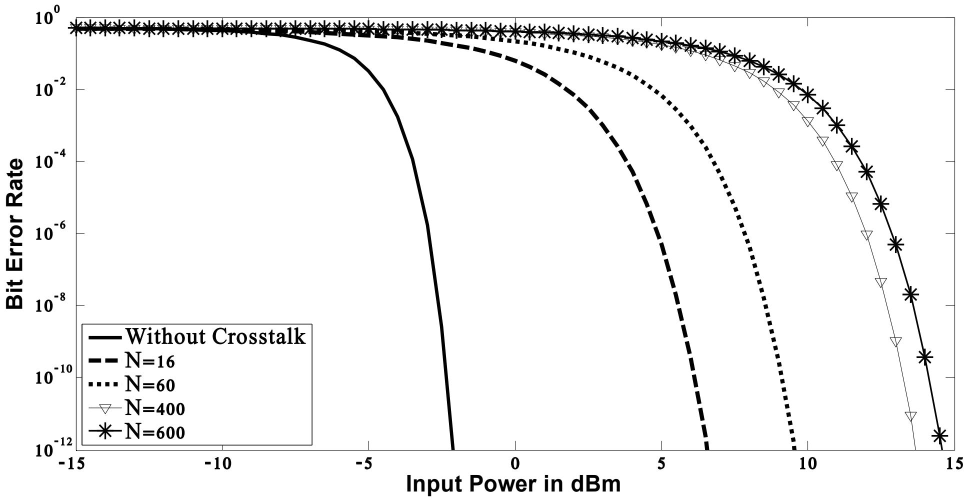

Fig. 4-c. Bit error rate in relation to input signal power at different number of Channels for bandwidth =10 GHz at the assumed set of the operating parameters. (Take BER=10^{-12} as reference).

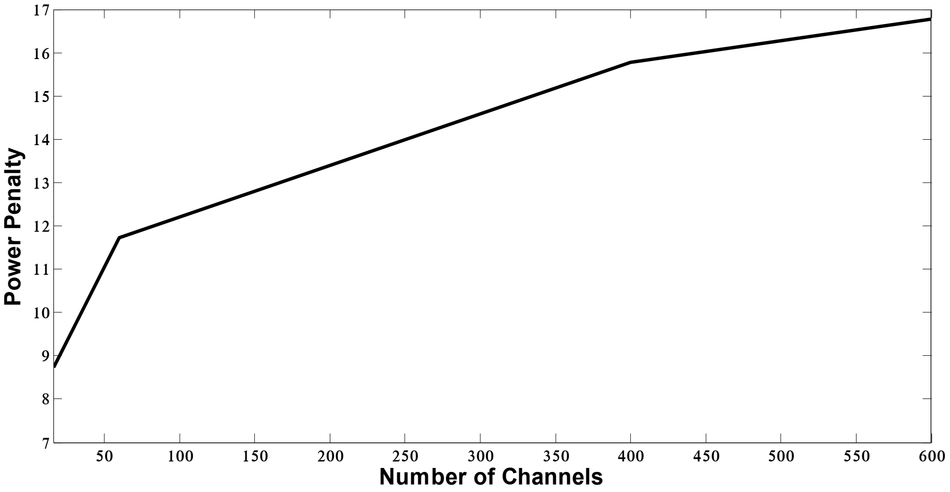

Fig. 4-d. Power Penalty in relation to number of channels at bandwidth =10 GHz.

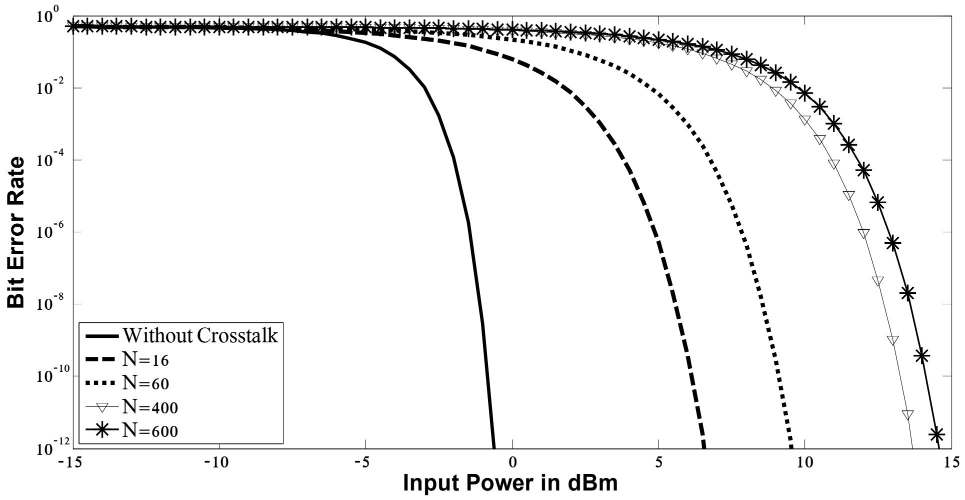

Fig. 4-e. Bit error rate in relation to input signal power at different number of Channels for bandwidth =40 GHz at the assumed set of the operating parameters. (Take BER=10^{-12} as reference).

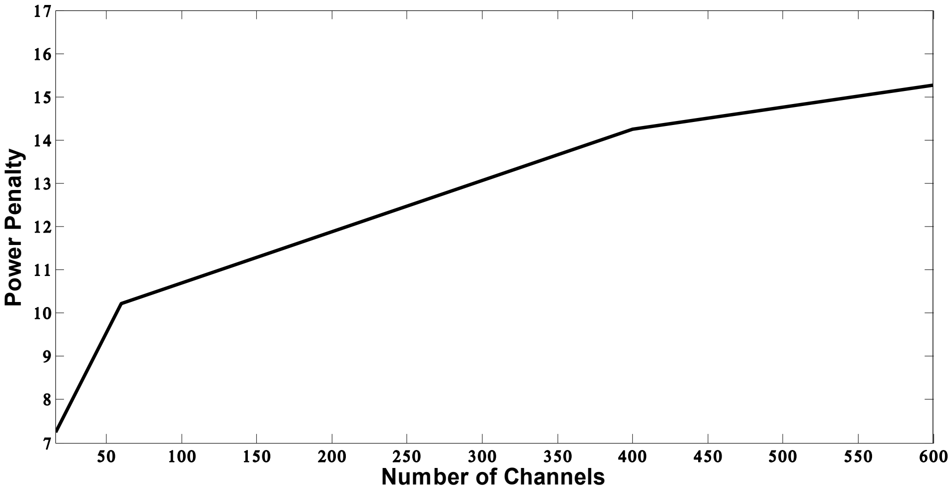

Fig. 4-f. Power Penalty in relation to number of channels at bandwidth =40 GHz.

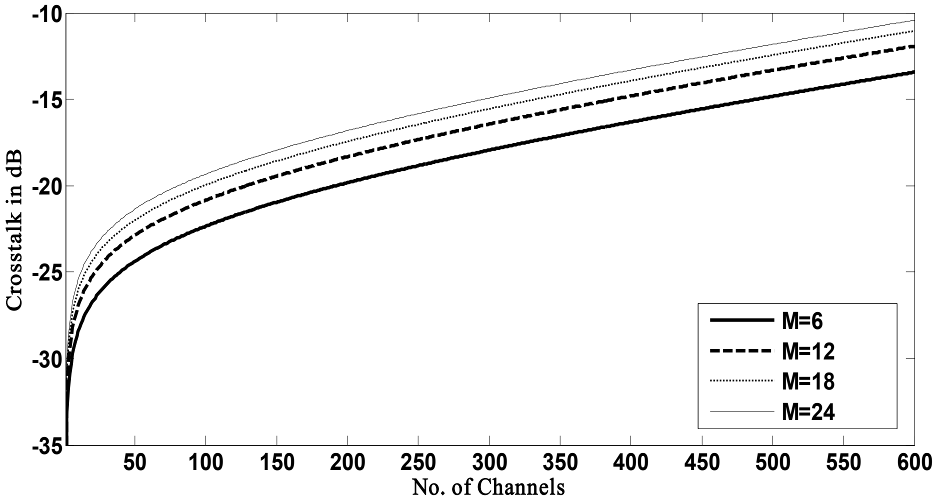

Fig. 5. Crosstalk in relation to number of channels at different number of hops.

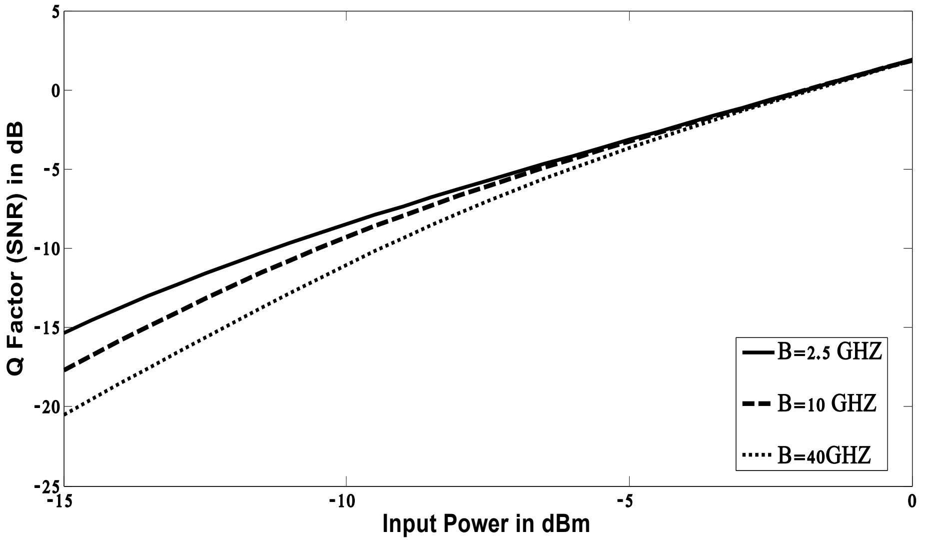

Fig. 6-a. Q Factor in relation to input power for CWDM at the assumed set of the operating parameters.

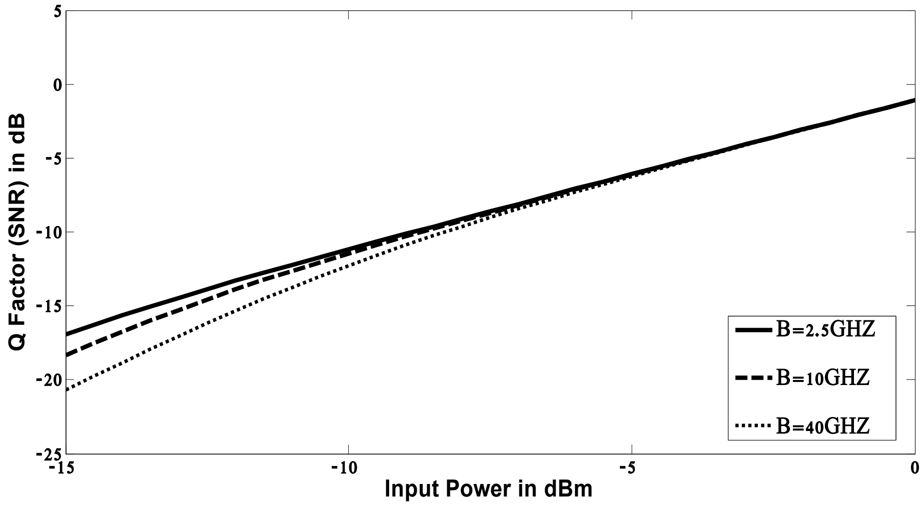

Fig. 6-b. Q Factor in relation to input power for WDM at the assumed set of the operating parameters.

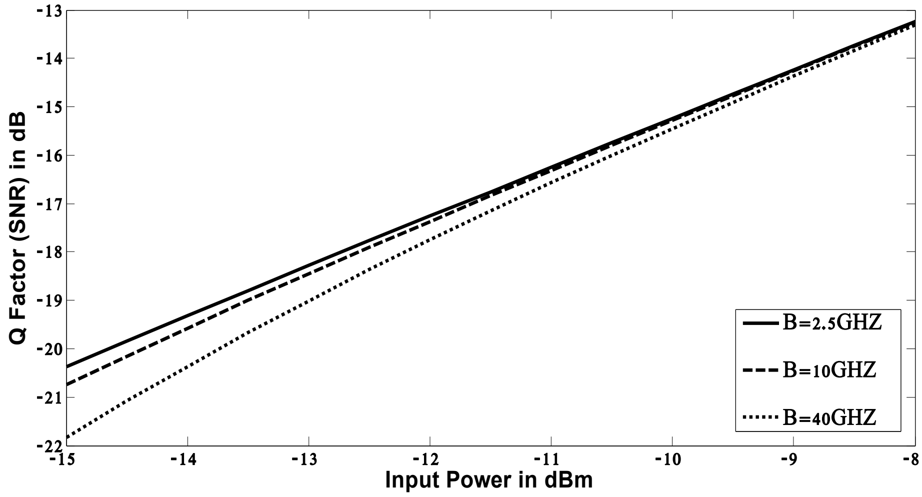

Fig. 6-c. Q Factor in relation to input power for DWDM at the assumed set of the operating parameters.

V. CONCLUSIONS

In a summary, we have deeply investigated the performance parameters for different multiplexing techniques based optical cross connects in the presence and absence of crosstalk. Coarse wavelength division multiplexing, wavelength division multiplexing, and dense wavelength division multiplexing are the most candidate multiplexing techniques for this current study at a certain number of transmitted channels. Power penalty and compensation input signal power are deeply analyzed in the presence of crosstalk. Optimization performance parameters based optical cross connects for different multiplexing techniques are listed in Table 6 below.

Table 6: Optimization performance parameters for different multiplexing techniques based OXC.

Performance parameters	Same conditions of operating parameters: P_S=-5 dBm-:20 dBm, λ=1550 nm, R_b=2.5-10-40 Gb/s, n_{sp}=1.8, R_d=0.85 A/W, G=10 dB, and M=6 BER=10^{-12}. [for maximum number of channels for each multiplexing technique]								
	CWDM (N=16 channels)			WDM (N=60 channels)			DWDM (N=400 channels)		
σ_c(Crosstalk), dB	-27.4			-23.9			-16.3		
Required transmitted bandwidth									
	B=2.5 GHz	B=10 GHz	B=40 GHz	B=2.5 GHz	B=10 GHz	B=40 GHz	B=2.5 GHz	B=10 GHz	B=40 GHz
Compensation input signal power to maintain BER at 10^{-12}, dBm	3.04	3.08	3.23	5.998	6.001	6.0121	10.1468	10.1469	10.1471
Power penalty (P_P) in case of increase number of hops , dBm	10.14	8.65	7.13	13.13	11.48	10.25	17.3	15.85	14.3
Power penalty (P_P) in case of increase number of channels, dBm	10.12	8.73	7.24	13.17	11.73	10.21	17.27	15.78	14.26

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