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IMPACT OF COHERENT AND INCOHERENT CROSSTALKS AND POWER PENALTY ON THE OPTICAL CROSSCONNECTS

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Abstract

Optical cross-connects are one of the most important components in the dense wavelength division multiplexer based optical networks. The crossconnects suffer from crosstalk due to the different wavelength light path channels during the switching process leading to the deterioration in bit error rate (BER) and hence in the system performance. This paper presents the study of impact of coherent and incoherent crosstalk and power penalty on the optical cross-connects in WDM Networks. The effect of accumulation of coherent crosstalk at different stages of crossconnect has been also investigated and analyzed for the blocking probabilities. Results of coherent and incoherent crosstalk are compared to identify their impact on the working of the cross-connect. The results show that the crosstalk increases with increase in either the number of wavelengths per fiber or the number of input fibers. The result also illustrates decrease in the interference penalty by correlating the crosstalk contributions with each other at the appropriate phase angle. We show that an acceptable blocking probability due to crosstalk is achievable for active wavelengths in the WDM network. The present study can be used to model the possible number of routing stages in such networks.

Keywords:

Coherent Crosstalk, Incoherent Crosstalk, Optical Cross-Connects, Blocking Probabilities, Power Penalty

1. INTRODUCTION

Optical networks are considered as a promising solution for the next generation optical networks fulfilling the increasing demand of bandwidth for the applications with high Quality of Service (QoS) requirements. Optical networks process the signals in optical domain enabling the faster and reliable communication through low power and compact optical integrated circuits (OICs) [1]. Switching and routing of the light packets is important process in optical networks and has to ensure correct delivery of packet to the appropriate port without incorporating any error. In optical networks, optical cross-connect (OXC) is responsible for switching and routing of the light packets entirely in the optical domain [2]. The major impairments found in optical networks include ASE (Amplifier Spontaneous Emission) noise from optical amplifiers, crosstalk from OXC nodes as well as attenuation, dispersion and nonlinear effects from the optical fibers.

A typical wavelength division multiplexed (WDM) OXC is composed of wavelength-selective and switching elements to route individual wavelength channels from several inputs to several outputs. While traveling through an optical cross-connect node, an optical signal experiences optical crosstalk due to narrow spacing between the light carrying waveguides. The crosstalk is contributed by the adjacent input-output WDM channels and delayed version of the desired signal that travels through different optical paths inside the crossconnect. Crosstalk in OXC can be classified on the basis of Interferometric delay time. If the Interferometric delay time is shorter than the light source coherence time then the crosstalk is treated as coherent crosstalk, while Interferometric delay time is longer than the light source coherence time, the crosstalk is treated as incoherent crosstalk [3]. In earlier studies [4], the crosstalk analysis is done for the static wavelength router structure. The study shows that the interference power penalty depends on the linewidth of the laser source. The parameters like extinction ratio, input power, bit error rate (BER) are not the part of analysis. While considering the coherent crosstalk in optical crossconnect it is necessary to consider the phase relation amongst all the interfering signals. The crosstalk specification requirement will increase drastically as the noise power increases linearly with number of stages of OXC. Here in our study we showed how the signal to interference ratio varies with the number of stages of optical crossconnect. In [5], various topologies of OXC are studied. OXC based on space switch is one of the topology considered there. The scalability of the OXC is studied in function of the number of wavelength channels. It shows that the crosstalk increases with increasing number of channels and optimal performance for a certain throughput is obtained if the number of fibers equals the number of wavelengths.

In our work, the performance analysis of OXC is carried out for coherent and incoherent crosstalk by considering phase, the coherence time and the linewidth of the laser source. For computation of crosstalk power penalty, 1-dB power penalty criterion is considered. We have studied the traffic carrying capacity of the OXC node to achieve required BER for these crosstalk. The organization of the paper comprises of four sections. Section 1 gives introduction to the types of crosstalk in OXC. The parameters such as source linewidth, the input power, BER and non-zero extinction ratio contribute to excessive power penalty. The basic OXC structure and the impact of these parameters on crosstalk are studied in the Section 2. Analytical results are discussed in Section 3. Finally the conclusion is discussed in Section 4.

2. ANALYSIS OF CROSSTALK

Optical in-band crosstalk occurs when a signal and interferers have close value wavelengths. As a consequence, the signal and interferers are within the pass band of practical optical filter. Generally such a filter is located at the front end of the receiver and interference causes a serious degradation in the system performance. As the interference is not mitigated, optical in-band crosstalk will propagate with the dense WDM (DWDM) channels. The destructive effect of this type of crosstalk accumulates in the optical nodes. In such case, the desired signal and the leak signal have an identical wavelength. If the light source, are locked to a weak external laser line, then they have coinciding wavelengths but still be individually uncorrelated with respect to phase noise process. There will be another situation where the channels of WDM system are sharing the same source but the difference of propagation delay between adjacent channels is greater than the laser coherence time. The frequency spacing in such cases is negligible or almost zero, therefore the power penalty is caused due to phase-to-intensity noise conversion.

At the output of the cross-connect, the multiplexers collect all wavelength channels together and the resulting output channels suffer from the crosstalk caused due to the demultiplexer and the space switch located at the output demultiplexer. The destructive impact on the desired channel is enhanced by the fact that both the signals have almost same wavelength and the resulting beat terms are spectrally located within the receiver bandwidth. If several cross-connects are connected in a cascaded configuration in the network then the in-band crosstalk grows dramatically causing more serious degradation in the system performance. Further, the coherent nature of the crosstalk degrades the performance.

The most general case in waveguide array based optical communication where, each of the channels is operated with an independent laser source or the desired signal is generated by a single source but the desired signal is delayed by much longer period than the laser coherence length while switching at the OXC, the beating product will have incoherent nature. In integrated optical crossconnects the circuit configuration can be chosen such that the amount of crosstalk is minimized and that the dominant crosstalk contributions are in the incoherent regime. Optical out-band crosstalk arises from inadequately suppressed neighboring wavelength channels in the de-multiplexers, which also contributes to the crosstalk [6]. To study the crosstalk, 4×4 OXC structure consisting four fibers at the input and four fibers at the output is considered as shown in Fig.1. The OXC is implemented by connecting the outputs of a WDM de-multiplexer to the inputs of a WDM multiplexer through space switches. A specified wavelength channel can be passed to a desired output by activating the switch either in cross or in bar-state.

During the switching, the fraction of interfering signals gets leaked into the other space switches. For M wavelengths per fiber and for N fibers at the input of OXC, interference with the desired signal can be written as $M-1+N-1=M+N-2$. In the present study we have considered M = N, where the scalability is possible in terms of number of nodes as well as number of wavelengths and input fibers. These contributions can be coherent or incoherent depending upon whether they combine with the desired signal within the coherence time of the source or not. We have analyzed these contributions for both, coherent as well as incoherent case, which was beyond the scope of earlier studies.

2.1 CROSSTALK MODELING

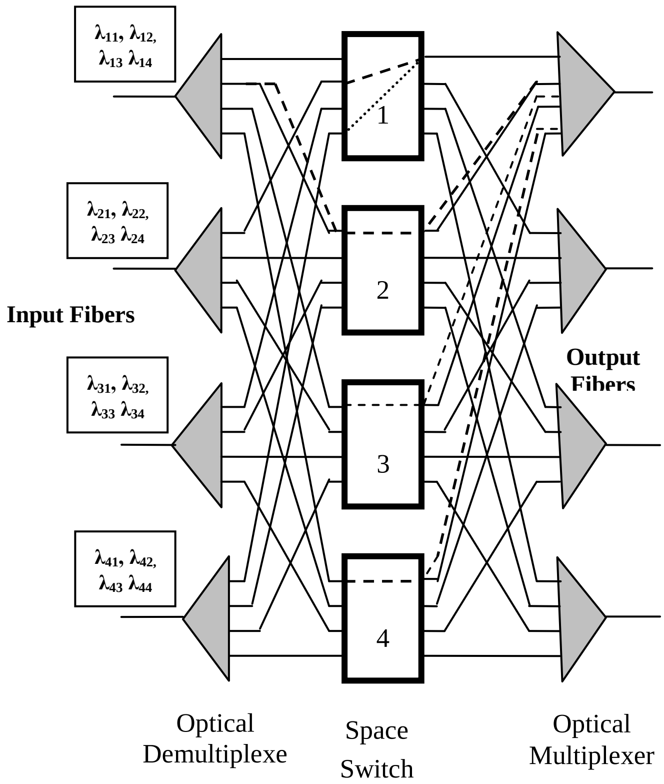

Fig.1. Structure of 4×4 Optical Crossconnect (OXC), the dotted line shows the crosstalk signal leak

Let an optical signal of peak power P_s is fed into an optical fiber with power levels, P_{ON} and P_{OFF} depending upon logical ONE's and ZERO's present in the input data sequence. The power levels can be related to the average input power P_{av}, and an extinction ratio $r=20$ [7], as

$$P_{ON}=\frac{2r}{r+1}P_{av};\ P_{OFF}=\frac{2}{r+1}P_{av} \qquad (1)$$

The optical field of the desired signal in the fiber corresponding to the laser source will be described as the complex form [8],

$$\vec{E}_S(t)=\vec{r}_S\sqrt{P}_S\exp[i\omega_S t+i\phi_S(t)+\theta_S] \qquad (2)$$

where, $\vec{r}_s$ expresses the state of polarization, ω_s the optical angular frequency, $\phi_s(t)$ the instantaneous optical phase and θ_s is the initial phase of the laser where '*s'* denotes the desired signal. This desired signal could be interfered by k crosstalk contributions from k-transmitted signals. The total interfering field $\vec{E}_x(t)$ can be written as,

$$\vec{E}_x(t)=\sum_k \vec{E}_k\left(t-\tau_d\right) \qquad (3)$$

where, $\vec{E}_k(t)$ is the field corresponding to interfering signals and τ_d denotes the Interferometric delay time. The total optical field, comprising the desired and the interfering fields ($M+N-2$ contributions), incident upon a photodetector is given as,

$$\begin{aligned}
&\vec{E}_{ph}(t) = \vec{E}_s(t) + \vec{E}_x(t) \\
&= \vec{r}_s \sqrt{P_s}\, b_s(t) \exp[i\omega_s t + i\phi_s(t) + \theta_s] \\
&+ \sum_{k=1}^{X} \sqrt{cP_s P_k}\, b_s(t-\tau_k) \exp[i\omega_s(t-\tau_k) + i\phi_s(t-\tau_k) + \Delta\theta_{sk}]\vec{r}_k \\
&+ 2c^2 \sum_{j=2}^{N} \sum_{l=1}^{X} \sqrt{P_j P_l}\, b_j(t-\tau_{jl}) \exp[i\omega_j(t-\tau_{jl}) \\
&+ i\phi_j(t-\tau_{jl}) + \Delta\theta_{jl}]\vec{r}_{jl}
\end{aligned} \quad (4)$$

where, C is the crosstalk parameter, given by the ratio of crosstalk power P_k to the input power $P_s.b_s(t)$ and $b_j(t)$ are the binary data sequences with the bit interval T of the desired signal and crosstalk signal, respectively. P_j and P_l are the crosstalk contributions from other wavelength channels in that fiber and other input fibers, respectively. $\vec{r}_k$ and $\vec{r}_{jl}$ are the states of polarization in the respective fibers. $X \in [1, M-1]$ is the number of crosstalk signals contributed by the different fibers in the each space switch. These contributions are generally treated as the delayed version of the desired signal and the signals leaked from other switches while propagating through the crossconnect. $\Delta\theta_{sk}$ and $\Delta\theta_{jl}$ are the phase differences between the signal with its delayed version and the number of beating terms generated due to contributions from other switches, respectively, where as τ_K and τ_{jl} are the corresponding propagation delay differences. Eq.(4) mainly comprises of three terms, first term is the desired signal, the second term is the beating effect between the desired signal and the interfering crosstalk which can be the delayed desired signal itself called as self crosstalk, and the third term is the interfering signal leaked from other signals at the same wavelength from same port or from the other input fiber port. The latter is called as co-channel or neighboring crosstalk [9].

The post detection filter was assumed to be an ideal integrator over the time interval [0, T].The photocurrent at the output of the photodetector is given by

$$i_{ph}(t) = R\left|\vec{E}ph(t)\right|^2 = R\left|\vec{E}s(t) + \vec{E}x(t)\right|^2 \quad (5)$$

where $R=\eta e/(hv)=1$ is the photodetector responsitivity. While detecting this combined signal at the receiver the dominant noise terms involved are the signal crosstalk beat noise, shot noise and thermal noise. Therefore the total noise power in the receiver bandwidth, $B_e=40GH_Z$ is given as [10]

$$\sigma_N^2 = \sigma_{shot}^2(t) + \sigma_R^2(t) + R_F^2 \int_{-Be}^{Be} S_N(f) \quad (6)$$

where, σ_N^2 is noise power at the output of the receiver, is the summation of quantum or shot noise, thermal noise, input amplifier noise current source and the input amplifier noise voltage source. R_F is the feedback resistance used in amplifier circuit. This noise power decides the minimum detectable signal power at the receiver. The third term in Eq.(6) $S_N(f)$ is the two-sided noise spectral density including the signal induced shot noise and amplified spontaneous emission (ASE) noise of the photodetector current. Wavelength and linewidth ($\Delta\nu$) for the laser source is 1550nm and 120 GHz respectively. When two or more crosstalk contributions from $M+N-2$ are coherent with the desired signal, the phase relation amongst the contributions determines the magnitude of each composite crosstalk. When the propagation delay difference is much less than a bit interval, it gets added to the signal amplitude. When the propagation delay time of the interfering signals is greater than the coherence time, the crosstalk channels are all incoherent. It is seen from the results that the power penalty is more for incoherent channels resulting in more BER. The adjacent channels in a WDM system cause more crosstalk as compared to the farthest channel from the desired signal in terms of the frequency separation [7].

2.2 BER CALCULATION

The Q - factor is calculated at the receiver, [12] which is related to the BER being the error probability. It is given by,

$$Q = \frac{I_{ON} - I_{OFF}}{\sigma_{ON} + \sigma_{OFF}} = \frac{2\frac{r-1}{r+1}P_{av}}{\left(\sqrt{\sigma_{ON}^2 + \sigma_{ON,CTK}^2}\right) + \left(\sqrt{\sigma_{OFF}^2 + \sigma_{OFF,CTK}^2}\right)} \quad (7)$$

$\sigma_{ON}, \sigma_{ON,CTK}$ and $\sigma_{OFF}, \sigma_{OFF,CTK}$ are signal and noise powers corresponding to ON state and OFF state respectively. Signal power fed in the desired signal is P_{ON} considering all ONE's. We have considered the unequal powered case of interferes [11].

$$BER(P_e) = \frac{1}{\sqrt{2\pi}}\left(\frac{\exp^{\frac{-Q^2}{2}}}{Q}\right) \quad (8)$$

The power penalty is calculated by taking the logarithmic ratio of the minimum received signal level to achieve specific *BER* with the crosstalk contributions to that of the minimum detected power to achieve the same *BER* without crosstalk contributions,

$$Power\ Penalty\,(dB) = \log_{10}\frac{P_{REC}}{R^2 P_s} \quad (9)$$

where, P_{REC} is the minimum detected signal along with the crosstalk terms [12]. The received and the input power are the function of linewidth to bandwidth ratio, extinction ratio, propagation time and initial phase of the signal, generated by the source. Therefore the results obtained are based on those parameters included in P_{REC}.

2.3 TRAFFIC BEHAVIOR AND BLOCKING PROBABILITY CALCULATION

By assuming maximum M wavelengths out of which only K active wavelengths, for the Poisson process with mean γ for the wavelength arrival request, the holding time of the active wavelengths with an exponential distribution and mean μ, the traffic load behavior based on Erlang's model [13],

$$P_K(k) = \frac{P_0}{k!}\left(\frac{\gamma}{\mu}\right)^k, \quad k = 0,1,\ldots\ldots K \quad (10)$$

where $P_K(K)$ is the PDF of K, and P_0 is obtained by considering the normalized condition $\Sigma P_K(K)=1$ as follows:

$$P_0 = \frac{1}{\sum_{k=0}^{K} \frac{1}{k!}\left(\frac{\gamma}{\mu}\right)^k} = \frac{1}{\sum_{k=0}^{K} \frac{1}{k!}(s)^k} \tag{11}$$

whereas $S = \gamma/\mu$ denotes the traffic load carried by the wavelength channels. The blocking probability due to crosstalk can be calculated as,

$$P_b = \sum_{k=1}^{K} P_{K(k)}\ P_{e(k)} \tag{12}$$

where, $P_e(k)$ is the error probability due to the active wavelengths.

3. RESULTS AND DISCUSSION

The plots of crosstalk versus power penalty for different values of phase angles are shown in Fig.2. It can be seen from the results that the amount of crosstalk induced power penalty is higher if all the crosstalk contributions are causing due to incoherent crosstalk. The coherent contributions are analyzed for the various phase angle conditions varying between [0, 2π]. The coherent contributions with the phase angles 180° are said to be maximally uncorrelated and called as incoherent. It is seen from the results that with the 1-dB power penalty criterion, crosstalk of -20 dB is tolerated in which the desired signal added to the delayed version of itself with zero correlation (with phase shift of 180°). For coherent crosstalk, the power penalty is reduced down to much lower level and crosstalk can be tolerated up to – 13 dB to satisfy 1-dB power penalty criterion. Smaller value of linewidth increases the coherence time, and more number of crosstalk contributions may fall in coherence with the desired signal, with the power addition effect coherent crosstalk will be less harmful to the system performance as seen in Fig.3. The effects of the coherent interference in optical networks can be fairly characterized by multipath fading effects in time scales of seconds to minutes. The error probability will be greatly affected when considering the incoherent crosstalk contributions. Plots of extinction ratio versus log of error probability for different crosstalk levels are shown in Fig.4. BER of 10^{-9} is achieved with the input power level of –38 dBm with the tolerable crosstalk of –30 dB at each OXC stage. Less than 10^{-9} BER is obtained at – 30 dBm.

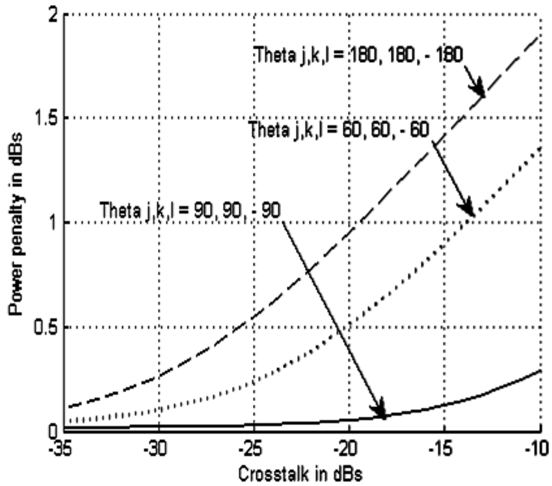

Fig.2. Coherent crosstalk versus power penalty

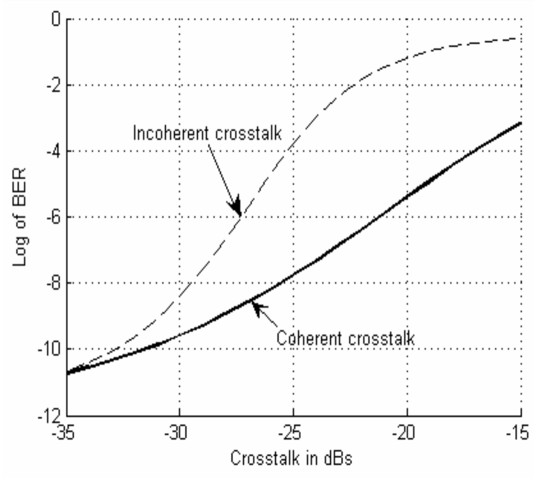

Fig.3. The coherent crosstalk and incoherent crosstalk plotted against BER

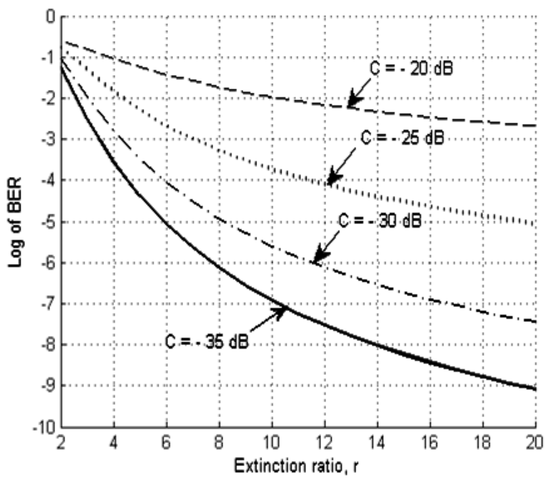

Fig.4. Extinction ratio Vs BER when crosstalk level C is varying between – 35 dB to – 20 dB

With the higher values of extinction ratio, larger tolerance towards power penalties is achieved. At smaller extinction ratios, average power at the input also reduces, causing more crosstalk and increased BER.

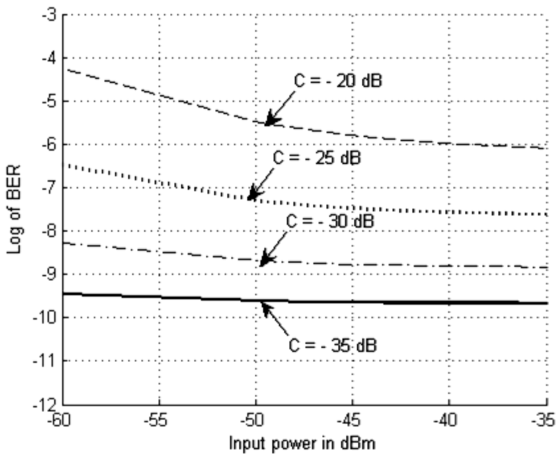

Fig.5. Input power versus error probability for different Crosstalk levels

By increasing the input power to the fiber channels, one can achieve the BER below 10^{-9}. Increasing the input power can cause saturation for the optical amplifiers if that are used at the input of the receiver. Fig.5 shows the error probability is almost constant beyond certain level of input power.

3.1 SCALABILITY OF OXC

To study the scalability of the optical crossconnects (OXC), we have considered L stages. For multistage OXC, the total crosstalk contribution grows drastically. For L stage OXC, the number of contributions goes to $L(M+N-2)$. If all these contributions are coherent, it degrades the overall system performance. The results of the number of stages versus Optical SNR for the different values of crosstalk are shown in Fig.6. A fair value of Optical SNR is achieved for a network with 20 stages OXC but satisfies 1-dB power penalty for crosstalk level of –20 dB. This is in good agreement with the results reported in [11].

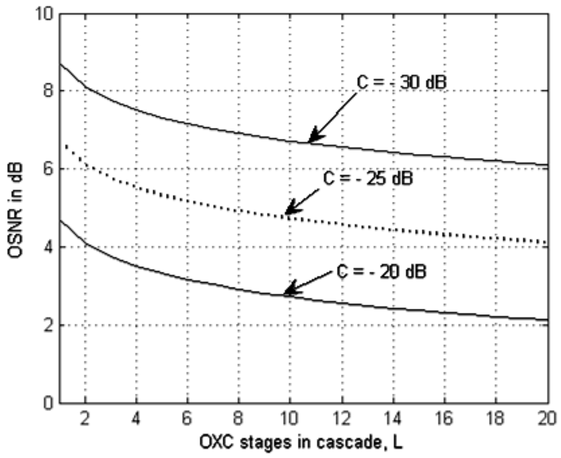

Fig.6. Optical SNR degrades with the amount of crosstalk and number of stages in cascade

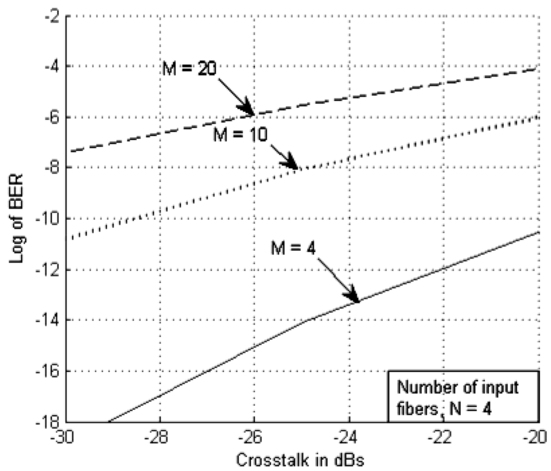

Fig.7. Variations of BER with crosstalk while considering the wavelength scaling

Results reported in Fig.7, shows that the best performance in cascade can be obtained when the number of wavelengths equals the number of input fibers *(M=N=4)* as the crosstalk varies from – 30 dB to – 20 dB and the BER can be obtained less than 10^{-9}.

The results as shown in Fig.8 illustrate that the blocking probability varies with the number of active wavelengths and will be less than 0.002 for 15 active wavelengths with traffic load of 300 Erlangs. Under the same settings, we achieve the blocking probability below 0.0033 for maximum value of k .

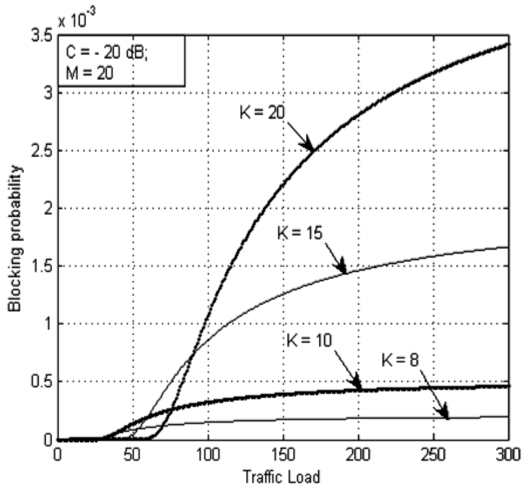

Fig.8. Blocking probability plotted against traffic load

Fig.9 shows the results for number of active users plotted against the BER. Increasing the active users reduces the power per input channel and hence increases crosstalk. If a crosstalk level is – 30 dB then acceptable BER is achieved even for large number of simultaneous transmitters or users.

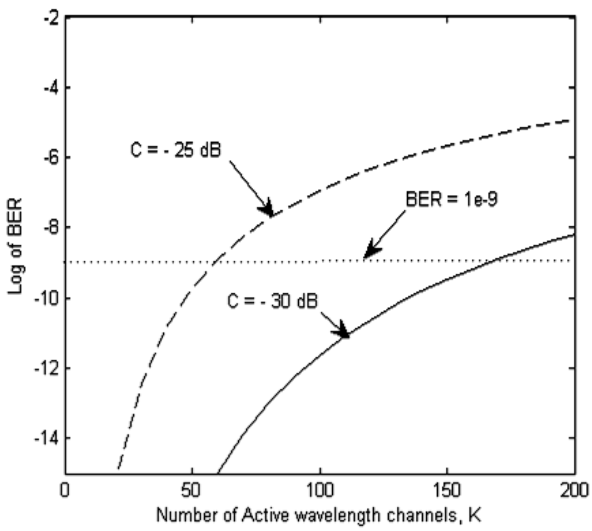

Fig.9. Number of Active Users Vs BER

4. CONCLUSION

We have analyzed and compared the performance of optical crossconnects by considering coherent and incoherent crosstalk. The effect of incoherent crosstalk can be reduced if the interfering channels are in maximum correlation. An extinction ratio of 20 is required to maintain lower limit of power penalty. A BER of 10^{-9}can be achieved with the input power of –38 dBm at the cost of crosstalk of –30 dB. Optical SNR reduces as the signal propagates from one stage to the other of OXC, and a minimum of 1 dB ratio will be maintained if crosstalk is –20 dB. The scalability of OXC is studied by considering the number of wavelength channels carried by the fiber at the input of OXC. The traffic model shows that a blocking probability of 0.003 is achievable for 20 active wavelengths. With the help of present study, the possible number of crossconnect based routing stages in WDM optical network can be modeled for tolerable thresholds of crosstalk, BER and power penalty.

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