

Performance Evaluation of Linear Crosstalk Impairments in Array Waveguide Grating Router in WDM Networks

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Abstract: Theoretical analysis is carried out to evaluate the performance of a Wavelength Division Multiplexing (WDM) network transmission system in the presence of crosstalk due to an array waveguide grating router. It is found that linear crosstalk induced by the array waveguide induces higher penalty when the number of add/drop channels is increased and therefore imposes severe limitation on the maximum number of add/drop channels and the number of users accessing the WDM network.

Keywords: AWG, BER, Linear crosstalk, Power penalty, WDM.

1. INTRODUCTION

Optical network provides the capability of easy adaptation to changes in the network traffic requirements with the use of proper switching technology. The network dimensions are limited by a number of effects such as optical crosstalk in the switch matrices and fiber nonlinearities, reflections, jitter accumulation, and signal bandwidth narrowing caused by filter concatenation. Hence it is necessary to estimate for advance the limits to the number of building blocks that can be cascaded. With the help of theory, a statistical model for the bit error rate (BER) at the receiver can be done.

Crosstalk is one of the major limiting factors that may degrade network performance because it leads to severe system performance impairments. Crosstalk can be defined as unwanted wavelength interfering with the desired channel. Crosstalk will not accompany the new channel if it is dropped from previous channels [1].

Two types of crosstalk are homodyne crosstalk, which occurs when the crosstalk has the same nominal wavelength as the signal but they are carried on different input routes (fibers) and heterodyne crosstalk, when both crosstalk and the signal are on different wavelength but are carried on the same input route (fiber). Homodyne crosstalk is considered more harmful because it cannot be removed by filtering at the receiver [2]. It is possible also to consider the two components of homodyne crosstalk as noise, and so, the two in-band crosstalk noise contributions are: the one resulting from the beating of the signal with the optical crosstalk noise and the other is resulting from the beating of the crosstalk noise with itself.

A combination of coherent and incoherent crosstalk has serious implications for network design [2]. To guarantee satisfactory performance, the link's maximum possible BER floor position must be below the required BER. Improving WDM components and/or design to reduce

amount of leakage, and this will reduce range and value of crosstalk-induced BER floors is other methods to reduce crosstalk effects.

The AWG that is under study is used to add/drop channels in OADMs generate crosstalk due to leakage from other channels into the desired channel. AWG is one of many implementations of wavelength routers, and also referred to as AWG multiplexer [3,4]. It provides a fixed routing of an optical signal from a given input port to a given output port based on the wavelength of the signal. Many signals with same wavelength can be input simultaneously to different input ports, with no interference with each other at the output ports. The disadvantage of the AWG is that it is a device with a fixed routing matrix, which cannot be reconfigured; It means that the selected channels cannot be dropped/added or passed through under remote software control unless that there are appropriate equipments have to be deployed in early stage for this purpose [4].

2. THEORETICAL MODEL FOR OXC WITH AN ARRAY WAVEGUIDE

Three crosstalk terms are generated in the system due to signal leakages from desired signal at λ_1 and channel added to λ_1 , leakage from channels entering AWG and channels added and finally, leakage from channels entering AWG and channels passed back. Let $P_{1,1}$ be output power at the receiver for bit '1' together with the crosstalk component due to same wavelength crosstalk in the added channels as the desired signal, $P_{1,0}$ be output power at the receiver for bit '0' together with the crosstalk component due to same wavelength crosstalk in the added channels as the desired signal, $P_{ADD_DIFF_1,0}$ be the output crosstalk power component at the receiver due to different wavelength channels crosstalk in the added

channels from the desired signal for bit '1' and bit '0' respectively, $P_{PASS_1,0}$ be the output crosstalk power component at the receiver due to all wavelength channels crosstalk in the passed channels through the AWG and back to the network for bit '1' and bit '0' respectively, as shown in Figure1. All these output powers are given by [3]:

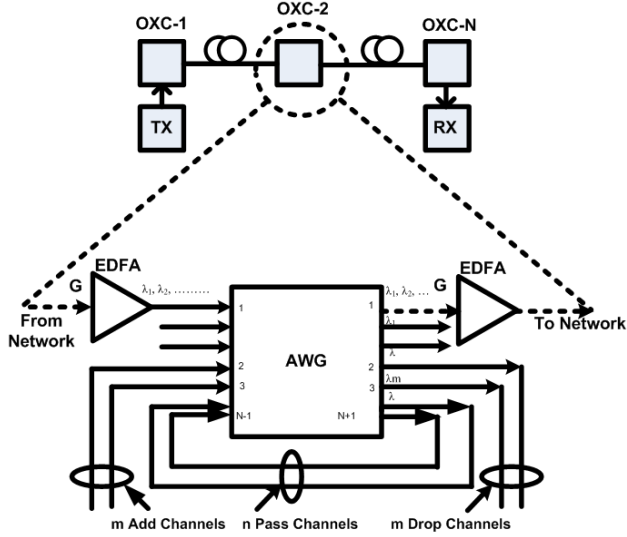


Figure 1. An OXC part of a WDM optical network with an AWG router

$$P_{1_1} = (2R_d L_i)^2 S_{XT} 2P_{in} P_A + (R_d L_i S_{XT} P_A)^2 \quad (1)$$

$$P_{1_0} = (R_d L_i S_{XT} P_A)^2 \quad (2)$$

$$P_{ADD_DIFF_1} = (R_d L_i S_{XT} P_{in})^2 + (R_d L_i S_{XT} P_A)^2 + (2R_d L_i S_{XT})^2 P_{in} P_A \quad (3)$$

$$P_{ADD_DIFF_0} = (R_d L_i S_{XT} P_A)^2 \quad (4)$$

$$P_{PASS_1} = (R_d L_i S_{XT} P_{in})^2 (1 + 4L_i S_{XT} + L_i^2 S_{XT}^2) \quad (5)$$

$$P_{PASS_0} = 0 \quad (6)$$

Simplifying the three crosstalk terms, the total linear crosstalk noise powers can be developed as:

$$P_{XT1} = (R_d L_i S_{XT} P_A)^2 \times \left[\frac{8}{S_{XT}} + 1 + 6(m-1) + n(1 + 4L_i S_{XT} + L_i^2 S_{XT}^2) \right] \quad (7)$$

$$P_{XT0} = m(R_d L_i S_{XT} P_A)^2 \quad (8)$$

Where R_d is the responsivity of the detector and is given in Equation (17), L_i is AWG insertion loss, S_{XT} is the crosstalk suppression, noting that the insertion loss for the AWG has a fixed value and will not change with node number, while the AWG crosstalk suppression is accumulative with node number within ASE noise. P_{in} is

the input power and P_A is the average power of the channels being added to the network. It is assumed that P_{in} and P_A is the same and for simplicity equals to 1 mW or 0 dBm. Meanwhile, m represents the number of channels added to the network and n is the number of channels passed back to the AWG. BER is given by [7]:

$$BER_{XT} = \frac{1}{2} \operatorname{erfc} \left(\frac{Q_{XT}}{\sqrt{2}} \right) \quad (9)$$

Then, using the bit '1' and bit '0' components for σ and P_{XT} gives the final expression for Q_{XT} :

$$Q_{XT} = \frac{2R_d L_i P_{in}}{\sigma_1 + P_{XT1} + \sigma_0 + P_{XT0}} \quad (10)$$

where σ_1^2 , σ_0^2 are the noise variances for bit '1' and bit '0' and are given by:

$$\sigma_1^2 = \sigma_{Shot}^2 + \sigma_{ASE}^2 + \sigma_{ASE-Sig}^2 \quad (11)$$

$$\sigma_0^2 = \sigma_{th}^2 + \sigma_{ASE-ASE}^2 \quad (12)$$

$\sigma_{ASE-Sig}^2$, and $\sigma_{ASE-ASE}^2$ are the beat terms noise variances for signal with ASE and ASE given by:

$$\sigma_{ASE-Sig}^2 = 4R_d^2 P_{rec} P_{ASE} B_e \quad (13)$$

$$\sigma_{ASE-ASE}^2 = R_d^2 P_{ASE}^2 (2B_0 - B_e) B_e \quad (14)$$

where P_{ASE} is the variance of the ASE noise, G is the amplifier gain, B_e is the electrical bandwidth, B_0 is the optical bandwidth, P_{rec} is the signal power at the receiver. The spontaneous emission noise factor is given by:

$$F_e = \frac{1}{2} F_n \quad (15)$$

where F_n is the noise figure, and takes the value of 6 dB for $BER = 10^{-9}$. The power spectral density of ASE due to the amplifier is given by [7]:

$$P_{ASE} = F_e h B_e (G-1) \quad (16)$$

where $h = 6.6261 \times 10^{-34}$ is Planck's constant. The responsivity is given by:

$$R_d = \frac{e \eta_{PD}}{h B_e} \quad (17)$$

where η_{PD} is the efficiency of the photodiode. In this paper $\eta_{PD} = 0.8$ is used. $e = 1.602 \times 10^{-19}$ C is electronic charge. For bit rate = 10 Gbps, $B_e = R_b/2$ where R_b is the bit rate $B_0 = 2B_e$;

The thermal noise is given by:

$$\sigma_{th}^2 = \frac{4KT}{R_L} B_e \quad (18)$$

where K is the Boltzman Constant (1.380658×10^{-23}), T is temperature in Kelvin and R_L is receiver front-end load. In this paper, $T = 300$ K and $R_L = 50 \Omega$ are used in this paper. The total shot noise of the receiver follows as:

$$\sigma_{Shot}^2 = 2eP_{rec}B_e \quad (19)$$

Using the model of [9] for comparison, the output power for bit '1', and bit '0' are expressed as:

$$\begin{aligned} P_{out1} = & R_d^2 \left(LP_{in} + 2L\sqrt{SP_{in}P_A} + LSP_A \right)^2 + \\ & R_d^2 \left(LSP_{in} + 2LS\sqrt{P_{in}P_A} + LSP_A \right)^2 (m-1) \\ & + R_d^2 \left(LSP_{in} + 2LSP_{in}\sqrt{LS} + L^2S^2P_{in} \right)^2 2n. \\ & - 2R_d^2 \left(LP_{in} + 2L\sqrt{SP_{in}P_A} + LSP_A \right) (LSP_{in} + \\ & 2LS\sqrt{P_{in}P_A} + LSP_A) \sqrt{m-1} \\ & - 2R_d^2 \left(LP_{in} + 2L\sqrt{SP_{in}P_A} + LSP_A \right) \times \\ & (LSP_{in} + 2LSP_{in}\sqrt{LS} + L^2S^2P_{in}) \sqrt{2n} \\ & - 2R_d^2 \left(LSP_{in} + 2LS\sqrt{P_{in}P_A} + LSP_A \right) \times \\ & (LSP_{in} + 2LSP_{in}\sqrt{LS} + L^2S^2P_{in}) \sqrt{2n(m-1)} \end{aligned} \quad (20)$$

$$P_{out0} = R_d^2 (LSP_A)^2 (1 - 2\sqrt{m-1}) \quad (21)$$

The model gives crosstalk free (reference) powers for bit '1' and bit '0' can be expressed as:

$$P_{out0}^{XTF} = 0 \quad (22)$$

$$P_{out1}^{XTF} = 10^{-3} \quad (23)$$

where P_{out0} is the real output for bit '0' (with crosstalk is available), P_{out0}^{XTF} is the ideal output for bit '0' if there is no crosstalk, P_{out1} is the real output for bit '1' (with crosstalk is available) and P_{out1}^{XTF} is the ideal output for bit '1' if there is no crosstalk. The model gives the crosstalk powers for bit '1' and bit '0' are expressed as:

$$P_{XT1} = P_{out}^{XTF} - P_{out1} \quad (24)$$

$$P_{XT0} = -P_{out0} \quad (25)$$

$$BER = \frac{1}{8} \left[\begin{aligned} & \operatorname{erfc} \left(\frac{1}{\sqrt{2}} \frac{I_1 + I_{XT0} - I_D}{\sigma_{1_0}} \right) + \\ & \operatorname{erfc} \left(\frac{1}{\sqrt{2}} \frac{I_D - I_{XT0} - I_0}{\sigma_{0_0}} \right) + \\ & \operatorname{erfc} \left(\frac{1}{\sqrt{2}} \frac{I_1 + I_{XT1} - I_D}{\sigma_{1_1}} \right) + \\ & \operatorname{erfc} \left(\frac{1}{\sqrt{2}} \frac{I_D - I_{XT1} - I_0}{\sigma_{0_1}} \right) \end{aligned} \right] \quad (26)$$

$$I_D = \frac{\sigma_{0_1} I_1 + \sigma_{1_1} I_0}{\sigma_{0_1} + \sigma_{1_1}} \quad (27)$$

3. RESULTS AND DISCUSSION

Computer simulations using MATLAB have been carried out to validate the analytical formulation presented earlier. The system parameters are chosen based on avoidance of repetitions after the other researches works and findings exceeding them as in [1,3,5,6]. To explore some more ranges of values for some of the system parameters that were not considered before since the purpose of the researches is always to find optimal values of parameters and towards optimal circuitry state with lower costs. For example, the number of channels for [1] was 4; for [2] was 32; for [5] and [6] was 16; but this paper investigates for 128 channels which is same as [3], whilst the difference with the latter is the avoidance of approximating the crosstalk expression that was done in [3]. Since this paper uses two different expressions for the crosstalk, so the comparison between them is a proper step to find the optimal case. Some of the system parameters used are number of channels, $N = 128$ channels, input power = 0 dBm, gain of amplifier is 20 dB, fiber loss coefficient $\alpha = 0.2$ dB/km, channel spacing of 100 GHz (0.8 nm), $L_i = -4$ dB, $S_{XT} = -22$ dB (as in [6]), $P_{in} = 0$ dBm, and $B_e = 10$ GHz. The distance (fiber length) varies from 25 km to 125 km.

Figure 2 shows the BER with number of add/drop channels in the presence of linear crosstalk for various bit rates. As the number of add/drop channels increases, the BER also increases and do not even reach the ideal BER of 10^{-9} ; The BER will increase with increasing the bit rates as well. It is obvious that linear crosstalk imposes severe limitation on the maximum number of add/drop channels and therefore limits the number of users accessing the network, which will be not able to serve more customers, as the performance of the network is no more satisfactory.

Figure 3 depicts the AWG induced crosstalk versus the received power with varying the number of transmitted channels. It can be seen that the crosstalk induced by the AWG increases when the received power is increased and therefore result in higher power penalties; the crosstalk increases when the number of transmitted channels increases as well.

Figure 4 shows a new result using BER in Equation (9). The latter represents the bit error rate (BER) versus received power P_{rec} for various numbers of nodes. The result shows that for any number of nodes between 10 to 2000, the BER is too high for lower values of received power (all the values below -9 dBm are giving high BER) for any number of nodes, then, with increasing the received power, the curve improves but faster for less number of nodes.

Comparisons with other researches of [1-3, 5, 6, 9] show that the maximum number of nodes in a network is not limited by crosstalk, whilst the maximum number of WDM channels in a network is limited by crosstalk. The crosstalk in any channel will not continue if the channel is dropped or converted [1], and that is why the suggestion to reduce crosstalk by ensuring that a node does not simultaneously add-drop channels at the same wavelength.

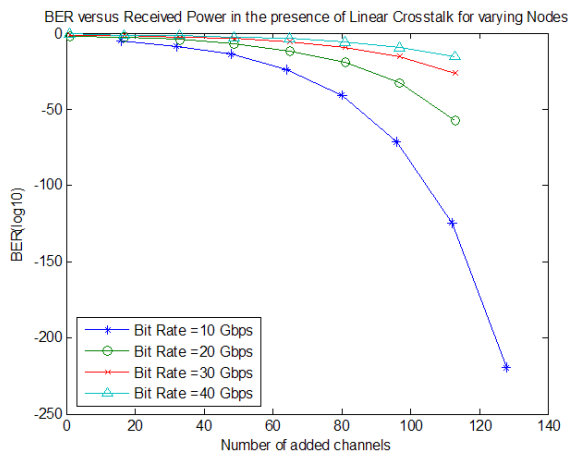


Figure 2. BER versus number of add/drop channels for an AWG in WDM optical network

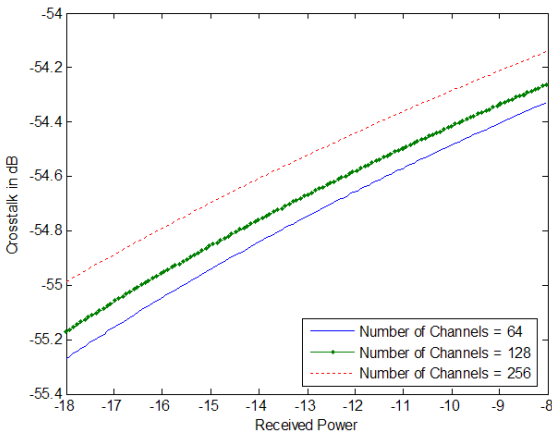


Figure 3. Crosstalk versus received power for an AWG in WDM optical network

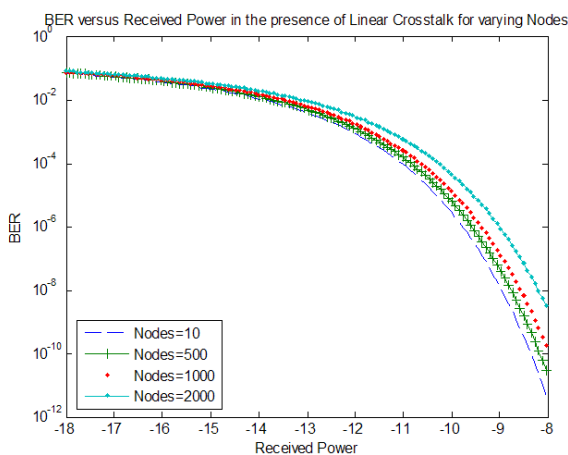


Figure 4. BER versus number of add/drop channels for an AWG in WDM optical network

4. CONCLUSION

In this paper, performance analysis has been carried out by examining the BER and AWG induced linear crosstalk versus the numbers of add/drop channels with varying the

number of transmitted channels. It is found that when the number of add/drop channels is increased, the BER also increases and do not even reach the ideal BER of 10^{-9} . It is obvious that linear crosstalk imposes severe limitation on the maximum number of add/drop channels and therefore limits the number of users accessing the WDM network, which will be not able to serve and support a large number of customers as the performance of the network is no more satisfactory. Hence, the system will suffer higher power penalties as a consequence.

The increasing crosstalk imposes power penalty as the number of nodes increases which means more users and more load in the network will reason larger power penalties. For lower received power the BER is high, and so, the network gets high values of BER in both of the cases: large number of nodes and low received power.

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REFERENCES

- [1] J. Zhou, R. Cadetdu, E. Casaccia, C. Cavazzoni, and M. J. O'Malony, "Cross talk in Multiwavelength Optical Cross-Connect Networks," *J. Lightwave Technol.*, vol. 14, no. 6, pp. 1423-1435, June 1996.
- [2] S. D. Dods, and R. S. Tucker, "A Comparison of the Homodyne Crosstalk Characteristics of Optical Add-Drop Multiplexers," *J. Lightwave Technol.*, vol. 19, no. 12, pp. 1829- 1838, December 2001.
- [3] K. D. Dambul, F. M. Abbou, H. T. Chuah, "Performance Analysis of IP Traffic over a WDM Ring Network in the presence of Crosstalk," *IEICE Electronics Express*, vol. 2, no. 5, pp. 149-153, February 2005.
- [4] R. Ramaswami., K. N. Sivarajan., "Optical Networks: A Practical Perspective," 2nd edition, Academic Press, 2002.
- [5] H. Takahashi, K. Oda, H. Toba, "Impact of Crosstalk in an Arrayed-Waveguide Multiplexer on N x N Optical Interconnection," *J. of Lightwave Technology*, vol. 14, no. 6, pp. 1097-1105, 1996.
- [6] S. M. Gemelos., D. Wonglumsom, L. G. Kazovsky, "Impact of Crosstalk in an Arrayed-Waveguide Router on an Optical Add-Drop Multiplexer," *IEEE Photonics Technology Letters*, vol. 11, Issue 3, pp. 349-351, 1999.
- [7] G. P. Agrawal, *Fiber Optic Communication Systems*, 3rd edition, John Wiley & Sons, 2002.
- [8] G. Keiser, *Optical Fiber Communications*, 3rd edition, McGraw-Hill, 2000.
- [9] Yasin M. Karfaa, M. Ismail, Abbou F. M and S. Shaari, "Homodyne Linear Crosstalk Impact in an Array Waveguide Router as an OADM for WDM Networks," *ICSE2006 Proc. Annual IEEE Conference*, Int. Conference on Semiconductor Electronics (ICSE2006), 2006, pp. 319-323.