Impact of physical layer impairments on the all-to-all broadcast in wavelength routed optical networks

M. SABRIGIRIRAJ* and M. MEENAKSHI**

* Department of Electronics and Communication Engineering, Coimbatore Institute of Engineering and Information Technology, Narasipuram post, Coimbatore – 641 109, INDIA.
sabari_giriraj@yahoo.com

** Department of Electronics and Communication Engineering, College of Engineering, Anna University, Chennai - 600 025, INDIA.
meena68@annauniv.edu

***Abstract*:** All-to-all broadcast is to disseminate a unique message from each node to every other node of the network. This paper investigates the impact of some of the physical layer impairments on the optical all-to-all broadcast in linear array, bidirectional ring and hypercube networks. The physical layer impairments include Amplified Spontaneous Emission (ASE) noise, switch induced crosstalk and demux/mux crosstalk. In all networks, the result shows that for shorter lightpaths, the ASE noise and demux/mux crosstalk are found to be much less as they traverse through few fiber links. Longer lightpaths due to their larger stretch experiences higher accumulated ASE noise and demux/mux crosstalk. In addition, lightpaths of a hypercube network suffer switch induced crosstalk at all the nodes along its path. A few measures to reduce the impact of transmission impairments are suggested since the control signals in a network should be highly reliable.

Keywords: All-to-all broadcast; Physical layer impairments; crosstalk.

1. Introduction

In a wavelength routed WDM network, a transmitted signal remains in the optical domain over the entire route (lightpath) assigned to it between the source and destination nodes. When routing lightpaths in such networks, it is generally assumed that all routes provide adequate signal quality. However, not all routes provide adequate signal quality [1].

The optical signal may have to pass through a number of intermediate nodes and long fiber segments. An optical crossconnect (OXC), realized with demultiplexer, optical switch and multiplexer, at each intermediate node facilitates the signal to propagate over the desired lightpath in the optical domain. OXC employs passive devices and therefore a signal experiences a loss during switching. The progressive losses incurred by the signal in all these intermediate nodes and long fiber segments warrant the use of optical amplifiers. The optical amplifier, usually Erbium Doped Fiber Amplifier (EDFA) is used possibly at each node and within the fiber segments [2]. The presence of OXC's and EDFA's along a lightpath introduces significant transmission impairments, such as

- crosstalk generation when two or more optical signals co-propagate through optical space switches at the nodes,
- generation of amplified spontaneous emission (ASE) noise in the EDFA's while providing signal amplification,

- crosstalk generation due to non-ideal filtering of wavelengths by the demultiplexers employed in the network nodes.

The crosstalk and the ASE noise generated at every intermediate node co-propagate along with the signal over the assigned lightpath. In addition, the crosstalk and noise experience variable gains at different wavelengths because of traffic-dependent, non-flat gain spectra of EDFAs. Thus, a signal degrades in quality as it passes through network nodes and fiber segments on its assigned lightpath towards the destination. When the signal finally arrives at the destination, the crosstalk and ASE noise that have accumulated along with the signal may result in significant decrease in signal-to-noise ratio (SNR), which might inturn increase the received bit error rate (BER) beyond its acceptable threshold. It is therefore necessary to capture all the physical layer impairments together to examine the reliability of the physical layer and estimate the achievable BER of a given lightpath.

All-to-all broadcast is to disseminate a unique message from each node to every other node. This is a fundamental problem in multiprocessor systems and telecommunication networks that need to collect information about other nodes in the network regularly in order to manage network resources efficiently. The need also arises in many form of parallel and distributed computing including many scientific computations and database management. An extensive coverage on the significance of all-to-all broadcast in optical networks can be found in [3]. Linear array and ring networks are very popular and find application in any form of network. A single ring is only a part of the overall network. The entire network typically consists of multiple rings interconnected with each other, and a connection may be routed through rings to get to its destination. The interconnection of these rings is an important aspect to be considered. Hypercube is a typical form of interconnected ring.

A comprehensive survey of Physical Layer Impairments aware Routing and Wavelength Assignment (PLI-RWA) algorithms in optical networks can be found in [4]. All the PLI-RWA algorithms, proposed in the literature, have been mainly proposed for dynamic traffic. In dynamic traffic, where connections are established one by one, the employed algorithm can examine the feasibility of a lightpath for each new connection request by calculating the effect of already established lightpaths to any candidate solution. But this approach is not suitable for all-to-all broadcast [5-7], which corresponds to static traffic. In static traffic, the assignment of lightpaths is to be decided for all connection requests simultaneously and interference among them cannot be avoided afterward. It is worth noting that PLI-RWA algorithms proposed for dynamic traffic, through repetitive execution, can also be used to solve the static traffic problem. However, such sequential approaches do not optimize the utilization of wavelengths for all connection requests jointly, and their performance is suboptimal, especially for heavy traffic.

In this paper, the effects of physical layer impairments on the all-to-all broadcast communication established on linear array, bi-directional ring and hypercube networks are examined. To the best of our knowledge, this is the first time, the effect of physical layer impairments is studied over all-to-all broadcast communication.

2. Wavelength Routing Node Architecture

Figure 1 shows the constituent optical components in a Wavelength Routing Node (WRN) [8]. The components include an OXC, a pair of EDFA's and optical power taps on either side of OXC at each port, for monitoring purposes. The EDFA with an unsaturated gain of G_{in} on the input side compensates for the signal attenuation along the input fiber and the loss at power taps. The EDFA with an unsaturated gain of G_{out} on the output side compensates exactly for the losses introduced by OXC. Each WRN consists of a transmitter array (Tx) and a receiver array (Rx) which facilitates local add/drop of any of the wavelengths at any of the nodes. The OXC is realized using three stages of components. The first stage consists of an array of demultiplexers, second stage consists of optical Wavelength Routing Switches (WRS) and the third stage consists of an array of multiplexers. All the demultiplexed signals on a given wavelength, say λ_1, are directed to the same optical switch. The switch routes the signal towards the desired output port. The multiplexers combine the optical signals on all the wavelengths and pass them to the desired output port.

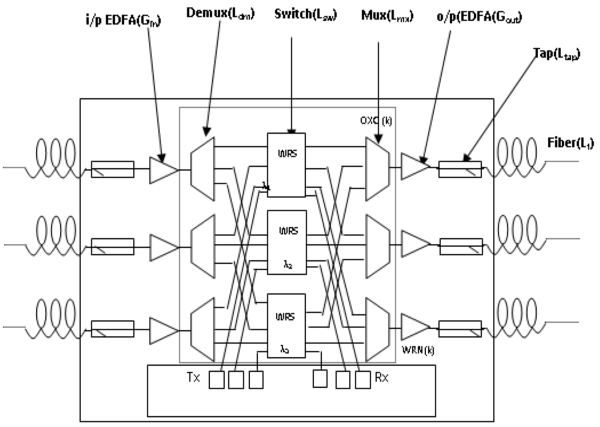

Fig. 1 Components in a wavelength routing node (WRN) [8]

The number of optical switches in an OXC equals the number of incoming wavelengths that may be passing through the node. Each switch has F input/output ports, where F is the number of input/output fibers and also an additional input/output port to enable local add/drop operations. Thus, the minimum number of input/output ports required is F+1. However, the number of input/output ports in a switch is required to be a power of two [8]. Even if a switch requires only three input/output ports, it is realized using a 4 x 4 switch in which one of the four ports on either side is unused.

3. Amplified Spontaneous Emission Noise

The dominant noise generated in the EDFA is ASE noise. The origin of this is the spontaneous recombination of electrons and holes in the amplifying medium. The combination gives rise to broad spectra of photons that gets amplified along with the optical signal. In this work, ASE is assumed to be small as compared to the signal so that it does not contribute to gain saturation. The ASE noise power associated with the i^{th} signal within an optical bandwidth B_o on a single polarization is given by

$$p_{ase(self)}(\lambda_i) = n_{sp}[G(\lambda_i)-1]hv_iB_o \quad (1)$$

where h is Planck's constant, v_i is the optical frequency at λ_i, n_{sp} is the spontaneous emission or population inversion factor and $G(\lambda_i)$ is the saturated gain at wavelength, $\lambda_i = c/v_i$ with c as the velocity of the light. Typical values for n_{sp} range from 1.4 to 4, depending on the wavelength and the pumping rate. To account for the two polarization modes present in a single mode fiber, $p_{ase(self)}(\lambda_i)$ is written as [9],

$$p_{ase(self)}(\lambda_i) = 2n_{sp}[G(\lambda_i)-1]hv_iB_o \quad (2)$$

An EDFA degrades the SNR at the receiver input due to the ASE noise. In this chapter, the impact of the ASE noise is considered during BER calculation without accounting for EDFA gain dispersion. Gain dispersion refers to the wavelength dependence of the gain of an EDFA. Since most commercially available amplifiers are able to provide gain flatness of less than 1 dB ripple across the nominal band, this assumption is justified [10].

4. In-Band Crosstalk

Crosstalk is regarded as one of the major transmission impairments in WDM optical networks [10]. The term crosstalk represents the effect of other signals on the desired signal [9]. Two forms of crosstalk can arise in WDM networks: interchannel crosstalk and intrachannel crosstalk. The first case arises when the crosstalk signal is at a wavelength sufficiently different from the wavelength of the desired signal that the difference is larger than the receiver's electrical bandwidth. The second form of crosstalk arises when the crosstalk signal is at the same wavelength as that of the desired signal or sufficiently close to it that the difference in wavelengths is within the receiver's electrical bandwidth.

Two types of in-band crosstalk can occur in a wavelength routed optical network [10] and are illustrated in Figure 2. The first type of in-band crosstalk is the switch induced in-band crosstalk which occurs when two or more lightpaths at the same wavelength pass through a node. This type of crosstalk is also called as co-wavelength crosstalk. The other type of crosstalk occurs due to the non-ideal adjacent channel isolation of the optical filters in the demultiplexers [11-12] and is called self crosstalk.

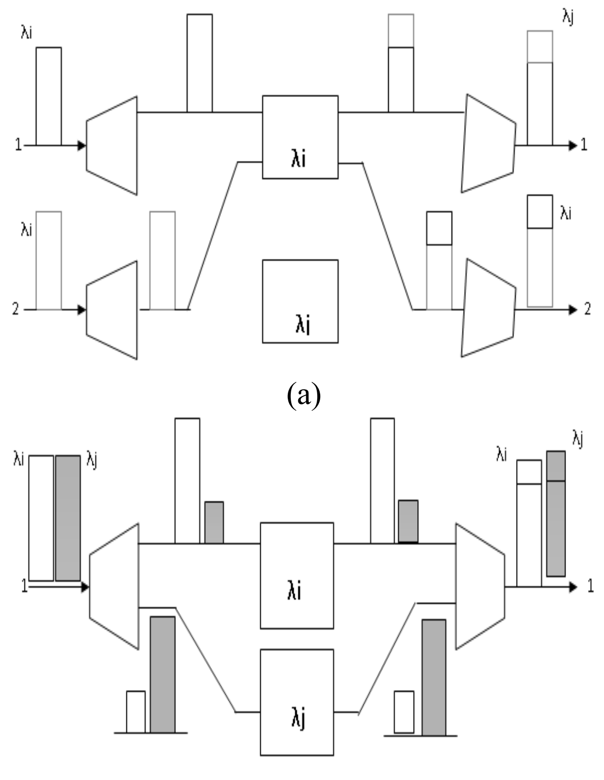

Fig. 2 Types of In-Band Crosstalk
(a) Co-Wavelength Crosstalk
(b) Self Crosstalk [13]

The first type of in-band crosstalk effect arises from another signal which is of the same wavelength as the desired signal and is referred to as incoherent crosstalk. The second type of in-band crosstalk originates from the same signal itself and is called as coherent crosstalk [10]. In this work, both the types of in-band crosstalk are considered along with ASE noise while determining the BER of a lightpath.

5. Bit Error Rate Estimation Model

In the absence of wavelength conversion, the computation of received power level along a lightpath can be described as follows. Consider a lightpath which is to be established on wavelength λ_i between nodes 1 and *N* in a network. The outbound power of the signal $\left(p_{sig}\left(k,\lambda_i\right)\right)$ on wavelength λ_i, at the output of the k^{th} intermediate node, can be expressed using the following recursive relation [8],

$$p_{sig}\left(k,\lambda_i\right) = p_{sig}\left(k-1,\lambda_i\right) L_f\left(k-1,k\right) G_{in}\left(k,\lambda_i\right) L_{dm}\left(k\right) L_{sw}(k) L_{mx}(k) G_{out}\left(k,\lambda_i\right) L_{tap}^2 \quad (3)$$

where $p_{sig}\left(k-1,\lambda_i\right)$ is the outbound power of the signal at λ_i from the $\left(k-1\right)^{th}$ node to the k^{th} node. $G_{in}\left(k,\lambda_i\right)$ is the gain at wavelength λ_i of the input EDFA of the k^{th} node and $G_{out}\left(k,\lambda_i\right)$ is the gain at wavelength λ_i of the output EDFA of the k^{th} node. $L_{dm}\left(k\right), L_{sw}(k), L_{mx}(k)$ and L_{tap} denote the losses encountered in the demux, switch, mux and power tap respectively at the k^{th} node. The demux, switch and mux losses are the same for all the nodes. The presence of *k* in the brackets indicates that losses are referred at the k^{th} node. The switch induced crosstalk at node k on wavelength λ_i is due to the crosstalk signal at λ_i arriving from previous node onto the desired input port of the WRS-λ_i of k^{th} node and the crosstalk arriving from local signal transmissions or signal arriving at other input ports of WRS-λ_i.

The outbound power of the switch induced crosstalk $\left(p_{xt}\left(k,\lambda_i\right)\right)$ on wavelength λ_i, at the output of the k^{th} intermediate node can be expressed using the following recursive relation [8],

$$p_{xt}\left(k,\lambda_i\right)=p_{xt}\left(k-1,\lambda_i\right)L_f\left(k-1,k\right)G_{in}\left(k,\lambda_i\right)$$
$$L_{dm}\left(k\right)L_{sw}(k)L_{mx}(k)G_{out}\left(k,\lambda_i\right)L_{tap}^2$$
$$+\sum_{j=1}^{J_k}X_{sw}p_{in}(j,k,\lambda_i)L_{sw}(k)L_{mx}(k)G_{out}\left(k,\lambda_i\right)L_{tap} \qquad (4)$$

where X_{sw} is the switch crosstalk ratio. Further $p_{in}(j,k,\lambda_i)$ is the power of the j^{th} propagating signal at the switch shared by the desired signal (i.e., the switch, WRS-λ_i, for wavelength λ_i) at the k^{th} node contributing to a first order switch induced homowavelength crosstalk with J_k being the number of such crosstalk sources at the k^{th} node.

The ASE noise power at the output of k^{th} node is the result of ASE noise power arriving from the previous node and the ASE noise generated by the input and output EDFA of the k^{th} node. The outbound power of the noise $\left(p_{ase}\left(k,\lambda_i\right)\right)$ on wavelength λ_i, at the output of the k^{th} intermediate node can be expressed using the following recursive relation [8],

$$p_{ase}\left(k,\lambda_i\right)=p_{ase}\left(k-1,\lambda_i\right)L_f\left(k-1,k\right)G_{in}\left(k,\lambda_i\right)$$
$$L_{dm}\left(k\right)L_{sw}(k)L_{mx}(k)G_{out}\left(k,\lambda_i\right)L_{tap}^2$$
$$+2n_{sp}[G_{in}\left(k,\lambda_i\right)-1]hv_iB_oL_{dm}\left(k\right)L_{sw}(k)$$
$$L_{mx}(k)G_{out}\left(k,\lambda_i\right)L_{tap}+2n_{sp}[G_{out}\left(k,\lambda_i\right)-1]hv_iB_oL_{tap} \qquad (5)$$

where B_o is the optical bandwidth, h is Planck's constant, n_{sp} represents the spontaneous emission factor for the EDFA's and v_i is the optical frequency at λ_i.

The outbound power of the demux/mux in-band crosstalk $\left(p_{mt}\left(k,\lambda_i\right)\right)$ on wavelength λ_i, at the output of the k^{th} intermediate node can be expressed using the following recursive relation [13],

$$p_{mt}\left(k,\lambda_i\right)=p_{mt}\left(k-1,\lambda_i\right)L_f\left(k-1,k\right)G_{in}\left(k,\lambda_i\right)$$
$$L_{dm}\left(k\right)L_{sw}(k)L_{mx}(k)G_{out}\left(k,\lambda_i\right)L_{tap}^2$$
$$+\sum_{z=1}^{z_k}Mp(z,k,\lambda_i)L_{dm}(k)L_{sw}(k)$$
$$L_{mx}(k)G_{out}\left(k,\lambda_i\right)L_{tap} \qquad (6)$$

The first term in equation (6) denotes the contribution of the demux/mux in-band crosstalk arriving from the previous node at the same port as the desired signal and the second term denotes the contribution to crosstalk by the leakage signals at λ_i, arriving from demultiplexers connected to current switch input port and M represents the filter crosstalk ratio, that is the fraction of power leaking from an adjacent wavelength due to non-ideal channel isolation of the optical filters in the demultiplexers. Further, $p\left(z,k,\lambda_i\right)$ is the power of z^{th} signal at λ_i which contributes to demux/mux inband crosstalk and is referred at the input of the demultiplexer in the k^{th} node. A fraction of $p\left(z,k,\lambda_i\right)$, namely $M\times p\left(z,k,\lambda_i\right)$ leaks into an adjacent channel at λ_j and will travel along with the adjacent channel and will appear as demux/mux in-band crosstalk at the multiplexer output as shown in Figure 2(b). The number of such crosstalk sources is z_k. Using the recursive equations (3) to (6) presented above, signal power, crosstalk power and noise power can be calculated at the destination node. The BER at the receiver is then estimated as explained below.

The lightwave received at the destination node in the presence of crosstalk and ASE noise can be expressed as [8],

$$E_R(t) = A\cos\left(2\pi v_i t + \phi(t)\right) + E_{ase}(t) + E_{xt}(t) \quad (7)$$

The equation for $E_R(t)$ consist of three components. The first component of $E_R(t)$ in equation (6.7) represents the lightwave field for the desired signal at frequency v_i, with A and $\phi(t)$ as the amplitude and phase noise of the signal while the second and third components represent the lightwave corresponding to the ASE noise and accumulated crosstalk (both switch induced and demux/mux in-band crosstalk) components respectively.

The received lightwave field, after photodetection, produces a photocurrent given by [13]

$$i_p(t) = R_\lambda \left\langle E_R^2(t) \right\rangle + i_{sh}(t) + i_{th}(t) \quad (8)$$

where the first component in the equation (8) represents the square-and-average response of the photodetector to the incident lightwave $E_R(t)$ with R_λ representing the responsivity of the photodetector, the second component is the shot noise produced by the incident lightwave, and the third component accounts for the receiver thermal noise. The first term $i_p(t)$ in equation (9) can be expressed as [13],

$$R_\lambda \left\langle E_R^2(t) \right\rangle = i_s(t) + i_{sx}(t) + i_{sm}(t) + i_{ssp}(t) + i_{xx}(t) + i_{spsp}(t) + i_{xsp}(t) \quad (9)$$

where $i_s(t)$ represents the desired signal and the remaining terms account for the beat noise components between signal and switch induced crosstalk $\left(i_{sx}(t)\right)$, signal and demux/mux in-band crosstalk $\left(i_{sm}(t)\right)$,signal and ASE $\left(i_{ssp}(t)\right)$, crosstalk with itself $\left(i_{xx}(t)\right)$, ASE with itself $\left(i_{spsp}(t)\right)$ and crosstalk and ASE $i_{xsp}(t)$ $\left(i_{xsp}(t)\right)$. The dominant beat noise terms are contributed by the signal-crosstalk and signal-ASE noise combinations, and representing all the noise components as a combined noise process $n_i(t)$, $i_p(t)$ can be written as [13],

$$\begin{aligned} i_p(t) &= i_s(t) + \left[i_{sx}(t) + i_{sm}(t) + i_{ssp}(t) + i_{sh}(t) + i_{th}(t)\right] \\ &= I_{sj}(t) + n_j(t) \\ &= R_\lambda p_{sig}^1(N, \lambda_i) b_j + n_j(t) \end{aligned} \quad (10)$$

where j in the subscripts of all the terms represent the data bit (1 or 0) being received, I_{sj} with $j = 1$ or 0 represent the corresponding signal components of the photocurrent, and $b_j = 2$ or 0 , for $j = 1$ or 0 respectively.

The combined electrical noise $n_j(t)$ is modeled as a zero-mean Gaussian random process by application of central limit theorem and the total noise variance is given by [13],

$$\sigma_j^2 = \sigma_{sxj}^2 + \sigma_{smj}^2 + \sigma_{sspj}^2 + \sigma_{shj}^2 + \sigma_{th}^2 . \quad (11)$$

The individual noise variances are expressed by [13],

$$\sigma_{sxj}^2 = 2\varepsilon_{pol} R_\lambda^2 b_j p_{sig}^1 (N,\lambda_i) p_{xt}^1 (N,\lambda_i) \quad (12)$$

$$\sigma_{shj}^2 = 2qR_\lambda B_e \begin{pmatrix} b_j p_{sig}^1 (N,\lambda_i) + \\ p_{xt}^1 (N,\lambda_i) + p_{mt}^1 (N,\lambda_i) + p_{ase}^1 (N,\lambda_i) \end{pmatrix} \quad (13)$$

$$\sigma_{smj}^2 = \varepsilon_{pol} R_\lambda^2 b_j p_{sig}^1 (N,\lambda_i) p_{mt}^1 (N,\lambda_i) \quad (14)$$

$$\sigma_{sspj}^2 = 4R_\lambda^2 b_j p_{sig}^1 (N,\lambda_i) p_{ase}^1 (N,\lambda_i) B_e / B_o \quad (15)$$

$$\sigma_{th}^2 = \eta_{th} B_e \quad (16)$$

In the above equations (11) to (16), $p_{sig}^1(N,\lambda_i), p_{xt}^1(N,\lambda_i), p_{mt}^1(N,\lambda_i)$ and $p_{ase}^1(N,\lambda_i)$ are the power referred at the receiver of the destination node and j in the subscripts represent the data bit (0 or 1) being received. B_o and B_e denote the optical and electrical bandwidths respectively, R_λ is the responsivity of the photodetector and ε_{pol} [14] is the polarization mismatch factor between the signal and crosstalk lightwaves. Highest beat noise between signal and crosstalk occurs only if all the components have the same polarization states. However, if all the crosstalk sources have random polarization states signal crosstalk beat noise power reduces by 50%. In this work, the polarization mismatch factor (ε_{pol}) is taken as ½ to account for the random polarization states. The spectral density of the thermal noise current in the optical receiver is represented by η_{th}. In this work, a 50% mark density of crosstalk channels is assumed while calculating the beat noise components between signal and crosstalk [14].

The receiver BER is evaluated with a given decision threshold choice, I_{th}. One can minimize the BER by an optimum selection of I_{th}. The optimum selection of I_{th} can be calculated using the following expression [8],

$$I_{th} = \frac{\sigma_0 I_{s1}}{\sigma_0 + \sigma_1} \quad (17)$$

However, an optimum choice of I_{th} can only be made with a prior knowledge of the received power levels of the signal, crosstalk, and ASE components. In the present network architecture, since all these components are dependent on the assigned lightpath and hence are variable, one cannot optimize the threshold in a static sense. On the other hand, dynamic control of threshold for each lightpath would need a significant communication overhead for the network. In view of the above reason and assuming a perfect laser extinction when $b_o = 0$ and hence $I_{so} = 0$, the receiver threshold I_{th} is fixed at $I_{s1}/2$.

Using the above threshold and noise variances, the receiver BER is expressed as [8],

$$P_b = 0.25 \left[erfc\left(\frac{I_{s1} - I_{th}}{\sqrt{2}\sigma_1} \right) + erfc\left(\frac{I_{th}}{\sqrt{2}\sigma_0} \right) \right] \quad (18)$$

Table 1. System parameters and their values used to study the impact f physical layer impairments

Parameters	Value
Number of wavelengths	25
Wavelength spacing	100 GHz
Wavelengths (in nm)	(1540.60,1541.40,1542.20,…,1560.60)
Bit rate per channel (r)	1 Gbps
Electronic bandwidth (B_e)	0.7r
Optical bandwidth (B_o)	3.77 THz
Multiplexer loss (L_{mx})	4 dB

Demultiplexer loss (L_{dm})	4 dB
Switch element insertion loss (L_s)	1 dB
Waveguide/fiber coupling loss (L_w)	1 dB
Switch loss (L_{sw}) (from Spanke 1987)	$2\log_2 B L_s + 4L_w$ dB (for a B x B switch)
Tap loss (L_{tap})	1 dB
Fiber loss (L_f)	0.2dB/km
Input EDFA gain (G_{in})	22 dB
Output EDFA gain (G_{out})	16 dB
ASE factor	1.5
RMS thermal current / $(R_{th})^{1/2}$ ($\sqrt{\eta_{th}}$)	5.3×10^{-12} Amp/$\sqrt{Hz}$
Max. laser power (P_t)	0 dBm (1 mW)
Switch crosstalk (X_{sw})	30dB
Demux/Mux crosstalk ratio (M)	30 dB
Responsivity (R)	0.73 A/W

6. Illustrative Numerical Examples and Discussion

In this section, some representative numerical examples are presented to describe the impact of switch induced crosstalk, demux/mux induced crosstalk and ASE noise on the all-to-all broadcast communication. The EDFA gain saturation is assumed to be constant which implies that EDFA always deliver the small signal gain irrespective of the input signal power. In Table 1, the system/device parameters used in the simulations are listed.

During all-to-all broadcast communication, all the connections are alive throughout the time span. The all-to-all broadcast connections are setup by means of multiple unicast connections. The internode distance is taken as 100km. The demux/mux induced crosstalk is generated along the path when two lightpaths on adjacent wavelengths traverse together atleast on two consecutive links. The ASE noise is generated at all EDFAs present along the lightpath.

The BER is first evaluated for the all-to-all broadcast connections of a 10 node linear array network whose nodes are numbered from 0 to 9. The wavelength assignment is carried out in order, as proposed in [5]. It can be easily noted here that switch induced crosstalk may be generated at source node and/or destination node, only for shorter lightpaths involving wavelength reuse. Consider the tagged call that is set up between node 0 and node 8. Figure 3 shows the powers of the received signal, demux/mux induced crosstalk and ASE noise at all the intermediate nodes and at the destination node. Note that the signal power remains constant, as the call propagates through the network. This is because the small-signal gain of each amplifier in the network was set to be exactly equal to the losses at intervening network components and the amplifiers are assumed to deliver the small signal gain irrespective of the input signal power. However, the ASE noise power grows due to accumulation of ASE at each EDFA stage. Also, the demux/mux induced crosstalk grows since fresh crosstalk is encountered along the path. The switch induced crosstalk is absent, as this tagged call is assigned a unique wavelength which is not reused by any other call. The resulting BER's of the tagged call at the receivers in nodes 1, 2, 3, 4, 5, 6, 7, and 8 turns out be 0, 10^{-110}, 10^{-55}, 10^{-38}, 10^{-29}, 10^{-23} , 10^{-20}, and 10^{-17} respectively. Due to the nature of all-to-all broadcast communication in a linear array, the BER calculation provided for the above call holds good for all the calls which are assigned unique wavelength and not reused by any other call. For shorter lightpaths, where there are wavelength reuse, there is presence of switch induced crosstalk at the source and/or destination nodes. The BER calculations for such calls are same as that of ring network which is discussed next.

Next, the BER is evaluated for the all-to-all broadcast connections of a 14 node bi-directional ring network whose nodes are numbered from 0 to 13. The wavelength assignment is carried out in order, as proposed in [6]. Consider the tagged call that is set up between node 0 and node 8. Figure 4 shows the powers of the received signal, switch induced crosstalk, demux/mux induced crosstalk and ASE noise at all the intermediate nodes and at the destination node. The powers of the received signal, demux/mux induced crosstalk and ASE noise at all the intermediate nodes and at the destination node are same as that of a linear array network discussed above. In addition, there is a switch induced crosstalk only at the source node and destination node due to wavelength reuse in the network. The resulting BER's of the tagged call at the receivers in nodes 1, 2, 3, 4, 5, 6, 7, and 8 turns out be 10^{-28}, 10^{-23}, 10^{-19}, 10^{-17}, 10^{-15}, 10^{-15}, 10^{-13}, and 10^{-12} respectively. Due to the nature of all-to-all broadcast communication in a ring network, the BER calculation provided for the above call holds good for all the other calls.

The BER is evaluated for the all-to-all broadcast connections of an 8 node hypercube network [7]. The wavelength assignment is carried out in order, as proposed in [7]. Consider the tagged call that is set up between node 000 and node 111. Figure 5 shows the powers of the received signal, switch induced crosstalk, demux/mux induced crosstalk and ASE noise at all the intermediate nodes and at the destination node. The powers of the received signal, demux/mux induced crosstalk and ASE noise at all the intermediate nodes and at the destination node are same as that of a linear array network discussed above. In addition, there is a switch induced crosstalk at all the nodes along its path including source node and destination node due to wavelength reuse in the network. The resulting BER's of the tagged call at the receivers in nodes 001, 011 and 111 turns out be 10^{-23}, 10^{-19}, 10^{-16} respectively. Due to the nature of all-to-all broadcast communication in a hypercube network, the BER calculation provided for the above call holds good for all the other calls.

The BER calculation for all the networks shows that for shorter lightpaths, the ASE noise and demux/mux crosstalk are found to be much less as they traverse through fewer number of fiber links and intermediate nodes. On the other hand, longer lightpaths due to their larger stretch and more number of intermediate nodes experience higher accumulated spontaneous emission (ASE) noise and demux/mux crosstalk. In addition, for shorter lightpaths of linear array network and all lightpaths of ring network, switch induced crosstalk is present only at source node and destination node. But a hypercube network experiences switch induced crosstalk at all the nodes along its path including source and destination nodes. This switch induced crosstalk increases with the number of nodes in the network.

Proceeding in the same manner, for any network, when the number of nodes is increased beyond a certain limit, the received BER of some lightpaths may be unacceptably high and may result in network performance degradation. Hence even if sufficient wavelengths are provided for all-to-all broadcast communication, certain control signals could be impaired resulting in overall network performance degradation. Hence, switch crosstalk ratio, filter crosstalk ratio and ASE noise should be eliminated or minimized as much as possible for the all-to-all broadcast communication to be reliable.

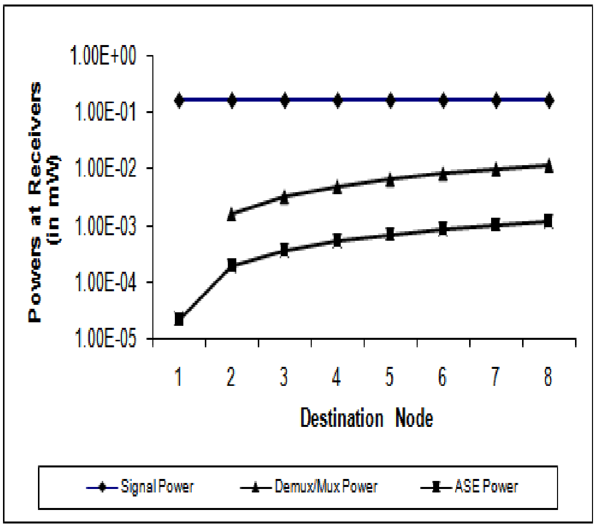

Fig. 3 Progress of a tagged call from Node 0 to Node 8 in a linear array network. The figure shows the signal, demux/mux crosstalk and ASE noise powers at the receivers of the intermediate nodes and the destination node

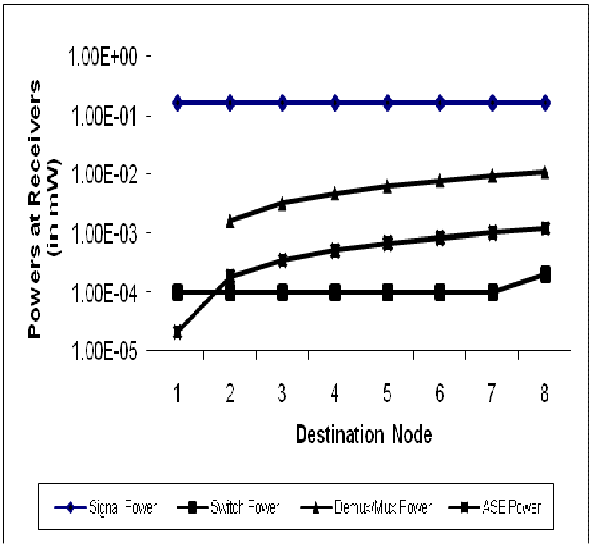

Fig. 4 Progress of a tagged call from Node 0 to Node 8 in a bidirectional ring network. The figure shows the signal, switch crosstalk, demux/mux crosstalk and ASE noise powers at the receivers of the intermediate nodes and the destination node

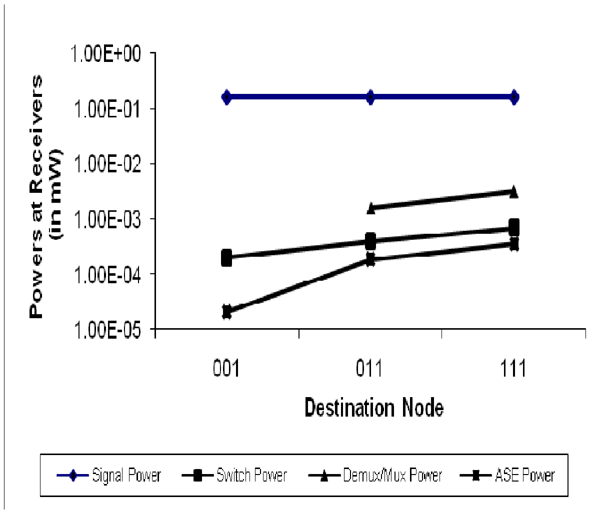

Fig. 5 Progress of a tagged call from Node 000 to Node 111 in a hypercube network. The figure shows the signal, switch crosstalk, demux/mux crosstalk and ASE noise powers at the receivers of the intermediate nodes and the destination node

7. Conclusion

In this chapter, the impact of ASE noise, crosstalk originating at the optical switches and the crosstalk arising due to non-ideal filter characteristics of demultiplexers have been considered to evaluate the BER of the all-to-all broadcast connections in a linear array, bi-directional ring and hypercube network. The results obtained show that BER of the lightpaths in linear array and bi-directional ring gets increased mainly by demux/mux induced crosstalk and ASE noise. But for a hypercube network, in addition to demux/mux induced crosstalk and ASE noise, switch crosstalk is also a major factor in determining the BER of the lightpaths. Hence, filter crosstalk ratio, ASE noise and switch crosstalk ratio should be eliminated or minimized as much as possible for the all-to-all broadcast communication in a network to be reliable. Future work includes studying the impact by taking into account other nonlinearities.

References

1. Strand J., Chiu A.L. and Tkach R., 'Issues for routing in the optical layer', IEEE Communications magazine, Vol. 39, 2001, pp. 81-87.

2. Saxtoft C. and Chidgey P. 'Error rate degradation due to switch crosstalk in large modular switched optical networks', IEEE Photonics Technology Letters, Vol. 5, 1993, pp. 828-831.

3. Pascu S. 'Optical control plane: Theory and Algorithms', Louisiana State University and Agricultural and Mechanical college, Doctor of Philosophy Thesis, 2006.

4. Azodolmolky S., Klinkowski M., Marin E., Careglio D., Pareta J.S. and Tomkos I. 'A survey on physical layer impairments aware routing and wavelength assignment algorithms in optical networks', Elsevier Computer Networks, Vol.53, 2009, pp.926-944.

5. Sabrigiriraj M., Meenakshi M. and Roopkumar R. 'Wavelength assignment in WDM linear array', IET Electronics letters, Vol. 43, No.20, 2007, pp.1111-1113.

6. Sabrigiriraj M., Meenakshi M. and Roopkumar R., 'Wavelength Assignment for All-to-all Broadcast in Wavelength Division Multiplexing Optical Ring', IETE Journal of Research, Vol.55, 2009, pp.236-241.

7. Sabrigiriraj M., Meenakshi M. and Roopkumar R., 'An Efficient Wavelength Assignment for All-to-all Broadcast in Optical WDM Hypercube Network', Journal of Optics, Vol. 35, No.4, 2006, pp.188-196.

8. Ramamurthy B., Datta D., Feng H., Heritage J.P. and Mukherjee B., 'Impact of transmission parameters on the teletraffic performance of wavelength-routed optical networks', IEEE/OSA Journal of Lightwave Technology, Vol.17, 1999, pp. 1713-1723.

9. Ramaswami R. and Sivarajan K.N., 'Optical Networks: A Practical Perspective', 2nd edition, San Francisco, CA: Morgan Kaufmann, 2001.

10. Deng T., Subramaniam S. and Xu J., 'Crosstalk – aware wavelength assignment in dynamic wavelength – routed optical network', proc. Broadnets' 04, 2004, pp. 140 -149.

11. Zhou J., Cadeddu R., Casaccia E., Cavazzoni C. and O'Mahony M.J., 'Crosstalk in multiwavelength optical cross-connect networks', IEEE/OSA Journal of Lightwave technology, Vol. 14, 1996, pp. 1423-1435.

12. Iannone E., Sabella R., Avattaneo M., and Paolis G.D., 'Modeling of in-band crosstalk in WDM optical networks', IEEE/OSA Journal of Lightwave technology, Vol.17, 1999, pp. 1135-1141.

13. Saminadan V. and Meenakshi M., 'In-Band crosstalk performance of WDM optical networks under different routing and wavelength assignment algorithms', Proc. of IWDC 2005, LNCS Vol.3741, 2005, pp. 159-170.

14. Takahashi H., Oda K. and Toba H., 'Impact of crosstalk in an arrayed-waveguide multiplexer on *N* x *N* optical interconnection', Journal of Lightwave Technology, Vol.14, 1996, pp. 1097-1105.