Evaluation of the Energy Consumption per Bit in BENES Optical Packet Switch

V. Eramo, E. Miucci, A. Cianfrani, A. Germoni, and M. Listanti

Abstract—We evaluate the average energy consumption per bit in Optical Packet Switches equipped with BENES switching fabric realized in Semiconductor Optical Amplifier (SOA) technology. We also study the impact that the Amplifier Spontaneous Emission (ASE) noise generated by a transmission system has on the power consumption of the BENES switches due to the gain saturation of the SOAs used to realize the switching fabric. As a matter of example for 32×32 switches supporting 64 wavelengths and offered traffic equal to 0,8, the average energy consumption per bit is $2,34 \cdot 10^{-1}$ nJ/bit and increases if ASE noise introduced by the transmission systems is increased.

Keywords—Benes, Amplifier Spontaneous Emission Noise, Energy Consumption, Optical Packet Switch.

I. INTRODUCTION

QUANTITATIVE models of energy consumption in a variety of switching devices have been developed and used in a simple model of a large switched network [1]. This model provides an estimate of the lower bound on energy in a global network. Using aggressive estimates of future improvements in different technologies, the relative contributions of various network subsystems and components to the overall global network energy consumption has been estimated and it has been demonstrated that the energy consumption of the switching infrastructure is larger than the energy consumption of the transport infrastructure [1].

Over the past decade, several research groups have proposed optical switch fabrics based on Arrayed Waveguide Grating (AWGR) [6] or Semiconductor Optical Amplifiers (SOA) [7]-[8], primary for telecom applications. However, the lack of practical optical buffer technology creates a difficulty; solutions relying on optical buffer delay lines or deflection routing [8] cannot guarantee arbitrary delays and prevent packet dropping. On the other hand, a traditional approach relying on the store-and-forward paradigm can cause most of the bottleneck typical of electrical switches (high latency, large power consumption and a limited number of ports and switching capacity), reducing the benefits offered by optical technology. For lacking of optical buffer, bufferless optical packet switches (OPSs) are promising nodes in reducing the power consumption [9]. To solve output packet contentions they use the wavelength domain. Contending packets are wavelength converted by using Wavelength Converters. Due to the high power consumption of WCs, especially for bit-rate increasing, Optical Packet Switching architectures with shared WCs have been defined [9].

V. Eramo, L. Piazzo, M. Listanti and A. Cianfrani are with the Department of Information, Electronic and Telecommunications Engineering, Sapienza University of Roma, Via Eudossiana 13, 00184 Rome, Italy e-mail: (see http://net.infocom/uniroma1.it/homepages/eramov).

A. Germoni is with Co.Ri.Tel., Via Cavour 256, 00184, Rome, Italy

In this paper we propose an analytical model to evaluate the average energy consumption per bit of an Optical Packet Switch equipped with a BENES switching fabric realized in Semiconductor Optical Amplifier (SOA) technology. Sophisticated analytical models are introduced to evaluate the the power consumption of the devices, in particular SOAs, needed to realize the switching fabric. The introduced models allow us to evaluate the impact that Amplifier Spontaneous Emission (ASE) noise, generated by a transport system, has on the SOA's power consumption due to the SOA gain saturation. By means of the these models, we are able to evaluate the average energy consumption per bit of the BENES switch as a function of the main system and traffic parameters and versus the characteristic of the transmission system (length, number of amplifiers, ...).

The remainder of the paper is organized as follows. Section II describes the BENES switch. An analytical model evaluating the average energy consumption per bit in BENES switches versus the offered traffic, the switch parameters and the characterics of the transmission system is described in Section III. The main numerical results are illustrated in Section IV where we provide some results on the power consumption of the BENES switch. Finally Section V provides some final remarks and concludes the paper.

II. BENES OPTICAL PACKET SWITCH

The studied general switching architecture is reported in Fig. 1. It is equipped with N input/output fibers (IF/OF) where each IF/OF supports M wavelengths channels. Let λ_i $(i = 0, \ldots, M - 1)$ be the wavelengths carried on each OF. In order to save power consumption, the OPS is equipped with fully shared Wavelength Converters (WC). Packets not requiring wavelength conversion are directly routed towards the Output Fibers (OF). On the contrary packets requiring wavelength conversion will be directed to a pool of WCs, wavelength converted and next routed to the OF to which they are directed.

An Optical Packet Switching architecture equipped with BENES switching fabric realized in Semiconductor Optical Amplifier (SOA) technology is studied. The BENES network belongs to a class of rearrangeably non blocking networks with 2×2 switching elements. Fig. 2.a shows a 8×8 BENES switch using 20 2×2 switching elements. It is one of the most efficient architectures in terms of used number of 2×2 switching elements. A $P \times P$ BENES switch requires $\frac{P}{2}(2 log_2 P - 1)$ 2×2 switching elements, with P being a power of 2 [10]. A single 2×2 switch can be realized in SOA technology as shown in Fig. 2.b. It is made by four SOAs, two splitters

World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
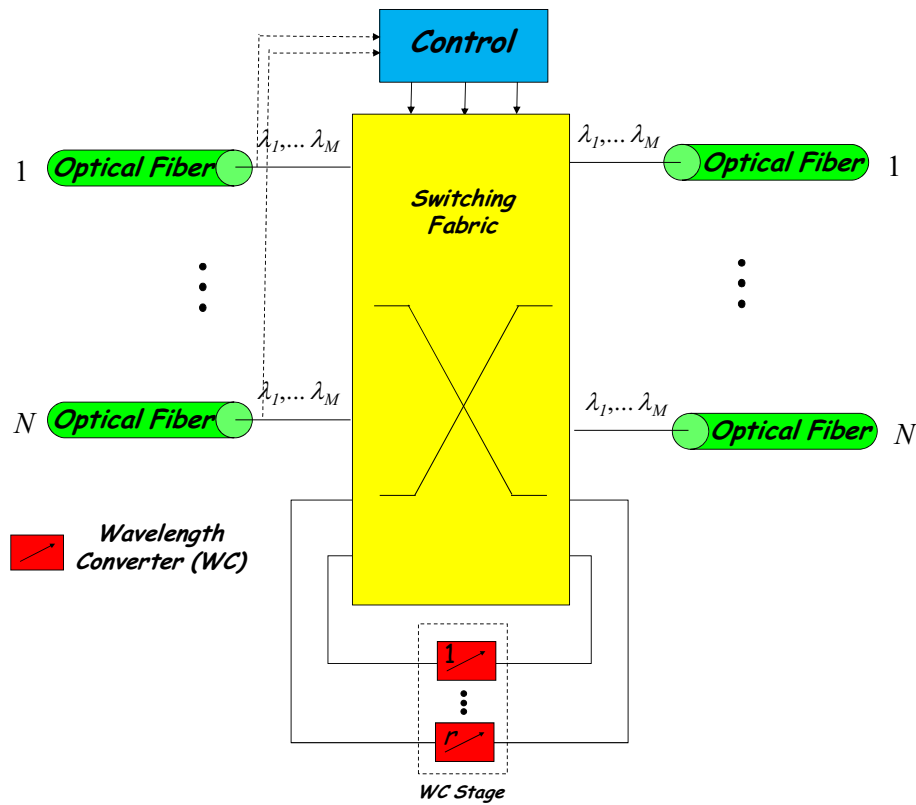Vol:5, No:9, 2011

Fig. 1   Optical Packet Switching Architecture with N Input/Output Fibers, M Wavelength and r shared Wavelength Converters.
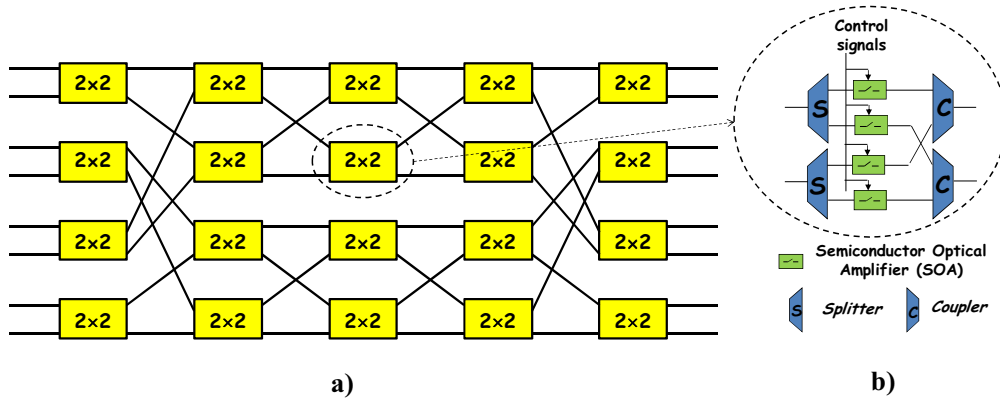

Fig. 2 8×8 BENES switching architecture realized with 20 2×2 switching elements (a). SOA technology based 2×2 switching element (b).

and two couplers and enables connectivity in both the *bar* and *crossed* states similar to a directional coupler fabricated in lithium niobate. The Optical Packet Switching architecture shown in Fig. 1 supporting N IF/OF, M wavelengths and r wavelength converters can be realized with an $2NM \times 2NM$ BENES network. An example of BENES switch is illustrated in Fig. 3 in the case N=2, M=2 and r=1. The total number of splitters and couplers can be reduced as illustrated in the switch of Fig. 4. It is obtained by starting from the switch reported in Fig. 3 and by combining in the adjacent stages with a 3dB Directional Coupler (DB) the output couplers on

the left-hand and the input splitters on the right-hand.

III. ANALYTICAL EVALUATION OF THE POWER CONSUMPTION IN BENES SWITCH

To evaluate the BENES switch energy consumption we use the model illustrate in [11] to evaluate the SOA's power consumption PC_{SOA}. According to this model, PC_{SOA} can be expressed as follows:

$$PC_{SOA} = V_b I_b = V_b \left(1 + \frac{log_e G^{us}}{\Gamma_{SOA} \alpha_{SOA} L_{SOA}} \right) i_t \qquad (1)$$
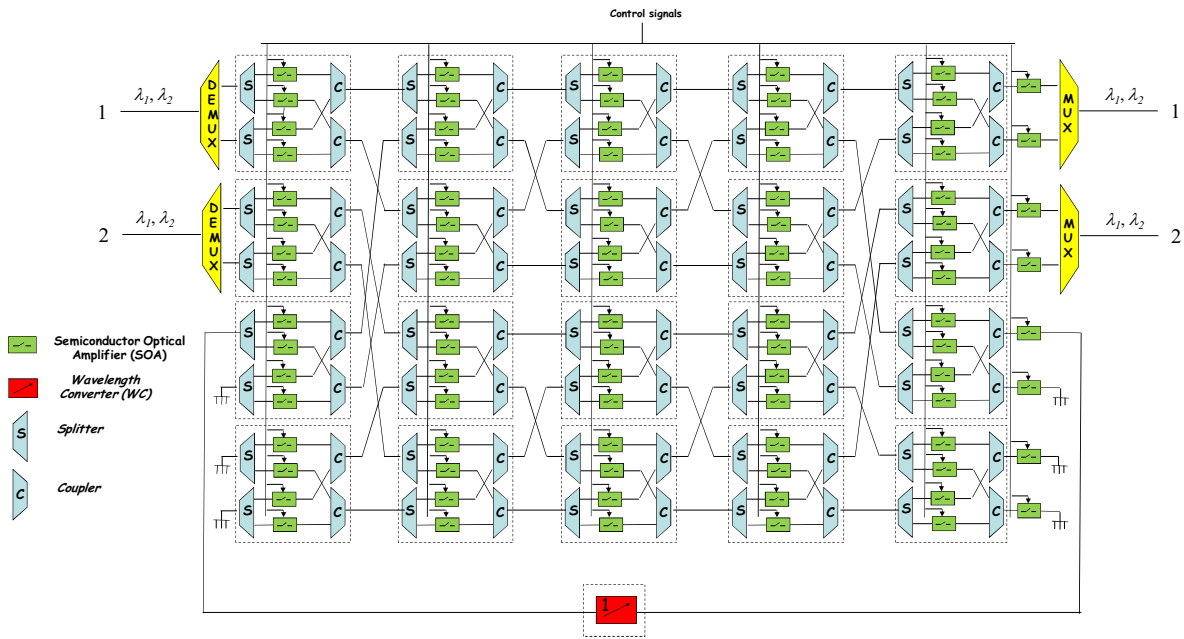
World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:5, No:9, 2011

Fig. 3   BENES Optical Packet Switch realized with splitters, couplers and SOAs (N=2, M=2, r=1).

where V_b is the SOA forward bias voltage, I_b is the polarization current, Γ_{SOA} is the confinement factor, α_{SOA} is the material loss, L_{SOA} is the length and i_t is the transparency current given by:

$$i_t = \frac{qw_{SOA}d_{SOA}L_{SOA}N_0}{\tau} \qquad (2)$$

w_{SOA} being the SOA active region effective width, d_{SOA} the active region depth, $q = 1,6\times10^{-9}C$ the electronic charge, N_0 the conduction band carrier density required for transparency, τ the carrier spontaneous decay lifetime. The amount of gain saturation G^s is a function of the SOA input power P_{SOA}^{in} and the following nonlinear equation gives the unsaturated gain G^{us} required to produce saturated gain G^s [12]:

$$G^{us} = G^s \exp\left((G^s - 1)\frac{P_{SOA}^{in}}{P_{sat}}\right) \qquad (3)$$

To evaluate the BENES switch power consumption we assume that each 1×2 splitter, 2×2 directional coupler and 2×1 coupler shown in Fig. 4 introduce an attenuation of 2 that is recovered by the SOAs located after each splitter, directional coupler and coupler. If a packet is directly forwarded it goes through the BENES switch once. Conversely if the packet has to be wavelength converted the BENES switch is crossed twice and a wavelength converter is used. The two paths involved are illustrated in Figs 5.a and 5.b in the cases of directly forwarded or wavelength converted packet respectively.

In particular notice as a directly forwarded packet needs the use of one 1×2 splitter, one 2×1 coupler, $2log_2 2NM - 2$ directional couplers and $2log_2 2NM$ SOAs each having a saturated gain equal to 2. On the contrary a wavelength converted packet needs the use of two 1×2 splitters, two 2×1 couplers, $4log_2 2NM - 4$ directional couplers and $4log_2 2NM$ SOAs. Let us denote with C_{df}^{SOA} and C_{wc}^{SOA} the sum of

the power consumption of the SOAs involved in the switch paths illustrated in Figs 8.a and 8.b respectively. We can write the following expression for the average power consumption $P_{av,T}^{BENES}$ of a BENES switch:

$$\begin{aligned} P_{av,T}^{BENES} &= E[N_a]C_{df}^{SOA} + E[N_c]C_{wc}^{SOA} + rC_{WC} + \\ &+ E[N_{SOA}^{BENES,off}]C_{off}^{SOA} \end{aligned} \qquad (4)$$

where

- $E[N_a]$ is the number of accepted packets;
- $E[N_c]$ is the number of converted packets;
- $E[N_{SOA}^{BENES,off}]$ is the number of turned off SOAs; it is given by the total number $N_{SOA}^{BENES,tot} = 4NMlog_2 2NM$ of SOAs in the BENES switch to the total number $N_{SOA}^{MVMC,on} = 2(E[N_a]+E[N_c])log_2 2NM$ of turned on SOAs that is:

$$E[N_{SOA}^{BENES,off}] = (4NM-2(E[N_a]+E[N_c]))log_2 2NM \qquad (5)$$

By using the expression of the power consumption of a cascade of SOA and passive elements reported in [13]-[15], the following expression can be obtained for C_{df}^{SOA} and C_{wc}^{SOA}:

$$C_{df}^{SOA} = \sum_{i=1}^{2log_2 2NM} V_b \left(1 + \frac{log_e 2 + \frac{(P_s^{in}+P_{ASE}^{in})+(i-1)P_{se}}{2P_{sat}}}{\Gamma_{SOA}\alpha_{SOA}L_{SOA}}\right) i_t \qquad (6)$$

$$C_{wc}^{SOA} = \sum_{i=1}^{4log_2 2NM} V_b \left(1 + \frac{log_e 2 + \frac{(P_s^{in}+P_{ASE}^{in})+(i-1)P_{se}}{2P_{sat}}}{\Gamma_{SOA}\alpha_{SOA}L_{SOA}}\right) i_t \qquad (7)$$

wherein:

- P_s^{in} is the input signal power;
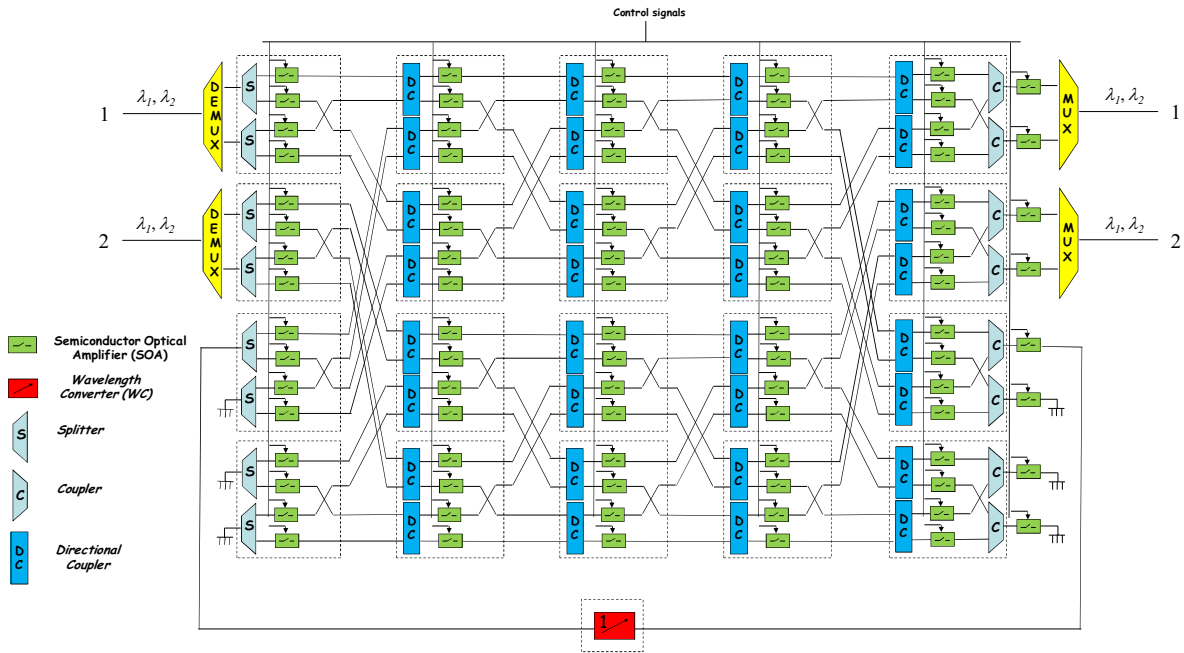- P_{ASE}^{in} is the Amplifier Spontaneous Emission (ASE) noise power;

World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:5, No:9, 2011

Fig. 4   BENES Optical Packet Switch realized with splitters, directional couplers, couplers and SOAs (N=2, M=2, r=1).
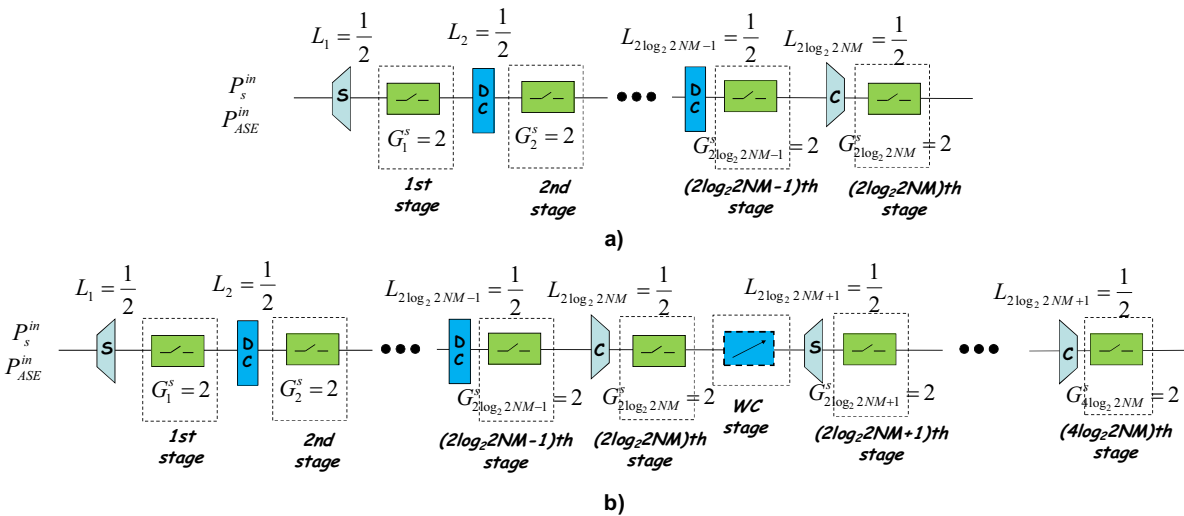

Fig. 5   Paths followed in the BENES switch by a packet in the cases in which it is directly forwarded (a) or it is wavelength converted (b) For each path the attenuation and the gain of the splitters, directional couplers, couplers and SOAs are reported.

- where $P_{se} = n_{sp}p_{eff}h\nu_c B_0$; each SOA is assumed to emit ASE with constant spectral density within the optical bandwidth B_0; ν_c is the center frequency, h is the Planck constant, n_{sp} is the excess spontaneous emission factor [16], p_{eff} is a factor which ranges from 1 for a device which amplifies only one polarization to 2 for a polarization-insensitive device.

Finally notice as by inserting Eqs (5)-(7) in Eq. (4) and by using the expressions of $E[N_a]$, $E[N_d]$ and $E[N_d]$ evaluated in [15], we can able to calculate the average power consumption $P_{av,T}^{BENES}$ of the BENES switch.

IV. NUMERICAL RESULTS

Next we use the analytical model introduced in Section III to evaluate the average energy consumption per bit $E_{av,T}^{BENES} = \frac{P_{av,T}^{BENES}}{NMB}$ in BENES switch, where N is the number of Input/Output Fibers, M is the number of wavelengths and B denotes the bit rate carried out on each wavelength. We will show how the ASE noise generated at the switch input may influence the power consumption of the BENES switch due to SOA gain saturation. We perform the analysis under the following assumptions:

- The SOA's power consumption model illustrated in [11] is

World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:5, No:9, 2011

adopted and allowing us, according to Eq. (1), to express the SOA power consumption as a function of the main SOA parameters (V_b, i_b, w_{SOA}, ...); A$\sharp$1 commercial SOAs [17] produced by manufacture A is used to implement the switching fabric. The A$\sharp$1 parameter values are reported in Table I.

TABLE I
MAIN PARAMETER VALUES FOR THE A$\sharp$1 COMMERCIAL SOAs

Symbol	Explanation	Value
V_b	Forward Bias Voltage	2 V
Γ_{SOA}	Confinement Factor	0.15
α_{SOA}	Material Loss	10^4
L_{SOA}	Length	$700\,\mu m$
w_{SOA}	Active Region Effective Width	$2\,\mu m$
d_{SOA}	Active Region Depth	$0.1\,\mu m$
N_0	Conduction Band Carrier Density	$10^{24} m^{-3}$
τ	Carrier Spontaneous Decay Lifetime	$10^{-9}s$
P_{sat}	Saturation Power	$50\,mW$

- As Wavelength Converter, the Delayed Interference Signal Wavelength Converter (DISC) proposed in [18] is used. DISC utilizes an SOA and an Optical Bandpass Filter placed at the amplifier output. It can be constructed by using commercially available fiber-pigtailed components. It has a simple configuration and allows photonic integration. Its power consumption has been evaluated in [18] when commercial SOA produced by some manufactures are employed. In particular we consider the A$\sharp$2 SOA characterized by a Multiple Quantum Well (MQW) type structure and produced by manufacture A. We report in Table II the main parameter values for A$\sharp$2. The power consumption, measured in [18], is also reported. It equals 187mW when the WC is operating at bit-rate B=40 Gb/s.

TABLE II
MAIN PARAMETER VALUES FOR THE A$\sharp$2 COMMERCIAL SOA; THE POWER CONSUMPTION OF DISCs REALIZED WITH A$\sharp$2 SOAs IS ALSO REPORTED AT BIT-RATE B=40 GB/S.

	Type	Active region Length (μm)	Active region width (μm)	Active region thickness (μm)	Confinement Factor	Consumed power (mW) (40Gb/s)
B#1	MQW	1100	1,25	0,038	0,2	187

- We assume that the ASE noise P_{ASE}^{in} is generated by a Wavelength-Division Multiplexing (WDM) transmission system comprising S identical stages, each of length (i.e., EDFA amplifier spacing) L as illustrated in Fig. 6.
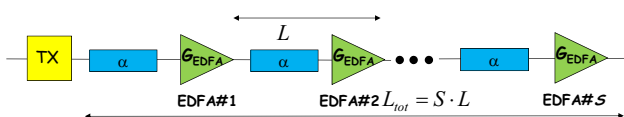

Fig. 6   Schematic of optically amplified link, comprising an optical transmitter, S identical stages of optical gain. Each stage has length L and the used fiber is characterized by an attenuation equal to α dB/Km. L_{tot} is the total length of the optically amplified link.

The total length of the transmission system is $L_{tot} = SL$.

Each stage in Fig. 6 is modeled by a fiber attenuation block with a power loss of $D_{fiber} = e^{\alpha L}$, where α is the power attenuation per unit length of the fiber and an amplifier gain block with power gain G_{EDFA} which is equal to the loss per stage (i.e., $G_{EDFA} = D_{fiber}$). At each wavelength, the ASE noise P_{ASE}^{in} is given by the following expression [19]:

$$P_{ASE}^{in} = 2n_{sp}^{EDFA}S(e^{\alpha L} - 1)h\nu_c B_0 \qquad (8)$$

where n_{sp}^{EDFA} is the excess spontaneous emission factor of each EDFA amplifier.

We choose the switch parameters N=32, M=64 and we report in Fig. 7 the average energy consumption $E_{av,T}^{BENES}$ per bit as a function of the offered traffic p. The pool of WCs is optimally dimensioned with the minimum number r_{th} of WCs needed to reach the saturation packet loss probability due to the lack of output wavelength channels [20]. The operation bit-rate is B=40 Gb/s and the optical bandwidth is B_0=100Ghz. The used SOAs are characterized by the parameters n_{sp}=3,5, p_{sp}=2. Power consumption is not taken into account for the turned off SOAs (i_{off}=0). The energy consumptions are reported varying the number S of stages from 0 to 30 of the transmission system generating ASE noise at the switch input. Each stage has length L=70Km with attenuation $\alpha = 0,2$ dB/Km and each EDFA is characterized by n_{sp}^{EDFA}=1. The case S=0 corresponds to the case in which no ASE noise is generated because electrical regeneration is performed before the switching operation. From Fig. 7 we can notice how the increase in ASE noise makes less energy efficient the BENES switch. For instance when p=0,6, $E_{av,T}^{BENES}$ increases from $1,67 \cdot 10^{-1}$nJ/bit to $6,10 \cdot 10^{-1}$nJ/bit when S increases from 0 to 30. That is consequence of the increase in ASE noise that saturates the SOAs gain leading to the need to increase the power consumption as indicated by the Eqs (5)-(6).
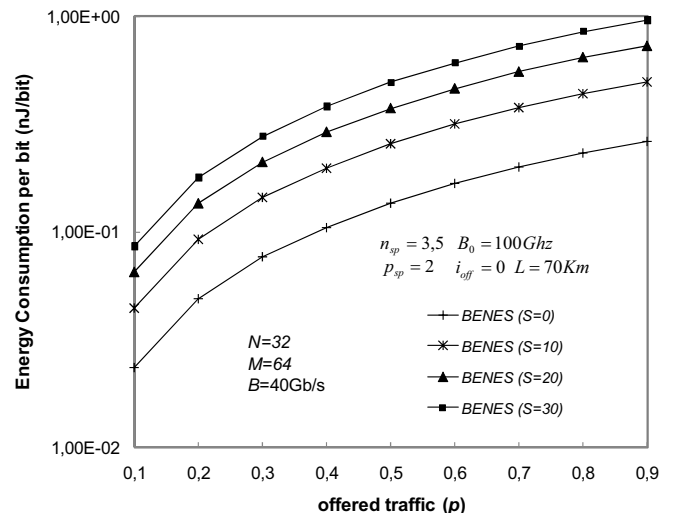

Fig. 7   Average energy consumption per bit $E_{av,T}^{BENES}$ in BENES switch versus the offered traffic p for N=32, M=64. The bit-rate carried on each input wavelength channel is B=40 Gb/s. The optical bandwidth is B_0=100Ghz and the used SOAs are characterized by n_{sp}=3,5, p_{sp}=2 and i_{off}=0. The ASE noise at the switch input is generated by a transmission system characterized by L=70Km, α=0,2 dB/Km and S varying from 0 to 30.

World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:5, No:9, 2011

The effect of the characteristics of the transmission system on the power consumption of the BENES switch is studied in Fig. 8 where we report $E_{av,T}^{BENES}$ as a function of the stage length L of the transmission system. The same switch parameters of Fig. 7 are used. The offered traffic p is varying from 0,2 to 0,8. The energy consumption evaluation is carried out when the total length L_{tot} of the transmission system is 2400Km. We can notice as the energy consumption $E_{av,T}^{BENES}$ quickly increases for stage length L greater than 60 Km. That is due to an exponential increase in fiber attenuation that leads to increase the EDFA gain and the noise and consequently the gain saturation of the SOAs needed to realize the BENES switch.
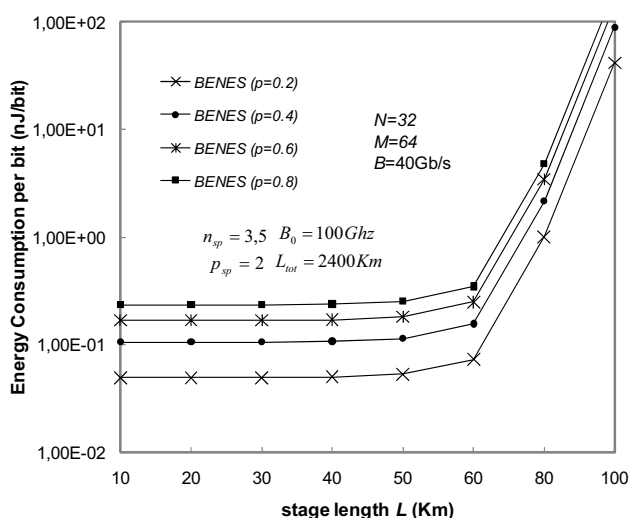

Fig. 8   Average energy consumption per bit $E_{av,T}^{BENES}$ in BENES switch versus the stage length L of the transmission system generating ASE noise. The switch parameters are N=32, M=64 and the offered traffic p is varying from 0,2 to 0,8. The bit-rate carried on each input wavelength channel is B=40 Gb/s and the optical bandwidth is B_0=100Ghz. The same SOA parameters of Fig. 7 are used. The total length L_{tot} of the transmission system is 2400Km.

V. Conclusion

The paper discussed issues concerning power consumption of future high-capacity optical packet nodes. We have proposed a sophisticated analytical model in order to evaluate the average energy consumption per bit of the BENES switch. In the evaluation of the energy consumption we take into account the ASE noise generated by the transmission system that can degrade the performance in power consumption because of the gain saturation of the SOA gates needed to realize the switching fabric. We have verified the the ASE noise generated by a transmission system may strongly degrade the switch performance in terms of power consumption. As a matter of example, if a switch with N=32 and M=64 is taken into account and the offered traffic p equals 0,6, the average energy consumption per bit is six times higher when the ASE noise of a transmission system characterized by S =30 spans each one of length 70Km.

References

[1] R.S. Tucker, *Green Optical Communications-Part II: Energy Limitations in Networks*, IEEE Journal of Selected Topics in Quantum Electronics, March/April 2011.

[2] R.S. Tucker, *Optical Packet Switching: A Reality Check*, Optical Switching and Networking, vol. 5, pp 2-9, March/April 2007.

[3] S. Aleksic, *Analysis of Power in Future High.Capacity Network Nodes*, IEEE/OSA Journal of Communications and Networking, vol. 1, pp. 245-258, August 2009.

[4] S. Aleksic, *Power Consumption Issues in Future High-Performance Switches and Routers*, ICTON 2008, Athens, Greece, June 2008.

[5] S. Aleksic, N. Fehatovic, *Requirements and Limitations of Optical Interconnects for High-Capacity Network Elements*, ICTON 2010, Munich, Germany, June 2010.

[6] J. Gripp, M. Duelk, J. Simsarian, S. Chandrasekhar, P. Bernasconi, A. Bhardway, Y. Su, K. Sherman, L. Buhl, E. Laskowski, M. Capuzzo, L. Stulz, M. Zirngibl, O. Laznicka, T. Link, O. Mayer, M. Berger, *Demonstration of a 1.2 Tb/s Optical Packet Switch Fabric (32·40) based on 40 Gb/s burst-mode clock-data-recovery, fast tunable lasers and a high-performance N · N AWG*, 27th European Conference on Optical Communication, Amsterdam, Holland, September 2001.

[7] S.J.B. Yoo, *Optical Packet and Burst Switching Technologies for the Future Photonic Internet*, IEEE/OSA Journal Lightwave of Technology, vol. 24, pp. 4468-4492, December 2006.

[8] O. Liboiron-Ladouceur, A. Shacham, B.A. Small, B.G. lee, H. Wang, C.P. Lai, A. Biberman, K. Bergman, *The Data Vortex Optical Packet Switched Interconnection Network*, IEEE/OSA Journal Lightwave of Technology, vol. 26, pp. 1777-1789, July 2008.

[9] V. Eramo, M. Listanti, *Power Consumption in Bufferless Optical Packet Switches in SOA Technology*, IEEE/OSA Journal of Communications and Networking, vol. 1, pp B15-B29 August 2009.

[10] V.E. Benes, *Mathematical Theory of Connecting Networks*, New York: Academic, 1965.

[11] K. Hinton, G. Rakutti, P. Farrel, R.S. Tucker, *Switching Energy and Device Size Limits on Digital Photonic Signal Processing Technologies*, IEEE Journal of Selected Topics in Quantum Electronics, vol. 14, pp. 938-945, May/June 2008.

[12] G. Jeong, J.W. Goodman, *Gain Optimization in Switches Based on Semiconductor Optical Amplifiers*, IEEE/OSA Journal Lightwave of Technology, vol. 13, pp. 598-605, April 1995.

[13] R.F. Kalman, L.G. Kazovsky, J.W: Goodman, *Space Division Switches Based on Semiconductor Optical Amplifiers*, IEEE Photonic Technology Letters, vol. 4, pp. 1048-1051, September 1992

[14] A. Ehrhardt, M. Eiselt, G. Groβkopf, L. Kuller, R. ludwig, W. Pieper, R. Schnabel and H. Weber, *Semiconductor Laser Amplifier as Optical Switching Gate*, IEEE/OSA Journal Lightwave of Technology, vol. 11, pp. 1287-1295, August 1993.

[15] V. Eramo, *Effect of ASE noise on the Power Consumption of MVMC and BENES Optical Packet Switches*, IEEE/OSA Journal of Communications and Networking, submitted to publication.

[16] C.H. Henry, *Theory of Spontaneous Emission Noise in Open Resonators and its Applications to Laser and Optical Amplifier*, IEEE/OSA Journal Lightwave of Technology, vol. 4, pp. 288-297, April 1986.

[17] V. Eramo, *Comparison in Power Consumption of Synchronous and Asynchronous Optical Packet Switches*, IEEE/OSA Journal Lightwave of Technology, vol. 28, pp. 847-857, March 2010.

[18] Y. Ueno, J. Sakaguchi, R. Nakamoto, T. Nishida, *Ultrafast, low-energy-consumption, semiconductor-based, all-optical devices*, 4-th Asia- Pacific Photonics Conference (APMP 2009), Bejing, China, April 2009.

[19] R.S. Tucker, *Green Optical Communications-Part I: Energy Limitations in Transport*, IEEE Journal of Selected Topics in Quantum Electronics, March/April 2011.

[20] V. Eramo, M. Listanti, C. Nuzman, P. Whiting, *Optical Switch Dimensioning and the Classical Occupancy Problem*, International Journal Communications Systems, vol. 15, pp. 127-141, March/April 2002.