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 $32 \times 32$ switches supporting 64 wavelengths and offered traffic equal to 0.8, the average energy consumption per bit is $2.34 \times 10^{-1}$ 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 simple models 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], primarily 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].

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 characteristics 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 $\lambda_i$ $(i = 0, \ldots, M - 1)$ 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 $2 \times 2$ switching elements. Fig. 2a shows a $8 \times 8$ BENES switch using $20 \times 2$ switching elements. It is one of the most efficient architectures in terms of used number of $2 \times 2$ switching elements. A $P \times P$ BENES switch requires $\frac{P^2}{2}(2\log_2 P - 1)$ $2 \times 2$ switching elements, with $P$ being a power of 2 [10]. A single $2 \times 2$ switch can be realized in SOA technology as shown in Fig. 2b. It is made by four SOAs, two splitters...
Fig. 1 Optical Packet Switching Architecture with \( N \) Input/Output Fibers, \( M \) Wavelength and \( r \) shared Wavelength Converters.

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:

\[
PC_{SOA} = V_b I_b = V_b \left( 1 + \frac{\log_{10} G_{\text{out}}}{\Gamma_{SOA} G_{\text{SOA}} L_{SOA}} \right) i_t \quad (1)
\]
To evaluate the BENES switch power consumption we assume the current given by:

$$i_t = \frac{q w_{SOA} d_{SOA} L_{SOA} N_0}{\tau}$$  \hspace{1cm} (2)

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

$$G_{sat} = G^* \exp\left(\frac{P_{in,SOA}}{P_{sat}}\right)$$ \hspace{1cm} (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 5a and 5b in the cases of directly forwarded and wavelength converted packet respectively.

In particular notice as a directly forwarded packet needs the use of one 1×2 splitter, one 2×1 coupler, $2 \log_2 2 N_M - 2$ directional couplers and $2 \log_2 2 N_M$ 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, $4 \log_2 2 N_M - 4$ directional couplers and $4 \log_2 2 N_M$ 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 8a and 8b respectively. We can write the following expression for the average power consumption $P_{av,T}^{BENES}$ of a BENES switch:

$$P_{av,T}^{BENES} = E[N_a] C_{df}^{SOA} + E[N_c] C_{wc}^{SOA} + r C_{WC} + E[N_{BENES,off}] C_{off}^{SOA}$$ \hspace{1cm} (4)

where

- $E[N_a]$ is the number of accepted packets;
- $E[N_c]$ is the number of converted packets;
- $E[N_{BENES,off}]$ is the number of turned off SOAs;

It is given by the total number $N_{SOA}^{BENES,tot} = 4 N M \log_2 2 N_M$ of SOAs in the BENES switch to the total number $N_{SOA}^{MVMC,off} = 2(E[N_a] + E[N_c]) \log_2 2 N_M$ of turned on SOAs that is:

$$E[N_{SOA}^{BENES,off}] = (4 N M - 2(E[N_a] + E[N_c]) \log_2 2 N_M$$ \hspace{1cm} (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 $C_{wc}^{SOA}$:

$$C_{df}^{SOA} = \sum_{i=1}^{2 \log_2 2 N_M} V_b \left(1 + \frac{\log_2 2 + (P_{in}^a + P_{in}^c) + (i-1)P_{se}}{\Gamma_{SOA SOA LSOA}}\right)$$ \hspace{1cm} (6)

$$C_{wc}^{SOA} = \sum_{i=1}^{4 \log_2 2 N_M} V_b \left(1 + \frac{\log_2 2 + (P_{in}^a + P_{in}^c) + (i-1)P_{se}}{\Gamma_{SOA SOA LSOA}}\right)$$ \hspace{1cm} (7)

wherein:

- $P_{in}^a$ is the input signal power;
- $P_{se}$ is the Amplifier Spontaneous Emission (ASE) noise power;
where \( P_{ae} = n_{sp}P_{eff}h\nu_{c}B_0 \); each SOA is assumed to emit ASE with constant spectral density within the optical bandwidth \( B_0 \); \( \nu_{c} \) 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 \( E[N_s] \), \( E[N_d] \) and \( E[N_d] \) evaluated in [15], we can able to calculate the average power consumption \( P_{av,T}^{BENES} \) of the BENES switch.

\[ P_{av,T}^{BENES} = \frac{P_{BENES}}{NMB} \]

**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...
adopted and allowing us, according to Eq. (1), to express
the SOA power consumption as a function of the main
SOA parameters ($V_a, b, w_{SOA}, \ldots$): $A\sharp 1$ 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>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_a$</td>
<td>Forward Bias Voltage</td>
<td>2 V</td>
</tr>
<tr>
<td>$I_{SOA}$</td>
<td>Confinement Factor</td>
<td>0.15</td>
</tr>
<tr>
<td>$d_{SOA}$</td>
<td>Material Loss</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$L_{SOA}$</td>
<td>Length</td>
<td>700μm</td>
</tr>
<tr>
<td>$w_{SOA}$</td>
<td>Active Region Effective Width</td>
<td>2μm</td>
</tr>
<tr>
<td>$N_d$</td>
<td>Active Region Depth</td>
<td>0.1μm</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Carrier Spontaneous Decay Lifetime</td>
<td>10$^{-10}$ s</td>
</tr>
<tr>
<td>$P_{sat}$</td>
<td>Saturation Power</td>
<td>50 mW</td>
</tr>
</tbody>
</table>

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 integra-
tion. Its power consumption has been evaluated in [18]
when commercial SOA produced by some manufacturers
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>
<thead>
<tr>
<th>Type</th>
<th>Active region Length ($\mu$m)</th>
<th>Active region width ($\mu$m)</th>
<th>Active region thickness ($\mu$m)</th>
<th>Confinement Factor</th>
<th>Consumed power (mW) (40Gb/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B31</td>
<td>MQW</td>
<td>1100</td>
<td>1.25</td>
<td>0.018</td>
<td>0.2</td>
</tr>
</tbody>
</table>

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.

Each stage in Fig. 6 is modeled by a fiber attenuation
block with a power loss of $D_{fiber} = \alpha L$, where $\alpha$
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]:

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

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 $E_{BENES}^{SW,T}$
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 $B_0=100$Ghz.
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 $\alpha = 0.2$
with stages from 0 to 30 of the
transmission system generating ASE noise at the switch input.

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 $\alpha$ dB/Km. $L_{tot}$ is
the total length of the optically amplified link.

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

Fig. 7 Average energy consumption per bit $E_{BENES}^{SW,T}$ 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 $B_0=100$Ghz 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 $L=70$Km, $\alpha=0.2$ dB/Km and $S$ varying from 0 to 30.
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 $E_{\text{BENES}}$ 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 $L_{\text{tot}}$ of the transmission system is $2400\text{Km}$. We can notice as the energy consumption $E_{\text{BENES}}$ quickly increases for stage length $L$ greater than $60\text{ Km}$. 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.

![Energy Consumption per bit](image)

The energy consumption per bit $E_{\text{BENES}}$ 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 $B=40\text{ Gb/s}$ and the optical bandwidth is $B_0=100\text{GHz}$. The same SOA parameters of Fig. 7 are used. The total length $L_{\text{tot}}$ of the transmission system is $2400\text{Km}$.

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 switching fabric. We have verified 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 $70\text{Km}$.

ACKNOWLEDGMENT

The research leading to these results has received funding from the European Community’s Seventh Framework Programme FP7/2007-2013 under grant agreements n 247674 (STRONGEST-Scalable, Tuneable and Resilient Optical Networks Guaranteeing Extremely-high Speed Transport).

REFERENCES