Modeling, Simulating, and Characterizing Performance in Optical Switching Networks

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ABSTRACT

Photonic packet switching for all-optical networks is a rapidly developing technology since it circumvents many of the traditional bottlenecks created by the use of electronics. All-optical networking has application to both long-haul communications systems and high-performance computing systems. In each case, all-optical technologies are responsible for the routing, switching and logic decisions of the network. Characterizing the performance of a network includes calculating the latency and scalability of a given architecture assuming ideal behavior of its physical components. However, the physical layer ultimately determines the feasibility of data transmission. Thus accurately calculating the accumulated bit-error-rate (BER) is fundamental to evaluating the optical network as a whole, regardless of the network architecture. A new simulation technique, which is based upon experimental findings, is introduced which characterizes the physical layer performance of a given network architecture known as the Data Vortex. Experiments show that almost all the physical layer penalty is generated by the nodes which are used for switching and routing. Specifically, at each node data packets are amplified by a semiconductor optical amplifier so that coupling and routing losses are compensated. In this process, the data packets receive a noise penalty which results primarily from amplified spontaneous emission and in small part from spectral broadening. By using a phenomenological approach to modeling the noise penalties, the performance of the network nodes can be characterized. The modeling allows for a comprehensive understanding of the network and is a highly efficient computational tool for evaluating performance when compared to conventional time-domain techniques.

Keywords: all-optical network, photonic switching

1. INTRODUCTION

Basic technologies for realizing all-optical networking configurations are rapidly being developed. The impetus for such efforts results from the ultra-high speeds possible when circumventing traditional electronic technologies and their inherent latency. All-optical networking has application to both long-haul communications systems and high-performance computing systems. In each case, all-optical technologies are responsible for the routing, switching and logic decisions of the network. Characterizing the performance of a network is a two-fold process. First the network architecture is itself evaluated. This includes calculating the latency and scalability of a given network assuming ideal behavior of its physical components. The second characterization involves the integration of the physical layer and its performance penalties. The physical layer ultimately determines the feasibility of data transmission. Thus accurately calculating the Q-factor and accumulated bit-error-rate (BER) is fundamental to evaluating the optical network as a whole, regardless of the network architecture. This aim of this paper is to characterize the physical layer performance of a given network architecture known as the *Data Vortex*.[1–3] To this end, simulation and modeling are used to calculate the cummulative Q and BER so that a comprehensive evaluation of the data vortex network is achieved.

Physical layer modeling of all-optical networks is an important aspect of characterizing a given network topology. In many respects, a physical layer performance evaluation is independent of the methods used to evaluate a

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given network architecture. Thus, once a viable network is chosen for in-depth study due to its high scalability and low latency properties, physical layer modeling provides insight into the true behavior of the network due to physical limitations and penalties of the all-optical devices and components responsible for processing the flow of data. Extensive evaluations of optical networks have been performed for long-haul transmission systems for which large penalties are incurred in optical fibers. These penalties are primarily generated from chromatic dispersion, self-phase and cross-phase modulation, polarization mode dispersion, amplified spontaneous emission (ASE) noise, and periodic attenuation and amplification. Numerical modeling is heavily utilized to quantify the penalties arising from these physical effects and characterize the performance of national and international long-haul systems. In contrast, we are considering the all-optical network for high-performance computing applications.[1–3] Thus the length of optical fibers used is limited to meters and the propagation penalties in the fiber are virtually non-existent. For this case, almost all the physical layer penalty is generated by the network nodes which are used for switching and routing. The modeling here will focus on the penalties incurred from the node only and will ignore any propagation penalties since they are orders of magnitude smaller over the meters of fiber used for propagating around the network.

2. MODELING THE NETWORK

The model to be described here is based upon the experimental performance of the node structures responsible for switching and routing. The bulk of the transmission penalty comes from the semiconductor optical amplifier (SOA) which offsets the attenuation of the propagating optical signal from the routing, switching and logic operations. Thus the node penalties will accumulate as data is propagated through the Data Vortex structure. This section will outline how the network architecture is dealt with along with calculating the transmission penalties.

2.1. Network Architecture

Although the analysis here does not provide a performance evaluation of the network architecture, it is the architecture which ultimately determines the mean-time a data stream propagates in the network and accumulates penalties from the node structures. The Data Vortex architecture[1–3] is free of optical buffers and enables simple routing logic for large scale, low latency packet switch fabrics.[1] The hierarchical system employs a synchronous timing and distributed control signaling to avoid packet contention and to achieve simplicity, scalability, and high throughput.

The Data Vortex architecture, illustrated in Fig. 1, is characterized by the parameters A and H which represent the corresponding nodes lying along the "angle" and "height" dimension respectively of the cylindrical geometry. The number of cylinders, C, in the architecture scales as $C = \log_2(H) + 1$. The data packets are processed synchronously within the switch fabric in a parallel manner. Within each time slot, every packet progresses forward by one angle ($a = a + 1$) by either staying on the same cylinder (solid line, $c = c$) or by moving toward an inner cylinder (dashed line, $c = c + 1$).

Data packets are inserted at nodes on the outermost cylinder ($c = 0$) and are propagated to the output ports on the innermost cylinder ($c = C - 1$). The packets are self-routed and proceed along the "angle" dimension until the appropriate output port has been reached. Along with the data payload, which is a collection of wavelength division multiplexed (WDM) channels each operating at 10 gigabits per second, there are two separate channels for header information and timing frame which are modulated at a slower rate. A testbed for studying the traffic control and WDM routing in the Data Vortex is presented in Ref..[3] The Data Vortex network is shown to have low-latency, high scalability, and requires no optical buffering: ideal qualitites for all-optical networking applications.

2.2. Node Structure and Penalties

The nodes of the optical Data Vortex serve the purpose of routing input data streams towards their output destinations. Each routing node (see Fig 2) consists of two SOAs. The packet comes from either North or West port. A small amout of optical power (≈10%) is tapped off for the header reading and routing purpose. Optical delay lines need to be inserted in the packet path to compensate for the delay associated with tap off and routing processor. Since the header and frame information is WDM encoded, simple, fixed band-pass filters are used

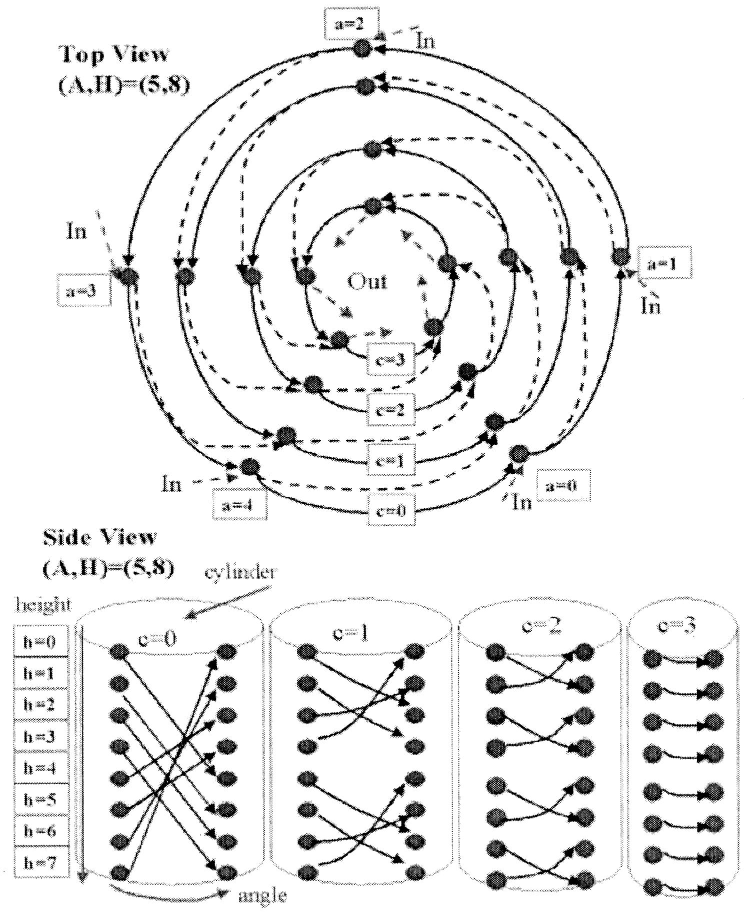


Figure 1. Data Vortex topology with the parameters $(A, H) = (5, 4)$ and nodes labeled by (a, c, h) where $0 < a < A, 0 \leq c < C$ and $0 \leq h < H$. The routing tours are seen from the top and side. Information is input on the outermost cylinder $(c = 0)$ and is propagated to the appropriate output port on the innermost cylinger $(c = C - 1)$.

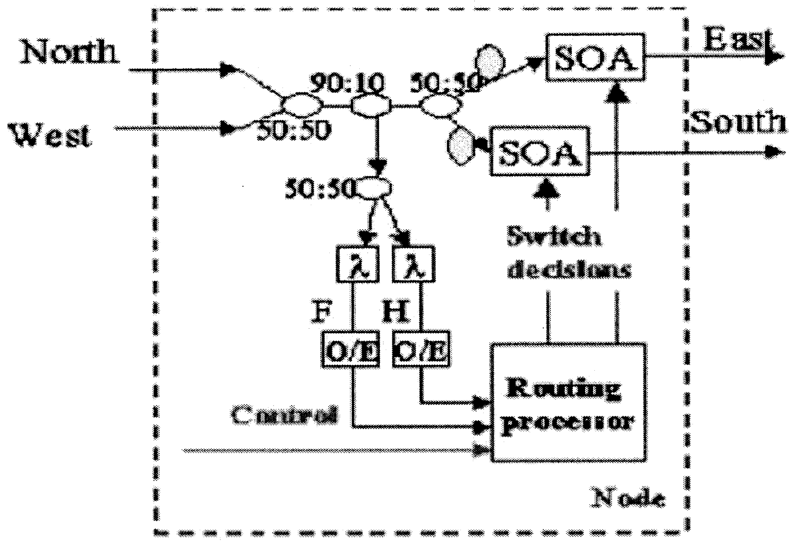
to retrieve the bit-per-wavelength encoded routing bits. All the nodes located on one cylinder would have the same setup of decoding filters since they all process the same specific bit wavelength. The routing information runs at rather low packet rates. Therefore it can be converted into electronics by low cost detectors prior to the routing processor. The routing processor also needs to examine the control signal, which may be transmitted through either optical links or electronic lines depending on the implementation choice. The routing processor thus output swiching decision that control SOAs on or off. The truth table for the routing processor is simple and is included in Fig. 2.

2.3. The SOA

Ordinarily utilized as amplifiers in long-haul lightwave systems, SOAs are also extraordinarily useful as the active switching elements within numerous lightwave systems.[4] Because high extinction ratios and reasonable switching times can be achieved, SOAs are often utilized in switching architectures.[5, 6]

Fabricated from III-V semiconductor materials, contemporary SOAs utilize the electronic transition from the conduction band to the valence band as a radiation source. Population inversion is achieved through the introduction of a pump current. This current can be modulated, effectively turning the amplifier on and off. Ideally, the switching speed is only limited by the carrier lifetimes. Moreover, the electronic transitions generally occur only when stimulated by incoming radiation, thereby functioning as an amplifying device.

However, as in all laser systems, unwanted spontaneous emissions can occur. These emissions may be amplified as they propagate through the length is the devices, and are often termed amplified sponaneous emissions (ASE).[7]



F	H	C	Switch-E	Switch-S
0	0	0/1	0	0
1	0	0	1	0
1	1	0	1	0
1	1	1	0	1

Figure 2. Routing node structure and its associated truth table. Note that the bulk of transmission penalties are incurred from amplification through the SOAs.

Fortunately though, this contribution is predictable and well-behaved: the noise figure is additive, accumulating in the spectrum as an increase in the noise floor.[8] Other minor nonlinear effect also occur due to homogeneous and inhomogeneous nonuniformities. All of these nonidealities together contribute to signal degradation in lightwave systems that rely on SOAs as amplifying or as switching elements.

3. PHYSICAL LAYER NETWORK MODELING

Transmission penalties leading to degradation of the Q-factor and BER are due primarily to the accumulated ASE noise from the SOAs. Experiments show the SOAs have two primary noise contributions. The first is the expected white-noise (broadband) contribution from ASE of the amplification process. The second is a colored noise component of a Lorentzian shape centered around the individual WDM channels. By incorporating these two dominant physical effects into our penalty model, a rough guide to the propagation efficiency can be numerically calculated. More sophisticated modeling requires the calculation of errors due to other physical effects such as time-domain cross-talk. For the present, only noise penalties will be considered as they are the dominant contributions to transmission degradation.

The physical layer node penalties can be incorporated into a network model by considering a data stream packet propagating from its input node to its output node. Each data packet will traverse a statistically deter-

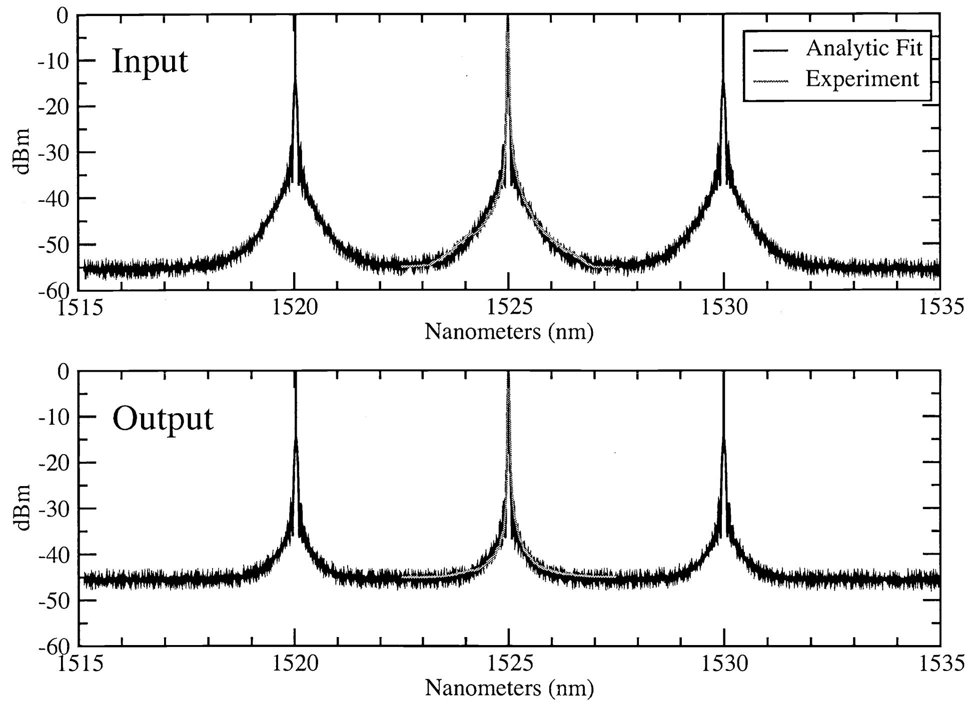


Figure 3. Analytic fit, using A, B, and C, to the experimentally measured noise penalties due to white-noise and a Lorentzian contribution. The analytic data corresponds to (1) where 500 realizations have been averaged over. Three channels have been used in the experimental fit with a channel spacing large enough so that no noticeable overlap occurs between neighboring Lorentzian contributions.

mined number of nodes which is determined by the size of the Data Vortex.[1,2] The model simply requires the mean number of nodes traversed and the associated variance in number of nodes. The algorithm developed for the network model then considers a large number of WDM data stream realizations each of which propagates through the network a statistically determined number of nodes. The eye diagrams, along with the calculation of Q-factor and BER, are then determined from the total set of data streams propagated through the network at the various WDM channels. Thus the model relies on accurate qualitative and quantitative accounting for the penalties incurred at each node.

To consider modeling the noise penalties, a single WDM channel is first considered. The pulse stream profile is assumed to be given by $u(t, z)$ where in optics coordinates z gives the distance propagated and t gives the temporal profile of a 10 gigabit per second, pseudo-random, non-return-to-zero (NRZ) data stream. Fourier transforming gives the spectral representation $\hat{u}(\omega, z)$. of the data. The white-noise and Lorentzian noise penalties are then incorporated into transmission via

$$\hat{u}(\omega,t)_+ = \hat{u}(\omega,t)_- + A(\eta_1 + i\eta_2) + B(\eta_3 + i\eta_4)\frac{1}{1+C(\omega-\omega_0)^2} \tag{1}$$

where $\hat{u}(\omega, t)_\pm$ represents a given spectral component before $(-)$ and after $(+)$ an SOA. Here the η_i are normally distributed random variables with mean zero and unit variance, the parameter A determines the strength of the white noise, and B and C measure the strength and width associated with the Lorentzian noise contribution which is centered at the WDM frequency ω_0.

The parameters A, B, and C are determined from fitting to experimental measurements. Figure 3 depicts a fit of these three parameters to an experimentally measured input and output relationship of an SOA. In order

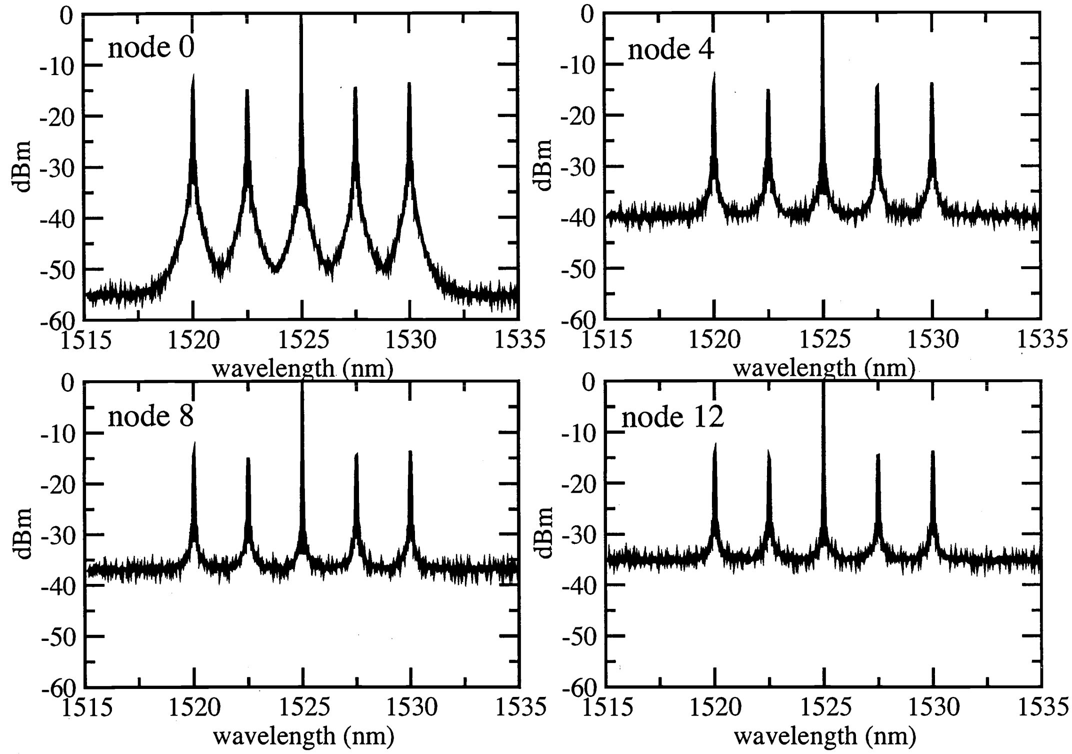


Figure 4. Evolution of the spectrum of five WDM channels spaced 2 nm apart over 12 SOAs (nodes). The transmission penalties at each node are derived from (1) with the parameters fit to Fig. 3. Two hundred realizations have been simulated.

for the analytic curve to be smooth as depicted in the figure, 2000 realizations of (1) where averaged together to produce the otherwise noisy fit. Further, the output was normalized to the same peak power as the input in order to preserve the correct signal-to-noise ratio.

To illustrate the penalties incurred from cascading SOAs together, we consider the penalty as modeled by (1) with the parameters A, B, and C fit according to Fig. 3. As a specific example, five WDM channels are transmitted, each with a 32-bit random data sequence. It is assumed that the only penalties are those generated by the SOA, i.e. perfect splicing and transmission through a fiber from one SOA to another SOA are assumed. Figure 4 shows the spectral evolution of the WDM channels over 12 cascaded SOAs. The simulation is performed using the penalties (1) with the parameters A, B, and C derived from the fit in Fig. 3. It is clear from this figure that the noise shelf is increased significantly with the number of SOAs (nodes) traversed.

A more formal way of calculating the transmission penalty is to construct the eye diagrams associated with Fig. 4. The statistics of the ones and zeros then allow for the calculation of the Q-factor and BER of transmission.[8] Figure 5 illustrates how the eye diagram closes as the number of SOAs is cascaded. Depending on network performance restrictions, the number of nodes physically possible for transmission can be calculated. For instance, the cascaded SOAs considered here allow for the transmission over five nodes with a BER below 10^{-9}. A BER rate of 10^{-12} can be maintained through four nodes and over eight nodes can be cascaded with a BER below 10^{-6}. Figure 6 depicts the drop in Q-factor and increase in bit-error as the data propagates through the cascaded SOA chain.

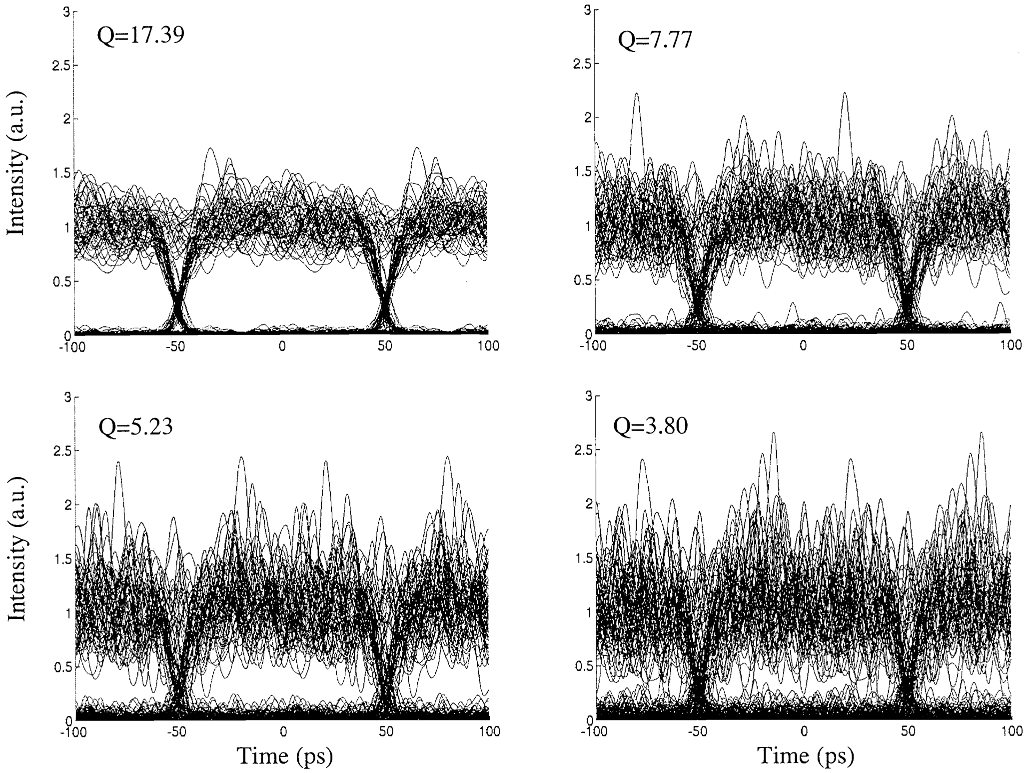


Figure 5. Evolution of the eye diagram for five WDM channels spaced 2 nm apart over 12 cascaded SOAs (nodes). The transmission penalties at each node are derived from (1) with the parameters fit to Fig. 3. Note that this is only a single realization of the data and noise.

4. CONCLUSIONS AND DISCUSSION

Network characterization can be accomplished through a qualitative modeling process which captures the primary physical sources of penalties. Experiments show that the growth of ASE noise is one of the primary sources for generating propagation penalties. The ASE noise has both a white-noise component and Lorentzian noise contribution. By fitting, the BER and Q-factor can be calculated for a data stream propagating through a given network.

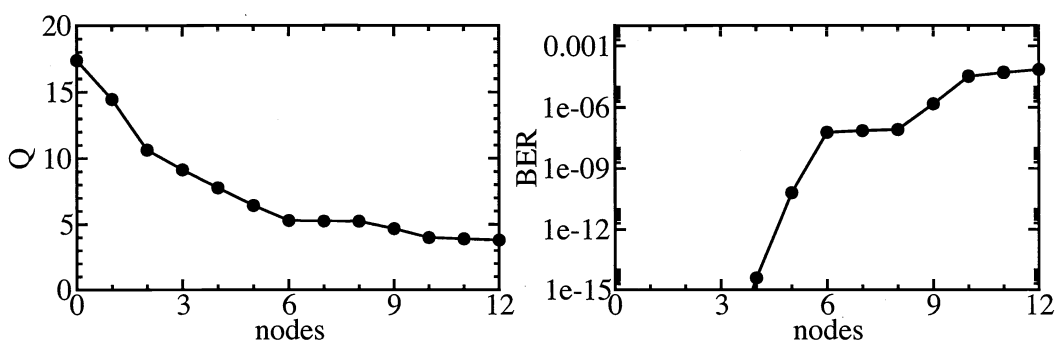


Figure 6. Q factor and BER for five WDM channels spaced 2 nm apart over 12 cascaded SOAs (nodes). The transmission penalties at each node are derived from (1) with the parameters fit to Fig. 3. Note that this is only a single realization of the data and noise.

Additional penalties can also be considered. Of most significant is the gain recovery and saturation dynamics in the SOA. These effects along with four-wave mixing penalties can all be considered within this qualitative model. Thus a realistic modeling tool can be created which significantly reduces the computational time of evaluating the optical switching network.

Additionally, the modeling results suggest how to improve network performance by illustrating the significant level of penalties incurred by various physical effects. Recently, several improvements have been made to greatly improve the number of hops achievable in the optical network architecture.

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