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Assessing the Impact of Design Options for an Optical Switch in Network Routing Impairments

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Abstract: In order to enable the maximum capacity in state-of-the art optical networks, a full orchestration with the physical layer is mandatory. Such an objective is obtained by abstracting network elements starting from the component design up to the networking management. To this purpose, a software (SW) environment which is vertically integrated across the networking layers is a mandatory support for engineering network infrastructure, or to virtually test the impact of a component design option on higher layer performance. Synopsys proposes an integrated SW environment for photonic integrated circuit (PIC) and system design that aims at satisfying this requirement: it is the integration of OptSim© -optical communication system, OptSim Circuit -schematic-driven photonic circuit, OptoDesigner© -mask layout, and RSoft component design tools. These tools have proven to be reliable aids to virtually designing and estimating the performance of optical transmission systems and photonic chips. In this work, we rely on such an integrated SW environment to assess the impact on networking operations of design options for an optical switch in Silicon Photonics using Analog Photonics (AP) Process Design Kit (PDK) component library elements [1]. Specifically, we address the transmission impairments and consequent reduction in Quality-of-Transmission (QoT) implied by multi-hop routing in meshed optical networks. Using the vertical integration of the Synopsys SW environment, we analyze the considered optical switch and by simulation, we obtain a layer-0 abstraction. So, we simulate its propagation impact, assessing a QoT-degradation depending on the design option and also depending of the choice for the transmission technique. Finally, we derive the impact of network routing addressing the QoT degradation vs. number of traversed switches.

1. Introduction

From a data-transport point of view, an optical network is an infrastructure connecting sites, generally with a meshed topology allowing traffic to be added/dropped or routed. Site-to-site links are bidirectional fiber connections implemented as one or more fiber pairs – one fiber for each direction. The signal may be periodically amplified by lumped and/or distributed amplification techniques: erbium-doped fiber amplifiers (EDFA) optionally assisted by some distributed Raman amplification constituting a hybrid fiber amplifier (HFA). These links are commonly defined optical line systems (OLS) and are managed by the OLS controller. In state-of-the-art optical networks relying on the coherent technology for optical transmission, routing operations are done at the optical transport layer thanks to re-configurable optical add/drop multiplexers (ROADM), including optical switches, implementing the transparency paradigm. The DWDM spectral grid can be either fixed or flexible, according to the ITU-T recommendations [2], defining the spectral slots enabling transparent source-to-destination optical transport. These are defined as lightpaths (LP) and are the circuits composing the routing space, i.e., the set of possible connections the routing wavelength assignment (RWA) may rely on to set traffic transport: the lightpath deployment. It is well accepted that the merit of Quality-of-Transmission (QoT) for the deployed lightpaths is given by the generalized signal to noise ratio (GSNR) that includes both the effects of the accumulated ASE noise and of the nonlinear interference (NLI) disturbance, and is defined as:

$$GSNR = \frac{P_{Rx}}{P_{ASE} + P_{NLI}} = 1/(1/OSNR + 1/SNR_{NL}) \,, \tag{1}$$

where $OSNR = P_{Rx}/P_{ASE}$, $SNR_{NL} = P_{Rx}/P_{NLI}$, P_{Rx} is the power of the channel under test (CUT), P_{ASE} is the power of the ASE noise and P_{NLI} is the intensity of the NLI. In particular, given the BER vs OSNR back-to-back characterization of the transceiver, the GSNR well predicts the BER, as extensively shown also in multivendor experiments using commercial products [3].

Given the cascade of N optical domains, each characterized by a generalized $GSNR_i$, with $i = 1, ..., N$, it is straightforward to demonstrate that the overall QoT is given by the $GSNR = 1/ISNR$, where

$$ISNR = \sum_{i=1}^{N} \frac{1}{GSNR_i} = \sum_{i=1}^{N} ISNR_i \,. \tag{2}$$

If we analyze the propagation effects on a given LP over a network route, we can abstract it as the cascade of the effects of each optical domain introducing QoT impairments, including OLS propagation, ROADM crosstalk and ROADM filtering effects. By modelling the effects of every network element through its QoT degradation, a network can be abstracted as a weighted graph corresponding to its topology. Graph nodes are ROADM network nodes, while the graph edges are the OLSs [4]. Weights on edges are the GSNR degradation for the corresponding OLS, while weights of nodes are GSNR degradation of ROADMs including wavelength selective switches (WSS), mostly given by filtering effects and losses. The abstraction of a deployed network enables automatic network management performed by the software-defined networking (SDN) controller. Also, a complete abstraction is useful during the engineering phase to test the effects of different physical layer solutions on the overall network performance [4].

In this work, taking advantage of the capability of the Synopsys multilayer design environment [5] [6], we show for the first time the expansion of the abstraction paradigm below the transmission layer – layer-0 –, going down with the network abstraction to the component-design layer. To demonstrate the merit of such an approach, we consider different design options for an optical switch in Silicon Photonics using Analog Photonics (AP) Process Design Kit (PDK) component library elements [1], and evaluate its effect as GSNR degradation. We show how component design options can also be effectively included in an overall network abstraction using the Synopsys vertical design suite.

2. The Synopsys multilayer design environment

The need for abstraction in communication is well represented by formalized network layers and is naturally driven by emerging ranges of relevant dimensions in space, time, and information. Abstraction is a means of dividing a design problem into orthogonal but nested and reusable components and is a formidable engineering tool. The generalization enabled by abstraction has value per se and enables engineers to make generic considerations and analyses by using parameters that represent whole categories of components. However, when the study is not generic, but the goal is engineering a specific sample that is one realization of all the abstraction levels underneath, the cohesion between them is key to success and their segregation results in failure.

The key value of a vertically integrated design environment such as Synopsys' [5] [6] is to enable design flow across different levels of abstraction, thus promoting their cohesion and avoiding their segregation. At the link level, OptSim enables the user to design and simulate optical communication systems using advanced modulation formats and digital signal processing (DSP) at the transmitter and receiver, and estimate the performance in terms of bit error ratio (BER), optical signal to noise ratio (OSNR), spectrum, eye diagram, etc. At the schematic-capture level, OptSim Circuit enables the user to design photonic circuits using high-level symbols and simulate them by taking into account bi-directional propagation of optical and electrical signals and feedback. At the mask layout levels, OptoDesigner assists the user in the photonic chip physical realization with advanced scripting capabilities supporting design intent, versatile flexible connectors, autorouting, and verification with design rule checking (DRC). At the component level, the RSoft Photonic Component Design Suite allows users to design and simulate photonic devices by solving the Maxwell equations for a given device geometry and material properties by using eminent algorithms of computational electromagnetics such as beam propagation method (BPM), finite difference time domain (FDTD), rigorous coupled-wave analysis (RCWA), eigenmode expansion (EME), etc.

The design flow literal meaning is that the design can be passed among different tools enabling the user to utilize an appropriate specific tool at each abstraction level. Interfaces among the tools implement the data exchange and enable the design flow. The better the interface, the more seamless and effective the separation of the design across several tools and abstraction levels. Specific to the Synopsys multilayer design environment, the interface between OptSim Circuit and OptSim enables the user to assess the performance of a specific PIC design at the link level by driving it with signal implementing advanced modulation formats and applying DSP algorithms at both link ends. In addition, the interface between the photonic circuit tool OptSim Circuit and the mask layout tool OptoDesigner is bidirectional and enables the user to design the circuit functional intent at the schematic level, and let the layout tool realize the connections in terms of both straight- and curved- with various profiles waveguide routing, and crossings. The bidirectional nature of the interface enables the user to then back-annotate the routing to the circuit level as photonic parasitics and analyze its effect on the circuit performance. Finally, the interface between the RSoft Component Design Suite, OptSim Circuit and OptoDesigner enables the user to design a custom parametric photonic device with the component design tools, and then automatically export it to the circuit as multi-dimensional scattering matrix (S-matrix) and to the layout tool as parametric cell.

3. Analysis of the impact of optical switches on 600G channels

To demonstrate the capabilities of the Synopsys design environment and describe a possible workflow to develop optical components, we analyze the impact of optical switches on transmission channels. We consider a PM-64QAM modulation at 64 GBaud gross symbol rate R_S, consequentely carrying 768 Gbit/s. Assuming a 25% hard-decision staircase FEC code, with a $1.7{\cdot}10^{-2}$ pre-FEC BER threshold, and an additional 3% overhead for pilot symbols and headers, it delivers 600 Gbit/s net data rate. Using OptSim and its DSP library for coherently detected systems, we start analyzing the back-to-back performance of the channel, finding a required OSNR of 18.8 dB. The OSNR is defined in a noise bandwidth equal to the symbol rate R_S. System performances are evaluated on the basis of the BER, estimated using direct error counting over 2^{17} bits. In optical networks, lightpaths are routed thanks to ROADMs based WSSs: they apply a filtering to the channels and when lightpaths go across many network nodes, they suffer a penalty. In this study we consider as elementary building block of WSSs a 2x2 silicon photonic crossbar switch based on micro-rings.

Using OptSim for layer-0 performance assessment, we first evaluate the overall transfer function of cascaded multiple switches mimicking a multi-hop LP routing, as shown in Fig. 1 left. If the -3 dB bandwidth of the single switch is 70 GHz, when many are cascaded it quickly reduces impacting the performance of a 64 GBaud channel, and consequently the QoT of the coresponding LP. For example, after crossing four switches, the bandwidth is narrowed down to only 30 GHz, with a non-negligible QoT degradation impact. The effect is significant even if the channel spectrum is properly Nyquist-shaped with a small roll-off factor (ρ): in this analysis, we set $\rho = 0.2$. Using the same tool we then perform a system level analysis evaluating the OSNR penalty of a filtered channel, whose results are shown in Fig. 1 right. For this specific implementation of the switch, we can see that a single element introduces a penalty of about 2 dB, but after four elements it increases up to more than 6 dB, because of the strong filtering shown in Fig. 1 left, and discussed above.

In this first phase, we have considered the cascade of 2x2 optical switches without taking into account a particular architecture to implement the WSS and assuming ideal connections between WSSs. The next step in designing the WSS is to select a specific structure: we opted for a 4x4 multi-stage switch with Benes topology presented in [7] utilizing 6 micro-rings. OptSim in combination with OptoDesigner allows a vertical abstraction below layer-0, which allows us to analyze the component structure starting from the physical layout of the building blocks, shown in Fig. 2 left, up to the estimation of system performance. We analyzed the transfer function for the whole 4x4 multi-stage switch: OptSim can consider both an ideal connection of the switch elements or can perform a realistic analysis of such interconnection by simulating waveguide routes and taking into account crosstalk, as shown in Fig. 2 right. It can be noticed that considering realistic interconnection has an impact on the transfer function of the switch that will results in a different system level performance. Results similar to Fig. 1 right, can be evaluated using OptSim also under these realistic conditions.

4. Conclusions

In this work, we have first addressed and described the vertical abstraction of an optical network based on the QoT degradation of lightpaths, and proposed to extend the abstraction below the transport layer by including also the component layer. Then, we described the Synopsys vertically integrated design environment that allows such an abstraction of components. To show the effectiveness of the proposed approach, we analyzed the impact of WSS design options on transmission performances of a lightpath consisting of a PM-64QAM 600G channel. We synergistically used OptSim for Layer-0 QoT assessment and OptoDesigner to abstract the component layer, and evaluate the QoT degradation in case of single- or multi-hop routing of the 600G LP.

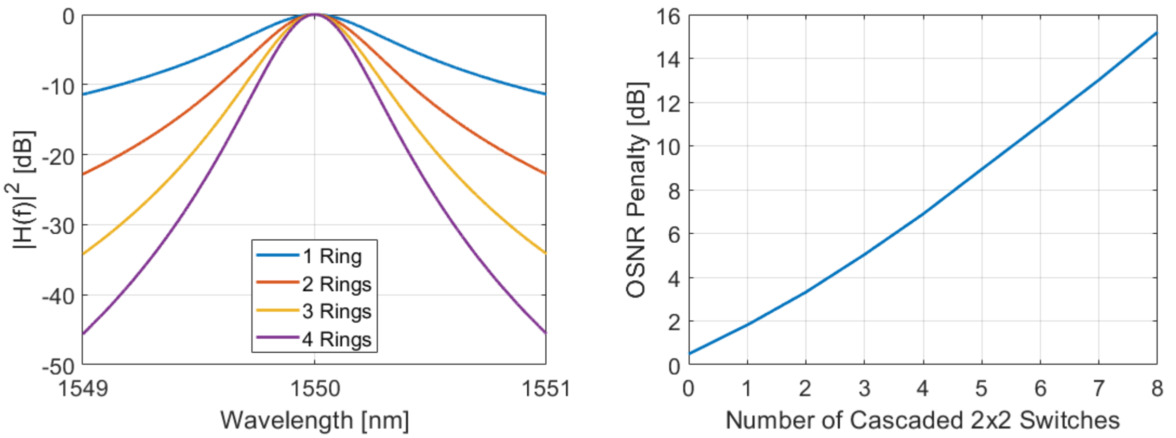

Fig. 1: Transfer function of the cascade of rings (left) and OSNR penalty as a function of the number of cascaded rings (right).

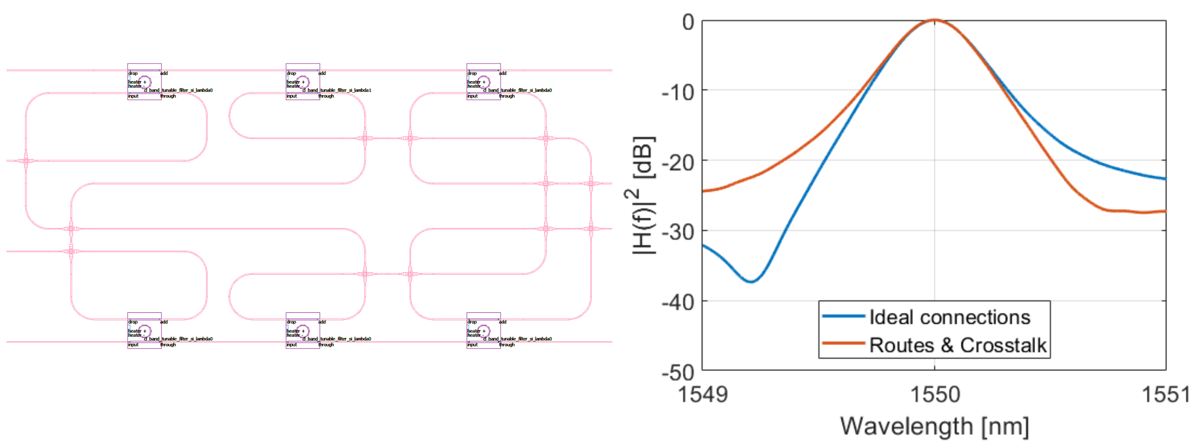

Fig. 2: Benes swtich 4x4 layout (left) and transfer functions of Benes switch through ports considering both ideal connections or realistic routing and cross-talk analysis (right).

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