Dynamic Events in Optical Networks – Emulation and Performance Impact Analysis

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Abstract—We present a framework for emulating dynamic network events and investigating the corresponding performance impact with a two-step approach consisting of parametric modeling of slowly varying effects and detailed bit-level simulations and discuss various application examples.

Keywords—optical fiber network, power coupling, gain-clamped EDFA, bit-error rate, teletraffic impairments, EDFA, WDM, receiver

I. INTRODUCTION

Transparent reconfigurable optical fiber networks [1,2] utilizing wavelength-division multiplexing (WDM) present new challenges on optical systems design and network management, as they may suffer from power transients due to slow amplifier gain and noise dynamics. Events such as automatic network re-configuration, failure of components, or switching of optical packets may cause abrupt changes of signal power in a few or many WDM channels. In conjunction with the slow (~ ms) nonlinear gain response of Erbium-doped fiber amplifiers (EDFAs), and stabilization circuits with finite response time, this may lead to strong power fluctuations in the other channels with negative effect on the bit error rate. The problem of transients is especially of importance in networks with complex topology, as they can be amplified significantly due to numerous feedback mechanisms in such networks.

The task of computer based emulation (or modeling) of optical transmission phenomena in transparent reconfigurable optical fiber networks differs significantly from modeling approaches targeting stationary applications. Among the problems that are challenging to address are the ability to take into account impairments such as different and dynamically changing residual chromatic dispersion values between different optical channels arriving at the same optical receiver, and the calculation of penalties from dynamically varying cascades of Reconfigurable Optical Add Drop Multiplexers (ROADMs). Of particular interest is also the analysis of non-stationary power perturbations (arising from channel switching, transients of amplifiers and control circuits) that propagate through the transparent optical network, and thus, change the average power level at components along the optical path and at the receiver. In the case of optical ring or mesh networks that are based on amplifiers without carefully adjusted gain clamping algorithms, for instance, channel switching effects can create chaotic oscillations of the signal power that ripple through the network [3].

We present in this paper a modeling framework supporting the emulation of power dynamic effects in EDFA-based fiber networks, including the study and optimization of controls in networks with complex topologies. Our approach provides a rapid design methodology and a method for verifying various equipment designs and network configurations. We show examples for burst-mode networking in a point-point link and propagation of power transients in a ring network using the commercial photonic design package VPItransmissionMaker and add-on developments.

II. MODELING FRAMEWORK

To emulate the characteristics of dynamic networks, it is necessary to combine investigations on bit-level (ns to sub-ps time scale) with the analysis of effects with much larger response times (up to a few ms). The evolution of signals in such applications is often affected by varying noise levels and transient processes in control loops with various characteristic times. Slowly varying physical processes make it difficult to apply common simulation techniques developed for much shorter signal durations. On the positive side, however, simulation of slowly varying processes in dynamic networks usually does not require the high level of detail that is typical for characterizing dynamic effects on the bit-level (requiring simulation techniques based on a full-field complex signal description).

Figure 1 shows the general workflow for emulating dynamic events in optical networks and analyzing their performance impact. Using a two-step approach, we first apply a parametric optical signal representation to emulate slowly varying network events, which accounts for the statistical average of dynamic effects occurring on the bit-level and accumulates information of signal attributes such as power, frequency, polarization, etc. When starting the network emulation, only changes to these parametric attributes are calculated in frame of a global evolution analysis considering all signal paths. To be able to find the origin of limiting effects the evolution of signal properties along different light paths can be additionally tracked by having the signals record the most important characteristics (accumulated chromatic dispersion, noise, nonlinear phase shifts, etc.) at adjustable distance or topology intervals [4].
Further on, it is important to account for the propagation delays when, for instance, signals traveling over different paths arrive at the same device, and there, impact its response. This is accomplished by recording the time dependence of signals and memorizing device states over multiple simulation iterations, where a single iteration corresponds to one step in time.

With the parametric information of signals that are propagated through the network, estimates of the system quality can be calculated using design rules, e.g., functional relationships that are derived from measurements or experience. In a second step, detailed simulations on bit-level can also be performed to reveal the physical limitations at a certain, definable time instance of the network (for instance during turn on of individual nodes, stable operation, switching of channels or failure of equipment). This can be done as the time-dynamic information of the network is characterized in the first step by a collection of signal and equipment state data at a sequence of discrete time instances, each defining the initial conditions for a detailed simulation on bit-level.

III. PERFORMANCE INVESTIGATIONS

A. Burst-Mode Networking in a Point-Point Link

This example illustrates signal power fluctuations when random traffic bursts are transmitted through the network. Four WDM channels are propagated over a point-to-point link consisting of five amplified and dispersion compensated fiber spans. Fast electronic gain-clamping of the EDFAs (using a proportional-integral (PI) controller for the pump power, [5]) is used to reduce power variations in the amplified spans. The bursts are emulated using a sequence of random ‘Power On/Off’ events with adjustable duration of individual bursts that can be controlled via a simple user interface (Figure 2, where Burst Duration defines the maximum inter-burst ‘Off’ time). A more advanced control (aka Design Assistant) allowing, for instance, to define ‘Power On’ and ‘Power Off’ for each channel independently can be created in a similar way using the flexible scripting environment that is provided with VPItransmissionMaker.

Figure 3 presents the dynamics of random bursts from four WDM channels. The channel powers after one, three and five amplified spans using gain-clamped EDFAs are displayed versus time. Figure 3 shows the growth of non-compensated power excursions with increased number of fiber spans (2.7% after one span, 8.3% after three spans, 13.4% after five spans) demonstrating the impact of one of the main limiting factors in burst-mode transmission [6]. Based on this initial application, one can study further possible optimization schemes for high-speed gain-clamping circuits, or investigate the statistical properties of output powers after varying number of amplified spans.

Figure 2. Dynamics of random bursts from four WDM channels: example of a simple control for the generation of bursts.

Figure 3. Dynamics of random bursts from four WDM channels: channel powers after one, three and five amplified spans using gain-clamped EDFAs.
B. Power Transients in a Ring Network

The four-node optical ring network discussed here represents a simple but realistic use-case for investigating the occurrence of higher order power transients [7]. We denote as first-order transient effect the amplifier reaction on signal power change just after the re-configured node. After dropping the affected channels, the amplifiers downstream will, in general, still experience transients as reaction on power excursions of the surviving channel(s). Depending on the number of independent channel groups involved in the power excursion propagation, there will be second-, third- and other higher-order transients.

Each of the four nodes is connected with its neighbor by amplified, dispersion compensated fiber spans using gain-clamped EDFAs. At each node, various numbers of channels can be added and dropped. Here, we assume that Node 2 and 4 are communicating using one band of eight channels, and Node 1 with 3 using another band of eight channels. Figure 4 shows the logical and topological configuration.

![Figure 4](image)

Figure 4. Four-node ring network where Node 1 and 3 communicate via Channels 1-8 while Node 2 and 4 via Channels 9-16.

We start with the steady-state of the network, where each node is adding & dropping its eight channels and all turn-on transients are subsided. Then, Node 2 initiates a series of power transients that propagate through the ring by continuously dropping its band of channels and interrupting the insertion of replacement channels between 0.01 ms and 2.5 ms.

Figure 5 shows the resulting power dynamics at the drop ports of all four nodes. Following Node 2, channels 1-8 at Node 3 show 1st and – after a full round trip – 3rd order power excursions. Node 4 shows the delayed band drop and later, the turn on transients of channels 9-16. Following Node 4, Node 1 shows 1st order power excursions of channels 1-8. After a full round-trip delay even Node 2 shows 2nd order power excursions of channels 9-16 as a result of the interactions with the 1st order transients propagating between Nodes 4 and 1. This application demonstrates how dynamic reconfiguration of one node can affect the operation of other nodes in the networks, even if no traffic is transmitted directly between them.

![Figure 5](image)

Figure 5. Propagation of power dynamics through a 4-node ring network. Traffic is continuously dropped at Node 2, and not reinserted between 0.01 ms and 2.5 ms.

It is important to note that modeling of complex networks requires not only the simulation of amplifier dynamics, control circuitry etc., but also demands the proper emulation of propagation delays between network nodes. The finite propagation time together with the nonlinear power coupling between different WDM channels in optical amplifiers are the actual reasons for higher-order transient effects [7] and possibly, chaotic network behavior [3].
C. Dynamics of Electronically Gain-Clamped EDFA

Besides determining the steady state characteristics, setting dynamic network events and analyzing resulting power transients (as discussed above), our framework can be used to estimate the impact of power transients on the quality of signal transmission. These detailed bit-level simulations comprise simulations of short time-scale performance characteristics (Eye, BER) at selected time instances using information from the database calculated during power transient analysis and steady-state estimation (as described in Figure 1). The main difference to conventional simulations of transmission systems is that the system characteristics and signals do not correspond to a stationary state, but to a snapshot of a long-term non-stationary evolution. Here, we investigate electronic gain clamping of an EDFA using the PI-controller [5] in a WDM link. The control algorithm can described as follows

\[
\Delta P_{pump}(t) = k \left( I_{err}(t) + \frac{1}{T} \sum_{\tau=0}^{t} I_{err}(\tau) \right),
\]

\[
I_{err}(t) = P_{in}(t) G_{target} - P_{out}(t),
\]

where \( \Delta P_{pump}(t) \) denotes the change of pump power at time instance \( t \), \( k \) and \( T \) are the controller gain and integration time, \( P_{in}(t) \) and \( P_{out}(t) \) are the total signal power at the amplifier input and output, respectively, and \( G_{target} \) is the nominal EDFA gain value. The electronically gain-clamped EDFA that is investigated here represents a fundamental building block for the power transient analysis in EDFA-based networks.

The typical values of the control parameters in our simulations are \( T = 0.1 \) ms and \( k = 1.5 \). For reliable results, the simulation time step must be smaller than the PI-controller integration time. The dynamics of the remaining channel power stayed qualitatively the same in a rather broad range of pump control parameters. In general, the more the PI-controller gain, the smaller is the residual power overshoot, but large values of the parameter \( k \) may lead to oscillations of optical power. A more sophisticated controller model is rather easy to implement and characterize using VPItransmissionMaker. Here we see for instance, a PI-controller with different values of proportional and integral gain, or a proportional–integral–derivative (PID) controller model.

Figure 6 provides examples of an analysis of the power dynamics of a surviving channel and the corresponding BER dynamics in a nearby probe channel when 8 out of 16 WDM channels are dropped/added. The power overshoot corresponds to an improvement of BER, while the power undershoot leads to an increase of BER. This is explained by the fact that the impact of optical receiver noise increases during the undershoot (as signal power is reduced). The effect is in good qualitative agreement with the results of experimental measurements presented in paper [8]. Additionally to the simulation of the BER dynamics itself, our proposed approach enables to also model the measurement of standard network performance characteristics, such as the BER versus received optical power (ROP) dependence.

IV. CONCLUSION

We presented a modeling framework that allows emulating dynamic events in optical networks and analyzing the corresponding performance impact. We demonstrated the operation of our two-step approach consisting of parametric modeling of slowly varying effects and detailed bit-level simulations on a burst-mode WDM transmission, and the investigation of higher-order power transients in a ring network. While delivering results that are in good agreement with published data of other groups, our proposed approach is very flexible as it enables to simulate effects such as EDFA transients, consider finite response times of control blocks and investigate phenomena caused by a finite signal propagation time in complex networks. One of the natural applications of the described approach is to estimate physical impairments on WDM reconfigurable optical networks carrying mission critical traffic, see discussion and further references in [9]. Note, that our proposed approach fills the gap between conventional physical-layer simulation, mainly focusing on point-to-point link performance, and network simulation on the ‘logical’ level, where aspects such as routing and survivability are addressed. Similarly our proposed framework can be used to design and optimize adaptive control circuitries in front of free space optical receivers that compensate for the dynamically varying propagation conditions.

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REFERENCES


