Dual-Time-Scale Simulation of Dynamics and Reconfiguration of Fiber Optical Networks

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ABSTRACT
We describe an approach to simulate the power transients in complex (branched, ring, or mesh) transparent fiber optical networks. Simulations are performed at two time scales: first, the signal power dynamics in Erbium-doped fiber amplifiers is modeled at (sub-) millisecond scale using statistical signal descriptions. Further, the teletraffic performance of the network, such as the bit error rate, can be investigated for selected time instances at nano-second to sub-pico-second time scale using a sampled signal model ('bit-level' simulation). For the detailed simulation on 'bit-level', signal information and internal states of the network components are re-used form the first simulation step at (sub-) millisecond scale. To illustrate our approach, we discuss simulations of 'higher-order' transients in a ring network.

Keywords: transient, EDFA, WDM, reconfiguration, BER, ROADM.

1. INTRODUCTION

In transparent reconfigurable networks, the non-stationary power perturbations can propagate across the network, changing operation points of nonlinear devices (e.g. amplifiers) and average power levels at receivers. Common examples of such power perturbations include channel switching, fiber cuts or equipment failures. Realistic modeling of prolonged physical-level effects in optical fiber networks is important for several applications, first of all for the design and optimization of reconfigurable network solutions with effective protection mechanisms.

It is necessary to underline, that the simulation of the physical layer impact of long-time transients at the network level is still an uncharted area on the map of photonics simulations. Established methods exist for modeling individual devices, fibers, subsystems (e.g., Erbium-doped fiber amplifiers, EDFA) and whole point-to-point links [1]. However, when considering the design and operation of a complete mesh network, it is common to address 'logical' network simulations only. The simulation of power transients is usually limited to cases of individual amplifiers or amplifier chains [2]. The studies described in the framework of the MONET project [3] served as an exception to this. However, the analysis focused mainly on cross-talk effects in steady network operation. A different tool for simulation of dynamic fiber networks is reported in [4], but neither the signal model, nor the overall organization of simulation framework was published.

An important aspect laid out in [3] is that because of the large difference between the characteristic times of the involved processes, it is necessary to use different simulation regimes for the network simulation as a whole and the more detailed analysis of signal distortions after propagation. More importantly, for detailed analysis of the optical signal propagation, an equivalent link model should be employed [5], in other words, different network models are necessary for full simulations.

The aim of the present paper is to provide a basis for the simulation of the physical layer impact of transient processes at the system level and to facilitate further research and discussions in this area. The described approach enables bit-level simulations within the same network model as the simulation of slow power transients, providing minimal necessary changes of settings of component and environmental parameters. The simulation framework is based on VPItransmissionMaker Optical Systems and further on-going developments.

2. SIMULATION APPROACH

The general workflow for simulating power transients in optical networks are summarized in Fig. 1. At first, the network model is defined, which includes the definition of topology, routing and wavelength assignment, and selection of models of network elements (fibers, nodes, amplifiers etc.). After that usually the steady-state of the network (i.e. normal operation conditions) needs to be estimated. A specific case of steady-state estimation is given by the study of network turn-on dynamics, which represents by itself an important case of long-time transient effects.

The analysis of transient effects normally starts from the steady-state of the network and consists of modeling the network evolution after applying of one or several '*events*' [6]. In the context of transient analysis, an event is described by one or several changes of parameters of network elements and can either be an accidental (e.g., fiber cut, component failure) or routine (e.g., network reconfiguration) change of the steady-state operation. Each

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event has specific start time, duration, and final value of the varied parameter. In some use cases, for example when investigating burst-mode networking, events can repeat several times representing periodic or random packet arrivals. The network dynamics are simulated using repetitive runs of the whole setup, where one execution of all network elements corresponds to a single time step. Signal information and internal states of simulation models of individual network elements (e.g., average inversion of the doped fiber inside the EDFA model) can be saved in a database for subsequent analysis. Together with information about events, which are stored as time instance and duration of an 'external' change in the network model, this database stores the network evolution information for analysis purposes and performing bit-level simulations.

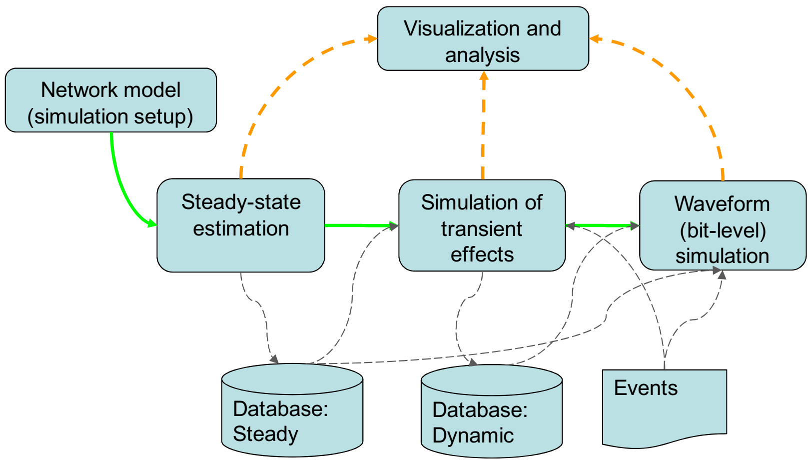

Figure 1. General outline of simulation principle.

An important part of the simulation framework is the signal model optimized for the studied effects, as well as for the time and spatial scales. In the described approach, we employ a modified variant of the parameterized signal model [7] (or 'wavelength domain representation' [3]): it is characterized by a coarse spectral resolution (tens or hundreds of gigahertz), with only time-averaged signal information available at each simulated time instant. This representation can describe the signal power distribution over large spectral ranges, and is suitable to capture signal transformations in complex large-scale network. Successive iterations of the signal are used to represent different time instances, just like the models of network components. In addition to time-averaged and spectral description, the used signal representation provides additional information, namely about the accumulation ('tracking') of the characteristic changes versus propagation distance. Lacking the strict connection between time- and spectral domain representation makes it possible to provide a simple but flexible notion of (long-scale) time for signals. Special rules are then required to switch from the time-averaged spectral domain representation back to the full-field signal model for fast time scale (bit-level) simulations. Another important aspect is that the simulation framework accounts properly for propagation delays between network elements: in actual networks long fiber spans necessarily produce delay between their transmitting and receiving ends. One millisecond, a typical time-scale of transient effects, corresponds roughly to the propagation through 200 km of optical fiber – a distance of two to four fiber spans.

Before describing our solution, it is worth to consider the simulation of complex (mesh) fiber networks from a different side: a complex network model can easily contain one or several loops. The calculations on the graphs (including the simulation setup described below) normally require breaking the loops into independent parts, see for example [8]. Optimal loop breaking is usually a non-polynomial complex problem. In the synchronous data flow model (SDF), which is the base of our simulation approach [7], the loop problem is solved by using 'logical delays' in the graph [9], which are normally set manually to prevent loops (deadlocks). In the presented approach, fiber span models include both propagation delays, and 'logical' delays necessary for breaking these loops. This permits to simulate a complex networks in a uniform way.

At the final stage of the modeling framework, the influence of power transients on the teletraffic performance of the network shall be estimated. These bit-level simulations [2], [10] include for instance the derivation of bit error rate (BER) variations, or changes of BER versus received optical power (ROP) using a full-field representation of the optical signals. The overall principle is to recover the setup state (signal powers, internal states of network components, externally controlled parameters – events) from the database at the given time instance and replace one or several channels by their full-field sampled representations. It is important that the sampled signal must not only be generated with the same power and state of polarization as its parameterized counterpart, but that it undergoes the same conditions (amplifier gains, interaction with other channels) as have been valid during the transient simulation. This means that the interval between sampled blocks in the bit-level simulation is of longer (possibly much longer) duration than the sampled signal block duration itself. In other words the bit-level simulation implies a signal model where each signal block corresponds to a small excerpt (representative) of a longer signal, with time interval between blocks being equal to the time step in the transient simulation. All parts of the simulation setup must be in the same network condition as they used to be in the power transient simulation. This means that all other channels must propagate through the network, and, even for the probe channel, a signal (from the database) must be present before the sampled signal will actually reach a particular point of the lightpath. On the receiving end, the first (dummy) signals in parameterized representation would normally be skipped.

3. EXAMPLE

Serving as a simple, but illustrative example, the analysis of transients in a ring network model is presented below. As depicted in Fig. 2 (left), a four-node ring network with two pairs of bands (8 channels each, 10 Gbps OOK signals), which communicate between non-adjacent nodes, is used for simulation. In this example, all four nodes are connected via single-span links of 64 km transmission fiber (with span propagation delay of 0.36 ms). Each span includes dispersion management (post-compensation) and optical amplification with electrical gain-clamping. Gain clamping is implemented using a proportional-integral (PI) controller, according to model [2].

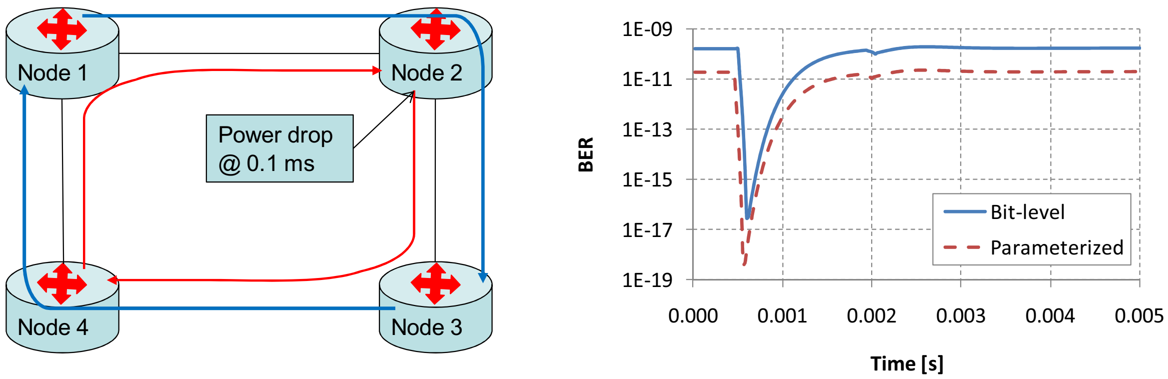

Figure 2. Outline of the simulated 4-node ring network (left), comparison of estimated BER values using transient and bit-level simulations (right).

The following scenario was investigated: starting from the steady-state operation of the network, the power of all channels propagating from Node 2 to Node 4 was suddenly dropped, without re-insertion of these channels at later time. The time-dependent change of power (transient) of the remaining channels is then propagated across the network, leading to the power dynamics as presented in Fig. 3 (left), where the power of one of the channels propagating from Node 1 to Node 3 is shown. The first peak of the power transient of the remaining channels at Node 3 is caused by changed operation conditions of the amplifiers along the connecting fiber links just after the event occurred. The second, smaller peak is caused by propagation of the power perturbation around the ring network. This case represents an example of 'higher-order' power transients, a term that was initially coined in Bell Labs to describe excursions of the optical power in WDM channel groups "not directly involved in the originating effect" [11] (see [12] for further references). In other words, higher-order transients are signal power perturbations propagating across the network because of power coupling in optical amplifiers and other network devices.

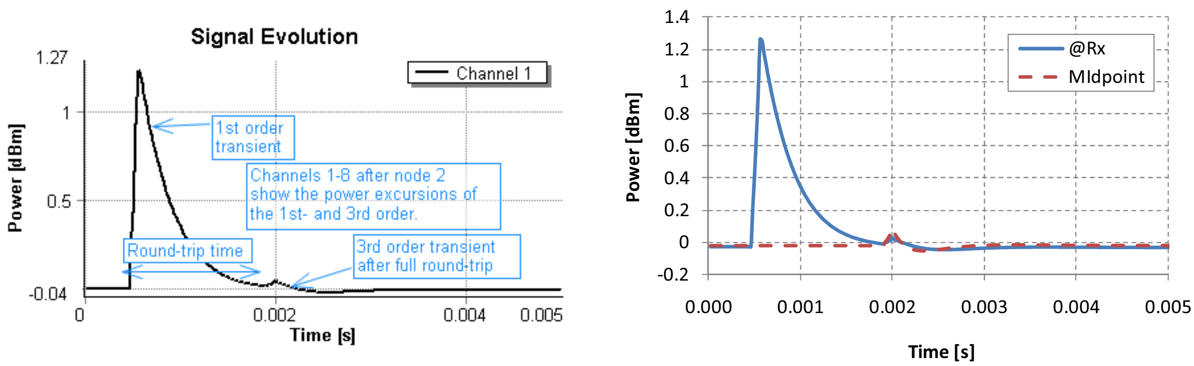

Figure 3. Power transient of the signal propagating from Node 1 to Node 3: example of higher-order transient (left), and power dynamics at different points in the lightpath (right).

It is worth noting that our signal model can be used to analyze the signal dynamics at different points along the signal path. The two lines in Fig. 3 (right) show the time dependence of one of the remaining channels – at the receiving point and at the propagation midpoint (after Node 2). The first-order transient presents itself only after the amplified fiber span, while the higher-order transient is caused by other parts in the network.

The signal representation used to model power transients also permits to estimate several signal quality measures, which are fully available only after full-field bit-level simulations. In particular, the BER and Q-factor of a signal can be evaluated for several modulation types from the optical signal to noise ratio (OSNR) and averaged signal statistics, assuming an optical noise limited propagation scenario. Figure 2 (right) shows BER estimation results for the remaining channel. For comparison, we present BER estimation results from the bit-level simulation as well. While both methods produce qualitatively similar results, approximate BER estimation during the transient simulation provides slightly underestimated BER values. This is due to the fact that only a limited signal representation is applied in transient simulation. It is necessary to note that in the shown example BER variations are due to changes of the impact of thermal noise at the receiver, where an increase of signal power leads to improved BER values. More complicated cases can be built similarly.

4. CONCLUSIONS

We presented a uniform simulation approach for numerical analysis of dynamic events and prolonged signal transients in optical fiber networks. We proposed two-step simulation approach consisting of a parametric simulation of slow power dynamics in a network followed by detailed simulation of bit-level effects using a full-field signal representation. The slow-scale transient simulations are based on an extension of the wavelength domain signal representation, which contains not only power (and polarization) information of signals at a specific point of a network at distinct time steps, but also includes the full 'history' of several other signal characteristics (e.g., OSNR, cross-talk, polarization and ASE distribution) along its propagation path. This signal model allows performing advanced network analysis tasks without re-calculation of the network evolution. For example, one can analyze wavelength and temporal dependence of specific signal characteristics not only at the receiver point, but also at arbitrary places in the network. This enables to uncover 'hidden' issues in optical network behavior, such as excess noise, power overshoots or other design rule violations.

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