Modeling and Simulation of Control Dynamics in Optical Transport Systems

Tin Kam Ho, Lawrence C. Cowsar, Roland W. Freund, Leon Vardapetyan, Todd R. Salamon

Bell Laboratories, Lucent Technologies, 700 Mountain Avenue, Murray Hill, NJ 07974
e-mail: {tkh, cowsar, freund, leonv, tsalamon}@lucent.com

Abstract: We describe a simulator for modeling complex control dynamics in optical line systems involving the interaction of multiple transmission, control, and monitoring elements in response to channel changes, component failure, and recovery events.

1. Introduction

The design and analysis of control strategies for state-of-the-art optical line systems require an understanding of complex dynamics that include time-dependent interactions of many components over millisecond and greater time scales. Simulators that use steady-state models or timescales on the order of sub-microseconds do not provide this insight. We developed system simulation software that is driven by discrete events such as channel add/drops, component failures and recoveries, and events triggered by message passing coupled to continuous physical-layer simulators. Preserving detailed time synchronization between elements, the simulator models signal and noise propagation in a line system consisting of multiple, independently controlled transmission elements and monitoring devices. The platform is essential for evaluating control algorithms, assessing system reliability, and systematic exploration of design parameters. We summarize the key features of the software design and show examples of control analyses that highlight its unique features.

2. Simulator Design

The simulator is implemented as a Java program where object classes are used to model various components, event sequences, and facilitate time synchronization.

Component Models

Three major classes of components are modeled: transmission elements, control modules, and monitoring devices.

- *Transmission elements* include transmitters, fiber links, optical amplifiers, gain equalizers, connectors, filters, and receivers. Models of these elements involve mathematical and algorithmic descriptions of their physical states given different signal and noise input. Transmission elements have explicit sets of dynamic parameters, such as pump laser powers, that may be actively adjusted during the simulation.
- *Control modules* adjust the dynamic parameters of transmission elements. Models of these modules often include components of the driver software used on the line system.
- *Monitoring devices*, such as photodiodes and optical spectrum analyzers, measure the state of the transmission elements and provide input to the control modules. Models of the monitoring devices may include calibration parameters and statistical models of measurement error.

The transmission elements are connected according to the system topology specified by the user. Our initial focus has been on linear line systems that are simple concatenations of transmission elements. The control and monitoring components are inserted at various points specified by the system architecture; see Figure 1.

Control modules are represented by temporal finite-state automata (FSA) with *transitions* such as “start a spectral scan", ”adjust pumps”, “wait for N minutes”, and *states* such as “standby” and “ready for measurement”; see Figure 2. Depending on the level of sophistication of the control strategy, there can be nested layers of FSA, the execution of which leads to discrete control steps. Each step may cause changes in the dynamic state of the transmission elements that in turn cause changes in the signal and noise evolution computed by the transmission elements of the physical layer.

Since traditional simulators [1] include transmission elements and monitoring elements, we do not discuss them in detail here. The choice of the level of physics to model the transmission elements greatly influences the runtime and utility of this simulator. We have found that average power and noise evolution modeled by systems of ordinary differential equations represents a useful tradeoff between the speed of computation and the accuracy needed.

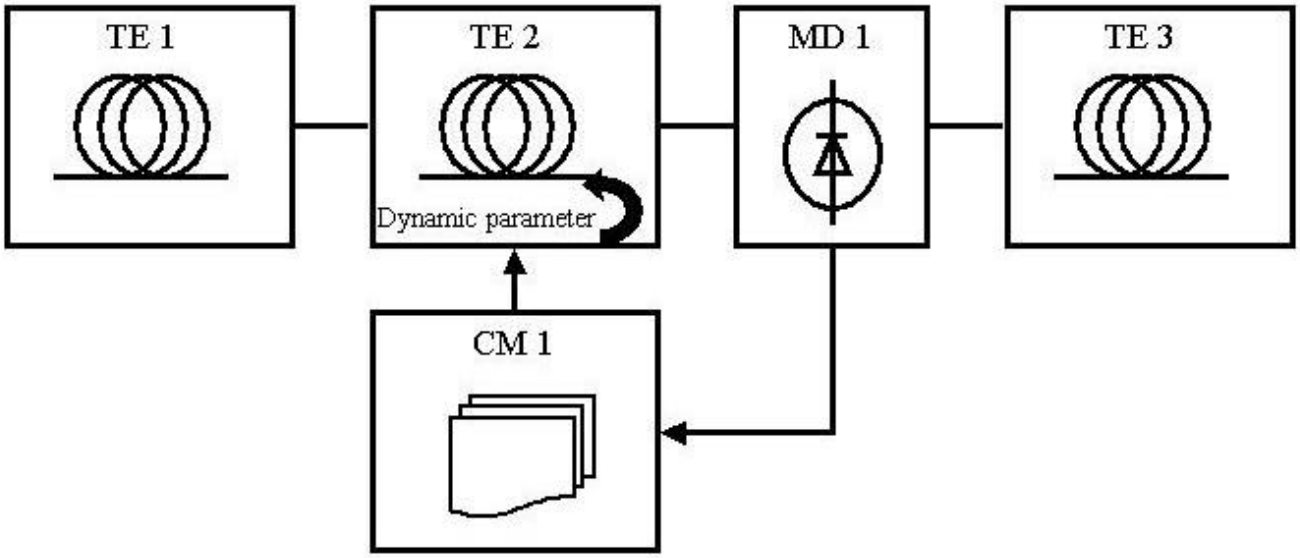


Fig. 1. A linear line system consisting of three transmission elements, one monitoring device, and one control module.

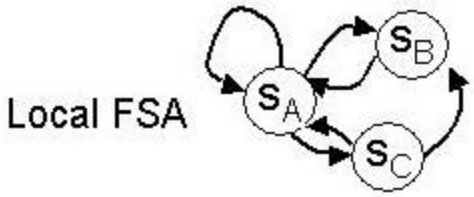


Fig. 2. A control module represented by an FSA.

Event Sequences

The control modules drive the internal settings of transmission and monitoring elements in response to external events. The key events are the addition or deletion of channels and installation, failure, or recovery of particular system components such as pumps or fiber links. There can also be alarms and messages passed between the elements. Events may occur in arbitrary order and at irregular time intervals. It is also possible that several events occur simultaneously.

Spatial and Temporal Synchronization

The physical state of the line system changes with every action of the control modules. Typically, control algorithms use iterative feedback to adjust the dynamic parameters of a transmission element to achieve a performance goal. When a large number of controllable transmission elements are being simultaneously, but asynchronously adjusted, the number of physical-layer simulations of the transmission elements needed to represent their effects quickly multiplies.

We have reduced the number of necessary simulations to a manageable amount by using two straightforward, but critical observations. First, the change of a dynamic parameter in a particular transmission element affects only the system state downstream. Whenever an end-to-end simulation is needed, one can start from the first component that has changed in the spatial order determined by the system topology. Second, the system state is observable only when there is a measurement by a monitoring device. Changes in transmission elements are not visible if all the monitoring devices are dormant during the

period. If control decisions are based solely on feedback from the monitoring devices, there is no immediate need to simulate changes in the transmission element. One can accumulate all the changes until the next time a measurement is made.

Each time a measurement is taken, physical-layer simulation is needed to capture the effects of all changes to the dynamic parameters of the transmission elements upstream of the monitoring device. The need for such a simulation becomes an internal event with a timestamp just like the external events. When there are a number of monitoring devices operating independently, the local events are interleaved and merged into the global event sequence, as depicted in Figure 3. A simulation scheduler searches this sequence for the next event and its location. The scheduler performs simulation between the first changed transmission element and the location of this event. If the control step causes a change downstream, this change is recorded, but its effects are not computed until a simulation is requested from a component downstream. The system clock then advances to the time of the next event in the queue and continues so forth.

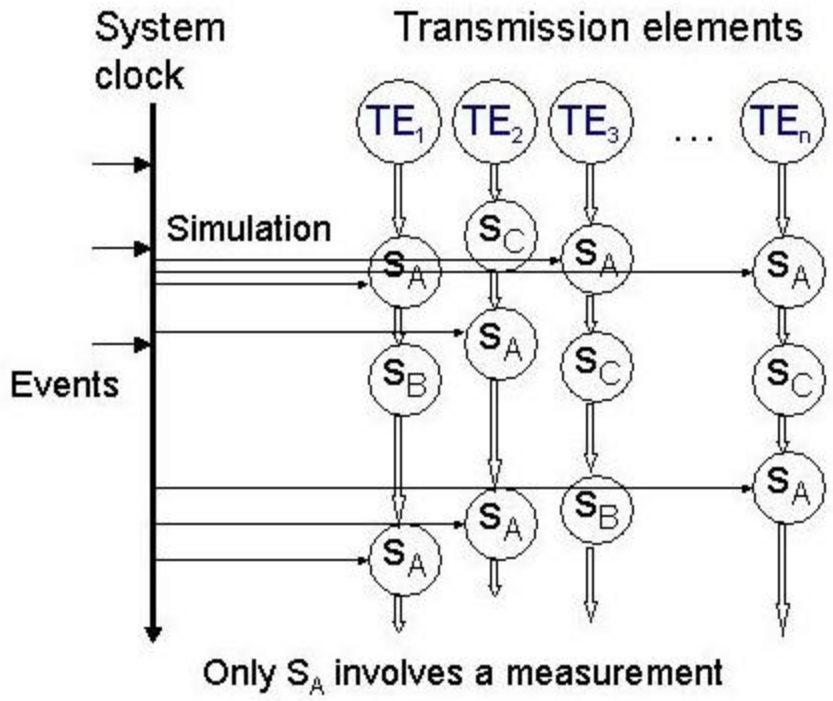


Fig. 3. An example of a global event sequence.

3. Support for Experimentation

An experiment in our simulation environment is completely specified by three groups of input. The *scenario* group includes descriptions of the topology of the line system and static parameters of each transmission element. The *event* sequence contains a list of timestamps, types, and details of external events. The *parameter* group specifies the type of the experiment and variables such as the choice of a high-level control strategy and verbosity of logging.

The traditional static analyses for the design of optical line systems are supported. In addition, two other types of experimentation are greatly enhanced: the evaluation of control algorithms and the assessment of reliability.

The design of control strategies and algorithms has become a central challenge in building modern optical systems. Local control decisions and adjustments at a transmission element cause changes in signal powers that are propagated to all elements downstream. Control algorithms need to respond not only to external events such as addition or deletion of channels, but also to power changes due to adjustments upstream. They must be robust with respect to inaccuracies in the monitoring devices. Experiments to study such interactions help validate a particular control strategy, and also guide the development of algorithmic details.

We have used the simulator to study power control in broadband Raman-amplified DWDM systems [2,3]. Figure 4 shows two pump power traces with respect to time. The one on the left results from a simple control strategy that ignores noise in the monitoring device; the one on the right results from a more sophisticated strategy including regularization. Figure 5 shows the signal powers resulting from two control algorithms that use different metrics for measuring power divergence. The simulation environment makes the difference between various control strategies readily apparent.

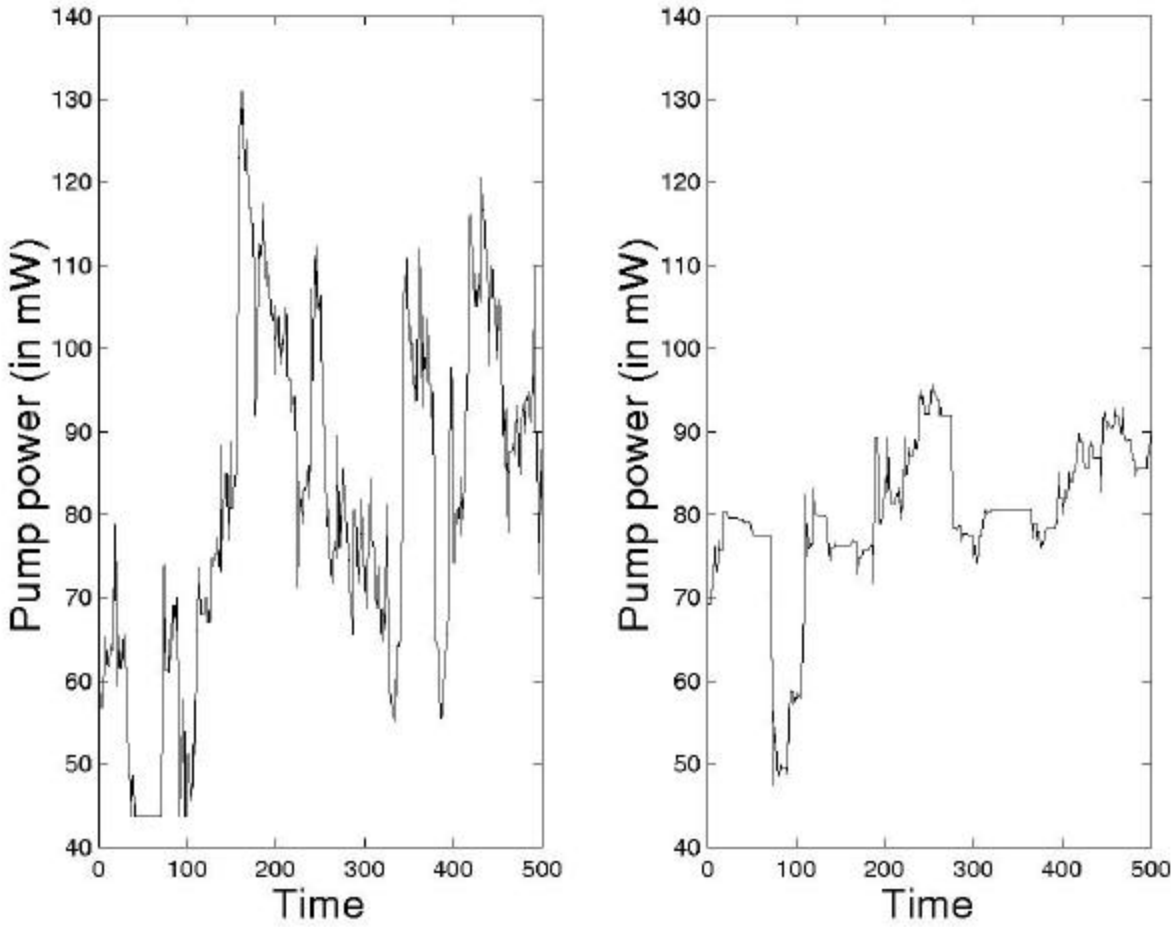


Fig. 4. Power evolution of a Raman pump in a DWDM system. The pump trace on the left results from a simple control strategy that ignores noise in the monitoring device; the one on the right results from a strategy that employs regularization to suppress noise.

Similarly, the robustness of a system can be tested under various modes of failure using events that represent the failure of all or part of a transmission element, such as a pump laser. This kind of simulation gives estimates of the impact of component failures after arbitrary event sequences. The estimates increase confidence in the performance of the system and guide the design of guards against potential damage.

4. Data Display and Analysis

Each simulation run produces a file that echoes the input variables, records a snapshot of the state of the system at time steps of interest, and logs run-time trace messages. A graphical interface can display a log file in time order, so that the run can be seen as an animation of the system's state changes. This allows for detailed tracing of individual control steps in a magnified timescale. The log file can also be parsed in other ways to extract numerical data for static plotting and further analysis.

A typical "parameter-sweep" experiment involves combinations of several design, control, or event variables and can easily produce hundreds or thousands of log files. This leads to a natural need for data mining tools and methods. We developed a graphical tool, **Mirage** [4], for interactive pattern recognition from such data sets. Each run is summarized as a feature vector where the components are the key variables of the simulation, relevant quantities in the system states, and figures of merit useful for evaluation.

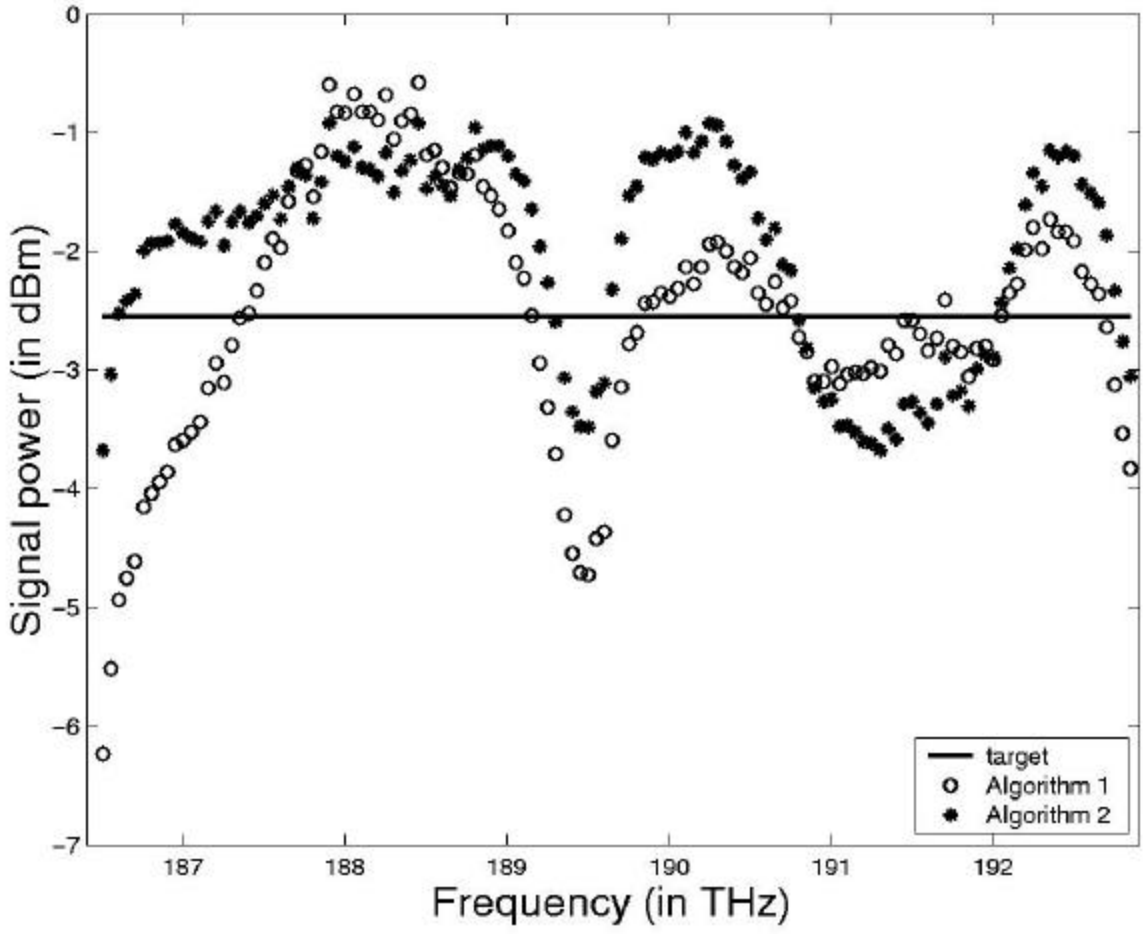


Fig. 5. Signal powers in a DWDM system resulting from two control algorithms that use different metrics for measuring power divergence. Algorithm 1 employs a standard least-squares approach, Algorithm 2 is a new method that was developed and tested within our simulator.

5. Conclusions

Reflecting on our simulation experiences, four issues were critical for its success. (1) The object-oriented software architecture provides a natural representation of the system. (2) Careful integration of discrete and continuous models yields a powerful combination of these two worlds. Computation time need not track physical time, and the flexibility of event-advance methods gives good handles for studying intricate effects of interactions in a magnified time-scale. (3) Thorough logging permits all results of a run to be exactly reproduced using the input parameters echoed in the log files. This helps avoid repetitions of the same experiments and makes it easy to compare effects of different design alternatives. (4) Data display and analysis methods should be completely decoupled from the simulator design. This permits easy re-analyses of archived results.

[1] A.J. Lowery, “Photonic simulation tools”, in *Optical Fiber Telecommunications IV B*, Academic Press, pp. 564-610, 2002.
[2] K. Rottwitt and A.J. Stentz, “Raman amplification in lightwave communication systems”, in *Optical Fiber Telecommunications IV A*, Academic Press, pp. 213-257, 2002.
[3] Y. Emori, S. Kado, and S. Namiki, “Broadband flat-gain and low-noise Raman amplifiers pumped by wavelength-multiplexed high-power laser diodes, *Optical Fiber Technology*, Vol. 8, pp. 107-122, 2002.
[4] T.K. Ho, “Exploratory analysis of point proximity in subspaces”, in *Proc.16th Int. Conf. on Pattern Recognition*, Quebec City, Canada, 2002.