Invited Paper

Optical simulations for experimental networks: lessons from MONET

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ABSTRACT

We have used optical simulation as a means of setting component requirements, assessing component compatibility, and designing experiments in the MONET (Multiwavelength Optical Networking) Project. This paper reviews the simulation method, gives some examples of the types of simulations that have been performed, and discusses the validation of the simulations.

1. INTRODUCTION

As optical communications networks grow in complexity, and particularly as WDM becomes an integral part of optical communications, it has become increasingly difficult to engineer optical networks. The large numbers of components, often from a variety of suppliers, component interactions, and the coexistence of many wavelengths, all make it difficult to predict accurately the performance of large networks. However, the expense of engineering and building a multiwavelength network, and the consequences of substandard performance make it imperative to evaluate the performance of the network before it is built and to assess the potential performance of various alternative components in the network. Thus, optical simulation has become a necessary tool for network planning and evolution.

Optical simulation has been part of the MONET (Multiwavelength Optical Networking) project from the start, providing a means of setting requirements for the network elements and fiber plant of the MONET DC Network. Simulation has also made it possible for us to anticipate problems of component compatibility before the network has been built, and to propose, test, and implement solutions.

A critical problem in simulation is testing the accuracy of the simulation against experiment. As local exchange and long distance testbeds have been built and tested in New Jersey, and now as the MONET DC Network has become operational, we have been able to test aspects of the validity of our simulations.

It is also necessary to specify the limitations of the simulation, i.e. the boundaries of its regions of applicability. Since the MONET DC Network currently involves no long fiber spans, our initial simulation tool did not include the ability to evaluate impairments associated with optical nonlinearities or dispersion. Limiting the capabilities of the simulator increased its speed and ability to evaluate complex network configuration. We will show how we expect to extend this tool to deal with these effects when necessary.

2. THE NETWORK SIMULATION MODEL

In any simulation approach there are necessarily trade offs between speed on one hand and accuracy and completeness on the other. For the evaluation of the end-to-end network performance, it is necessary to take into account the impact of transmission impairments, including signal power variations, amplified spontaneous emission (ASE) noise accumulation, and crosstalk. The need for speed was one of our motivations for developing a wavelength-domain[1] rather than time- or frequency-domain simulator to be used in studying large optical networks. However, this increased speed is obtained only by sacrificing the ability to evaluate explicitly time domain effects including those due to optical nonlinearities, and the effect of chromatic and polarization mode dispersion.

One key assumption underlies wavelength-domain simulation: in transparent multiwavelength networks, optical signals can be characterized exclusively by their carrier wavelength and average power. For many purposes the modulation and phase of signals can be ignored. For the representation of ASE noise, the optical bandwidth is divided into wavelength bins, and the ASE noise is defined as the average ASE noise power at the central wavelengths of

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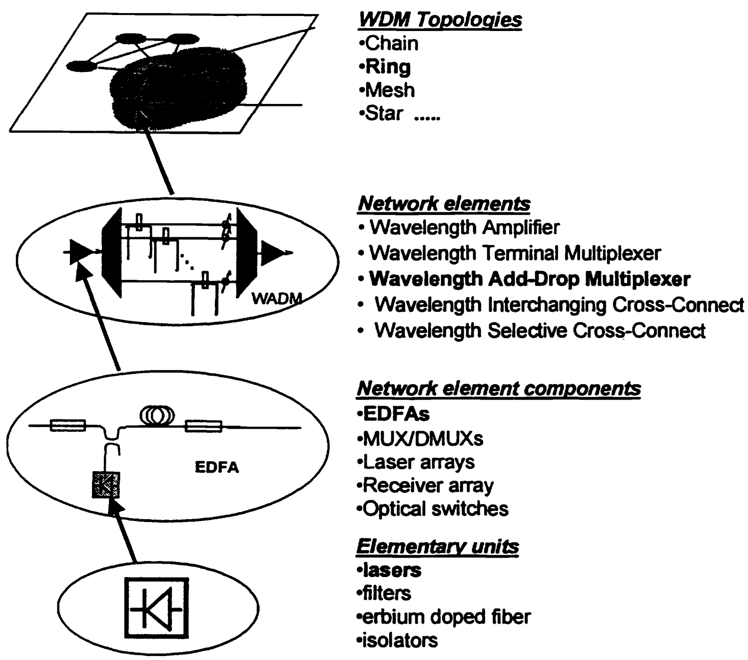


Figure 1 . The simulation tool is hierarchical and is performed in the wavelength domain, for a 100x increase in speed.

these wavelength bins.

This method makes it possible to take into account certain other physical effects such as linear optical crosstalk, and transient power fluctuations caused by either the dynamic interaction of servo-controlled attenuators and saturated EDFAs, or reconfiguration in multiwavelength optical networks when channels are added/dropped or failures occur. While this method makes it possible to take into account a range of physical effects, whole classes of transmission impairments (e.g. chromatic dispersion, optical non-linearities, polarization effects, etc.) cannot be simulated in this way. Thus the wavelength-domain simulator provides the speed that makes simulation of large networks possible at the cost of limiting the range of the physical effects it can model. For the case of the MONET DC network, where distances are small, we believe that this tradeoff is acceptable. For networks in which transmission impairments are more important or where multiple types of impairments must be evaluated, a combination of wavelength-domain and time-domain simulation will be necessary.

We have been able to include certain time domain behavior by taking a two step approach to simulating multiwavelength optical networks. During the first step, the wavelength-domain simulator is applied to the entire network. The wavelength-domain tool evaluates the power spectra of optical signals, of ASE noise and of linear optical crosstalk at every point of the linear network segments. The system performance can be evaluated in terms of optical signal-to-noise ratio (SNR). During the second step, selected optical paths can be studied using conventional time-domain simulation. Parameters extracted from the wavelength-domain simulator in the first step are used in the second step to characterize the paths under study. The fiber model includes both the linear polarization and third order nonlinear polarization effects. During the second simulation step, the parameter set provided by the wavelength-domain tool is therefore associated with error probability and effects which depend on signal modulation and phase. Since the MONET DC Network currently involves no long fiber spans, optical nonlinearities and dispersion are not limiting impairments. Therefore, our initial simulation tool included only the first step above. This integration of

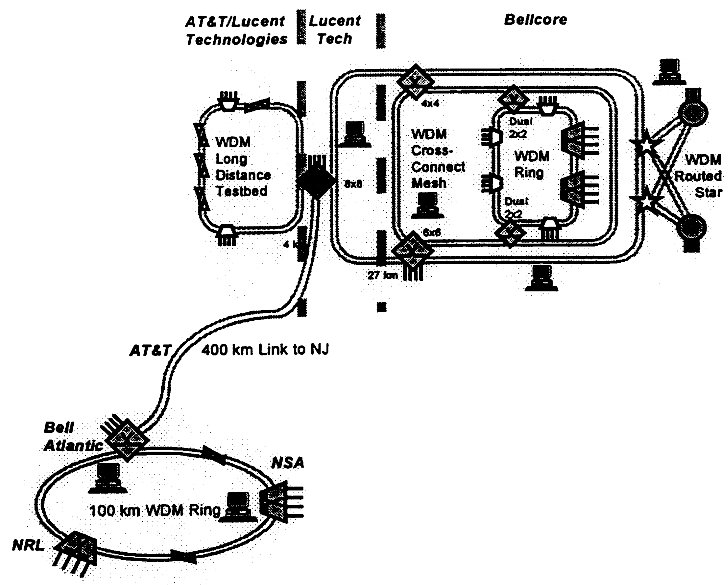


Fig. 2 Initial planned configuration of MONET Network, with a New Jersey Network, a DC ring, and a 400 km amplified link connecting them.

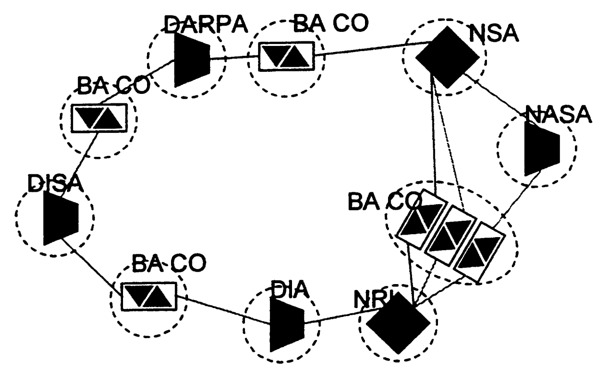


Fig. 3 Current design of MONET DC Network, with Network Elements from two suppliers.

wavelength and time domains has only been started in the simulations performed for MONET, but will be a large part of the NIST-supported PCAD[2] program in which Telcordia Technologies is now involved.

3. THE MONET DC NETWORK

The MONET Network has undergone substantial change during the life of the project. Initially, the network was to consist of the MONET New Jersey Network, a 3 node ring in the DC area, and a 400 km amplified link between the two, as shown in Fig. 2. The longest optical path through this network included 63 EDFAs, 16 passes through MUX/DEMUX pairs (in wavelength add/drop multiplexers or crossconnects), 63 sources of crosstalk, and 19 passes through a lithium niobate switch fabric. Initially simulations were performed to aid in setting requirements for the optical filters making up the wavelength add-drop multiplexers, for laser-filter wavelength registration, and for EDFA noise performance.

We are currently concentrating on providing a ring around Washington, DC., that now connects six, rather than three agencies. No long distance link is included at this time. As shown in Fig. 3, the network consists of two interconnected rings. The Network Elements on the East Ring are provided by Lucent, a member of the consortium, and those on the West Ring are provided by Tellium, an outside vendor. The Network Elements on the two rings have very different optical behavior, including different EDFA design. Thus simulations of the current network need to deal with fewer total components, but must be able to deal with the added complexity introduced by the presence of Network Elements supplied by two vendors.

4. SAMPLE SIMULATIONS OF THE MONET NETWORK

Among the simulations of the MONET Network that we have performed are:

1. Long chains of wavelength add-drop multiplexers (WADMs)[3] as shown in Fig. 4, simulated to answer the questions:

- Through how many network elements can a signal pass and maintain acceptable quality? How does this depend on the design of the optical wavelength filters? Signal quality will be degraded by the accumulation of ASE noise from EDFAs and by crosstalk from the wavelength multiplexers, demultiplexers, and switches.

- Are channel power equalizers (variable attenuators with feedback, used to maintain per channel power at a target level) needed in network elements? In a static network, it is possible to control output power in each channel using preemphasis, and channel power equalizers are not needed. In a reconfigurable network, the path that a given wavelength channel takes is not fixed, and therefore dynamic adjustment of per channel power is needed.

- Given a particular filter spectral transmission, what are the requirements on laser wavelength alignment? Misaligned wavelengths suffer greater loss when passing through Network Elements and consequently accumulate SNR degradation faster.

2. Behavior of servo control attenuators,[4] simulated to understand their effect on network stability immediately following reconfiguration. These simulations were based on experimental characterization of opto-mechanical attenuators from two manufacturers.

3. Behavior of optical amplifiers, with and without gain control, to understand their effect both in a steady state and during reconfiguration of the network. If there is no gain control, changing the number of wavelength channels passing through a saturated EDFA changes the output power for each channel; this is undesirable, and several methods have been proposed to stabilize the gain when the input power or number of input channels changes. Our simulations of EDFAs were based on well-understood physical models of EDFA behavior and have led to the development of several methods to stabilize EDFA gain.[5]

4. Interactions of attenuators and amplifiers, which may result in instabilities following reconfiguration. These simulations were stimulated by the observation of per-channel power instabilities after wavelength channels were

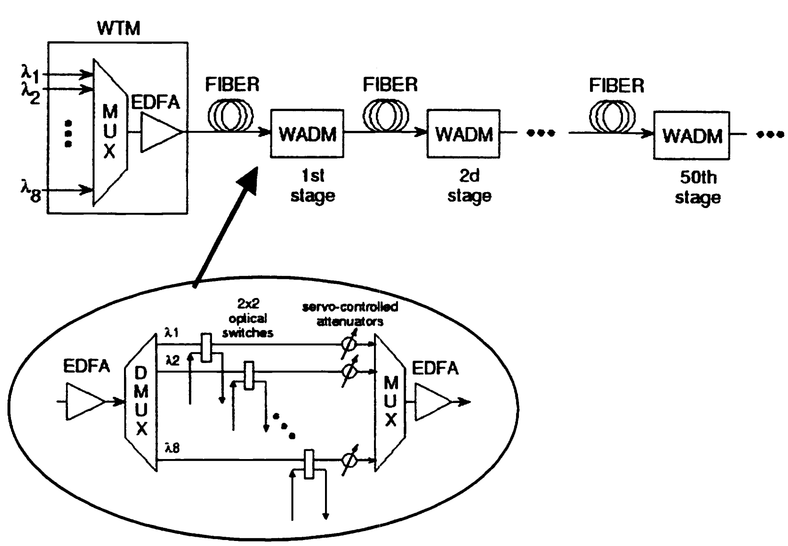


Fig. 4 WADM Chain and construction of WADM. Note EDFAs at input and output.

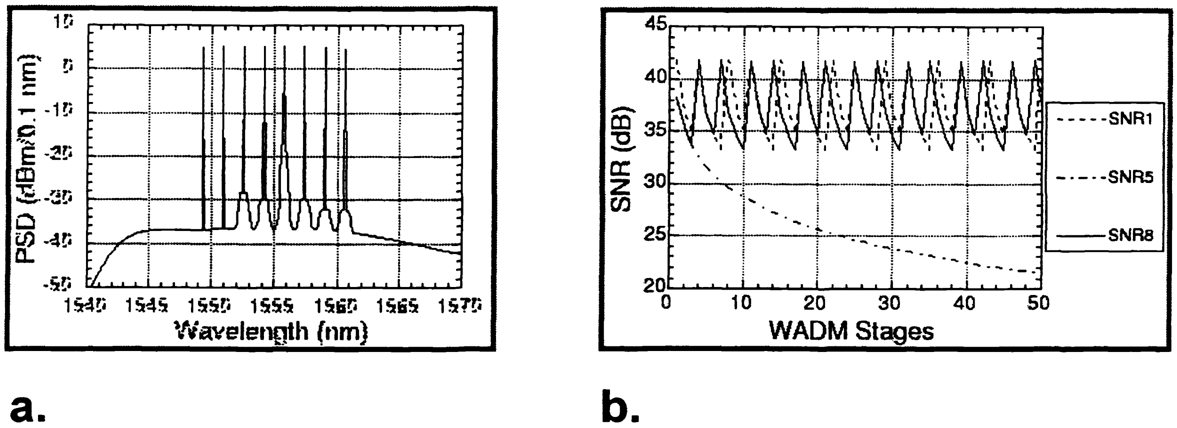


Fig. 5 (a) Output spectrum assuming all channels except channel 5 added and dropped every 5 WADMs, and channel 5 passes through the entire 50 WADM chain. (b) Signal to noise ratios for channels 1,8, and 5. Perfect laser-filter alignment is assumed.

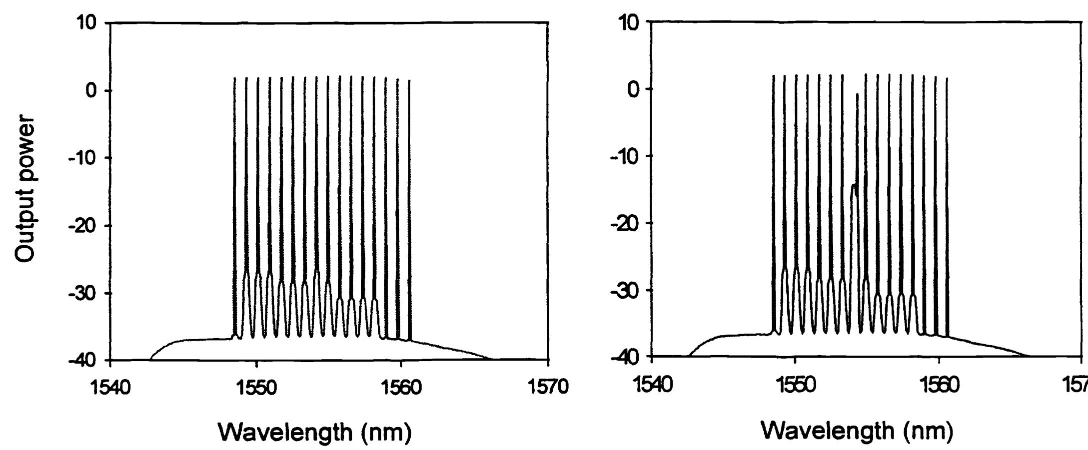
added in rings.[6] We have used simulation to investigate how instabilities are generated and sustained.

5.Interactions of EDFAs with different gain control mechanisms, to determine potential interoperability problems. EDFAs with different gain stabilization mechanisms are not necessarily compatible with each other. Our simulations were part of a study of the interoperability of the equipment supplied by different vendors.

5. RESULTS OF SIMULATIONS

Simulation has enabled us to set requirements for the performance of various components to be used in this network. Fig. 5 shows the outcome of one of these simulations. Here 8 wavelength channels are sent through a chain of 50 WADMs. Most channels are dropped and added every five WADMs; one is allowed to pass through the entire chain. This Figure shows the evolution of optical SNR for three of the channels. SNR is degraded by the accumulation of ASE noise in the EDFAs. For perfect laser-filter alignment even such a long WADM chain allows acceptable SNR.

Similar simulations where laser-filter alignment is imperfect show much faster accumulation of SNR. Fig. 6 shows the output spectrum for a 4 WADM chain with 16 wavelengths present for (a) perfect laser-filter alignment, and (b) 30 GHz misalignment of a single channel. The misaligned channel can be seen to have both lower power and lower



a. perfect alignment b. 20 GHz misalignment

Fig. 6 Output spectrum after 4 WADMs with 16 wavelength channels. (a) With perfect laser-filter wavelength alignment, (c) wavelength 8 misaligned by 30 GHz. The misalignment results in lower channel power and degraded SNR.

SNR than the channels which are perfectly aligned. Without the use of simulation, we could predict that misalignment would lead to these kinds of degradations, but quantitative measures of dependence of degradation on the displacement could not be obtained. The results shown also assume that particular types of filter, in this case multilayer interference filters, are used in the MUX/DEMUX pair. Similar simulations using different filter designs have shown different degradations.

The simulations shown in Fig. 5 and 6 both assume that the WADM includes variable attenuators to equalize the power in all the channels. We can ask whether the cost of providing channel power equalization can be justified. The simulation shown in Fig. 7 shows the effect of eliminating the channel power equalizers and helps answer that question. It is clear that without the variable attenuators, large differences in channel powers accumulates after only a few WADMs.

Simulations of this kind have led to requirements both for the wavelength filters in the multiplexers and for the wavelength alignment and stability of the lasers and have made it clear that variable attenuators are needed to maintain appropriate per-channel power levels in a reconfigurable optical network.

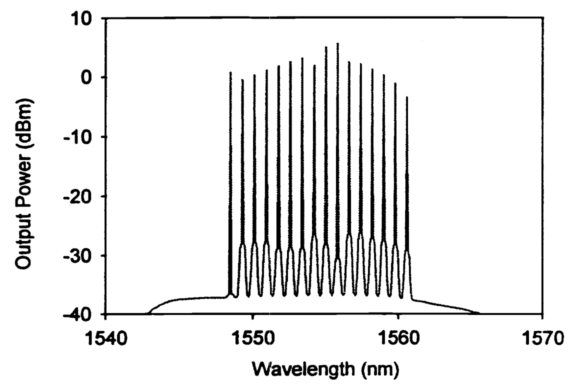


Fig. 7 Output spectrum after 4 WADMs with 16 wavelength channels, perfect laser-filter alignment, with no channel power equalizers. After only a few WADMs channel power can vary by as much as 10 dB.

6. VALIDATION ISSUES

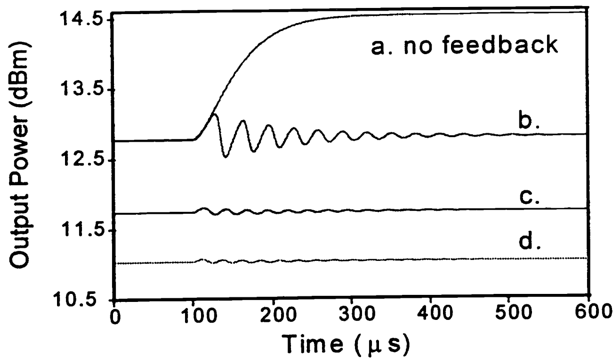
Complex simulations can yield results that are impressive and convincing, but it is always necessary to ask whether they correspond to reality. The validation of simulation can be broken into several parts: baseline validity of the simulation method, the validity of the models used in the simulation, the accuracy of the simulation given approximations (for example step size) that are made during execution, and accuracy of the input data.

The first of these is the most fundamental. Clearly the validity of the wavelength-domain approach is limited, since it explicitly neglects certain physical effects. The simulation can be correct only to the extent that these effects are negligible.

The validity of certain models within our simulation, for example the EDFA models, has been studied. They are based on and tested against measurement, used a physics-based mathematical description of the EDFA, their regimes of validity are well characterized, and their shortcomings (for example, the assumption of homogeneous broadening) can be taken into account. Our models of optical filters are also based on measurement, and simulations of filter cascades of limited size have shown good agreement with experiment.

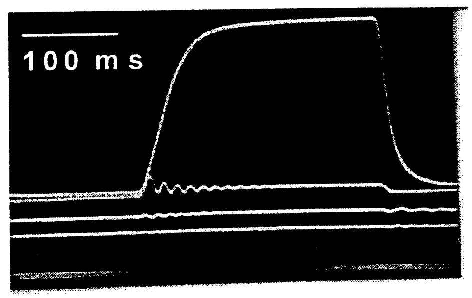
All simulation, even "exact solution" of the equations describing a device requires some approximation, since the equations represent an idealization of the actual device. The validity of a given approximation, such as the size of a wavelength step can be assessed by performing the simulation with various step sizes and looking for limits. It is then possible to estimate the difference between the results obtained with a given step size and with an arbitrarily small step, and thus estimate an error. We have performed preliminary studies of the scaling of error with step size and the number of components simulated.

However, regardless of the validity of the simulation method and the approximations used within it, the accuracy of simulation will always depend on the quality of data that is used. Where we can measure components directly, the



a.

Fig. 8a Transient output power in a single channel of a gain stabilized EDFA with (a) no feedback, (b) minimum stabilizing channel for full compensation when channels drop. (c) Stabilizing channel present when all channels are present. (d) As in (c) but with more power in stabilizing channel.



b.

Fig. 8b Experimental results corresponding to conditions of Figure 2a. Vertical scale is power rather than dBm.

quality of the data can be assured, but commercial equipment vendors may be reluctant to share data. The quality of simulations therefore depends on establishing relationships with vendors who can supply data on equipment, including information on the variability of parameters, rather than simply equipment specifications. This will also allow statistical treatment within simulation, which is necessary for a realistic view of a network.

When we assess the validity of our simulations all the above must be taken into account. For individual components and simple combinations of components, simulations based on accurate data and well defined models can give high accuracy. Thus, for example, we have a high degree of confidence in the simulations of WADM-EDFA chains. Measurements of shorter (8 WADM) chains are in good agreement with simulations and give us confidence in the extension of these simulations to larger networks.

7. VALUE OF QUALITATIVE RESULTS

However, other simulations are based on poor data and at best we can expect only qualitative agreement of simulation and measurement. For example, simulations of output power transients for multiwavelength EDFAs after wavelength channels are added or dropped depend not only on the EDFA model but on the specific characteristics (absorption and emission spectrum) of the erbium doped fiber. Since we have data for only a limited range of fibers, which do not necessarily correspond to those used in the EDFAs we had available for measurements, we cannot expect good quantitative agreement with experiment. Fig. 8 demonstrates qualitative agreement between simulation and measurement for an all-optically gain clamped EDFA with 4 of 8 wavelength channels added and dropped.

The simulations and experimental results shown in Fig. 8 represent only one approach to EDFA gain stabilization. We have also simulated the behavior of EDFAs stabilized using pump power control. Again, our results give qualitative insight but not quantitative predictions of performance, in this case because we do not have data describing the time required either for the initiation of pump power adjustment or for its completion. We can, however, compare our results with reported measurements for this kind of gain control.[7] Agreement of the simulations and the published measurements is excellent.

How useful is a simulation with only qualitative agreement with experiment? In some cases it can be valuable. Simulations similar to those shown in Fig. 8, as well as those describing gain stabilization through adjustment of pump power, have given useful information about the way in which chains of EDFAs function, with and without gain clamping, and, despite the qualitative nature of the results, have made it possible to understand the behavior of networks with different types of gain control.

One of the most critical uses of simulation occurred when we looked at signals passed between EDFAs from different suppliers. The simulations showed that the different gain control mechanisms of the two types of EDFAs were incompatible, although each satisfied the network specifications. More important, the simulations allowed us to propose and test modifications that could make the EDFAs compatible within the network. This ability to test alternatives without building an expensive network is one of the key values of optical simulation.

8. CONCLUSIONS

We have found optical simulation to be an invaluable tool in engineering the MONET network. Validation of our simulations have been primarily at the component level. Where adequate data exists, simulations agree well with measurements; where data is limited, simulations agree only qualitatively. We find that lack of good data limits our ability to validate simulations, particularly when commercial equipment is involved. It is our hope that partnerships with commercial photonics manufacturers that will be developed within the PCAD program will make it possible to develop and validate more accurate simulations.

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