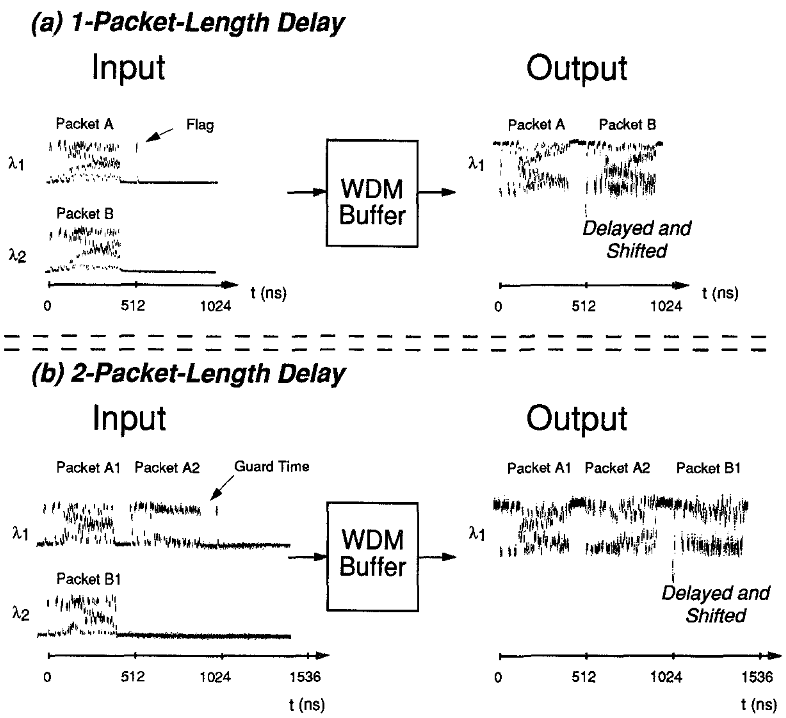
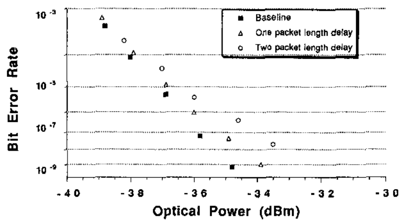


CFI2 Fig. 2 (a) Oscilloscope trace of the inputs (λ_1 and λ_2) and output (λ_1) for one-packet-length delay. (b) Oscilloscope trace of the inputs (λ_1 and λ_2) and output (λ_1) for two-packet-length delay.



CFI2 Fig. 3 BER versus received optical power of the active WDM fiber loop buffer.

delayed by one packet length and then shifted onto λ_1. In the second case, only every third packet time slot at λ_1 is empty, requiring that the packets at λ_2 are experimentally delayed by two packet lengths.

Figure 3 shows the bit error rates for buffering and contention resolution across one and two packet delay slots. Issues such as contrast ratio degradation, incoherent beat noise crosstalk,[5] and polarization sensitivity will limit the ultimate number of delay packet time slots, although several time slot delays can be realized with existing technology; note that even a few delay packet slots will still provide a significant decrease in packet dropping probability as a result of output-port contention.

1. I. Chlamtac *et al.*, IEEE J. Selected Areas in Communication **14**, no. 5, 1014–1029 (1996).
2. S. L. Danielsen, B. Mikkelsen, C. Joergensen, T. Durhuus, K. E. Stubkjaer, IEEE Photon. Technol. Lett. **8,** 434–436 (1996).
3. D. J. Blumenthal, R. J. Feuerstein, J. R. Sauer, IEEE Photon. Technol. Lett. **6,** 457–460 (1994).
4. W. Shieh, A. E. Willner, OFC'96, paper PD-36 (OSA, Washington, DC, 1996).
5. E. L. Goldstein, L. Eskildsen, IEEE Photon. Technol. Lett. **7,** 93–94 (1995).

CFI3 11:00 am

Frequency-domain simulation of a chain of 50 wavelength add-drop multiplexers

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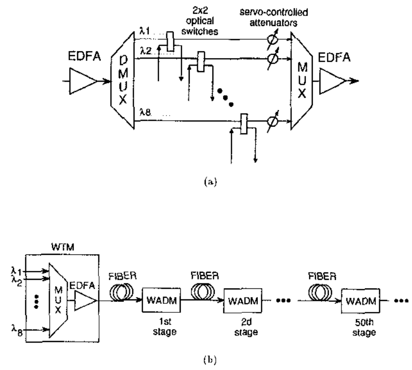
In recent years enormous progress in WDM networking has been made and various WDM scalable and transparent architectures have been studied.[1]

A proposed WDM network for the multiwavelength optical networking (MONET) program[2] consists of rings and chains of wavelength add/drop multiplexers (WADMs). A WADM is a key network element used for selectively dropping and inserting optical signals into the network. Its main functions are shown in Fig. 1a and consist of 2 × 2 optical switches (for signal adding/dropping), a preamplifier and a booster amplifier, a multiplexer/demultiplexer (MUX/DMUX) pair, and variable attenuators for power equalization.

Amplified spontaneous emission (ASE) noise resulting from the erbium-doped fiber amplifiers (EDFAs) is filtered inside each WADM by the MUX/DMUX pair. However the part of ASE noise inside the passband of MUX/DMUX accumulates and eventually degrades the optical SNR at the receivers. In this paper we use frequency-domain simulation to study the accumulation of ASE noise in a cascade of WADMs. Our goal is to investigate if 50 WADMs, on the order of a national scale mul-



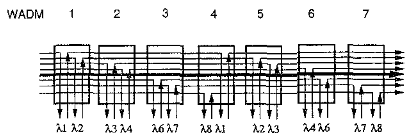
CFI3 Fig. 1 (a) Block diagram of a wavelength add-drop multiplexer (WADM); (b) block diagram of a cascade of WADMs.

tiwavelength network, can be cascaded together before the optical SNR drops below acceptable levels.

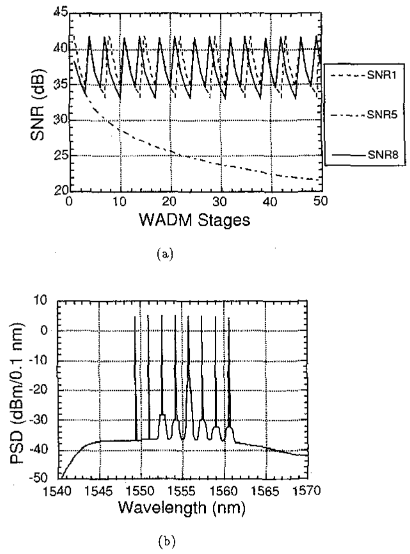
The block diagram of the system under study is shown in Fig. 1b. Eight signal channels at the MONET wavelengths λ_1–λ_8 are multiplexed and propagated through a cascade of equidistant WADM pairs. Fiber spans are assumed to have 17 dB flat attenuation. The two EDFAs in the WADMs are assumed identical single-stage forward-pumped amplifiers including a notch filter for ASE peak rejection. The input power per channel in the EDFAs is assumed −13 dBm. The EDF fiber length and pump power at 980 nm are adjusted so that the amplifiers provide an average gain of 17 dB/channel to compensate for the span loss. Maximum gain variation between channels is equal to 0.5 dB and the noise figure of the EDFAs is 4.23 dB at 1550 nm. The MUX/DMUXs in the WADMs are made by cascades of multilayer interference (MI) filters.[3] The insertion loss of a MUX/DMUX pair is 6.6 dB per channel. The 2 × 2 switches are assumed to have 1 dB insertion loss/channel. Optical crosstalk is neglected. The servo-controlled attenuators are automatically adjusted to equalize the signal power at −13 dBm per channel at the input of the second EDFA. This efficient equalization scheme prevents any power variations between channels from accumulating during the propagation through the WADM cascade.

In the simulation, the steady-state EDFA model of Ref. 4 is used. The MI filters in the MUX/DMUXs are modeled as third-order Butterworth filters. Since in a 50 WADM chain there are 8 × 50 2 × 2 optical switches, the total number of possible add/drop scenaria is $2^{400} \simeq 10^{120}$. In our study we consider a reasonably worst case scenario where at least one of the channels (i.e., channel 5) propagates through the whole WADM chain (Fig. 2), with all other channels periodically added and dropped in pairs at successive WADMs.

Figure 3a presents the optical SNR of selected channels measured in a 0.1 nm resolution bandwidth as a function of the number of WADMs traversed. The optical SNR of channel λ_5 that traverses all WADMs drops to 21.8 dB, which is above the acceptable level necessary to achieve a bit error rate (BER) lower than 10^{-9} at 10 Gb/s.[5] This result is very close (within 0.1 dB) to the theoretical optical SNR[5]



CFI3 Fig. 2 Simulation add-drop scheme indicating the exact WADM where each channel pair is dropped and then added. Channels correspond to frequencies from 192.100 THz (for channel 8) to 193.500 THz (for channel 1) in 200 GHz steps. The add-drop scheme is periodically repeated after every seven WADMs.



CFI3 Fig. 3 (a) Optical signal-to-noise ratio (SNR) in 0.1 nm resolution bandwidth as a function of the number of WADMs traversed. SNR varies between 34 dB at the drop site and 42 dB just after addition for all wavelengths except λ_5 whose SNR drops to 21.8 dB; (b) Power spectral density (PSD) in dBm/0.1 nm after the 50 WADM cascade.

for a chain of 100 ideal EDFAs where the amplifier gain is equal to the span loss (17 dB). Figure 3b shows the power spectral density (PSD) after 50 WADM stages. No significant power variation between the eight channels is observed. Irregularities of the ASE noise level are due to the specific add/drop scheme of Fig. 2.

The above results show that a WDM network with more than 50 WADM stages in cascade and with 900 dB of total interstage losses is theoretically feasible. This conclusion is exclusively based on the study of the optical SNR. The impact of other physical effects such as laser/filter misalignment, chromatic dispersion, nonlinearities, crosstalk, polarization-dependent loss or polarization dispersion will be part of future simulator enhancements.

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**Currently with the Center for Telecommunications Research, Columbia University*

1. J. Lightwave Technol. **14,** No. 6 (1996).
2. R. E. Wagner *et al.*, J. Lightwave Technol. **14,** No. 6, 1349–1355 (1996).
3. M. A. Scobey, D. E. Spock, "Passive DWDM components using MicroPlasma optical interference filters," Technical Digest, OSA Optical Fiber Conference, San Jose, Calif, Feb. 1996.
4. R. M. Jopson, A. A. M. Saleh, in *Fiber Laser Sources and Amplifiers III,* vol. 1851 (SPIE, 1991), pp. 114–119.
5. E. Desurvire, *Erbium-Doped Fiber Amplifiers: Principles and Applications* (John Wiley & Sons, 1994), Ch. 3.

CFI4 **11:15 am**

Light-emitting diode source for chirped wavelength division multiplexed local access network

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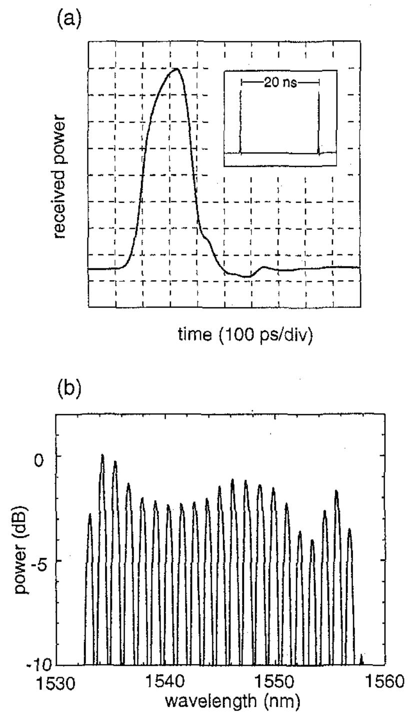
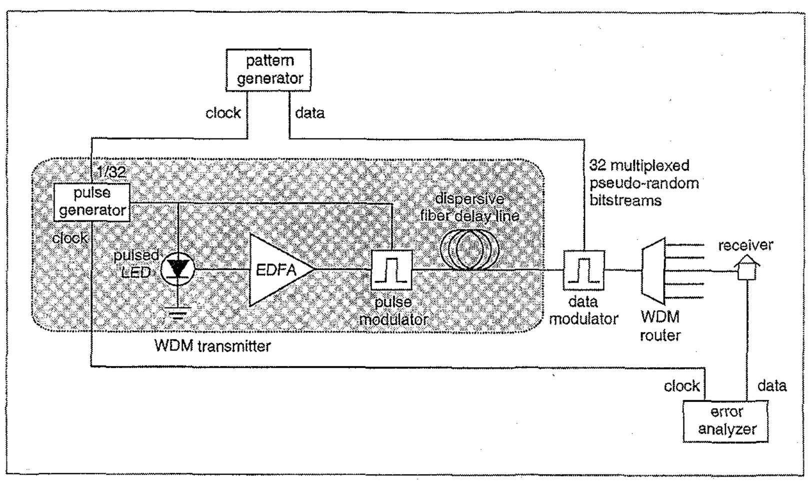
The light source in a chirped wavelength division multiplexed (WDM) system produces an output having a time-varying wavelength, so that light for each WDM channel is emitted sequentially from the source.[1] In this manner, a time-division-multiplexed (TDM) datastream can encode a WDM signal using a single modulator. We demonstrate a chirped WDM local access network based on a pulsed light-emitting diode (LED). Error-free data was transmitted in a 20-channel system, at a baseband rate of 50 Mb/s, with and without crosstalk interference.

A chirped WDM transmission system, Fig. 1, consists of a transmitter, producing a train of pulses whose wavelength is swept linearly in time, a modulator, encoding subsequent bits onto the successive wavelength components, an optical fiber transport link, a WDM router, for demultiplexing the WDM transmission, and one receiver for each WDM channel. The transmitter, in this case, is a pulsed LED, delivering −18 dBm at 50 MHz, with a pulsewidth of 600 ps, and a spectral bandwidth of 72 nm, centered at 1510 nm. These pulses are amplified in an erbium-doped fiber amplifier (EDFA), with a bandwidth of 30 nm centered at 1545 nm. A lithium niobate modulator cleans the wings of the pulse and eliminates residual amplified spontaneous emission (ASE), shortening the pulse width to 200 ps, Fig. 2a, and dropping the average power to −3.8 dBm. The inset to Fig. 2a shows the full base-band bit period of 20 ns, indicating the low duty-cycle used to generate the chirped pulse. This pulse is then dispersed in 30 km of AT&T 5D optical fiber, with a dispersion of



CFI4 Fig. 2 WDM transmitter optical power in 0.05 nm bandwidth (a) after power-splitting tap, showing 200 ps pulses at 50 Mb/s bitrate. Inset shows full 20-ns bit period. Spectrum (b) after data-encoding modulator, driven by an RZ pattern with all channels on, showing 20 signal channels, spaced at 1.2 nm.



CFI4 Fig. 1 Schematic of chirped WDM transmission system. Light from a pulsed LED transmitter is encoded at modulator with 32 multiplexed pseudorandom bitstreams. Wavelength channels are demultiplexed at an optical bandpass filter or WDM router, with individual bitstreams received and analyzed for errors.