The MONET New Jersey Network Demonstration


(Invited Paper)

Abstract—The multiwavelength optical networking (MONET) consortium has demonstrated national-scale optical networking in a multilocation testbed in New Jersey. The demonstration involves transparent optical connections over path lengths as long as 2290 km, through several network elements (NE’s) controlled by two interoperating network control and management (NC&M) systems. This paper describes in detail the three constituent testbeds and the experiments.

Index Terms—Optical amplifiers, optical communication, optical networking, optical switching networks.

I. INTRODUCTION

The vision of a national-scale, high-capacity optical backbone network using wavelength-division multiplexing (WDM) technologies involves signal transport and network management between three distinct sectors—local exchange network, long-distance carriers, and cross-connect gateway providers. The members of the multiwavelength optical networking (MONET) consortium [1] have designed and interconnected three testbeds and two network control and management (NC&M) software systems that allow us to perform experiments in an environment that mimics a national-scale WDM network, in terms of both fiber distance and system complexity [2]. The testbeds include a local-exchange testbed (LEC-TB) at the Bellcore Newman Springs facility, a long-distance transmission testbed (LD-TB) at the Lucent/AT&T Crawford Hill facility, and a cross-connect testbed (XC-TB) at the Lucent Holmdel facility. The demonstration of our New Jersey network is an ambitious task that not only shows the feasibility of an optically reconfigurable network, but also provides the opportunity to identify and resolve issues in the performance of both the optical and the NC&M layers.

The MONET New Jersey optical networking demonstration described in this paper involves the characterization of the physical performance of the three linked testbeds and the demonstration of connection setup across the domain boundary between the local exchange and long-distance NC&M systems. Four goals were set for this demonstration.

• Interaction between the two NC&M domains to set up a two-way optical connection traversing all three testbeds.
• Transmission of eight MONET wavelengths over the resulting optical connection.
• Simultaneous transmission of wavelengths modulated with different signal formats, specifically 2.5-Gb/s digital signals and FM subcarrier modulated video signals.
• Assessment of the network performance against MONET performance targets.

During these experiments, we made several discoveries related to the deployment of networking technology over national-scale WDM networks. Some interesting issues include polarization dependence of wavelength demultiplexing and switching devices, dispersion management between the long distance and local exchange network, and multiwavelength signal power equalization and gain clamping in the cascaded erbium-doped fiber amplifiers (EDFA’s) of the network.
Section II of this paper is an overall description of the New Jersey network followed by Sections III–V, containing brief descriptions of the three testbeds as they are configured for the network demonstration. These testbed descriptions are not exhaustive but, rather, focus on the features required for our demonstration. Section VI describes the outside fiber plant interconnecting the three testbeds, illuminating issues that confront the implementation of sophisticated optical technologies over an existing deployed fiber plant. Section VII describes the NC&M software supporting this demonstration. Again, the description is not meant to be complete, but serves to indicate the current state of the software and to highlight issues associated with connection setup across network domain boundaries. Section VIII describes the networking experiments and compares our results with the MONET performance targets. The final section summarizes this work.

II. NEW JERSEY NETWORK CONFIGURATION

The MONET New Jersey network consists of three interconnected networking testbeds in three separate locations. These include an LEC-TB located in the Bellcore Newman Springs location, an XC-TB located in the Lucent Technologies Holmdel location, and an LD-TB jointly operated by AT&T and Lucent Technologies and located in the Lucent Crawford Hill location. A map showing the relative positions of the three facilities within Monmouth County, NJ, is shown in Fig. 1. The successful performance of these individual testbeds has been previously demonstrated, although the individual testbed configurations, as befits the research character of the MONET program, are constantly evolving. The successful interconnection of these testbeds to form the New Jersey network is the culmination of much early planning and preparation, such as the definition of target signal parameter specifications for all testbeds. These initial specifications and subsequent refinements enabled the complex equipment of the individual testbeds to develop independently while ensuring the later successful integration of the testbeds into a functional optical networking testbed. This paper reports on the successful interconnection of these testbeds and the subsequent characterization of the resulting optical network.

A. Physical Layer

As illustrated in Fig. 2, the physical layer of the New Jersey testbed network includes the fiber, network elements (NE’s), network components of the individual testbeds and the embedded fiber interconnecting the testbeds. The testbeds contain both NE’s and network components. NE’s are defined as optical entities that may be controlled by the NC&M system; network components are entities that perform the same transmission functions as NE’s but are not controlled by the NC&M.

B. Management Layer

Fig. 3 illustrates the view of the New Jersey network physical layer as seen from the NC&M layer. Whereas the physical layer of the MONET New Jersey Testbed Network comprises all of the physical elements and the interconnecting fiber infrastructure, the management layer comprises all of the managed elements and valid client and interdomain end points within the network. The management view of the network is the view available to the combined management systems operating in the two management domains within the network. NE naming is shown in Fig. 3. Client interfaces
Fig. 2. Physical layer of MONET New Jersey Testbed Network.

Fig. 3. Management layer view of MONET New Jersey Testbed Network.

and interdomain interfaces have a common set of names (for interdomain reference) as discussed in Section VII-C.

C. Data Communication Network

Included in the physical layer of the New Jersey network is an asynchronous transfer mode (ATM) fiber network supporting the data communications network (DCN) required by the MONET NC&M system. As shown in Fig. 4, the DCN links all controlled elements (NC&M management workstations and NE controllers) within the New Jersey network and transmits NC&M information both within and between the two NC&M domains.

III. AT&T/LUCENT LONG DISTANCE TESTBED

The LD-TB plays a crucial role in the MONET program demonstration of the feasibility and benefits of truly national-scale optical networking. The long-distance propagation studies are necessary to provide the understanding required to generate specifications for commercial large-scale optical networks. The key transmission issues are chromatic dispersion and optical nonlinearity in the optical fiber, gain flatness in the optical amplifiers, and maintenance of sufficient signal-to-noise ratio (SNR) throughout the network.

Each of the two 1040-km long-distance fiber spans of the LD-TB consist of seven 80-km lengths of negative nonzero dispersion shifted fiber [(N-NZDSF), \(-2.3 \text{ ps/nm-km}\)] and six 80-km lengths of positive NZDSF [(P-NZDSF), \(+2.3 \text{ ps/nm-km}\)] fiber connected between 14 MONET EDFA’s [3] operating at 5 dBm/ch. Thus, each fiber span has low total dispersion while maintaining finite local dispersion to reduce nonlinear effects. The individual 80-km fiber lengths of the two long-distance spans were carefully chosen to result in closely matched total dispersion values of \(-83 \text{ ps/nm}\) and \(-47 \text{ ps/nm}\), measured at 1555 nm. When the LD-TB is connected to the New Jersey network, additional negative dispersion is required to compensate for the dispersion of the 200 km of conventional single-mode fiber (CF, \(+17 \text{ ps/nm-km}\)) of the LEC-TB and the testbed interconnection fiber. To accomplish this, we connected three dispersion-compensating fiber (DCF)
spans to the long-distance transmission spans before returning signals to the XC-TB. DCF has high dispersion ($\geq 80$ to $\leq 90$ ps/nm-km), high loss (more than 0.5 dB/km), and a high nonlinearity coefficient. Therefore, the compensating spans consist of an EDFA, an in-line optical attenuator to reduce the input power to the DCF, and an 8-km DCF span that compensates for the dispersion of 40 km of SMF. The DCF spans are not considered to contribute to the length of the LD-TB.

The long distance testbed currently contains six one-way network add/drop sites (WADM-NC) that are not under NC&M control. Within each WADM-NC, the eight wavelengths are demultiplexed, equalized with in-line optical attenuators, and remultiplexed. Both multilayer thin-film and waveguide phased-array (WGR) multiplexing devices were used. It should be noted, however, that transmission through all 2080 km has been achieved with acceptable performance on all wavelengths without any power leveling. The total WADM-NC insertion loss is 10 dB with thin-film mux/demux devices and 20 dB with WGR mux/demux devices. Each WADM-NC is always followed by a MONET EDFA to boost the output power back to standard levels.

There are two basic configurations for connecting the LD-TB to the XC-TB. In the first, each 1040-km span connects an output port of the WSXC to the corresponding input, as shown in Fig. 5. The spectral characteristics of each 1040 km span are shown in Fig. 6. The spectra of the two spans are nearly identical, with output SNR’s of 30.3 and 29.4 dB for the center wavelength and minimal spectral broadening, respectively. In the second configuration, the two spans are interconnected through a WADM-NC to form one 2080-km span between a single XC-TB output and input for long-distance studies. The corresponding output spectrum is shown in Fig. 7, with the output SNR ranging from 23.0 to 24.1 dB and a small increase in spectral broadening. Fig. 8 shows bit error rate (BER) measurements taken on this configuration. The sensitivity is $-27$ dBm at baseline and $-25.5$ dBm with a 0.5-dB spread after a 2080-km transmission.

IV. Lucent Cross-Connect Testbed

A. XC-TB Functionality

The XC-TB contains a wavelength-selective cross-connect (WSXC) which has four transport interfaces (TI’s) to transport multiwavelength signals between NE’s of the other two testbeds. The WSXC supports two-way constituent single-wavelength signal cross-connection, i.e., multiwavelength signals are demultiplexed into constituent single-wavelength signals, which are then cross-connected without wavelength interchange and remultiplexed. The WSXC accepts signals with the specific set of MONET wavelengths at MONET TI’s. The flexibility of switching a subset of the traffic from one TI to another, and vice versa, is useful for segregating and grooming traffic at the various transport nodes in the network.
Fig. 6. Input and output spectra of the two 1040-km spans showing minimal spectral broadening and nearly identical SNR degradation.

Fig. 7. Optical spectra at input and output of two 1040-km spans interconnected by a WADM-NC to form one 2080-km span. A final WADM-NC at the output accounts for the noise filtering.

**B. XC-TB Layout and Interconnection**

Each of the four TI’s can transport up to eight wavelengths, with each wavelength supporting up to 2.5-Gb/s traffic. As shown before in Fig. 2, two TI’s connect to dual 2 × 2 liquid crystal cross-connects (LCXC’s) in the LEC-TB, and two TI’s connect to the LD-TB. Since transmission between NE’s is two way, each TI consists of two fiber ports. There are a total of six fibers interconnecting the XC-TB to the LEC-TB, including two pairs for WDM signals and one pair for the ATM data network, to support NC&M communications. Four fibers interconnect the XC-TB to the LD-TB. NC&M communications between the two Lucent locations are supported via the use of an existing data network.

**C. WSXC Features**

The WSXC features are listed in Table I. The WSXC provides strictly nonblocking 4 × 4 cross connections with disconnect and 1 × 2 bridging capability using Lithium Niobate (LiNbO₃) switch fabrics [4]. The WSXC includes...
optical backplane interconnections, optical signal performance monitoring on all TI's, and a system controller with an NC&M interface. The NC&M/NE interface is transmission control protocol/Internet protocol (TCP/IP) over ATM on an OC-3c physical layer. The WSXC responds to NC&M commands and messages. In addition, a local craft interface will be supported with approximately 50 operations, administrations, maintenance, & provisioning (OAM&P) messages.

The WSXC is designed to meet the target specifications, including signal power requirements for TI interfaces and end-to-end transmission impairments, in terms of crosstalk, eye margin, and SNR. The WSXC is transparent to signal attributes such as signal format, bit rate, and modulation format over a specific set of wavelength at the MONET TI’s. Table II demonstrates the WSXC performance against the target requirements.

The WSXC provides two levels of performance monitoring (PM) to detect failures and degradation of optical signals and components. The first level (PM for a single wavelength signal and PM(λ) for multiwavelength signals) responds quickly to detect the presence or absence of single wavelength or multiwavelength signals. The second level, enhanced performance monitoring (EPM) (EPMX) for multiwavelength signals, is more accurate and can measure the wavelength, power level, and SNR of any signal to be cross-connected. The WSXC can, with the aid of its performance monitoring capability, isolate a fault due to equipment failure within the NE. Loopback features facilitate testing and fault isolation between nodes, including split-loopback, bidirectional loopback, and manual loopback. The WSXC supports visual alarm indications and provides alarm indication messages for failures of individual circuit packs. In addition, it contains a set of three system LED’s to indicate overall system status with alarm levels of minor, major, or critical.

### D. WSXC Architecture

As shown in Fig. 9, the WSXC is implemented as a single bay cabinet. It consists of a system controller complex, an optical transmission module, a multiwavelength meter, and a power supply and fuse panel. The optical transmission module includes input transfer interface (TI_IN) interfaces, input transfer output (TI_OUT) interfaces, the SWITCH, and monitoring. The multiwavelength meter is used for optical signal performance monitoring of signal levels, SNR, and wavelength misalignment on an individual wavelength ba-
sis. As shown in Fig. 10, the transmission architecture of the WSXC, in total, utilizes four input optical amplifiers, four demultiplexers, an eight-layer $4 \times 4$ switch fabric, four remultiplexers, and four output optical amplifiers.

Each TI_IN optical input signal is monitored for the power level, wavelength registration, and SNR of each wavelength, and amplified and then demultiplexed into single-wavelength signals ($\lambda_1$–$\lambda_8$). Each single wavelength signal is then monitored for power level and connected to the appropriate layer of the switch fabric. The switch fabric consists of eight separate wavelength layers with a $4 \times 4$ LiNbO$_3$ switch for each layer. Any of the four inputs on each wavelength layer can be connected to any of the four outputs of the same layer. Loss compensation and the switch configuration are controlled by the system controller. At the switch output, the single-wavelength signals (one from each of the eight layers of the switch fabric) are multiplexed together and amplified to produce the four TI_OUT signals. Each optical TI_OUT output signal is monitored for total power and for constituent wavelength signal power, wavelength registration, and SNR.

V. BELLCORE LOCAL EXCHANGE TESTBED (LEC-TB)

A. LEC-TB Configuration

The LEC-TB plays three important roles: 1) assessing local exchange network architectures; 2) providing NC&M managed client signals for the network demonstration; and 3) evaluating a variety of NE’s with essential functions for WDM optical networking. Two levels of network layers were designed and integrated in the LEC-TB: a WDM transport layer and an overlay ATM data communication layer.

The WDM transport layer consists of a WDM survivable ring with four NE’s, including two wavelength add/drop multiplexers (WADM’s), two dual $2 \times 2$ LCXC’s, and five network components, including one wavelength selective cross-connect (WSXC-NC) and four WADM-NC’s. The control and management of the four NE’s of the LEC-TB formed the basis of a reconfigurable New Jersey network for adding and dropping single wavelength client signals to demonstrate a national-scale, two-domain, three-testbed, LEC-LD-LEC experiment. The LEC-TB configuration is depicted in Fig. 2, where the five network components were deployed to ensure adequate $8\times$-signal conditioning. In particular, one of the network components was used to inject $8\times$-filling signals into the fiber rings. Thus, the input power levels to all EDFA’s employed in the NE’s and components were maintained to attain an optimized flat gain curve to meet the MONET target specifications. The detailed design and operation of the LCXC’s will be described in Section V-C. We summarize the performance and requirements of the WADM’s in Section V-D.

1) DCN for the LEC-TB: The four NE’s, WADM1, WADM2, LCXC1, and LCXC2, in the LEC-TB were connected to NC&M stations through the ATM switched DCN. The architecture of this ATM overlay layer is depicted in Fig. 11. NE controllers located in the four NE’s are communicating with NC&M agents residing in SPARC-5 stations, through ATM computer interface modules operating at the OC-3 rate. The NC&M agents communicate with the NC&M stations, SPARC-20, connected to ATM switches through separate ATM-computer modules. The intent is to build a robust data communication network. Transmitters and receivers for the DCN operate at 1310 nm.

B. LCXC

1) LCXC Overview: Two dual $2 \times 2$ LCXC’s are used to route individual wavelengths between two two-fiber rings in opposite transmission directions. Both switches are designed for the MONET wavelength spacing of 200 GHz. Fig. 12(a) shows the schematic configuration of the eight-wavelength 2
\( \times 2 \) LCXC where any wavelength originating at an input port can be individually routed to either one of the two output ports. Fig. 12(b) shows the schematic layout of the LCXC employed in the LEC-TB. Each \( \times 2 \) switch is recognized by the NC&M and NE controller software as an equipment slot in the LCXC network element. Therefore, each \( \times 2 \) switch can be individually controlled. In the schematic layout, the switch configurations are defined for each wavelength. For example, in Fig. 12(b), slot 1 could be in the cross-state while slot 2 is in the bar-state for MONET \( \lambda 1 \). For any other wavelength, slot 1 may be in the bar-state or cross-state while slot 2 is in the bar-state or cross-state.

Fig. 12(c) shows the bay layout for the dual \( \times 2 \) LCXC. It includes an NE controller, a local craft graphic interface display, and two \( \times 2 \) liquid-crystal switches. The NE is running a local NE server on the Windows NT platform. A common message set is adopted to communicate across different NE’s and testbed boundaries using TCP/IP protocol over ATM signaling channels. The NE controller provides local access and diagnostic capabilities for the LCXC. LED indicators on the front panels of the LCXC shows the switching state for each wavelength.

2) LCXC Functionality: The LCXC provides single wavelength signal cross-connections. The multiwavelength signals are demultiplexed into single wavelength signals, cross-connected, and multiplexed back to a new set of signals. It allows flexibility of traffic control and dynamic network reconfigurability. It provides wide spectrum transmission transparency, flat passbands, and reasonably low insertion loss. Due to the limitations inherent to the structure of the liquid crystal switch, however, there are no power or performance management functions in the LCXC. It is also difficult to scale these switches to larger sizes.

3) Dual \( 2 \times 2 \) LCXC Features:

- **Ports**
  - Two sets of 2 bidirectional ports.
- **Capacity**
  - Two \( 2 \times 2 \) switches.
  - 8 wavelengths per port with signal transparency.
- **Transparency demonstration:**
  - Analog (FM-Video) and Digital (OC-3, OC-48, and OC-192) signals on different wavelengths at the same time.
- **Communication Interface:**
  - ATM communication over OC-3 with NC&M.
- **Control Interface**
  - User-friendly Graphic User Interface (GUI).
  - Reboot
    - Start-up default reconfiguration.
  - Reconfigurability
    - Reconfiguration on per wavelength base.
- **Provision**
  - NC&M remote reconfiguration.
  - Local GUI craft interface and remote network-element GUI control.
  - Local access of switching states.
  - Local network-element server communication provision.
- **Compatibility**
  - MONET NC&M and MONET NE’s.

4) LCXC Characteristics: Fig. 13(a) and (b) shows the transmission and switching characteristics of LCXC1 from input port 1 to the output port 1 (the bar-state) and port 2 (the cross-state), respectively. Table III shows insertion losses (<10 dB) and the channel flatness (within 4 dB). The performance of each channel in the LCXC is characterized by both the 3- and 20-dB bandwidths and the center of each passband. The 3- and 20-dB points are normalized to the value at the center of the passband. The 3-dB bandwidth gives the flatness of each passband, and the 20-dB bandwidth provides the information about filter cutoff slopes. Table IV shows the results. The module is designed to have a 200-GHz MONET channel frequency spacing. Fig. 14 shows the 3-dB bandwidth in spectrum for each channel. The ratio of the total 3-dB bandwidths within eight channels over the entire wavelength range is the channel efficiency. One advantage of liquid-crystal switches over other switching techniques is high channel efficiency.

Two crosstalk levels are characterized in the liquid-crystal switches. The interchannel crosstalk can be directly observed from the insertion-loss measurement by switching the alter-
Fig. 13. Transmittance of an eight-wavelength 2 x 2 LCXC1. (a) In the bar state. (b) In the cross state.

TABLE III

INSERTION LOSSES AND CHANNEL FLATNESS FOR LCXC1

<table>
<thead>
<tr>
<th>Ch.</th>
<th>Bar state (dB)</th>
<th>Cross state (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.21</td>
<td>8.76</td>
</tr>
<tr>
<td>2</td>
<td>7.40</td>
<td>8.05</td>
</tr>
<tr>
<td>3</td>
<td>7.22</td>
<td>7.66</td>
</tr>
<tr>
<td>4</td>
<td>6.50</td>
<td>7.25</td>
</tr>
<tr>
<td>5</td>
<td>6.50</td>
<td>7.09</td>
</tr>
<tr>
<td>6</td>
<td>7.05</td>
<td>7.40</td>
</tr>
<tr>
<td>7</td>
<td>7.83</td>
<td>7.44</td>
</tr>
<tr>
<td>8</td>
<td>9.44</td>
<td>8.27</td>
</tr>
<tr>
<td></td>
<td>Flatness</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.94</td>
<td>1.67</td>
</tr>
</tbody>
</table>

PDL data obtained from LCXC1. The reflectivity was also measured for each port, with return losses better than 34 dB for all states of all input and output ports.

As a transparency test, OC-48 (2.488 Gb/s) and OC-192 (9.952 Gb/s) signals were applied through the LCXC on two wavelengths (λ3 and λ5, respectively) while FM-video signal was applied on one wavelength (λ4) at the same time. The primary degradation from passing through the LCXC will be crosstalk from the other inputs. Figs. 15 and 16 show the eye-diagrams both before and after passing through the switch for the OC-48 and OC-192 signals, respectively, with no significant change in eye shape. Fig. 17 shows the BER measurements after passing the LCXC for the OC-48 and OC-192 signals, as compared with the baseline measurements with a pseudorandom data 223 - 1 and 231 - 1, respectively. The sensitivity of -33.6 dBm at the OC-192 rate was attained using an optically preamplified receiver in conjunction with a tunable narrow band filter.

C. WADM

1) WADM Functionality: The WADM supports optical add/drop capability from a multiwavelength transport facility. Individual demultiplexed channels can be arbitrarily added to or dropped from the transport facility or transparently passed through. This functionality forms the basis for linear chain architectures in both point-to-point configurations and self-healing ring networks.

2) WADM Features: The Bellcore WADM for the LEC-TB supports both chain and ring network architectures. Four-fiber bidirectional line-switched operation in analogy with current SONET ring systems is provided through installation of an optional protection switch circuit pack. The WADM allows full optical add/drop (8 x 8, 100% of line capacity) compatible with both compliant and noncompliant (wavelength-regenerated) interfaces. An all-optical internal design provides full optical transparency for all wavelength channels. The Bellcore WADM supports several unique features: 1) an all-optical amplifier fixed-gain control; 2) hardware-based dynamic channel equalization; and 3) multimode line protection switching.

Channel-dependent behavior of optical amplifiers can disturb nonparticipating wavelength signals in the event of dynamic reconfiguration, network upgrade, and fiber or node failure situations [5]. The WADM incorporates all-optical feedback stabilized amplifiers [6] to maintain constant gain in environments where channel powers and numbers fluctuate. The all-optical feedback control regulates the gain within microseconds, sufficient to stabilize transients over ten or more network element stages.

In addition to overall multiwavelength changes, variations between channels due to rerouting and client signal irregularities necessitate the introduction of dynamic per-channel signal conditioning. The WADM uniquely provides hardware-based equalization using high-speed mechanical attenuators. Stabilization of 1-dB transients within 10 ms can be achieved for each channel. Slower software-based solutions can limit the network reconfiguration speed and allow performance degrading transients to affect other wavelength channels.
TABLE IV
BANDWIDTHS AT 3- AND 20-dB FOR EACH CHANNEL OF LCXC1

<table>
<thead>
<tr>
<th>Ch.</th>
<th>Passband Center (nm)</th>
<th>Bandwidth 3-dB (nm)</th>
<th>Bandwidth 20-dB (nm)</th>
<th>λ Deviation (nm)</th>
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<tbody>
<tr>
<td>1</td>
<td>1549.08</td>
<td>1.51</td>
<td>2.13</td>
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</tr>
<tr>
<td>2</td>
<td>1550.84</td>
<td>1.50</td>
<td>2.04</td>
<td>-0.078</td>
</tr>
<tr>
<td>3</td>
<td>1552.50</td>
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<td>4</td>
<td>1554.19</td>
<td>1.52</td>
<td>2.02</td>
<td>0.056</td>
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<td>5</td>
<td>1555.88</td>
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<td>0.133</td>
</tr>
<tr>
<td>6</td>
<td>1557.48</td>
<td>1.47</td>
<td>1.97</td>
<td>0.117</td>
</tr>
<tr>
<td>7</td>
<td>1559.21</td>
<td>1.48</td>
<td>1.85</td>
<td>0.227</td>
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<tr>
<td>8</td>
<td>1560.78</td>
<td>1.37</td>
<td>1.92</td>
<td>0.174</td>
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TABLE V
LIQUID CRYSTAL SWITCH CROSSTALK

<table>
<thead>
<tr>
<th>Crosstalk</th>
<th>Bar state (dB)</th>
<th>Cross state (dB)</th>
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</thead>
<tbody>
<tr>
<td>Crosstalk 1</td>
<td>&gt;37</td>
<td>&gt;38</td>
</tr>
<tr>
<td>Crosstalk 2</td>
<td>&gt;42</td>
<td>&gt;41</td>
</tr>
</tbody>
</table>

TABLE VI
POLARIZATION DEPENDENT LOSSES FOR LCXC1

<table>
<thead>
<tr>
<th>Ch.</th>
<th>Bar state (dB)</th>
<th>Cross state (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.21</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>1.57</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>0.55</td>
<td>0.17</td>
</tr>
<tr>
<td>4</td>
<td>0.59</td>
<td>0.36</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>0.17</td>
</tr>
<tr>
<td>6</td>
<td>0.10</td>
<td>0.19</td>
</tr>
<tr>
<td>7</td>
<td>0.20</td>
<td>0.39</td>
</tr>
<tr>
<td>8</td>
<td>0.25</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Max. 2.21 dB

Fiber cuts present the most common failure mechanism for network systems and the Bellcore WADM incorporates advanced line-switched protection. In the event of fiber cuts, integrated optical protection switching using hardware detection and logic takes place, providing survivability and restoration within 15 ms. All traffic is bypassed to alternate fibers offering protection to all traffic, without requiring client intervention as in path-protected systems. Furthermore, no extra sources or channel-selective optics are required to provide full survivability, thus further enhancing reliability and scalability.

In accordance with MONET requirements for interoperability, the WADM features a complete implementation of the NE-NC&M software interface operating over the standardized OC-3 ATM signaling channel. The craft interface, which also operates over TCP/IP and, thus, is accessible from any point within the data communications network, offers a rich graphical interface into the network element functionality. In addition to the full NC&M command set, the WADM provides access to numerous element-specific features, including hardware status registers, real-time performance monitoring, and internal notifications.
3) WADM Description and Architecture: The Bellcore WADM resides in a single-bay rack, and it consists of a multiwavelength performance monitor module, system controller, and two transmission shelves for EAST and WEST directions, respectively. The transmission equipment includes six optical circuit packs: (optional) automatic protection switch (APS), TI_IN, TI_OUT, switch fabric (SF), channel power equalization (CPE), and compliant client interfaces (CCI). Each shelf represents a single transmission path and contains one of each circuit pack, as well as an embedded electronic controller and monitoring modules.

The TI’s provide multiplexing and demultiplexing of the constituent channels and appropriate amplification to overcome fiber and component losses. Reliable high-performance opto-mechanical $2 \times 2$ switches then switch the individual channels to provide local access or pass through. All add and drop operations are performed through the client interfaces circuit pack. The channel power equalizer conditions the wavelength channels independently, using high-speed hardware feedback-controlled variable optical attenuators.

Performance monitoring takes place both at the network element edges (to isolate external failures) as well as at internal locations. All input and output ports are sequentially polled and monitored for channel power, wavelength registration, and SNR. Within the client interfaces the individual connections are optical combined to resemble TI’s. A wavelength meter, in tandem with a $1 \times 12$ optical switch, is used to provide the detailed channel measurements. Internally, fast individual channel power measurements using optical taps and fast photodetectors are made at add, drop, and equalization points for rapid detection of failures.

As indicated in Fig. 11, overall element control is provided by a dual-processor system computer inside the WADM. The controller system includes an interface to the embedded circuit packs and wavelength meter, as well as the OC-3 ATM optical interface to the NC&M system. Optionally, a video display is provided for convenient access for network element provisioning. The entire network element is powered by 120 V AC through a rack line conditioner.

VI. NEW JERSEY FIBER PLANT

Six single-mode fibers, approximately 27.3 km in length, provided by Bell Atlantic, connect the LEC-TB at the Bellcore Newman Springs location and the XC-TB at the Lucent Technologies Holmdel location. The Lucent XC-TB and the Lucent/AT&T LD-TB, located at Lucent Technologies Crawford Hill Laboratory, are then connected by four single-mode fibers, approximately 5 km in length, belonging to Lucent.

A. Fiber Usage

Of the six fibers provided between Bellcore on Newman Springs Road, and Lucent Technologies in Holmdel, four fibers connect MONET NE’s and two fibers connect the MONET NC&M systems via ATM switches placed at each location. The four fibers with the best transmission loss characteristics were chosen to connect the high-speed MONET NE’s, and the two remaining fibers connect the lower speed NC&M data communications network. All four fibers between the Lucent Technologies locations at Holmdel and Crawford Hill were used to connect MONET NE’s. NC&M functions between these two locations are accomplished over an existing Lucent data network.

B. Fiber Outside Plant Testing

The six Bell Atlantic fibers were examined using a Tektronix FiberMaster test set, with results listed in Table VII. The results indicate total fiber transmission losses between Bellcore, Newman Springs Road, and Lucent Technologies in Holmdel well within the specified limits of less than 18 dB in the 1550-nm window. In most cases, optical return loss measured better than the target 40 dB, but several fiber cross-connect points did not meet this requirement. During early July of 1996, Bell Atlantic technicians replaced an entire fiber patch panel at the Lucent Technologies Holmdel location and cleaned or replaced fiber cross-connects in the Bell Atlantic central offices. There are still some points in the Bell Atlantic MONET New Jersey Fiber Network that do not meet the 40-dB optical reflectance criteria. It has been confirmed, however, that the current readings are acceptable for optical transmission rates of 2.5 Gb/s.
TABLE VII

<table>
<thead>
<tr>
<th>Fiber Span Bellcore to Lucent</th>
<th>Span Loss dB (dB/Km)</th>
<th>Bell Atlantic CO L (dB)</th>
<th>R (dB)</th>
<th>Bell Atlantic CO L (dB)</th>
<th>R (dB)</th>
<th>Lucent Technologies L (dB)</th>
<th>R (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 7</td>
<td>12.11 (0.47)</td>
<td>1.02</td>
<td>34.9</td>
<td>0.78</td>
<td>47.6</td>
<td>1.41</td>
<td>13.8</td>
</tr>
<tr>
<td>2 to 8</td>
<td>13.26 (0.51)</td>
<td>0.80</td>
<td>34.4</td>
<td>0.61</td>
<td>27.8</td>
<td>0.57</td>
<td>46.8</td>
</tr>
<tr>
<td>9 to 9</td>
<td>10.86 (0.42)</td>
<td>0.62</td>
<td>48.1</td>
<td>0.80</td>
<td>30.3</td>
<td>0.26</td>
<td>34.8</td>
</tr>
<tr>
<td>10 to 10</td>
<td>9.61 (0.37)</td>
<td>0.22</td>
<td>41.6</td>
<td>1.12</td>
<td>44.7</td>
<td>0.34</td>
<td>46.8</td>
</tr>
<tr>
<td>11 to 11</td>
<td>13.34 (0.44)</td>
<td>0.80</td>
<td>38.9</td>
<td>1.38</td>
<td>43.4</td>
<td>0.43</td>
<td>49.3</td>
</tr>
<tr>
<td>12 to 12</td>
<td>12.43 (0.48)</td>
<td>0.74</td>
<td>48.9</td>
<td>1.68</td>
<td>33.4</td>
<td>1.18</td>
<td>46.9</td>
</tr>
</tbody>
</table>

L = Loss  R = Reflectance

TABLE VIII

<table>
<thead>
<tr>
<th>Fiber Span Lab to Lab LEC-TB to XC-TB</th>
<th>Lab-to-lab Loss dB</th>
<th>Lab-to-Lab Loss dB @ 1550 nm</th>
<th>Span Loss dB (dB/km) @ 1550 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 7 brown*</td>
<td>18.77</td>
<td>13.61</td>
<td>1x1</td>
</tr>
<tr>
<td>2 to 8 green*</td>
<td>22.07</td>
<td>16.0</td>
<td>2x8</td>
</tr>
<tr>
<td>3 to 9</td>
<td>19.11</td>
<td>12.94</td>
<td>3x9</td>
</tr>
<tr>
<td>4 to 10</td>
<td>17.18</td>
<td>11.80</td>
<td>4x10</td>
</tr>
<tr>
<td>5 to 11</td>
<td>18.67</td>
<td>14.15</td>
<td>5x11</td>
</tr>
<tr>
<td>6 to 12</td>
<td>18.77</td>
<td>13.61</td>
<td>6x12</td>
</tr>
</tbody>
</table>

TABLE IX

<table>
<thead>
<tr>
<th>Characterization of Lucent Holmdel-to-Crawford Hill Fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflectance (dB)</td>
</tr>
<tr>
<td>Location</td>
</tr>
<tr>
<td>Crawford Hill Comp. Rm.</td>
</tr>
<tr>
<td>In Ground</td>
</tr>
<tr>
<td>Holmdel Basement</td>
</tr>
<tr>
<td>Holmdel Computer Room</td>
</tr>
<tr>
<td>Total Reflectance</td>
</tr>
<tr>
<td>End-to-end Loss</td>
</tr>
</tbody>
</table>

The New Jersey fiber transmission loss characteristics for all MONET fibers, when measured on a lab-to-lab basis between Bellcore on Newman Springs Road and Lucent Technologies in Holmdel, are well within specified loss limits of no more than -18 dB for the MONET fibers. With the Bellcore/Lucent Technologies test results of Bell Atlantic fiber end-to-end loss of about -16 dB, fiber no. 2 now meets the overall loss budget of less than -18 dB. Table VIII depicts the lab-to-lab transmission characteristics of these fibers. Lab-to-lab measurements include both Lucent Technologies and Bellcore premises fibers connected to the Bell Atlantic fibers.

C. The Lucent Technologies Holmdel to Crawford Hill Fibers

Fiber cables between the Holmdel and Crawford Hill locations are connected by four existing single-mode fibers placed by AT&T/Lucent Technologies for previous experiments. Optical time-domain reflectometry (OTDR) measurements show that the fibers are approximately 5.1 km long with three underground mechanical splices each. The properties of these fibers are summarized in Table IX. Once again, while the reflectance values are slightly higher than the target specifications, the embedded nature of the fibers make correction difficult.

VII. NETWORK CONTROL AND MANAGEMENT

At the beginning of the MONET program it was recognized that commercial success requires not only optical transport technology, but also the ability to manage it as a network. This is based on the practical observation of current network technologies that, all too frequently, had been introduced with insufficient management support to be useful in the network. MONET intended to avoid this problem with WDM networks by ensuring that both management and technology were considered from the very start. While many network management problems are, by nature, independent of specific technology, it was recognized that optical networks, specifically some of the planned features for the MONET network, were sufficiently interesting to be included. Specifically, the issues involved in managing a transparent network had not been previously well addressed. Likewise, the desire to have customer control of connections in MONET was seen as a new problem. This requirement, in particular, leads to the need for interoperable network management systems in a way that has not been achieved previously. Finally, it was desired to apply the experience derived from MONET to the emerging standards for optical networking and its management, and vice versa.
In keeping with current trends in network management standards and computing practices, the management system is designed around distributed computing concepts and uses the ITU-T Recommendation SG15 specification techniques for interface design. To ensure that interoperability issues were really addressed, it was decided to use two different system infrastructures, as would be expected in a very large network. We did not want to achieve interoperability that depended strongly on the choice of computing platform.

A. NC&M Architecture and Design for the Lucent Domain (XC-TB and LD-TB)

1) System Architecture: The Lucent Technologies NC&M system for the MONET New Jersey Testbed is a scaleable and fully distributed management system implementation which utilizes pertinent existing and evolving standards applicable to WDM optical networking. Fundamental to the architecture is use of a new enabling technology that supports distributed graphs. Underlying distribution support and related distribution transparencies are provided by the CAST+HOTframe platform, where HOTframe is a leading edge CORBA-compliant (common object request broker architecture) distributed infrastructure, and CAST consists of the interface definition language (IDL) and module interconnection language (MIL) for easy specification of distributed object-based systems. HOTframe also provides support for persistence and dynamic reconfigurability of distributed systems necessary for achieving fault tolerance. This distributed NC&M system may be used to support multilayered TMN management architectures, as well as fully distributed management architectures which have not been traditionally used by telecommunications networks, but which are arising in evolving data networking/internet arenas.

The following are its features.

1) It implements NC&M-NE Interface to XC-TB WSXC (including inventory, configuration, connection setup, disconnect).
2) It implements the NC&M-NC&M nterface to the Bellcore domain (for connection setup/tear-down).
3) It implements optical amplifier control and monitoring, using distributed virtual instruments.

The distributed NC&M system is being used within the New Jersey network to support the management needs/capabilities of NE’s and components within the XC-TB and LD-TB (i.e., functionalities as provided by the WSXC in the XC-TB and the optical amplifiers in the LD-TB). In addition to Lucent domain management, it is being used to support interdomain connection setup with the LEC-TB, which is performed via interface to the Bellcore NC&M system. The graphical user interface (GUI) of the system provides dynamic visualization for views of interest to the user and implements the distributed virtual instrument approach to provide for functionality, having a recognizably common look and feel across various GUI platforms (including the WEB based). This is achieved via a location independent (i.e., from any computing platform and hence distributed) and platform independent description of the user interface (virtual instrument), in addition to a dynamic graph manipulation software module developed on the basis of the graph theoretic approach described above.

In addition to supporting interoperable and future-proof network management, we expect the above approaches to enable more efficient and simplified operations and management for evolving commercial optical networks.

2) Capabilities: Some examples of specific features include the following.

1) Performing basic configuration and connection management (see Fig. 18) functionalities as provided by the WSXC in the XC-TB viz. a) initial equipment inventory of available circuit packs, derive connectable endpoints and the network topology by relating them to the transport fibers and b) communicating connection setup/tear down requests/replies for connections across the two domains.
2) Performing configuration and performance management (see Fig. 19) functionalities on the optical amplifiers in the long distance testbed by controlling and monitoring them, using distributed virtual instruments.
3) Handling connection setup/tear down requests within the Lucent domain and between the Lucent and Bellcore domains.

3) System Overview: A further description of the system architecture is provided below. Fig. 20 describes the Lucent NC&M system objects and their interrelations. The anchored objects are residing on the boundary of the distributed system, interacting directly with parties that are outside the
Lucent Technologies management domain viz. the WSXC or the Bellcore NC&M system. Hence, they are located on fixed workstations. The rest of the system objects can be located on any of the workstations that are part of the same distributed environment, as enforced by the distributed infrastructure.

The NE anchored object interacts with the WSXC and the interdomain anchored object interacts with the similar object on Bellcore NC&M domain via the DCN. The optical amplifiers (OA’s) of the LD-TB are controlled by the OA anchored object using a GPIB bus. The subnetwork object is concerned with connections involving CTP’s on the Lucent subnet while the New Jersey network object handles connections across both Lucent and Bellcore subnetworks. The GUI objects provide end-users with the graphical interface to interact with the Lucent subnet and can interact with any object inside (hence the connectivity with rest of the system is not specified explicitly).

B. NC&M Architecture and Design for LEC-TB

1) System Architecture: The Bellcore MONET network management system (NMS) is a next-generation network management system prototype designed to provide network management support for emerging WDM optical networks. It is a fault-tolerant distributed NMS, with its design based on the ITU-T multitier TMN-based network management architecture and CORBA-based distributed object computing platform, as shown in Fig. 21. The WDM NMS supports basic configuration, connection, performance, and fault management capabilities for wavelength add–drop multiplexers and wavelength cross-connects. It also provides a user-friendly graphical user interface for network/site maps, faceplate, alarms, and performance monitoring displays. It optimizes and simplifies the operations of future WDM optical networks and ensures their viability and deployability.

2) Features:

a) Configuration management: The configuration manager provides capabilities to manage the network topology, such as network connectivity, network resources, and the network map. It also provides the capabilities to manage individual NE’s, such as circuit packs inventory, NE wavelength cross-connection, and support for remotely setting the ports and wavelengths to be in service or out of service. A user-friendly graphical user interface is provided to allow the user to access and control the network resources. As shown in Fig. 22, the GUI interface provides pull down menus and easy point-and-click invocation of management functions. Easy to understand icons are used to represent the network objects, such as network map, link, site, faceplate, and port.

b) Connection management: The connection manager provides remote end-to-end connection setup and release for WDM paths and automatic route creation capability. Simply specify the end points of the connection to be created, and the system will compute the shortest feasible path, issue the commands to the NE’s along the path, and automatically create the route. These paths can be created within the LEC-TB or can be constructed from the LEC-TB, to the Lucent domain, and into the LD-TB. In the MONET LEC-TB at
Bellcore, this capability was used to support the experiments described in following sections. Human users, such as network administrators or researchers, can also query the system to find the paths traversing a network element, a link, or a port by clicking on the particular object of interest. Network resource utilization, such as wavelength assignment, is automatically maintained by the system.

c) Performance management: A network administrator can use the capabilities provided by the performance manager to monitor the optical signal power level and SNR of the optical signals. By simply pointing and clicking on an optical path, the system can display the signal performance at the end points of the selected path, as shown in Fig. 23. Should a quality-of-service problem develop, a user can step through the intermediate nodes to display the performance data. These data can provide valuable information for troubleshooting the problem.

d) Fault management: The fault manager receives alarms from NE’s in the network. It collects alarms and correlates them with the network topology and connection information in order to locate the root cause of network failures. Once it detects and identifies the failed resource, it will alert the human network administrators through the alarm notification window. The network administrator can then initiate corrective actions.

e) Summary: The management functions outlined above have all been implemented for the WADM’s. Only the configuration, connection, performance, and fault management capabilities provided by the Bellcore WDM network management system optimize and simplify the operations of WDM optical networks, and ensure their viability and deployability.

C. NC&M Integration for the New Jersey Network Demo

As shown in Figs. 2 and 3, the NC&M system controls NE’s in two domains. It reads in configuration information sent out by the respective NE software systems and sets up/tears down connections by sending appropriate command requests over the ATM DCN according to the NE-to-NC&M interface message set, described in earlier quarterly reports. In the LD-TB, the optical amplifiers are monitored by the NC&M system and are integrated into the network view.

In order to allow interdomain connection, the two management domains have been modeled as two subnetworks with connection termination points (CTP’s) on them, representing the connectable endpoints according to the ITU-T Recommendation SG 15 standards for functional modeling of transport networks. A hierarchical naming scheme has been generated for identifying CTP’s across two subnetworks. A name appears as $A_B.C.D$ with the following connotations.

1) $A$ is member of $\{\text{NVC, CH, HO}\}$ representing the location.
2) $B$ indicates the fiber trunks viz. transport interface (TI) or client interface (CI)—possible values being 1, 2 (for Navesink CI’s), 1, 2, T1, T2, T4 (for Navesink TI’s), $E_1, E_2, W_1, W_2$ (for Holmdel TI’s), $A, B$ (for Crawford Hill TI’s).
3) $C$ gives the wavelength on the trunk—1, 2, 8 for TI’s and $C_1, \ldots, C_2$ for CI’s.
4) $D$ is a member of $\{\text{IN, OUT}\}$ for direction.

This describes the current NJ network topology, while hiding the internal details of each domain. An NC&M-to-NC&M interface has been designed with a message set currently containing four commands.

1) setup_sn_conn_req—request a subnetwork connection to be set up.
2) setup_sn_conn_rsp—respond to such an above request.
3) release_sn_conn_req—request that a subnetwork connection be released.
4) release_sn_conn_rsp—a response to the above request.

VIII. NEW JERSEY NETWORK EXPERIMENTS

A. 8 x 2.5 Gb/s Optical Layer Transmission Experiments

The first task was to test the quality of the signals on all eight wavelengths after transmission over the longest path through the three network sites. Fig. 24 shows the configuration of our first experiments. The eight 2.5-Gb/s nonreturn to zero (NRZ) signals originated in the LD-TB and were connected through the XC-TB to the LEC-TB, and back through the XC-TB to the LD-TB. The signals then traveled through both 1040-km long-distance transmission spans and were terminated. At this stage, the LEC-TB contained eight WADM-NC’s and six 25-km spans of conventional fiber (CF). In total, the signals traveled a distance of 2294 km, with 214 km of CF and 2080 km of NZ-DSF fiber. There were a total of 24 MUX/DMUX filters
in this configuration, demonstrating good filter cascadability. The output SNR’s ranged from 21.8 to 23.7 dB in a 0.1-nm bandwidth, with a spread of 1.9 dB from EDFA gain shaping and wavelength-dependent loss in the NE’s. The resulting BER data for all eight wavelengths is shown in Fig. 25, both (a) measured after the signals return from the WSXC and (b) after the following 2080-km transmission span. The transmission penalties at the network output ranged from 1.3 to 3.1 dB, with a spread of 1.8 dB. The poorest channel sensitivity is approximately −24 dBm. The corresponding optical spectra are in Fig. 26(a) and (b), showing noticeable spectral broadening in the higher wavelength channels at the output.

This experiment was later repeated with the fully equipped LEC-TB. Within the LEC-TB, the signals went through a WADM-NC and crossed the liquid-crystal switch array LCXC1 to the inner loop. After a WADM-NC, two WADM’s, and another WADM-NC, each separated by three 25-km spans of CF, the signals crossed LCXC2 to a WADM-NC and back to the XC-TB to the LD-TB. This experimental setup is shown in Fig. 27. Again, the resulting BER data for all eight wavelengths are shown in Fig. 28(a) after the signals return from the WSXC and (b) after the 2080-km transmission span, with the corresponding optical spectra shown in Fig. 29(a) and (b). The transmission penalties are very similar to those in the above experiment, except for chapter 6, which demonstrated the highest instability and polarization dependence. All channels operate error free for power levels above −22 dBm.

In these experiments, spectral broadening from nonlinear index effects in the low-dispersion LD-TB results in increased pulse distortion penalty from dispersion in the conventional fiber LEC-TB, greatly reducing the effective network dispersion limit. To ameliorate this effect, the EDFA output powers can be reduced in the LD-TB so that the nonlinear broadening is reduced or the accumulated dispersion in the LEC-TB can be reduced. Both of these remedies come at a price: reduced output power from amplifiers necessitates
either more amplifiers with shorter amplifier spacing or shorter transmission distances to maintain SNR. Reduced dispersion in the LEC either decreases transmission distance or increases complexity and cost with dispersion compensation. These results show that transparent optical networks will require careful design to optimize both the loss compensation and dispersion maps, because the two characteristics are not independent. In later work inspired by these results, the network performance was greatly improved by decreasing the EDFA power levels to 3 dBm/ch to reduce self-phase modulation in the NZ-DSF of the LD-TB while maintaining sufficient signal SNR for 2.5-Gb/s transmission. These results point out the complications that can occur when interconnecting existing fiber network segments built from different types of optical fiber.

B. Two-Domain Connection Setup Demonstration

In order to emulate national-scale WDM networking using the MONET New Jersey Network, bidirectional connections were set up, originating in the LEC-TB, traversing the LD-TB with two transits through the XC-TB, and returning to the LEC-TB. Referring to Fig. 2, SONET signals are added and dropped through CCI’s connected to WADM1 west shelf, WADM1 east shelf, and WADM2 west shelf. Note that all eight wavelengths are used to carry modulated signals throughout the MONET New Jersey Network.

The New Jersey testbed is divided into two independent administrative domains (Bellcore for LEC-TB and Lucent for XC-TB and LD-TB). Each domain is managed by its own NC&M system, and the two systems interact via well-defined interface and message conventions over the data communications network that connects the domains. NC&M commands are sent from the two NC&M processor platforms, one for each domain, to the five managed MONET NE’s in the MONET New Jersey Network. These commands and queries fall into five categories: 1) network topology management; 2) network element configuration management; 3) connection management; 4) performance monitoring; and 5) fault management.

The two-domain connection setup experiment consisted of setting up and tearing down two bidirectional connections between two client interfaces at the LEC-TB. Given the restrictions of the physical NE connectivities and the testbed topologies, each bidirectional connection is accomplished by four unidirectional connections. The connection setup and release requests are submitted to the Bellcore NC&M system, which computes the connection routes, configures the LEC-TB NE’s, and forwards the connection requests to the Lucent domain NC&M system for further processing.

As indicated in Fig. 30, bidirectional LEC-XC-LD-XC-LEC connections, initiated by either domain, were demonstrated. The eye patterns are from an OC-48 receiver attached to three drop client interfaces in the LEC-TB. The upper set of eye patterns correspond to bidirectional connections from WADM1 west shelf, through the LD-TB, back to WADM1 east shelf, on λ5. The bottom eye patterns demonstrate a reconfiguration of the NJ network for λ5. The MONET NE’s were reconfigured by the NC&M system to establish a bidirectional connection between WADM1 east shelf and WADM2 west shelf in the LEC-TB, again traversing 1040 km in the LD-TB in each direction. Note that all other wavelengths carried 2.488 Gb/s data, but only the path for λ5 was reconfigured in this demonstration.

C. Optical Transparency Demonstration, Digital Plus Analog Signal Formats

The optical transparency of the New Jersey network was demonstrated with FM analog video signals sent bidirectionally at λ4, simultaneously with 2.488-Gb/s data on the other seven channels. In this demonstration, bidirectional connections were set up by the NC&M system between the WADM1 east shelf and the WADM1 west shelf. Fig. 31 shows the spectrum of the received FM analog signal. After network transmission over 1100 km, the CNR of the FM analog signal exceeded 16-dB optical, or equivalently, 32-dB electrical. The CNR after 1100 km transmission was well above the required CNR of 16-dB electrical and excellent video images were obtained.

The inset eye patterns in Fig. 31 verify bidirectional network transmission of 2.488-Gb/s data carried by λ5 simultaneous with FM analog video transmission on λ4. The BER performance for 2.488-Gb/s signals on λ5 is shown in Fig. 32. Low error rates below 5 × 10⁻¹² were obtained for both connections.

IX. SUMMARY

While the experiments described in this paper have demonstrated successful operation of the MONET New Jersey Network, the performance measured has, in some respects, fallen short of our target specifications. This was not unexpected since these performance goals were meant to challenge the technology and provide targets rather than requirements. Polarization dependence in NE’s in some cases exceeds the 1-dB target and this target may, itself, be too lenient. End-to-end transmission performance penalties are slightly in excess of the 1-dB target. Power levels at the output TT’s are not currently leveled automatically at all NE’s and, hence, are not always within the 1-dB range called for. This variation in power levels
accounts for much of the variation in performance across the channels. All of these issues will be addressed as the NE’s are refined and features are added. Additionally, transmission performance will be improved by careful attention to the choice of fiber type and placement in the network. Section VIII–A showed an example of how network performance critically depends on not only the magnitude of the fiber chromatic dispersion, but also on the particular arrangement of the fibers used. In addition to refining the performance of the network, we anticipate that the target specifications themselves will also be adjusted as our understanding increases with operation of the New Jersey network.

The experiments described above have been performed on a transparent optical network testbed of unprecedented scope and complexity. This testbed spans three locations in New Jersey and contains five NE’s in two network domains managed by two distinct NC&M software systems. Signals traverse paths as long as 2290 km. The experiments described here involve two-way connections being set up across the two domains, transporting both analog (FM SCM video) and digital (2.488 Gb/s) signals. Signal integrity has been verified over the longest paths available in the network.

While the optical layer performance of this testbed is impressive and noteworthy, the complexity of both the physical layer and the software control is at least as significant. Bringing together two network management systems to control a single transparent optical network is extremely challenging, and essential if such networks are to be of national scale.

REFERENCES

A. M. Vengsarkar, (S’88–M’90) photograph and biography not available at the time of publication.

C. Wolf, photograph and biography not available at the time of publication.

J. L. Zyskind, (M’83) photograph and biography not available at the time of publication.

A. Chester, photograph and biography not available at the time of publication.

B. Comissiong, photograph and biography not available at the time of publication.

G. W. Davis, photograph and biography not available at the time of publication.

G. Duverney, photograph and biography not available at the time of publication.

N. A. Jackman, photograph and biography not available at the time of publication.

A. Jozan, photograph and biography not available at the time of publication.

V. Nichols, photograph and biography not available at the time of publication.

B. H. Lee, photograph and biography not available at the time of publication.

R. Vora, photograph and biography not available at the time of publication.

A. F. Yorinks, photograph and biography not available at the time of publication.

G. Newsome, photograph and biography not available at the time of publication.

P. Bhattacharjya, photograph and biography not available at the time of publication.

D. Doherty, photograph and biography not available at the time of publication.

J. Ellson, photograph and biography not available at the time of publication.

C. Hunt, photograph and biography not available at the time of publication.

A. Rodriguez-Moral, photograph and biography not available at the time of publication.

N. V. Srinivasan, photograph and biography not available at the time of publication.

W. Kraeft, photograph and biography not available at the time of publication.

J. Ippolito, photograph and biography not available at the time of publication.