

Results From Proof-Of-Concept Time-Based Communications Testing

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Time-based communications is a concept whereby the synchronous layer of a communications channel is used as a vehicle for two-way time transfer. The technology originated in 1995 (Ref 1) with prototype hardware designs for a self-calibrating optical two-way time transfer system. Point-to-point systems were built in 1996 and demonstrated synchronization error in a laboratory between a master clock and a recovered slave clock at the sub-nanosecond level over 10 km distribution distances using SONET. Since then, the communications payload capability has been added to the optical two-way system providing a true time-based communications channel with two-way time transfer functionality embedded in a OC-3 (155 Mb/s) data channel. In February 1997, two weeks of testing were performed at Lincoln Laboratory (MIT/LL) to collect an extensive data set on the timing and communications performance of the system. The test objectives included:

- A) *Measure system performance with long-range (>10 km) cable runs in a laboratory environment.*
- B) *Establish timing and communications performance in a laboratory environment with typical communications hardware in the fiber link.*
- C) *Characterize system performance using "real-world" (outdoor) links exhibiting temperature dynamics that change the length of the fiber.*
- D) *Determine the suitability for application in future wavelength division multiplexed (WDM) optical communications networks.*

This paper presents the results of the time-based communications testing performed at Lincoln Labs (MIT/LL) using an Optical Two-Way Time Transfer Communications System. A short explanation of system design and two-way time transfer implementation in a communications channel will be followed by a presentation of data sets from the Lincoln Laboratory testing. Time transfer measurement data will be presented from tests conducted from within the laboratory, as well as tests conducted over long-distance, outdoor links. The laboratory measurements to be presented include two-way time transfer results over fiber in a controlled (constant temperature) environment with typical communications hardware inserted in the link between clocks. The hardware used for laboratory measurements includes electro-optic repeaters and erbium-doped fiber-optic amplifiers. The outdoor fiber links (intended to represent real-world links) include a 75-km fiber run with OC-3 repeaters inserted at the midpoint, and 100-km with wave-division multiplexing equipment in the link.

Synchronization error measurement data are presented for each test configuration. Two-way delay data will be presented for the real world links to show the changes in fiber length induced by temperature variations in the outdoor environment.

1.0 BACKGROUND OF TIME-BASED COMMUNICATION

Time-Based Communications is a concept where continuous two-way time transfer information is embedded in an active communications channel (Ref. 1). The synchronous layer of the communications channel is exploited as a two-way vehicle. In the case of SONET (Synchronous Optical Network), the framing structure is used to provide an event to measure, and a byte in the administrative channel is used to provide a data channel between the ends of the link. Point-to-point SONET systems have been built and fielded by Timing Solutions Corporation (TSC) to provide sub-nanosecond time transfer capability in a controlled (indoor) environment for fiber links up to 10 km. Figure 1 shows the time transfer performance of the TSC system for the point-to-point case using the first generation equipment. These first generation systems were not capable of carrying data and only contained fiber between the two nodes (no repeaters or other communications equipment).

With the second generation hardware came the ability to transfer user data between nodes. The user data are not associated with the timing function and can be framed in any fashion that is applicable to the SONET frame. The TSC SONET Time Transfer System described in this paper utilizes a data payload which transfers 155 Mb/s of user data framed in ATM cells. This provides full use of the communications link for data transport with the two-way time transfer computation continuously running in the background.

2.0 OBJECTIVES OF PROTOTYPE TESTING

The primary objective of the testing was to extend the performance verification of the TSC SONET Time Transfer System past the point-to-point case. Since the desire is to field the system over a

typical communications network, the testing was aimed toward determining the feasibility of using the system over commercial links. The following areas were considered in determining the suitability of the TSC SONET Time Transfer System over commercial links:

- A) Long-range links: The first generation systems had a 10-km limit based on the power of the transceiver pair on either end of the fiber. Extending this limit to allow runs that are typical to the commercial communications environment was of interest. This includes the use of higher power transceivers, as well as amplification in the fiber links. Results presented in Sections 4 and 5 include high power transceivers and different methods of signal regeneration.
- B) Laboratory Testing of Communications Components: Fielding systems in a commercial environment requires a departure from the point-to-point case. Real-world links will likely contain regeneration equipment in order to maintain the required SNR over longer distances. Prior to fielding the equipment over real-world links, tests were run to establish timing and communications performance in a laboratory environment. Data were collected in the lab with typical communications hardware in the fiber link. Comparisons of the different data sets are presented in Section 4.0.
- C) Field-Testing of Communications Components: The MIT/LL test-bed includes links, which represent a "real-world" link. Fiber connections between MIT/LL in Lexington MA and the MIT campus in Cambridge were used to determine system performance in a dynamic environment. 12-24 hour tests were run to allow diurnal temperature effects to stress the system. Results from these tests are presented in Section 5.1.
- D) Future Networks: The MIT/LL test-bed also contains next generation communications hardware. This hardware includes All-Optical Network (AON) hardware, which utilizes wave division multiplexing to carry large amounts of data over a single fiber. Tests were run using the AON test-bed to determine the performance of the SONET Time Transfer System and the applicability of the technology to future communications systems. Results of the AON application are discussed in Section 5.2.

3.0 MIT/LL TEST-BED

The MIT/LL test-bed (Figure 2) provided an excellent environment in which to achieve the diverse test goals. The timing equipment was initially set up in a laboratory where links could be constructed to collect data against a specific goal or device. The timing configuration in the lab consisted of a TSC SONET Master and Slave, which were operated using two independent clocks. The SONET Master transferred time to the SONET slave where 5-MHz and 1-PPS signals were regenerated and steered to the clock source via optical two-way time transfer. The synchronization

error between the SONET Master and the SONET Slave was measured using the TSC 55000 Precision Time Measurement System. The TSC 55000 was used to measure the phase of a 5-MHz signal from the clock source and a 5-MHz signal from the slave and compute the time difference between the clock source and the slave signals. Once the system was calibrated, the time difference plot provided a direct measurement of the slave's ability to track the clock source.

The communications portion of the test set-up consisted of the data source and the link. The data source was a CERJACK ATM bit error rate tester, which provided data to the master and collected data from the slave. The unit provided a direct measurement of the number of bit errors over a period of time. The link for each test was constructed using the Lincoln Laboratory equipment either in the lab, in the field, or a combination of the two. The abundance of equipment in the lab allowed links to be constructed in an incremental fashion, beginning with short spans of fiber and culminating with an all-optical configuration with 100-km outdoor fiber spans containing optical routers and erbium amplifiers.

4.0 LABORATORY TESTS

In order to completely characterize the system performance in a commercial environment, it was necessary to get a "best case" baseline in the laboratory. The system was configured as seen in Figure 3 with the SONET master and SONET slave connected via a 90-km link with the component under test in the middle of each span. The following components were tested:

1. Optical Attenuator (baseline)
2. Electro/Optic Regenerator
3. Erbium Amplifier

The Optical Attenuator is of interest since it does not contain any active components and represents a negligible departure from the point-to-point case. It is used as the baseline data set to which to compare the other components. The Electro/Optic Regenerator converts the light signal to an electrical signal, where it is re-shaped and re-clocked before being converted back to the optical frequency. The Electro/Optic regenerator is used in many terrestrial links and is likely to be encountered in a commercial environment. The Erbium amplifier is an all-optical repeater where the signal is passed through a small section of erbium-doped fiber to increase the intensity. The erbium amplifier is used in transoceanic links and is of interest when considering optical time based communications between continents.

Each configuration was run overnight with measurements collected every 20 seconds using the TSC 55000. Comparison of the data sets collected (Figure 4) results in the conclusion that the addition of the components in the fiber path has a measurable but negligible effect on the synchronization error. By comparing the standard deviation of the data sets (72 ps for the Optical Attenuator, 103 ps for the Electro/Optic regenerator, and 152 ps for the Erbium Amplifier), it is noted that the erbium amplifier produced a factor of 2 increase in the noise level. This is still well within the acceptable operating range of the system. The main result gleaned from the laboratory tests is that the departure

from the point-to-point case is not significantly degraded by addition of (one stage of) regeneration equipment. This is a crucial test, as it allows the optical two-way time transfer technique to be considered for long-distance links.

5.0 FIELD TESTS

The field tests involve operating the SONET Time Transfer System in an environment that is typical for the target implementation, i.e. a typical commercial link. Two such links were considered using the MIT/LL test-bed: an implementation using technology encountered in today's commercial links, and an all-optical implementation using next generation technology. The goal of the field tests was to expose the system to a dynamic environment where the link is changing and the steering loops in the SONET slave must compensate appropriately. This differs from the lab case, where the fiber is held within a small temperature range by building climate control. In the field tests, the fiber used is exposed to the outdoor elements and, as a result, will experience temperature changes due to diurnal cycles and changing weather patterns. The tests detailed in the following sections present the SONET time transfer system performance over long links in a dynamic environment.

5.1 PERFORMANCE OVER CURRENT GENERATION LINKS

The test set-up using a link representing currently used commercial hardware is depicted in Figure 5. The optical signal (at 1310 nm) from the TSC SONET master (slave) was routed over a 37-km fiber to a remote facility where the signal was amplified using an Electro/Optic regenerator (regenerator had full clock recovery and data regeneration). The signal was then routed back (over a different fiber in the same fiber bundle) to MIT/LL, where the TSC SONET slave (master) received it. The system was run over a 24-hour period in order to experience one full diurnal temperature cycle.

System performance for the configuration in Figure 5 is plotted in Figure 6. Synchronization error is plotted, as well as the change in the round-trip delay. A round-trip delay measurement is provided by the SONET system as a by-product of the two-way process. The round-trip delay value includes the front-end electronics of the TSC SONET hardware and is of little interest as an absolute measurement. As a relative measurement (by subtracting the first value), the data provides a measurement of the change in the propagation delay of the link. Since propagation changes occur only for the part of the link exposed to temperature variation, this measurement provides an indication of the changes seen by the fiber between the nodes. The two plots contain data from the same measurement interval. Figure 6 shows that the SONET time transfer system demonstrated excellent performance in a dynamic environment over the 24-hour test period (standard deviation of 305 ps). With the exception of a 2-ns perturbation at the end of the data set (MJD 50501.4), the signals from the SONET slave remained within 1 ns of the master while the propagation delay in the fiber changed by over 100 ns (from -40 to +60). Correlation between the synchronization error and

the delay change is seen in Figure 6, but the system is able to remove the effects of the delay change and maintain the slave to within 1 ns of the master. The perturbation at MJD 50501.4 is caused by a change in the delay state in the front-end electronics of the SONET hardware (an effect which is being corrected in the third generation hardware).

5.2 TIME TRANSFER PERFORMANCE OVER NEXT GENERATION LINKS

The development of the time-based communication technology is geared toward application in future communications networks, as well as current generation networks. One example of a future communication network is the MIT/LL All-Optical Network, or AON (Ref 2), which utilizes wave division multiplexing to combine 20 channels of optical data (in the 1550 nm band) over a single fiber. Data sent over the AON are routed and amplified as optical signals, never needing conversion to electrical signals. This all-optical implementation is ideal for SONET time transfer, since the SONET frame, once created, remains intact from end to end (rather than going through electrical switching equipment, like in a typical SONET ADM or an ATM switch, where the SONET framing information is regenerated).

The equipment configuration for the AON test is seen in Figure 7. The optical signal from the SONET master is first routed through an optical terminal, which changes the wavelength from 1310 nm to 1556.6 nm. The link between the SONET master and slave contains three optical routers with erbium amplifiers, which have the ability to change the optical frequency of the signal as well as amplify the intensity. Prior to reception at the SONET slave, the wavelength must be converted back to 1310 nm. The total distance of the link between Lincoln Labs (MIT/LL) and MIT campus is 102 km.

System performance for a 12-hour test on the AON is plotted in Figure 8. With the exception of a small perturbation at the beginning of the data set, due to the same delay change effect discussed in Section 5.1, the system demonstrated sub-nanosecond performance (standard deviation of 657 ps). There was no degradation in system performance due to the wave division multiplexing equipment in the link. As in the current generation case, Section 5.2, the system was able to track a large temperature swing and maintain sub-nanosecond synchronization error

6.0 CONCLUSIONS

The MIT/LL field-test has demonstrated the compatibility of two-way time transfer and commercial SONET equipment. Typical components such as repeaters and erbium amplifiers resulted in small, but acceptable, degradation of signal-to-noise ratio (for the number of repeaters tested). The field test also demonstrated that the two-way technique is able to compensate for delay changes encountered by fiber in typical outdoor installations, including long above-ground runs. Finally, the tests demonstrated that the All-Optical Network is an ideal platform for the integration of timing and communications, since the SONET signals are transmitted unaltered through all AON equipment.

7.0 REFERENCES

- [1] S.R. Stein, G.A. Gifford, T.P. Celano, *The Role of Time and Frequency in Future Systems*, Proceedings of the 27th Annual Precise Time and Time Interval Applications and Planning Meeting, November 29-December 1, 1995, pp. 51-58.
- [2] E.A. Swanson , I. P. Kaminow, C. Doerr, C. Dragone, T. Koch, U. Koren, A. A. M. Saleh, A. Kirby, C. Ozveren, B. Schofield, R. E. Thomas, R. A. Barry, D. M. Castagnozzi, V. W. S. Chan, B. R. Hemenway, D. Marquis, S. A. Parikh, M. L. Stevens, S. G. Finn, and R. G. Gallager, A Wideband All-Optical WDM Network, *Journal of Selected Areas in Communications*, **14**, 780-799, June (1996). Invited Paper

8.0 FIGURES

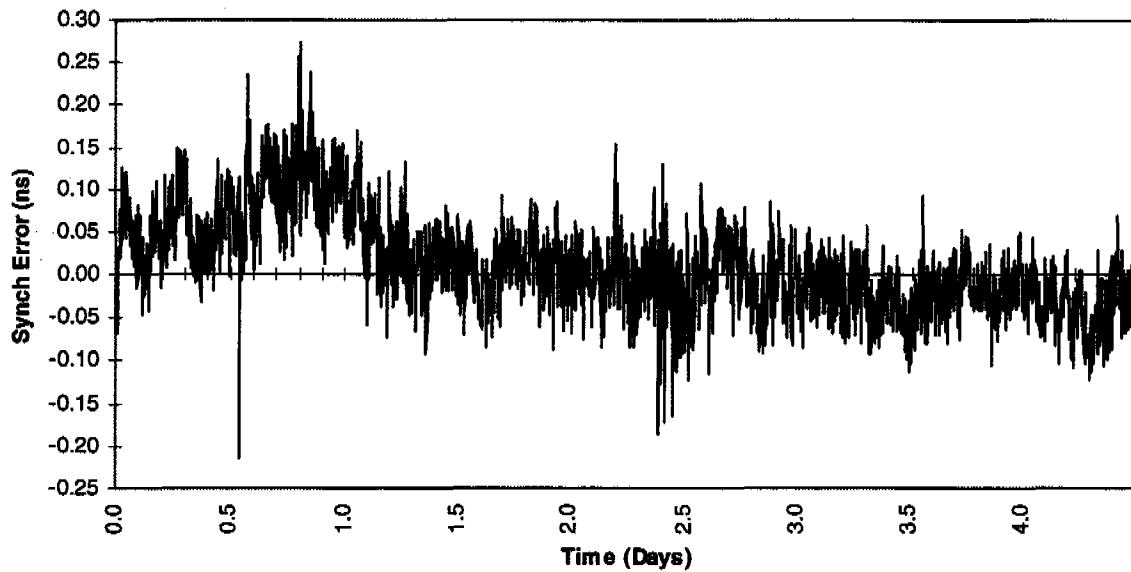


Figure 1: Point-to-Point Optical Time Transfer Performance

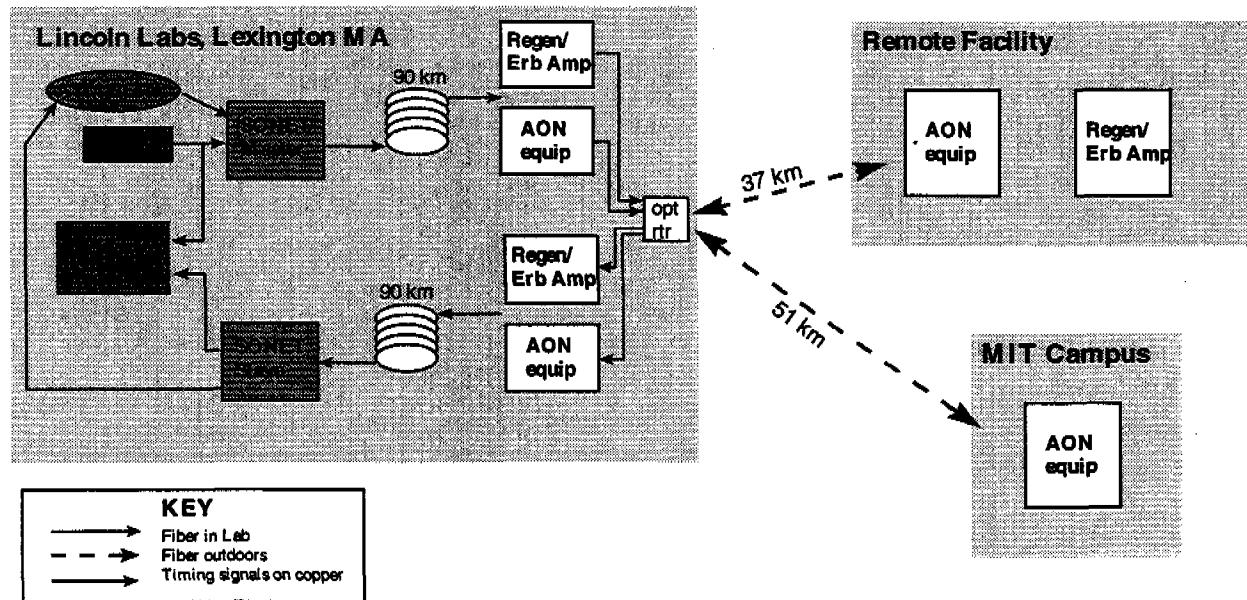


Figure 2: MIT/LL test-bed configuration

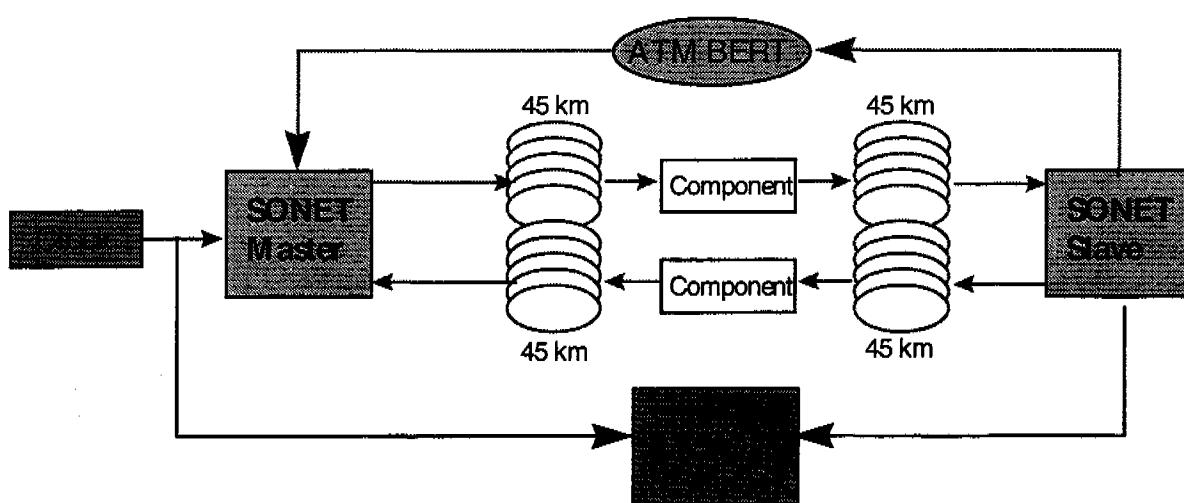


Figure 3: Laboratory configuration

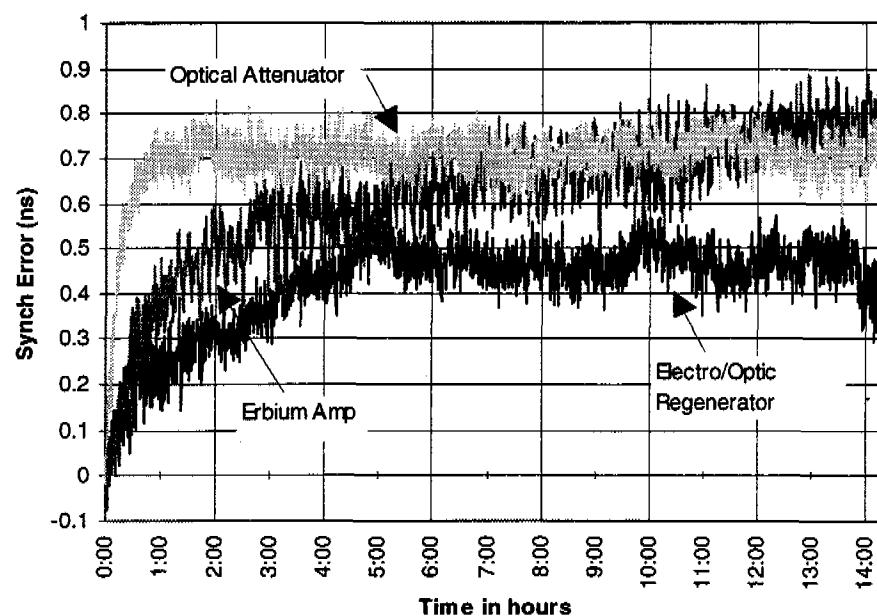


Figure 4: System Performance vs. various communications components in a lab environment

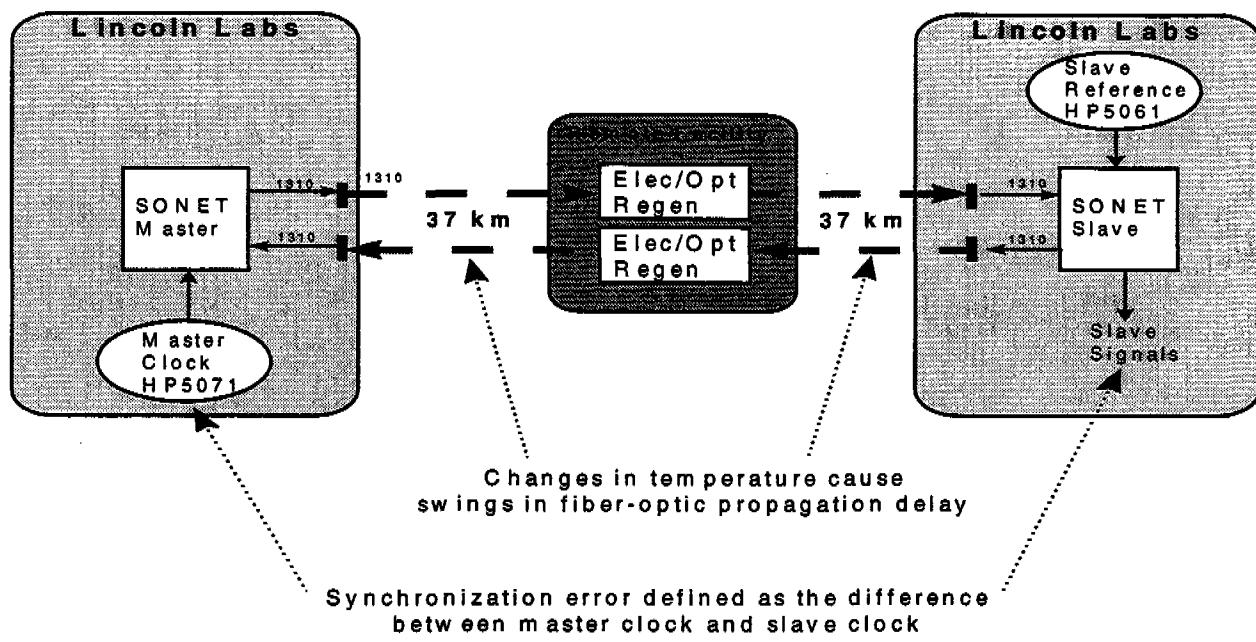


Figure 5: Equipment Configuration for Commercial Link Simulation

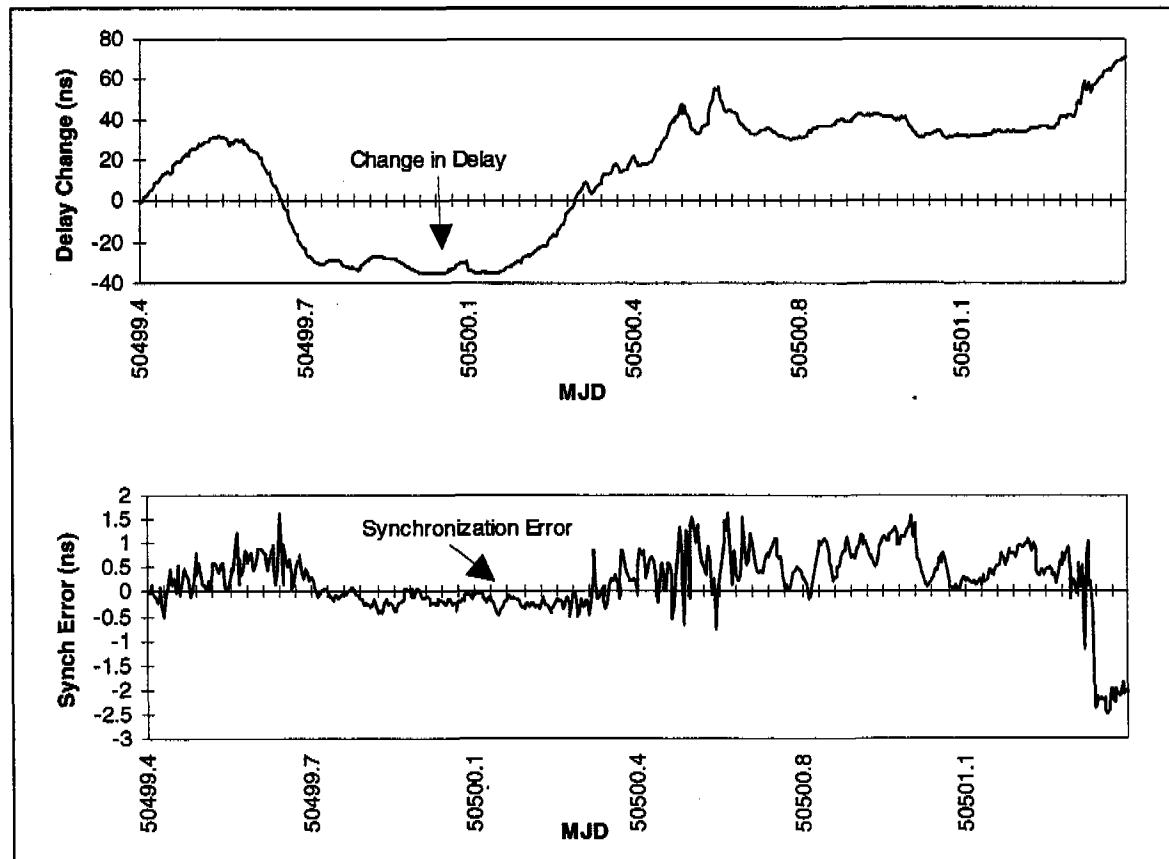


Figure 6: System Performance vs. Delay Change (74-km link)

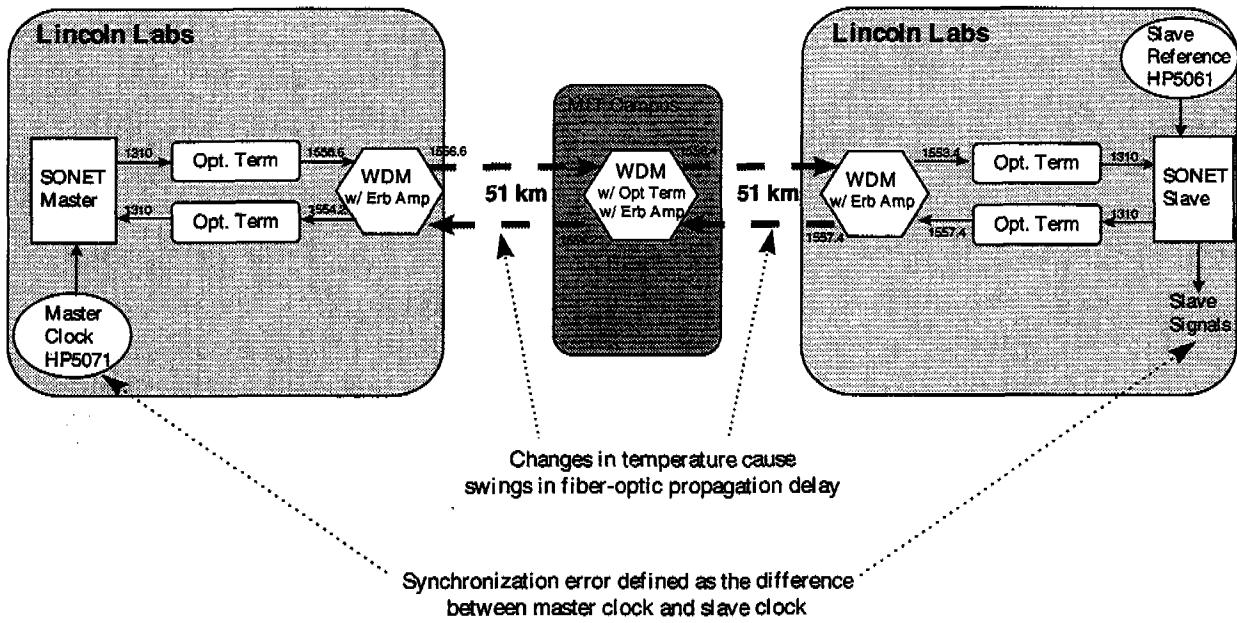


Figure 7: Hardware Configuration for All-Optical Link

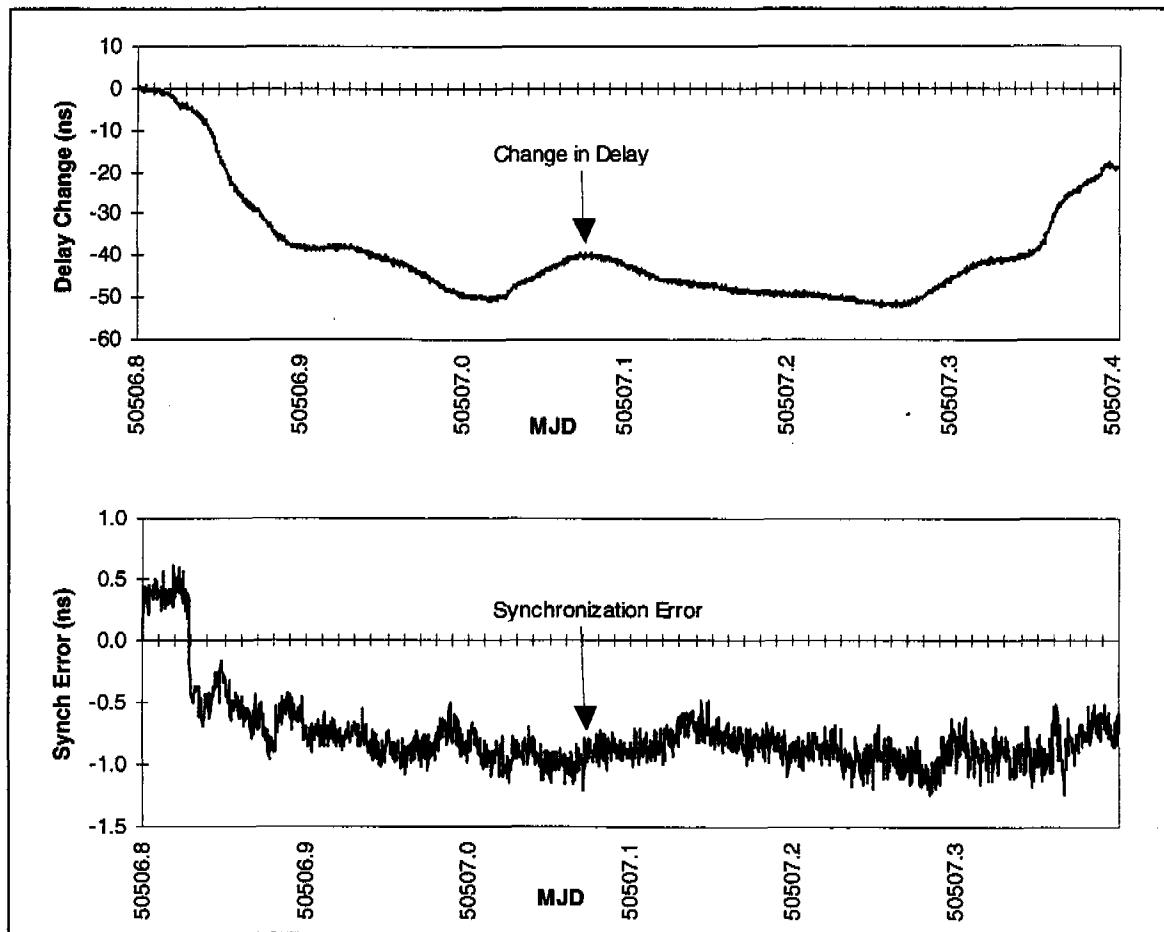


Figure 8: System Performance vs. Delay Change (102 km AON link)

Questions and Answers

MASAMI KIHARA (NTT): I would like to ask about fiber dispersion. You tested a long distance, and you used a very crossed wave length. It is okay. But if you wanted to expand the system to a long way, I think that you have to think about fiber dispersion. What do you think about that?

SAM STEIN (TIMING SOLUTIONS): You are right. For instance, fiber dispersion would probably be the limiting factor for use in an undersea cable. We looked at that a little bit because the optical terminals on the WDM system, the AON, are tunable. So we were able to actually offset the frequencies while the system was running and study the dispersion.

DAVE HOWE (NIST): Sam, it looks like there is a scaling between the round-trip delay and the noise that you encounter with two-way. Can you predict what levels of noise you might see if the round-trip delays are extended beyond 50 nanoseconds in their variations and what situations that might occur?

SAM STEIN: I guess I do not understand why you think there is a scaling.

DAVE HOWE: It just appeared from your plots, but maybe you have not experienced that generally.

SAM STEIN: Normally, for instance, in manufacturing, we evaluate these systems with 20 feet of fiber; we ship them to a customer where they are typically installed with one or two kilometers of fiber; and here we show data with 100 kilometers of fiber. I would say there is not a noticeable difference in performance in the three cases.