Sub-Picosecond Active Timing Control over Fiber Optic Cable

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1.0 Introduction

Two-way time transfer over fiber optic cable [1] has been demonstrated over long baselines [2] and has been used recently to provide coherence to enable L-Band interferometry. In order to support coherent interferometry at higher frequencies and enable other high precision applications over long baselines, an active control concept was developed that enables sub-picosecond control of the propagation delay of an optical fiber. In previous implementations, time synchronization over fiber optic channels was achieved by steering time at a remote node to time at a master node by changing the frequency of a direct digital synthesizer (DDS) based on processed two-way time and two-way phase data [3]. In this paper, we introduce a different approach to active synchronization over fiber optic. This approach eliminates the dominant noise source from previous implementations (the DDS) by using an all-optical scheme to actively control the propagation delay of a long-haul fiber. Two loops using different mechanisms enable the control of the time delay of a fiber to the sub-picosecond level.

This paper provides detailed information on the system design and performance results. Section 2 details the hardware implementation as well as data processing algorithms. Section 3 presents the performance results.

2.0 Hardware Implementation

The hardware design for the sub-picosecond active control system is depicted in a block diagram in Figure 1. The system uses a cesium standard as

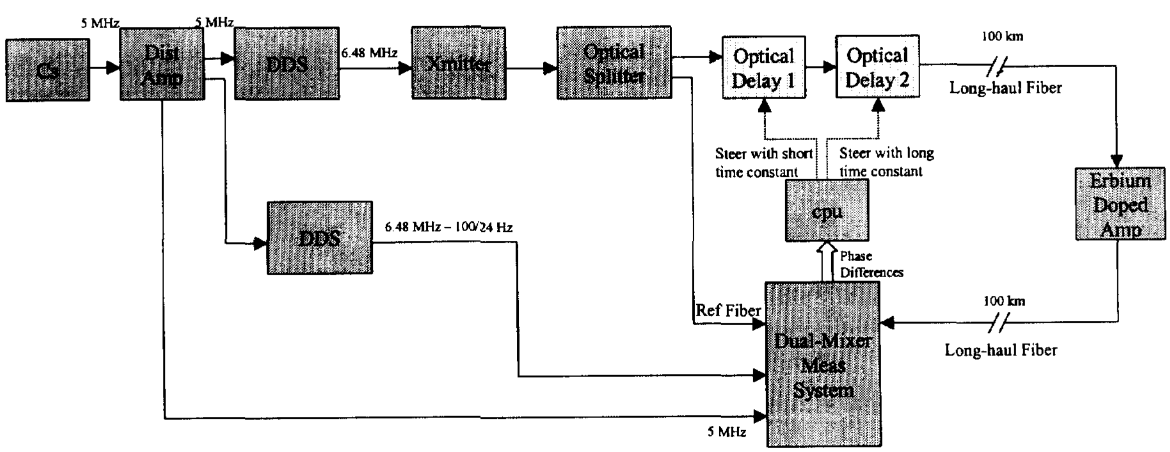

Figure 1: System Block Diagram

the reference for all time and frequency signals. A 5 MHz signal from the cesium provides a reference to a direct digital synthesizer where a 6.48 MHz signal is created. The 6.48 MHz signal provides a frequency reference to an optical transmitter where a carrier frequency is created by multiplying the 6.48 MHz signal by 24. The 155.52 Mbps optical signal is split into two fibers: a long-haul fiber and a reference fiber. The reference fiber is a small (~1 m) piece of cable that provides a copy of the transmitted signal to the measurement system. The long-haul fiber is a 200 km length of fiber that represents a telecom link between two nodes of interest. The long-haul fiber includes erbium doped fiber amplifiers to maintain a signal with sufficient optical power for commercial optical receivers. The signal fed to the long-haul fiber is passed through an active control segment consisting of two control loops (green boxes in Figure 1). Each of the loops contains a device capable of changing the propagation delay of the optical signal. One loop is operated with a short time constant (~10 seconds) and the other loop is operated with a long time constant (~1 hour). Optical signals from the two fibers (reference and long-haul) are inputs to a dual-mixer measurement system (seen in the block diagram in Figure 1 and in detail in Figure 2) where phase differences are measured [4]. The use of identical hardware was used wherever possible in the measurement system to maximize common mode noise rejection. The optical signals are converted to electrical and passed through identical circuitry for clock recovery, frame detection, and mixing. The signals are mixed with an offset sub-multiple of the optical carrier (produced by a second DDS) to produce a 100 Hz signal for measure. The zero crossings of the 100 Hz signal are timed using a zero-crossing detector. Phase ambiguities are resolved using a precision timer that detects the framing pattern. Each second, 100 time tags are collected from the timer by a software process in the controlling cpu. This data represents the difference of the delay between the reference fiber and the delay in the long-haul fiber.

In order to provide sub-picosecond active control of the delay of the fiber, a sub-picosecond measurement of the delay is required. Sub-picosecond measurement performance is enabled by the heterodyne measurement technique seen in Figure 2 [4]. The performance

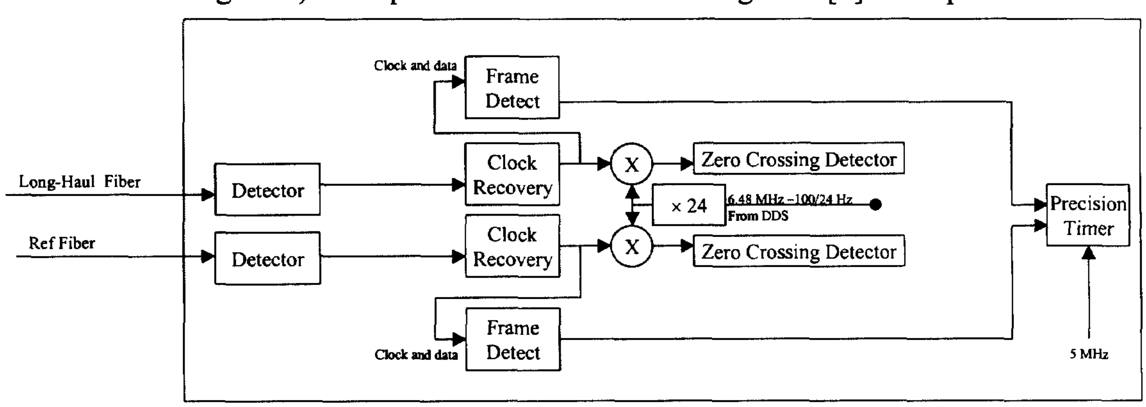

Figure 2: Dual Mixer Measurement System (expanded from Figure 1)

of the measurement system of Figure 2 is plotted in Figure 3. This data was taken in an open loop configuration (the feedback and green blocks seen in Figure 1was not connected) using a short piece of fiber for both the reference fiber and the measurement fiber.

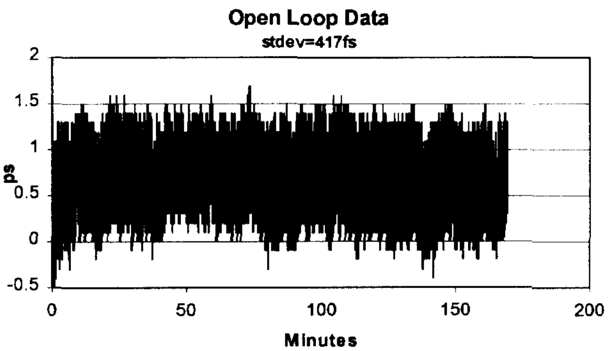

Figure 3: Open Loop Measurement Data

The fibers were held at the same temperature to optimize the stability of the measurement. The standard deviation of this open loop data set is 0.4ps.

2.1 Closed Loop Control

The objective of the system design is to maintain the delay of a long haul fiber system to the sub-picosecond (RMS) level. By maintaining the changes in the delay of the transmission fiber at the sub-picosecond level, transmission of time over the fiber at the sub-picosecond level is enabled. The primary effect that changes the propagation delay of the fiber is a change of temperature. A change of temperature causes two effects: a physical change in length and a change in the index of refraction [5]. These effects combine to cause the delay of the fiber to change. This delay change must be measured and removed in order to maintain a constant delay at the sub-picosecond level. Figure 4 shows the changes in round trip delay (top plot) recorded over fiber deployed over a 200 km link between Phoenix and Tucson, Arizona as well as the change in temperature

(bottom plot) over the same time period. Diurnal delay change is seen to be on the order of a few nanoseconds while seasonal changes can be much bigger. The data in Figure 4 were collected to determine the required range of the control loops.

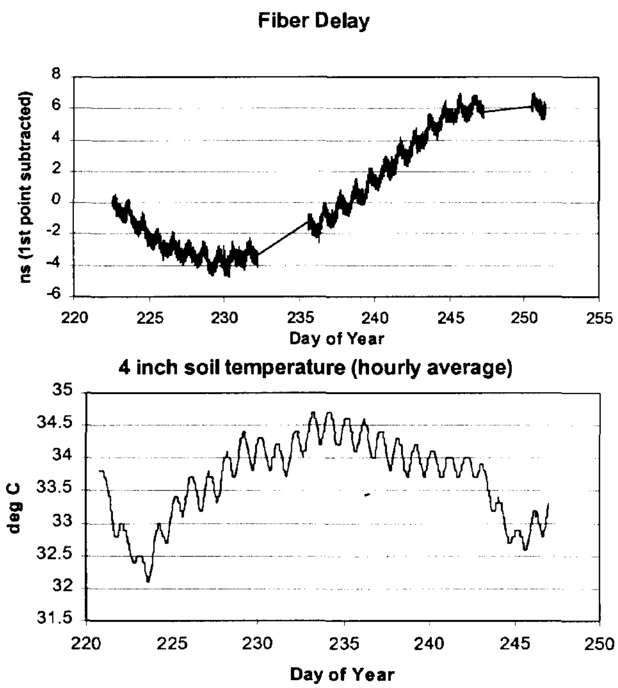

Figure 4: Fiber Delay Changes and Temperature Profiles

Delay compensation is accomplished via two control loops (green blocks in Figure 1) using two different methods with two different time constants. Short time constant control is conducted using optical delay lines (ODLs) to remove the small changes that occur over short time periods. The ODLs, seen in Figure 5, utilize an optical transmitter/receiver pair on a moving baseline to enable fine control of delay changes. Each ODL yields 300ps of delay range with .001 ps resolution. Delay changes are implemented by adjusting the length of the air gap optical channel using a stepping motor. A combination of three ODLs produces a total range of 900 ps for the short time constant loop.

Long time constant control is implemented using a 20 km length of fiber in a temperature controlled environment. For this, a double peltier oven unit was designed that houses a spool of bare fiber. Mechanical drawings of the peltier oven (with the spool shown in the center) are seen in Figure 6. Peltier cells are distributed around the inside of the oven to control the temperature (and thus delay) of the fiber spool. Peltier cells allow for cooling or heating depending on the direction of the current flow. This makes them ideal for controlling temperature (up or down) in the fiber pool. The peltier cells are commanded with a temperature change that will change the delay of the fiber spool in such a way to keep the air gap delay devices in the center of their range.

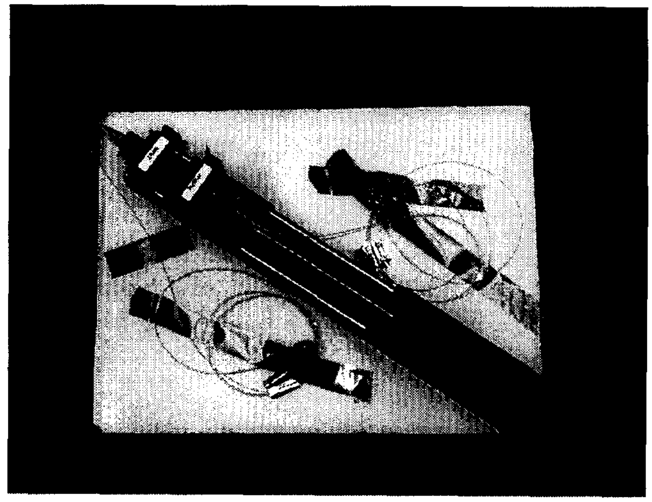

Figure 5: Optical Delay Line (shown at minimum delay)

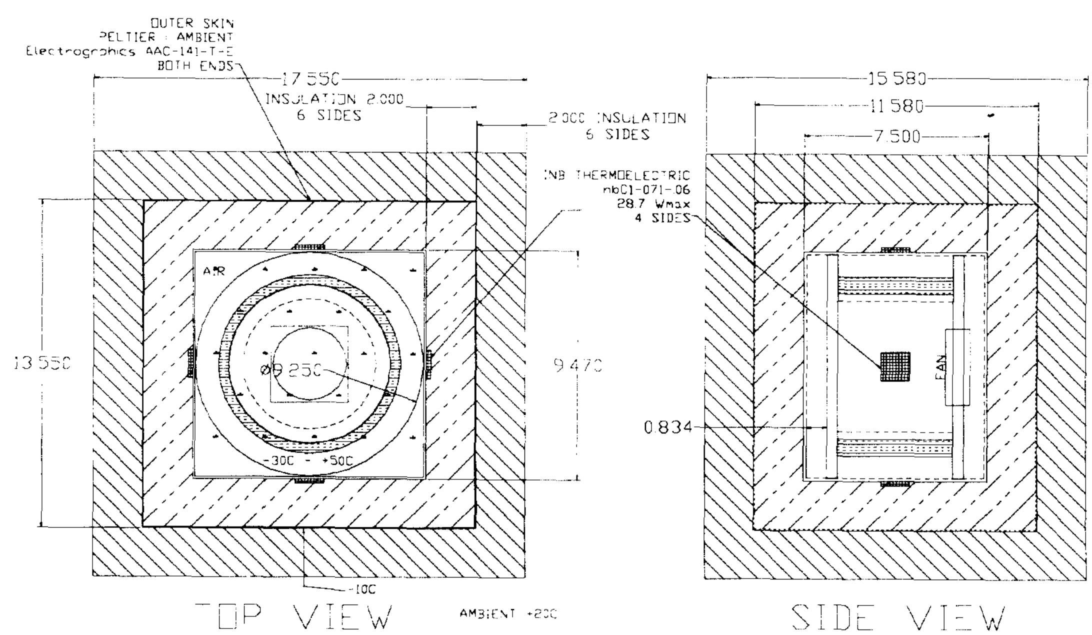

Figure 6: Double Peltier Oven with Fiber Spool

3.0 Results

The system was installed at a telecommunications facility in Phoenix, Arizona in December 2002. The system was connected to a 200 km piece of fiber that travels from Phoenix to Randolph, AZ and back. Erbium doped fiber amplifiers were installed both at Phoenix and Randolph to provide sufficient signal power to allow detection at each node.

The open loop performance of the system is seen in Figure 7. This plot of fiber delay shows that in the absence of active control, the delay of the fiber changes considerably. During the period of the day when the temperature is changing rapidly, the delay changes by as much as 5-10 ps/min.

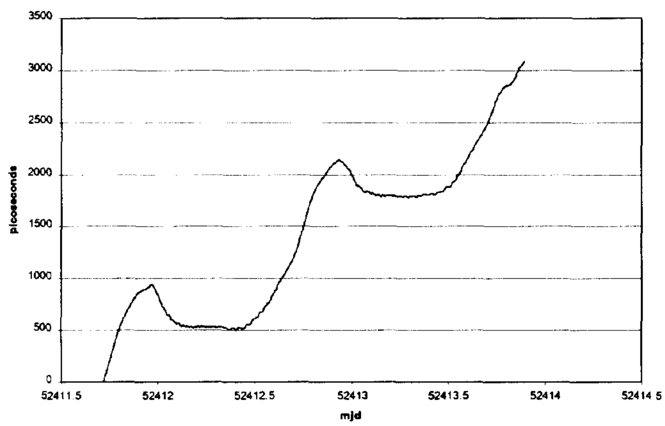

Figure 7: Open Loop System Performance

The measurement of closed loop system performance over a four-day period is seen in Figure 8. The top plot in Figure 8 is a record of the measured fiber delay over the test interval. Fiber delay of the 200 km fiber was maintained to < .65 ps RMS over the full collection period. The control required to maintain this performance is seen in the bottom plot of Figure 8.

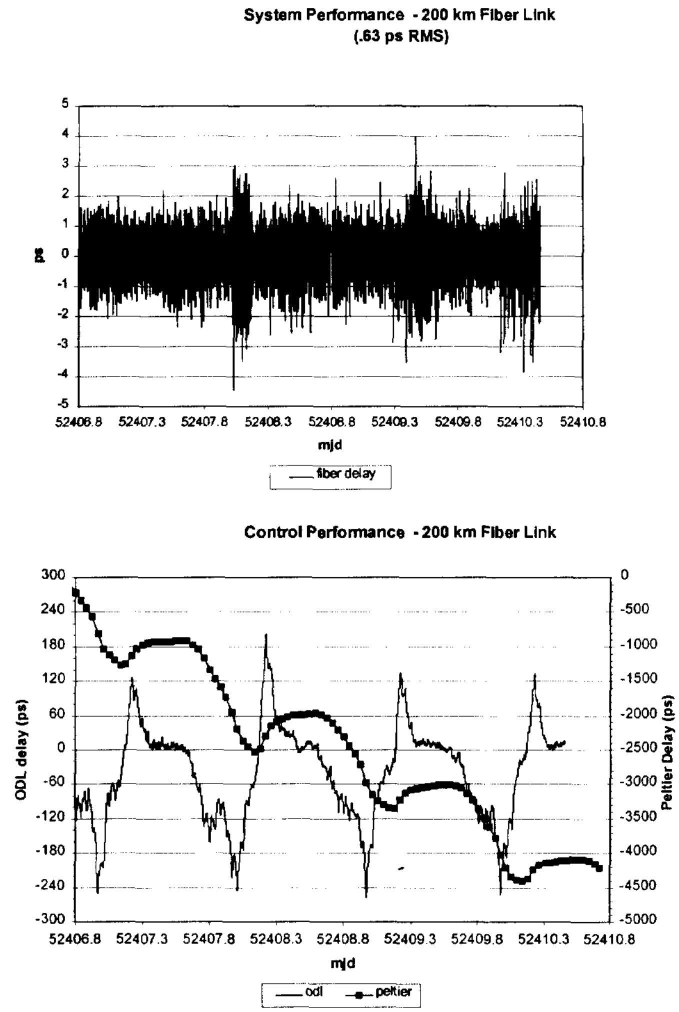

Figure 8: Closed Loop Performance

The bottom plot shows the response of the three ODLs and peltier oven required to maintain the delay of the fiber at the sub-picosecond level. The response of the ODLs is seen in the thin line curve with the left y-axis showing the level of commanded control. The response of the peltier oven is seen in the block line curve using with the right y-axis showing the magnitude of the commanded control. The ODL control swings approximately ±200 ps in a diurnal cycle. The peltier oven also exhibits a diurnal cycle with an increasing negative trend. This negative trend matches the positive trend of temperature for the Phoenix area (seen in Figure 9). Over the 4 days of this test, 4 nanoseconds of oven delay was required to maintain sub picosecond fiber delay control.

Figure 8 shows that the system works as designed and that sub-picosecond delay control is enabled with this all-optical approach. The ODLs were kept in their operating range even during the periods of the day when rapid temperature changes caused the fiber delay to change by more than 5 ps/min.

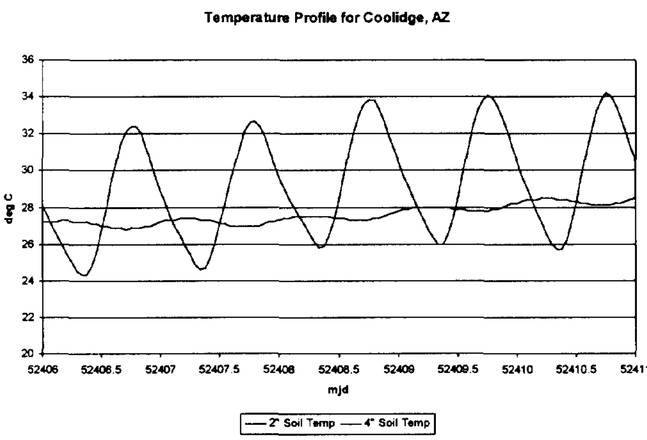

Figure 9: Temperature in Phoenix over measurement period

4.0 Conclusions

We have presented an all-optical active delay control system that was used to demonstrate sub-picosecond control of fiber delay over a 200 km link. Control hardware and algorithms were developed to demonstrate the ability to maintain the propagation delay of a fiber optic channel to less than 1 picosecond. The system was demonstrated using real-world fiber in Arizona. The results show that the performance limits encountered by the existing electrical control systems can be broken by implementing an all-optical approach. By pushing the performance envelope of time synchronization by more than an order of magnitude, this system enables coherent interferometer processing at RF frequencies up to 10 GHz.

While this design enables control of fiber optic delay at the sub-picosecond level, it does not fully address the delivery of timing signals to the user at the sub-picosecond level. Further development work is required in the areas of absolute calibration of path symmetry, characterization of path delay changes in fiber optic equipment, and creation of sub-picosecond level signals or time tags for user equipment.

5.0 References

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