Practical Evaluation of a 50 km Fiber Link Utilizing a Commercial Modem

Corey Barnes, Archita Hati, Craig Nelson, David Howe

Time and Frequency Metrology Group
National Institute of Standards and Technology, Boulder, CO USA

***Abstract*— We evaluate the stability of two-way time and frequency transfer over a 50 km fiber optic link established using a commercially available fiber optic modem. For this evaluation we report the residual phase noise, total Allan deviation, total time deviation, and temperature fluctuations of the optical time and frequency transfer network. This two-way transfer is transmitted over an underground, dark fiber optic path in an urban environment. The measurement serves as a practical evaluation for establishing a long term fiber optic link between clocks or timescales intended for synchronization over short baselines where dark fiber may be available. In addition to measuring the time and frequency transfer stability we discuss other obstacles in fiber optic communication such as patch insertion loss and fiber availability.**

Keywords—optical communications; optical fibers; dark fiber; phase noise; two-way-time-transfer; frequency stability

I. Introduction

Two-way time transfer (TWTT) is used to synchronize stable timing networks in separate locations. This process is essential for ensuring accuracy in many technological infrastructures by allowing users to compare atomic clock stability at remote locations. Fundamental applications relying on TWTT include precise navigation, network synchronization, power grid management, gravitational potential studies, and comparison of national time scales. Keeping these infrastructures in synch plays a crucial role in research, national security, public safety, stock market regulation, communication bandwidth usage, time standardization, and SI (International System of Units) traceability (among many practices).

Over the last few decades optical frequency dissemination has been shown to be sufficient for transferring stable signals from frequency references such as H-masers (hydrogen maser), cesium standards, and other atomic clocks [1][2][3]. We discuss the stability of time and frequency transfer over a 50 km dark urban fiber optic link using a commercial optical time transfer modem transmitting through existing underground fiber. This fiber loop-back measurement utilizes the BVSD (Boulder Valley School District) fiber optic network in Colorado (See Figure 1). We evaluate the correction capabilities and environmental sensitivity of the OSTT-2 fiber optic modem manufactured by PikTime*. This modem was chosen because of its attractive cost to performance ratio and its commercial availability. The location of NIST (National Institute of Standards and Technology) Boulder laboratories is ideal for testing the limits of these phase correction capabilities due to the extreme temperature changes presented by the both mountainous and desert-like environment of Colorado.

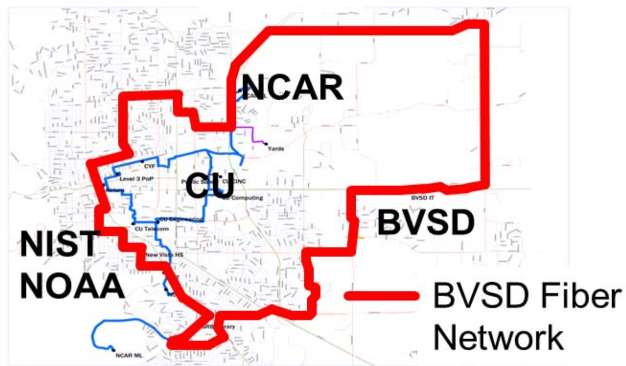

Figure 1: Map of BVSD (Boulder Valley School District) optical fiber network in Boulder, CO.

II. Background

There are several emerging design schemes for optical frequency distribution modems with delay correction capabilities [4]. Timing of signals through optical fibers are subject to error due to fluctuations in path length, chromatic dispersion (CD), and polarization mode dispersion (PMD). These instabilities are introduced by changes in environmental conditions such as temperature, humidity, and vibration of the fiber link. Many modems can correct delay fluctuations in the fiber path length and reduce the effects of CD and PMD with low optical modulation frequencies. However, we have found that patch connection loss and local temperature instabilities in the modem's environment can deteriorate link performance. Patch connection loss can be reduced by use of bi-directional erbium-doped fiber amplifiers [5].

The TDEV (time deviation) stability of a satellite TWTT achieves in the range of 100 ps over a day of averaging [6]. This 50 km bi-directional optical fiber network has a TDEV lower than 1 ps over a 1000 s average (see Measurements section). While satellite time-transfer is sensible to use for long baseline applications, optical frequency time-transfer is more cost effective for short baselines. Current fiber optic time and frequency dissemination schemes can have comparatively low noise, however, the availability of dark fiber infrastructure is extremely limited. Until dark fiber is readily available GPS time comparisons and satellite two-way time transfer will be the most practical solutions for time transfer synchronization.

III. Apparatus

A 10 MHz signal (generated by a H-maser) is disseminated via a 1550 nm optical carrier to transfer time and frequency over an optical link. The optical modem allows for correction of CD and PMD distortion to minimize instability in the 10 MHz transfer. To analyze the performance of the OSTT-2 modem and the 50 km fiber link we evaluated a loop-back fiber network by measuring the residual phase difference of the 10 MHz and PPS (pulse per second) input signals against the returned signals at the remote module. The 10 MHz signal generated by a H-maser was split 4 ways for use as a measurement system reference signal, a TIC (time interval counter) reference clock, a PPS generator reference, and a test signal for the optical modem. Phase fluctuation data of the transmitted 10 MHz signal was collected by a DPMS (digital phase-noise measurement system) to determine the residual phase noise, total ADEV (Allan deviation), and total TDEV of the 10 MHz loop-back at the remote module. A TIC was used for measurement of the returned PPS signal (Figure 2).

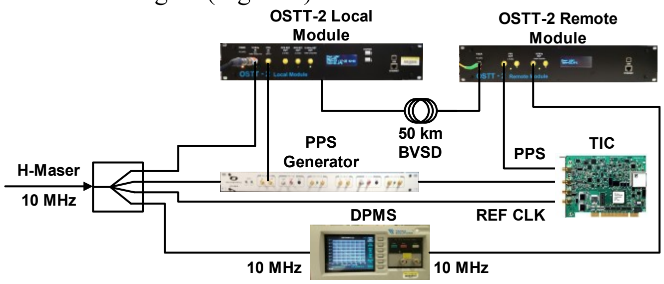

Figure 2: Block diagram of measurement configuration. TIC (time interval counter), DPMS (digital phase measurement system), REF (reference), CLK (clock), PPS (pulse per second).

The 10 MHz signal from a H-maser was carried over the 50 km loop by the optical modem and compared to the returned signal to measure the residual total ADEV and phase noise of the link by use of a low noise DPMS. Using the same 10 MHz we also generated a PPS (25 µs pulse width) signal and compared this signal to a returned PPS (20 µs pulse width) at the output of the remote modem using a high resolution TIC. The temperature was measured simultaneously with phase difference to isolate the effect of the laboratory temperature on the modem's performance.

There are fourteen patched fiber connections over the 50 km fiber loop used in this experiment. Eight of the patches in this fiber network are used to connect the fiber between the NIST and NOAA (National Oceanic and Atmospheric Administration) buildings. The approximate loss for the first 47 km of fiber is 10 dB (optical power) at NOAA. The total loss of the fiber loop-back at the NIST building is approximately 20 dB. This indicates that approximately 10 dB of loss can be attributed to the patch connections between the two buildings. The modem is designed for losses less than 25 dB. As a result, the transmission path length of these experiments is limited to 50 km.

IV. MEASUREMENTS

Initial measurements were implemented with the optical modem exposed to temperature fluctuations in a typical laboratory environment. The temperature stability of the laboratory was ± 1.5 ºC. Figure 3 shows the measured phase difference of the returned 10 MHz signal plotted with the temperature in the laboratory against time. Through observation of Figure 3 and Figure 4 we noticed a linear correlation between temperature fluctuations in the modem's operating environment and the fiber link's residual phase difference.

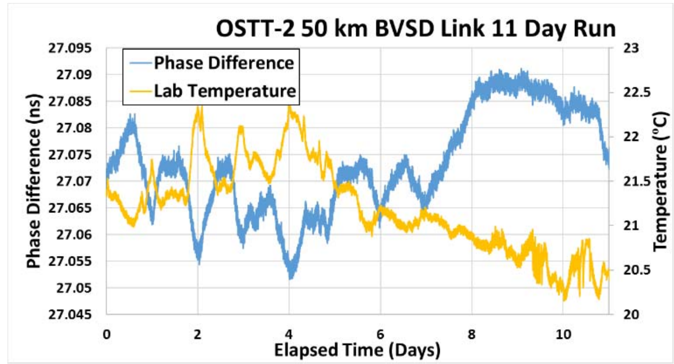

Figure 2: Residual phase difference of the 50 km loopback (blue), lab temperature (yellow).

The laboratory temperature and the fiber phase fluctuations are both directly correlated to the outside temperature. We used the temperature data to separate the effects of temperature fluctuations in the modem's operating environment from the fiber length fluctuation correction errors in the modem delay lock loop. By plotting the phase difference against temperature we were able to determine an approximate temperature coefficient of ~ 16 ps/ºC for the optical modem (Figure 4). This coefficient was then used to post-process the raw phase difference by subtracting the temperature induced phase fluctuations. We then compared the total ADEV for the modem operating in this environment to the total ADEV of the post-processed data.

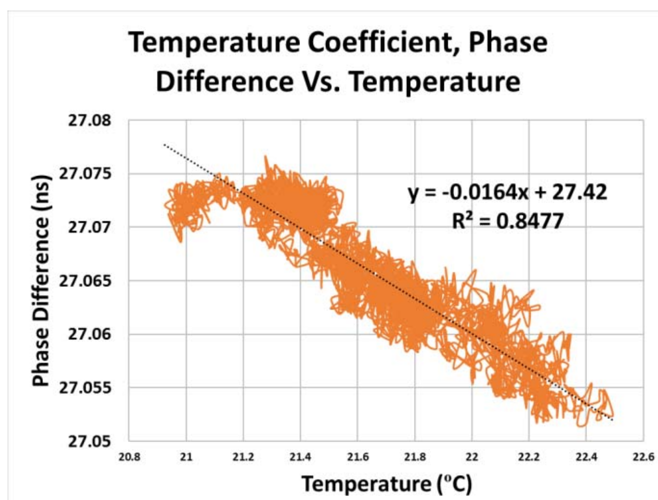

Figure 3: Residual phase difference of 50 km fiber link plotted against lab temperature.

Figure 5 shows the frequency stability for the optical modem operating in the normal laboratory environment compared against the post-processed data for the same measurement (green and yellow curves, respectively). Post-processing phase difference data reduced the diurnal fractional frequency

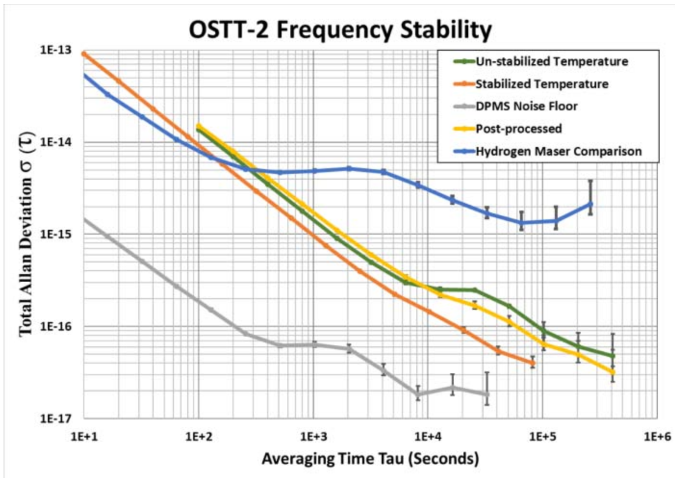

Figure 5: Total Allan deviation of: fiber link with optical modem in a lab environment under normal temperature fluctuations (green), fiber link with optical modem in a temperature stable environment (orange), DPMS measurement system noise floor (gray), fiber link after post-processing data with temperature coefficient (yellow), comparison of 2 hydrogen masers (blue).

fluctuations indicated by the total ADEV bump at a half day demonstrating that the variability may have been related to laboratory temperature instability and not errors in the fiber delay correction.

To verify that the phase fluctuations of the frequency transfer were caused by the operating environment we placed the local and the remote modems inside of a Peltier incubator that held temperature to within ±200 mºC. As seen in Figure 5 (orange curve "stabilized temperature") holding the temperature to a more stable value reduced the short term total ADEV in addition to reducing the diurnal effect.

We measured the residual phase noise of the returned signal using a DPMS to measure the short term noise of the link. Figure 6 shows the residual phase noise of the OSTT-2 remote module. The white PM noise does not bias the total TDEV results [7] [8], since the phase data used for the total TDEV are averaged over tau = ntau0 to remove noise below tau0.

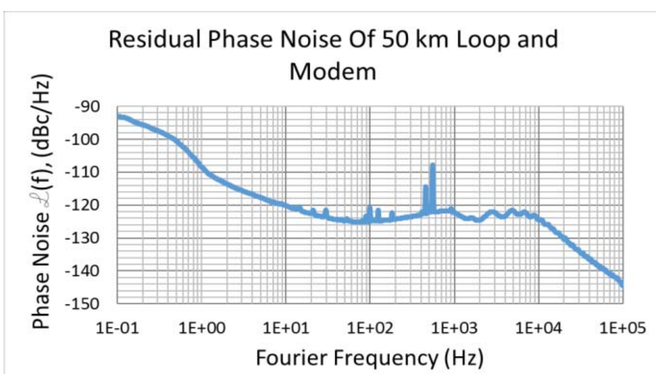

Figure 6: Residual phase noise of the OSTT-2 50 km fiber loop-back measurement.

We produced total TDEV plots from the phase data for the PPS and the 10 MHz time and frequency transfers (Figure 7). The returned PPS signal from the remote modem was at or very close to the noise floor of the TIC until an averaging period of around 1000 s. Temperature stabilization showed no improvement for the total TDEV of the 10 MHz signal at low averaging periods. However, similar to the total ADEV keeping the temperature of the modem's operating environment constant did reduce the diurnal.

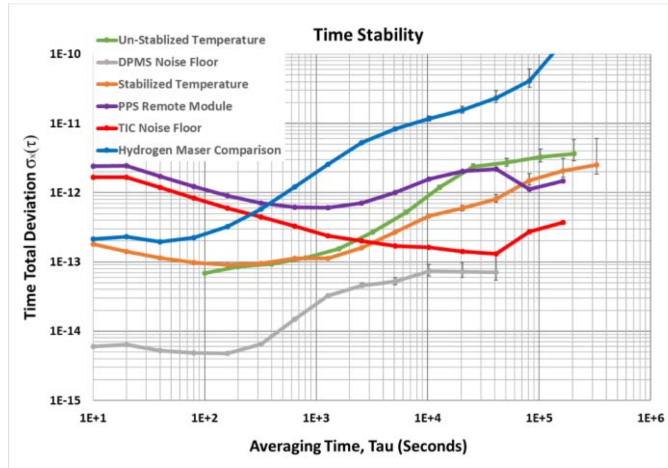

Figure 4: Total time deviation of: fiber link with optical modem in a lab environment under normal temperature fluctuations (green), fiber link with optical modem in a temperature stable environment (orange), DPMS measurement system noise floor (gray), comparison of two hydrogen masers (blue), PPS (pulse per second) signal from remote modem (purple), TIC noise floor (red).

The total ADEV and total TDEV plots both included a comparison of two H-masers measured against each other to determine if the optical modem was capable of transferring the stability of a H-maser without degrading the signal. Where time transfer is the main concern a minimum 10 s averaging period would be required to see the H-maser's signal. Furthermore, the total TDEV shows that 1000 s averaging period would be required for a PPS synchronization of timing signals to achieve stable timing below 1 ps. Similarly, 1000 s averaging period would be required to transfer a H-maser's frequency without introducing link noise above the H-maser noise.

V. CONCLUSIONS

We analyzed the performance of a commercially available OSTT-2 fiber optic frequency transfer modem manufactured by PikTime. The measurements performed for our analysis included the residual phase noise, total ADEV, and total TDEV of the transmitted 10 MHz and PPS signals. We have determined that the performance of the transfer is highly dependent on the temperature stability of the operating environment for the optical modems. The results of our measurements indicate that the frequency transfer of the optical modem studied has a fractional frequency stability of 1 x 10^{-13} and a time transfer stability of better than 2 x 10^{-13} s for a 10 s averaging period (when temperature fluctuations were minimized). This optical modem also enables a PPS time synchronization stability of less than 3 ps after a 10 s averaging period.

ACKNOWLEDGEMENT

The authors thank Josh Savory of the Time Scale Group at NIST in Boulder, CO for providing H-maser stability data, the reference signal used in these experiments, and for useful discussion regarding theory. We thank Alex Hsia from NOAA for acquiring access to the BVSD fiber loop.

*This report names several commercial products for completeness. No endorsements are implied.

REFERENCES

[1] G. F. Lutes, “Optical Fibers for the Distribution of Frequency and Timing References,” *12th Ann. PTTI Meet.*, vol. 12, pp. 663–680, 1980.

[2] F. R. Giorgetta, W. C. Swann, L. C. Sinclair, E. Baumann, I. Coddington, and N. R. Newbury, “Optical two-way time and frequency transfer over free space,” *Nat. phtotonics*, vol. 7, no. 6, pp. 434–438, Jun. 2013.

[3] A. Bauch, J. Achkar, S. Bize, D. Calonico, R. Dach, R. Hlavac, L. Lorini, T. Parker, G. Petit, D. Piester, K. Szymaniec, and P. Uhrich, “Comparison between frequency standards in Europe and the USA at the 10^{-15} uncertainty level,” *Metrologia*, vol. 43, no. 1, pp. 109 – 20, 2006.

[4] J. MacDonald and G. Conway, “COMPENSATED FIBER-OPTIC FREQUENCY DISTRIBUTION EQUIPMENT,” *42nd Annu. Precise Time Time Interval Meet.*, pp. 437–450, 2010.

[5] Ł. Śliwczynski, P. Krehlik, Ł. Buczek, and M. Lipinski, “Frequency transfer in electronically stabilized fiber optic link exploiting bidirectional optical amplifiers,” *IEEE Trans. Instrum. Meas.*, vol. 61, no. 9, pp. 2573–2580, 2012.

[6] T. E. Parker and V. Zhang, “Sources of instabilities in two-way satellite time transfer,” *Proc. IEEE Int. Freq. Control Symp. Expo.*, vol. 2005, pp. 745–751, 2005.

[7] W. J. Riley, *Handbook of Frequency Stability Analysis*. 2008.

[8] S. Stein, “The allan variance - Challenges and opportunities,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 57, no. 3, pp. 540–547, 2010.