ONE WAY TIME TRANSFER UTILIZING ACTIVE DETECTION OF PROPAGATION DELAY VARIATIONS OF DUAL WAVELENGHTS IN AN OPTICAL FIBER NETWORK

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Abstract

For time transfer on baselines exceeding 100km, GPS is the most common technical solution. The main benefit is that it is easy to install, but it is a single point of failure and it is sensitive to interruption by radio noise. For time transfer requiring high reliability a complementary backup method is therefore desirable, and time and frequency transfer utilizing optical fiber is a favorable alternative technique. The connectivity is simplified by the deployment of dense fiber optic communication networks in most countries and since it does not rely on transmission using radio waves in open air, it is robust against perturbations. The simplest and most straightforward method for high performance time transfer is the two-way technique, which is an excellent choice when the user has access to the whole system, and when both transmission paths are equal or with a known and predictable asymmetry. Furthermore it is most practical when the numbers of users are limited and when no security issues limit the bidirectional connectivity.

A proof-of-concept for an alternative technique for fiber based time and frequency transfer, utilizing a one-way co-propagation of two light waves, has been presented previously. The technique utilizes dual wavelengths and measures the difference in group velocity to estimate the delay variation of the timing signal in one of the wavelength channels. This paper presents the recent improvements on this method, including new equipment, new algorithm and a demonstration of real-time compensation of delay time variations.

INTRODUCTION

The need for high performance time and frequency transfer is ever increasing, and the interest of utilizing the existing fiber network for a robust and reliable channel is well spread. The techniques enable robust solutions with resistance towards perturbations both natural and man-made. Nevertheless, the delay time through the fiber experiences daily and yearly variations, which requires a constant monitoring of transfer time to enable an active continuous compensation. Several transfer methods using optical fibers have been developed or are under development **[1-5],** using dedicated fibers or already existing fiber networks. A common denominator for all these actively compensating techniques, is the need for two way transfer with the presumption that both directions are symmetrical, which in most of the cases of using two different transmission paths is not true. Solutions using bidirectional signals in a single fiber results in a close to perfect match, but other limitations do occur. The solution with single direction time and frequency transfer is therefore beneficial if the delay variations can be sufficiently compensated.

BACKGROUND

The technique relies on a measurable correlation between the group velocity and the dispersion in optical fiber. This has been investigated previously **[6-10]** resulting in a scale factor of approximately 300 when the wavelengths are 23 nm apart **[10]**. The wavelengths are preferably chosen in the standardized channel of wavelength division multiplexed (WDM) systems. The challenge is to measure a small difference in arrival time between the two wavelengths, whether the aim is to use in a feedback pre-compensation **[10]** or a post-compensation, as shown below.

EXPERIMENTAL SETUP

The experimental setup is presented by the schematics in Figure 1. Two tunable lasers emitting light at different wavelengths 8 nm apart (1550nm and 1558nm) are individually modulated by a 10MHz sinusoidal signal. The modulated light is combined in a WDM multiplexer and launched into two sequential sections of 80km fiber each, both with an optical pre-amplification ensuring that the input to each section is +12 dBm. At the receiving end the light is split in a WDM demultiplexer and connected to APDs (avalanche photodiodes) for conversion to an electrical signal. To enhance the signal to noise ratio, the electrical signals are amplified before being combined in the phase comparison sub-system. The output voltage of this will be determined by the input phase difference of the two signals, and the slave oscillator is used to further enhance the signal. Finally, the splitters in the signal paths enable reference measurements at different positions. During the evaluations, the two oscillators in Figure 1 are synchronized.

Even though the theory predicts that the output voltage depends on the cosine of the phase difference, the experiment uses a linear approximation, which is presumed acceptable while the output is much smaller than the amplitude. A separate analysis when changing the phase a full circle verifies that the amplitude of the output is 175 mV, and thereby a voltage variation below 10% will be considered tolerable.

In addition to the analysis of the variation of arrival time for the two wavelengths, the experimental setup includes a digital delay unit, as shown in Figure 1. The voltage measured by the voltmeter is sampled once every 15 s, in conjunction with the detector currents of the two APDs. The voltmeter reading is entered into a 240 value running average process, multiplied by the two currents and a constant scale factor to create a desired delay addition. The delay is entered into the digital delay unit, and both TICs are monitored to create a log for stability evaluation.

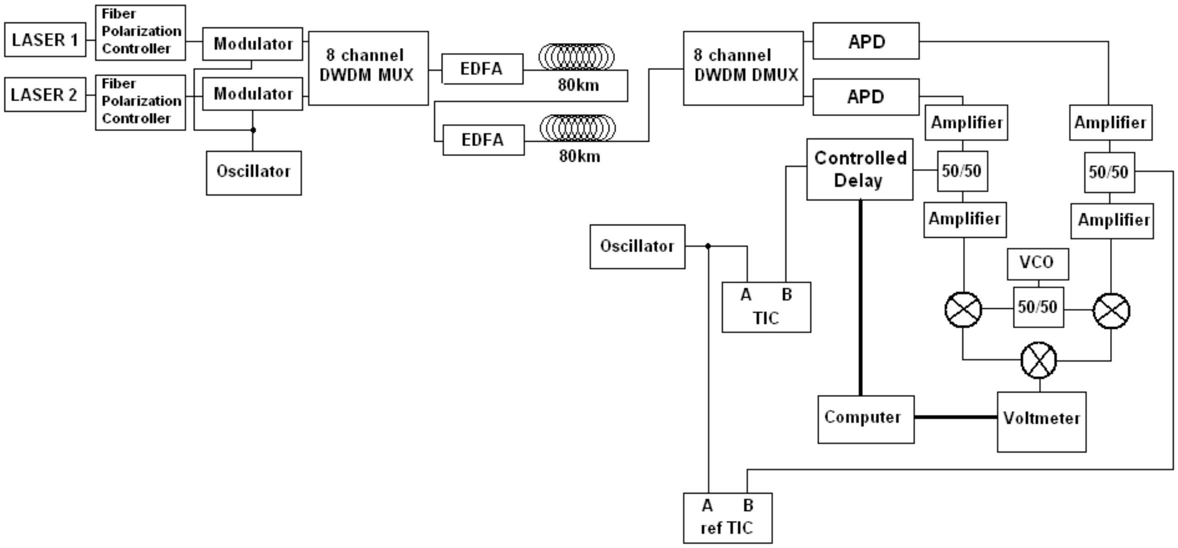

Figure 1. Experimental setup 1. The modulators are telecom Mach Zehnder modulators, the EDFAs are Erbium Doped Fiber Amplifiers, and the APDs includes avalanche photodiodes and electrical trans-impedance amplifiers. The VCO is a free running slave oscillator and TIC is time-interval counter. Both the Oscillator and the VCO emit 10 MHz sine.

RESULTS

While it is apparent from the theory that a variation in output voltage of the last mixer of the phase comparator may be caused both by a variation in phase, and in power, the compensation requires a distinction between these two. Since none of the electrical amplifiers are saturated, the input amplitude into the phase comparator can be assumed to be proportional to the input optical power to the APD, which can be monitored by the photocurrent. The main cause for these amplitude fluctuations is a variation in polarization along the fiber, influenced by a polarization dependent loss in the WDM demux. These variations are detected through the measurement of the photocurrents, and during the days of measurement, these current variations were less than 1.6 dB, as can be seen in Figure 2.

In view of the fact that saturation would be a problem and all equipment except the phase comparator in the electrical domain have been investigated, it is important to perform the same evaluation there. For normal operation the amplitude of the signals coupled into the phase comparator is 2Vpp. During the evaluation of its active working range and linearity, similar signals were applied on the inputs with the possibility of arbitrary phase shift. The result when the VCO emitted the same signal amplitude is presented as the black line in Figure 3 and it shows a linear behavior with an operating range of ±175mV. The same procedure was performed with 10Vpp VCO output and is shown as the red line in Figure 3. Even for this higher amplitude the response for the phase comparator is linear and the operating range has increased to ±200mV.

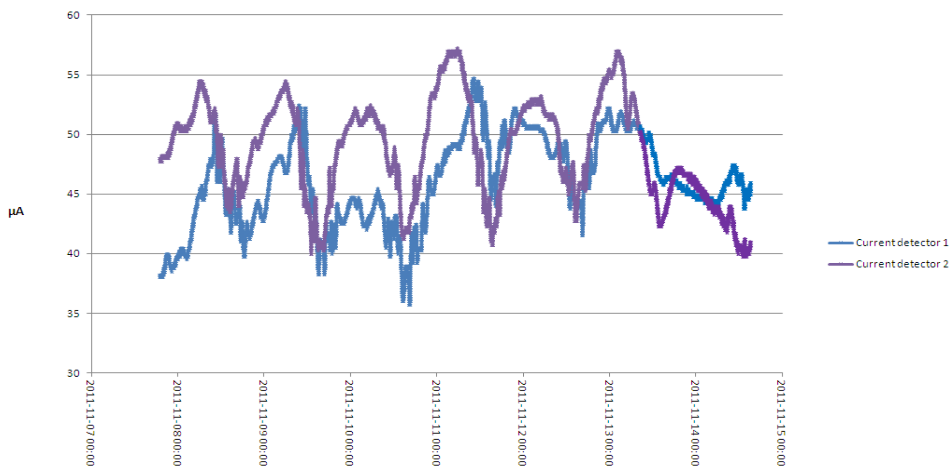

Figure 2. These graphs presents the photocurrent of the photoreceiver in this system and it seems like the polarization variations transfer to amplitude variations in DWDM demux.

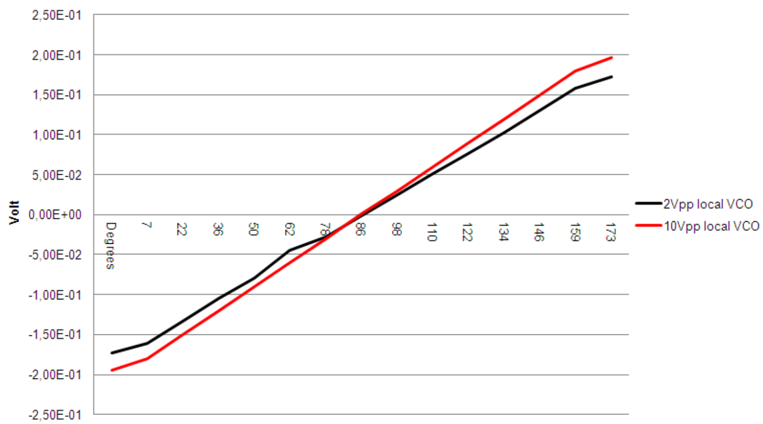

Figure 3. Phase comparator evaluation regarding nonlinearity applying a 2Vpp sine VCO signal presented in black and a 10Vpp sine VCO signal presented in red.

The conducted experiment results are in two sections hereafter and the first section will cover a seven day long data set that has been evaluated by creating and applying a steering algorithm on the measured results as through a post processed progression. The second section will present the results from an actual electrical delay compensation being steered in real time by an algorithm created by measurements from the phase comparator assembly and photocurrent from the APDs in the receiver end.

Post Processed Results

In the post processing algorithm, data from the measurements of the phase comparator as well as the photocurrents are used to create a smoothing and compensating algorithm. Three different kinds of algorithms are presented in Figure 4, all of which are scaled. The scale factor used is determined from an initial one hour startup process that uses the reference TIC and dividing those results with the measurements by the phase comparator assembly divided by the product of the photocurrents. The calculation of the scale factor, S_{cf}, can thereby be described by

$$S_{cf} = \frac{\sum_{i=0}^{240} TIC_{ref,i}}{\sum_{i=0}^{240} V_i / i_{lb1,i} i_{lb2,i}} \quad (1)$$

where TIC_{ref} is the delay through the system, V is the output voltage of the phase comparator and i_{lb1} and i_{lb2} are the photocurrents of the two APDs. The sampling period is 15 s. This initial scale factor divided by the product of the photocurrents is then applied to phase comparator measurements which results in a noisy raw data algorithm presented in green in Figure 4. In an attempt to reduce the noisiness, two types of running averages are applied on this steering algorithm, one for one hour and one for four hours and these are also presented in Figure 4, in black and in red, respectively. All results in Figure 4 have an arbitrary offset.

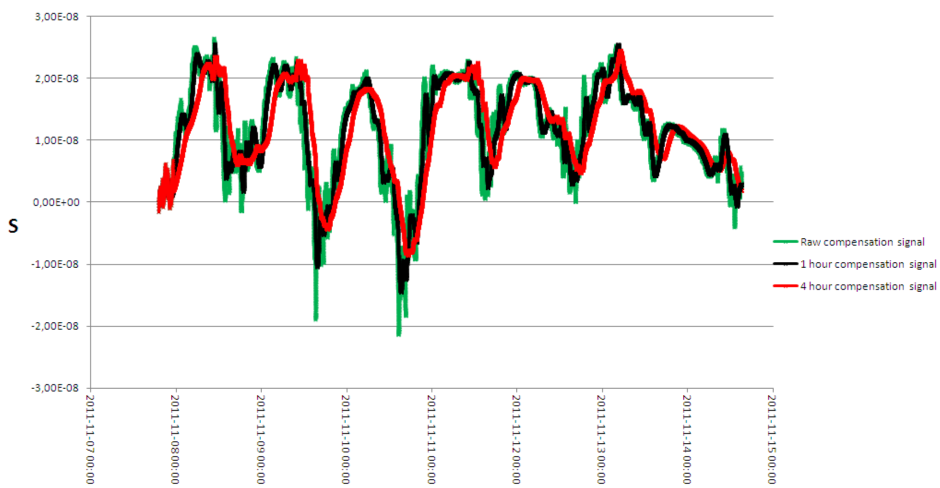

Figure 4. The green curve presents the raw compensation signal and the black presents a 1 hour running average of the raw compensation signal while the red graph presents a 4 hour running average.

These two types of compensation algorithms are subtracted from the data in the measurements performed by the reference TIC and are presented in Figure 5. In green the reference transmission time variation and in blue the transmission time variation after compensation by 1 hour running average of phase comparator output are presented. Finally the transmission time variation after compensation by 4 hour running average of phase comparator is presented in red. The one hour average reduces the daily variations well but introduces a large amount of noise while the four hour average still suffers from daily variations. For the one hour averaging the variations is reduced by approximately 3dB.

The modified Allan Deviation plot, which is shown in Figure 6, confirms the previous presented results as it is obvious that the one hour averaging decreases the daily variations and introduces more noise, as shown in the blue curve. Also the four hour average decreases some of the daily variations shown as the red curve in Figure 6, but its benefits compared to the one hour solution is the lower noise introduction in the 300 – 7000 s averaging time region. The green graph presents the uncompensated reference transmission time variation.

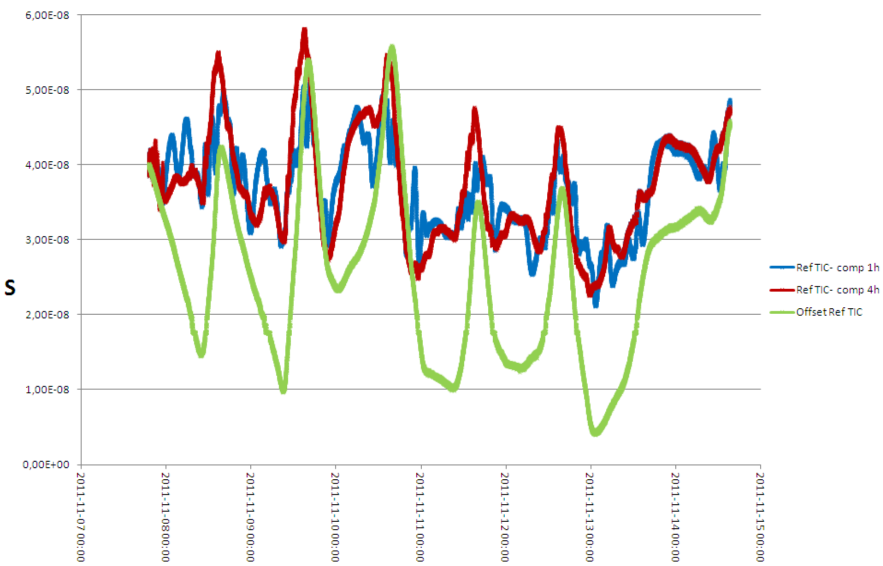

Figure 5. Result during 1 week after post processed compensation. In green the reference transmission time variation and in blue the transmission time variation after compensation by 1 hour running average of phase comparator output are presented. Finally the transmission time variation after compensation by 4 hour running average of phase comparator is presented in red.

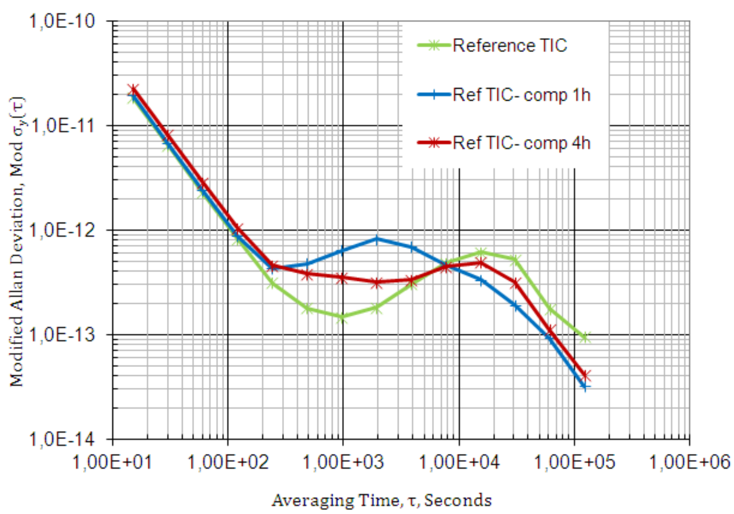

Figure 6. Modified Allan deviaton plot of the reference transmission time variation presented in green and in blue is the transmission time variation after compensation by 1 hour running average of phase comparator presented. Finally is the transmission time variation after compensation by a 4 hour running average of phase comparator presented in red.

REAL TIME DELAY COMPENSATION

At the receiver end in Figure 1, the electrical real time delay compensation is introduced and in this section it is steered from a software algorithm created from measuring the output voltage of the phase comparator, and the photocurrents as presented in the previous section. The scale factor is chosen by empirical evaluation of suppression of daily variations.

The real time compensation of time transfer is evaluated during more than 4 days, and continuously compared with the uncompensated transfer in the link. While the uncompensated transfer varies with 50 ns peak to peak, the compensated link decreases the variation to 20 ns. In the transfer time graphs in Figure 7, the Modified Allen deviation reveals the addition of noise in averaging time spans less than 7000 s, to the benefit of better stability at time constants larger than 7000 s. The main improvement is the minimizing of daily variations.

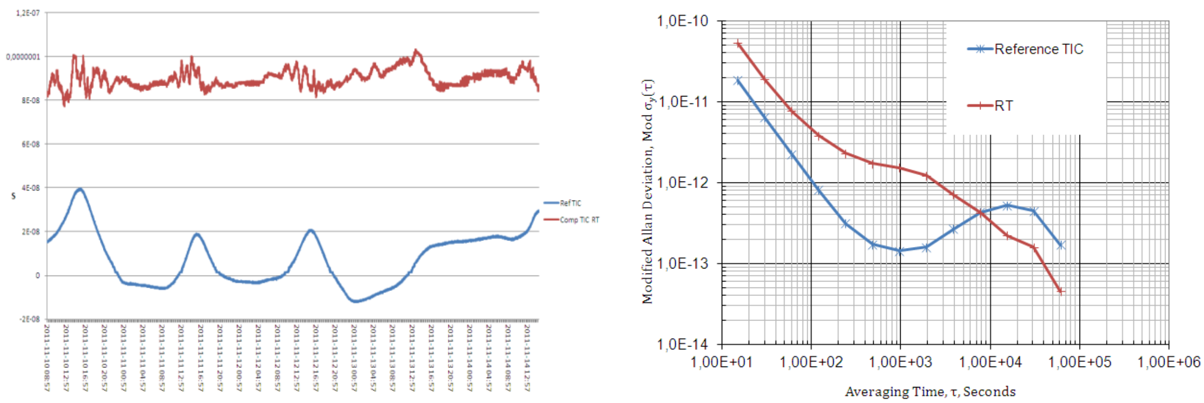

Figure 7. The left figure presents the compensated results in red and it varies ±20ns while the uncompensated reference in blue varies ±50ns. The modified Allan deviation for the results in the left graph are displayed at the right and it shows that the compensated signal introduced noise and reduced daily variations.

The results after real time compensation perform in a similar way as the result presented in the post processed section, with the addition of noise at the shorter time base. The results indicate the limitations of better performance are the phase comparator implementation and the steering algorithm. The data can be used as reference in the progress of further improvements.

CONCLUSION

The proof of concept for baselines larger than 100 km is made and the system is able to perform active compensation of transfer time variations with two wavelengths as narrow as 8nm apart within the C-band. The first evaluation with post compensation in software reduces the time variations by approximately 3dB and the second evaluation verifies the possibility of real time delay compensation. Both evaluations are consistent and confirm a possible decrement of the variations on the order of 3 dB. For these evaluations, two different running averages have been used, although without weighting the samples. This is, to the best of our knowledge, the first implementation of an electrical real time post-compensation of variations in the optical fiber transmission delay based on the two-wavelength one-way technique. The technique has the possibility to change the time and frequency transfer landscape through a new broadcast concept.

REFERENCES

[1] S.R. Jefferts, M. Weiss, J. Levine, S. Dilla, and T. E. Parker, 1996, "*Two-Way Time Transfer through SDH and Sonet Systems,*" European Frequency and Time Forum EFTF'96, 5-7 March 1996, Brighton, United Kingdom, pp. 461-464.

[2] M. Kihara, A. Imaoka, M. Imae, and K. Imamura, 2001, "*Two-Way Time Transfer through 2.4 Gb/s Optical SDH Systems,*" **IEEE Trans. Instr. Meas.**, **Vol. 50**, 709-715.

[3] F. Kéfélian, H. Jiang, P. Lemonde and G. Santarelli, 2009, "*Ultralow-frequency-noise stabilization of a laser by locking to an optical fiber-delay line,*" **Optics Letters**, **Vol. 34**, No. 7, 914-916.

[4] R. Emardson, P.O. Hedekvist, M. Nilsson, S.C. Ebenhag, K. Jaldehag, P. Jarlemark, C. Rieck, J. Johansson, L. Pendrill, P. Löthberg and H. Nilsson, 2008, "*Time Transfer by Passive Listening over a 10 Gb/s Optical Fiber*," **IEEE Trans. Instr. Meas.**, **Vol. 57**, 2495-2501.

[5] S.C. Ebenhag, P.O. Hedekvist, C. Rieck, H. Skoogh, P.Jarlemark, and K. Jaldehag, 2009, "*A fiber based frequency distribution system with enhanced output phase stability*", 23rd European Frequency and Time Forum, EFTF'09, 20-24 April 2009, Besançon, France, pp. 1061-1064.

[6] S.C. Ebenhag, P.O. Hedekvist and K. Jaldehag, 2011, *"Active Detection of Propagation Delay Variations in Single Way Time Transfer Utilizing Dual Wavelengths in an Optical Fiber Network,"* 25th European Freq. and Time Forum, EFTF'11, 1-5 May 2011, San Francisco, California, Paper 7084.

[7] W. Sellmeier, *"Zur Erklärung der abnormen Farbenfolge im Spectrum einiger Substanzen,"* 1871, **Ann. der Phys. und Chem.**, **Vol. 219**, 272-282.

[8] G. Ghosh, M. Endo and T. Iwasaki, *"Temperature-Dependent Sellmeier Coefficients and Chromatic Dispersions for Some Optical Fiber Glasses,"* 1994, **J. Lightwave Technol**., **Vol. 12**, 1338-1342.

[9] P.O. Hedekvist and S.C. Ebenhag, 2011,*"Time and frequency transfer in optical fibers,"* **Optical Fibers / Book 3** (ISBN 979-953-307-652-1, InTech Open Access Publishing).

[10] J. Hanssen, S. Crane, and C. Ekstrom, 2011, *"One-Way Temperature Compensated Fiber Link,"* 25th European Frequency and Time Forum, EFTF'11, 1-5 May 2011, San Francisco, California, Paper 7273.