

SINGLE-WAY FIBER-BASED TIME TRANSFER WITH ACTIVE DETECTION OF TIME TRANSFER VARIATIONS

Sven-Christian Ebenhag¹, Per Olof Hedekvist¹, and Kenneth Jaldehag
SP Technical Research Institute of Sweden
Box 857, SE 50115 Borås, Sweden
Tel: +46 105 165569, Fax: +46 105 165620
¹ also with Chalmers University of Technology, Gothenburg, Sweden
svен-christian.ebenhag@sp.se

Abstract

With an increasing demand for distributing accurate time, preferably accessible in real time, better techniques for time transfer is needed. The inevitable variations in the time transfer delay must be detected and compensated for, if an absolute precision better than μs -level is needed, for transmission distance exceeding a few km. This is usually solved through two-way transfer, where the transmitter can estimate and forward the information on the actual transfer time at every instant, and this can be performed both over aerial transmission and fiber. If the number of users is high, there will be a complex and large network of two-way time signal transmissions. In comparison a single, one-way broadcasting is more desirable, and would be enabled if the variations in transmission time could be estimated from the received data at the far end. Some preliminary results of this time transfer technique based on transmission of a repetitive signal, modulated on two lasers at different wavelengths and transmitted through an optical fiber, has been presented previously. These data showed a strong correlation between a change in transfer time at one wavelength, and the transfer time difference for the signals at the two wavelengths. In this paper, the setup and the measurement results have been improved and new data are gathered, which shows improvement in the reliability and quality of this technique. There is to our knowledge no other technique for time transfer over wire-line solutions, where the variations in transfer time is measured and compensated for, that only needs transmission in one direction.

INTRODUCTION

The request for better performing time and frequency transfer over baselines longer than 100 km has increased with development of new communication systems. Several transfer methods using optical fibers has been developed or are under development [1-4], using dedicated fibers or already existing fiber networks. The choice of method is often the limiting factor for the performance of the transfer, where the long-term stability relies on an accurate estimate of the variations of transfer delay. A common way for high-performance transfer is the two-way method, which is an excellent method when the user has easy access to the whole system and when both transmission paths are equal. For the best results, both

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE NOV 2010		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Single-Way Fiber-Based Time Transfer with Active Detection of the Transfer Variations				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) SP Technical Research Institute of Sweden Box 857, SE 50115 Borås, Sweden				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADA547222 . Precise Time and Time Interval (PTTI) Systems and Applications Meeting (42nd Annual) Held in Reston, Virginia on November 15-18, 2010., The original document contains color images.					
14. ABSTRACT With an increasing demand for distributing accurate time, preferably accessible in real time, better techniques for time transfer is needed. The inevitable variations in the time transfer delay must be detected and compensated for, if an absolute precision better than 1/4s-level is needed, for transmission distance exceeding a few km. This is usually solved through two-way transfer, where the transmitter can estimate and forward the information on the actual transfer time at every instant, and this can be performed both over aerial transmission and fiber. If the number of users is high, there will be a complex and large network of two-way time signal transmissions. In comparison a single, one-way broadcasting is more desirable, and would be enabled if the variations in transmission time could be estimated from the received data at the far end. Some preliminary results of this time transfer technique based on transmission of a repetitive signal, modulated on two lasers at different wavelengths and transmitted through an optical fiber, has been presented previously.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	unclassified	unclassified	SAR	14	

directions in the transfer should operate in the same transmission line to be able to cancel out transmission path delays. The two-way transfer can be implemented very efficiently when operating on existing data traffic [5-6]; however, when data format or other limitations require that the time and frequency transfer must operate on dedicated communication channels, the techniques' administration scales with the number of users and becomes very capacity consuming.

The one-way dual wavelength time transfer technique uses the variations of group velocity between two wavelengths to estimate the delay variation of the timing signal in one of the wavelength channels. The proof-of-concept was previously presented [7-8] using modulated lasers one at 1310 nm and the other at 1550 nm. The results showed that it is possible to perform a one-way time and frequency transfer with two wavelengths and, by evaluating these two against each other, create a correction signal for compensation for influences along the transmission path. However, to enable long baselines, the optical signal must be possible to amplify and it is desirable to cover both wavelengths inside the optical C-band (1530 – 1560 nm). This evaluation is, therefore, performed with two wavelengths 18 nm apart. The presented result shows that is possible to perform a single-way time and frequency transfer if two wavelengths are used and, by evaluating these two against each other, create a correction signal for compensation of transmission time variations with a 38 km fiber link that includes amplification in terms of erbium-doped fiber amplifiers (EDFAs).

BACKGROUND

Two-way transfer, performed in free space or with coaxial or fiber cables, is in general a good method for comparing clocks with each other, but it has some disadvantages, such as the use of two different paths for transmitting and receiving for the cable-based transfer. This will result in an unmodelled asymmetry that can be difficult to make corrections for. This asymmetry is due to many components such as ageing, connector connections, and different length in the transfer paths and equipment in and between the nodes. With this classic transfer method as reference point, this paper will discuss a different method based on a single path.

A single-way time transfer is standardized in the IRIG-B system, and fiber-based frequency transfer is available in commercial systems. Neither of these, however, takes variations in transfer time into account, mainly because they are supposed to be used over short distances. When distance increases, and a vast amount of the transmission media is outdoors, temperature will vary and, therefore, also the propagation properties of the material. Assuming transmission over optical fiber, even cables buried below ground will experience temperature variations of 20°C over the year [9], and with parts of the distance mounted with the power grid through air-lines, the variations will follow the air temperature.

Since not only the transfer time changes, but also the dispersion, which can be measured at the receiving end of the fiber, the correlation between these two parameters can be used. The measurement technique for fiber dispersion is well known [10] and the variation with respect to temperature have been studied previously [9,11]. Nevertheless, the correlation to the time transfer delay has not yet been fully investigated or utilized for time transfer.

In a fully operational solution, the time from the Master clock can be distributed to a Slave clock, with a precision better than what would be the case if a single signal was transmitted.

For a common one-way time transfer, as illustrated in Figure 1, there is a time-varying part associated with ΔT_A , as also is included in (1). Even though the average transfer time can be calibrated for, the time-varying part will pose as an uncertainty unless it continuously is measured and compensated for.

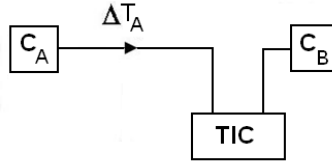


Figure 1. The figure is a sketch of a one-way time transfer between clock A (C_A) and clock B (C_B).

$$(1) \quad C_A - C_B = TIC - \Delta T_A(t).$$

The proposed solution to solve for $\Delta T_A(t)$ is by transmitting two wavelengths in the same fiber and detect the propagation delay differences between these [11-14]. The difference is then applied as a correction term for the delay variations in $\Delta T_A(t)$. Development of this one-way transfer method with enhanced stability should result in transfer quality comparable with well established two-way methods. Furthermore, it should be operating within the C-band of commercial DWDM networks for distances $>100\text{km}$. The reason for using the C-band is that the commonly used EDFAs have a gain spectrum 1530-1560 nm. Previously presented results showed proof of concept [8]. Those experiments used two wavelengths 18 nm apart

THEORY

The theory for single-way dual wavelength optical fiber time and frequency transfer is based on the transit time τ for propagation of a single mode in a fiber [14] expressed as the group velocity for a certain distance L and the wavelength λ .

$$(2) \quad \tau = \frac{L}{c} \left(n - \lambda \frac{dn}{d\lambda} \right)$$

where n is the refractive index and c is the speed of light in vacuum. The transit time τ , sometimes known as the group delay time, in a fiber is, thus, dependent on the refractive index and the wavelength. This means that two different wavelengths will propagate at different velocity in the same fiber. A standard single-mode fiber is temperature dependent, to an extent shown in previous studies [9], and the most important factor to include in the calculations. By calculating the derivative of the transit time with respect to temperature, both wavelength and refractive index will be taken into account as follows:

$$(3) \quad \left. \frac{d\tau}{dT} \right|_{\lambda_N} = \frac{1}{c} \left(\frac{dL}{dT} \left(n - \lambda \frac{dn}{d\lambda} \right) + L \left(\frac{dn}{dT} - \lambda \frac{d^2n}{d\lambda dT} \right) \right) \quad N=1,2$$

Polarization mode dispersion is omitted, since it is small compared to chromatic dispersion over the wavelength span.

The variation in transit time as a function of temperature can, thus, be calculated where λ_N $N=1,2$ represents the two wavelengths. The equations for the two wavelengths are subtracted from each other, resulting in:

$$(4) \left. \frac{d\tau}{dT} \right|_{\lambda_1-\lambda_2} = \frac{1}{c} \left(\frac{dL}{dT} \left((n_{\lambda_1} - n_{\lambda_2}) + \lambda_2 \frac{dn_{\lambda_2}}{d\lambda_2} - \lambda_1 \frac{dn_{\lambda_1}}{d\lambda_1} \right) + L \frac{d}{dT} \left((n_{\lambda_1} - n_{\lambda_2}) + \lambda_2 \frac{dn_{\lambda_2}}{d\lambda_2} - \lambda_1 \frac{dn_{\lambda_1}}{d\lambda_1} \right) \right)$$

This expression shows how the refractive indices of the two wavelengths are influenced by temperature, and based on this the variations in the time transfer delay can be calculated. The time transfer technique uses the property that the variations are different, but correlated, which also is supported by experimental results.

The difference in transit time through the fiber will, as shown in equation (4), depend on the variation of length, L, and the variation in refractive index, n. Both these effects will affect the chromatic dispersion of the fiber, but through different properties.

The refractive index of the fiber can be described by the Sellmeier equation [15,16].

$$(5) \quad n^2 = A + \frac{B}{1 - C/\lambda^2} + \frac{D}{1 - E/\lambda^2}$$

where λ is the wavelength in μm and the Sellmeier coefficients A, B, C, D and E have been empirically fitted for different glasses. Empirical data for fused silica [16] are used in Table 1.

Table 1. Empirically fitted values for Sellmeier coefficients.

Sellmeier coefficient	Fitted constants (SiO ₂)
A	6,90754*10⁶T + 1,31552
B	2,35835*10⁻⁵T + 0,788404
C	5,84758*10⁻⁷T + 1,10199*10⁻²
D	5,48368*10⁻⁷T + 0,91326
E	100

From these equations, the material dispersion can be calculated as:

$$(6) \quad D_M(\lambda) = \frac{1}{cn} \left[-\frac{4}{\lambda^5} \left\{ \frac{BC^2}{(1 - C/\lambda^2)^3} + \frac{DE^2}{(1 - E/\lambda^2)^3} \right\} + \left(\frac{dn}{d\lambda} \right)^2 + 3n \frac{dn}{d\lambda} \right]$$

where the equation (6) is corrected with respect to the reference and the left side of the equation begins with a “-“.

$$(7) \quad \frac{dn}{d\lambda} = -\frac{1}{n\lambda^3} \left(\frac{BC}{(1 - C/\lambda^2)^2} + \frac{DE}{(1 - E/\lambda^2)^2} \right)$$

Using these parameters, the material dispersion of SiO₂ is calculated and shown in Figure 2. It may vary slightly in communication fibers where the silica is doped with small amount of other substances. Nevertheless, the overall behavior is comparable.

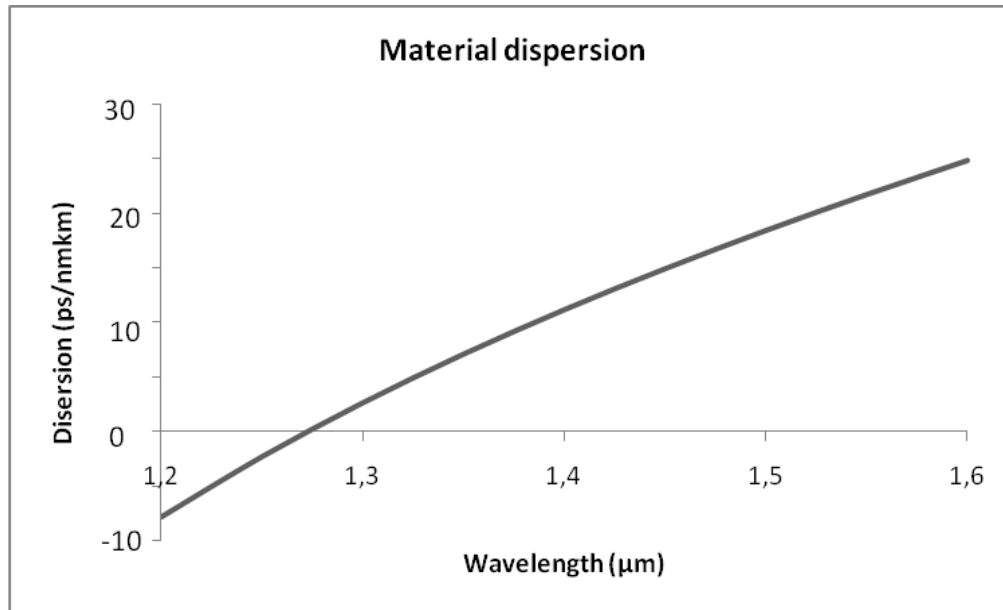


Figure 2. Calculation of material dispersion in fused silica at 20°C.

Using the equations above, it is possible to estimate the amount of time transfer delay variations with respect to temperature. Assuming a fiber where material dispersion is dominant (as is the case in standard single mode fiber), at a length of 20 km and measurement at 1530 nm and 1560 nm, the result is shown in Figure 3. The slope of the calculated dispersion is -0,0016 ps/(nm·km·°C), which is comparable to previously reported results -0,0025 ps/nm/km/°C for non-zero dispersion shifted fiber (NZDSF) and -0,0038 ps/nm/km/°C for large core fiber [9].

The solid curve (left axis) shows the calculated time transfer delay for a signal at 1530 nm, and the dashed curve shows the arrival time difference for two signals at 1530 nm and 1560 nm. Both curves are normalized with respect to the value at 20°C, and it is apparent that the time transfer delay within a single, 20 km long fiber varies with almost 0.5 ns when affected by a 40°C temperature difference. This variation can be detected and compensated for, using transmission at two wavelengths and a measurement system that can measure time variations on the ps level with sufficient precision.

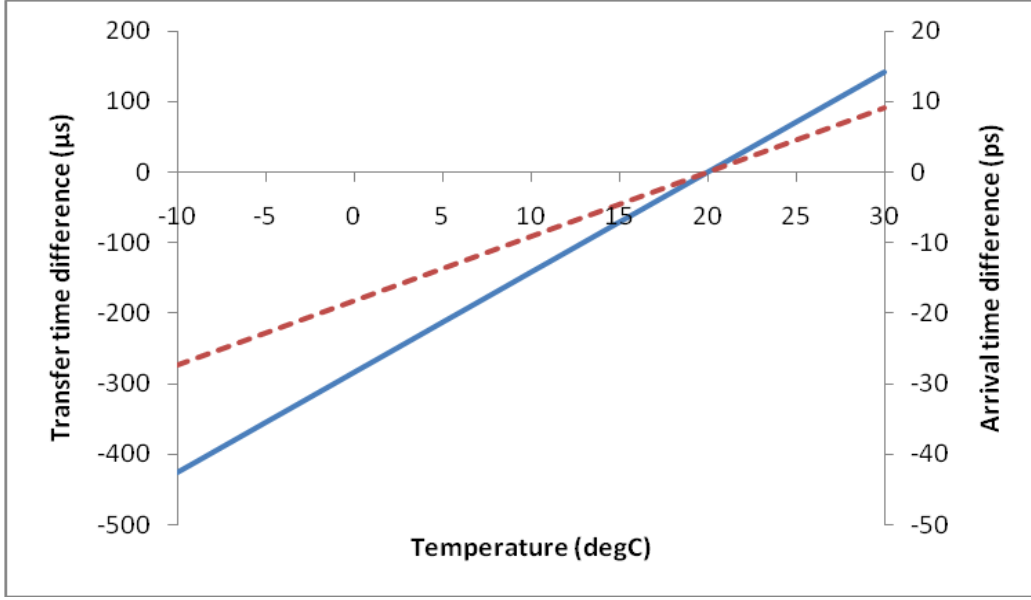


Figure 3. Temperature dependence of transfer time (solid blue, left axis) and arrival time difference (dashed red, right axis).

This evaluation assumes that the cabling or mounting will stretch the fiber at increasing temperature, however leaving the volume intact. The variations in dimensions of the glass are assumed to be negligible. If the core of the fiber is modeled as a glass cylinder, of length L and diameter d , a geometrical approach gives that the variation in temperature will change the length with $\Delta L(T-T_0)$ and the diameter with $\Delta d(T-T_0)$, such that

$$(8) \quad \frac{\Delta d(T-T_0)}{d} = -\frac{\Delta L(T-T_0)}{2L}$$

where T is the temperature and T_0 is the reference temperature.

This change in diameter will change the dispersion according to the variation in waveguide dispersion [17,18]:

$$(9) \quad D_w(\lambda) = -\frac{n_2 \Delta}{c\lambda} V \frac{d^2(Vb)}{dV^2}$$

where n_2 is the refractive of the cladding and Δ is the relative difference of refractive index in the core and in the cladding. V and b are the normalized frequency and the normalized propagation constant, respectively, and can be found through:

$$(10) \quad V = ka\sqrt{n_1^2 - n_2^2} \cong kan\sqrt{2\Delta}$$

$$(11) \quad b = \frac{(\beta/k)^2 - n_2^2}{n_1^2 - n_2^2}$$

where k is the free-space propagation constant, β is the propagation constant, and $a = d/2$ is the fiber core radius. From these equations, it is apparent that fibers with notable waveguide dispersion, e.g. dispersion shifted fibers, dispersion compensating fibers, etc., will have different response to a change in diameter d , than standard fibers where material dispersion is dominant. However, this response must be evaluated for each fiber design, since the term $V(d^2(Vb)/dV^2)$ is between 0 and 1.2, with a maximum at $V \approx 1.2$. These equations show nevertheless that the system of detecting a variation in transfer time through a fiber with substantial waveguide dispersion is possible, but must be optimized for the actual fiber parameters.

EXPERIMENTAL SETUP

The experimental setup for the verification of the proposed time and frequency transfer technique is shown in Figure 4. Two lasers at wavelength 1535 nm and 1553 nm are directly modulated by a 10 MHz reference oscillator and the light is launched into the SMF through a 50/50 power combiner. The reference oscillator is frequency stabilized by an AOG connected to an H-maser as the Master clock. In the experiment, the oscillator is also used as reference to the measurement equipment, connected as an oscillator to the TIC, in order to evaluate the one-way technique. The total sum of fiber length is measured with an OTDR (optical time-domain reflectometer) to be 38 km. Included in this length is 188 m of transfer fiber between the lab and the outdoor fiber spools. The fiber path starts and ends in the laboratory for evaluation. The use of several fiber spools instead of one creates a similar case to a commercial link, which will be assembled of multiple fibers spliced by connectors, and there is no possibility to know the age or ageing of all optical fiber along this.

At the receiving end, the two wavelengths are separated in a 50/50 power splitter, filtered in optical narrow band pass filters and detected in two 10 Gb/s p-i-n receivers. The signals are amplified and connected to the RF ports of two double balanced mixers. One of the signals is also divided and connected to the reference time-interval counter (TIC), which measures the total transfer time between the transmitters as reference. The output of the TIC is interpreted as the precision of an uncompensated single-way time and frequency transmission. By measuring the voltage from a third mixer connected to the other two mixers, a correction signal is achieved and can be used for a real-time delay control of the uncompensated signal. Most of the equipment is housed in a laboratory with controlled environment, except the spools of SMF28 which are placed outdoors for emulation of an actual environmental condition.

The optical filters that are used separates two wavelengths, since the optical splitter will divide both wavelengths to both fibers equally. Measurement equipment detects the two 10 MHz sine waves after propagation through the fiber link, and amplifies and compares with a reference signal, as shown schematically in Figure 5.

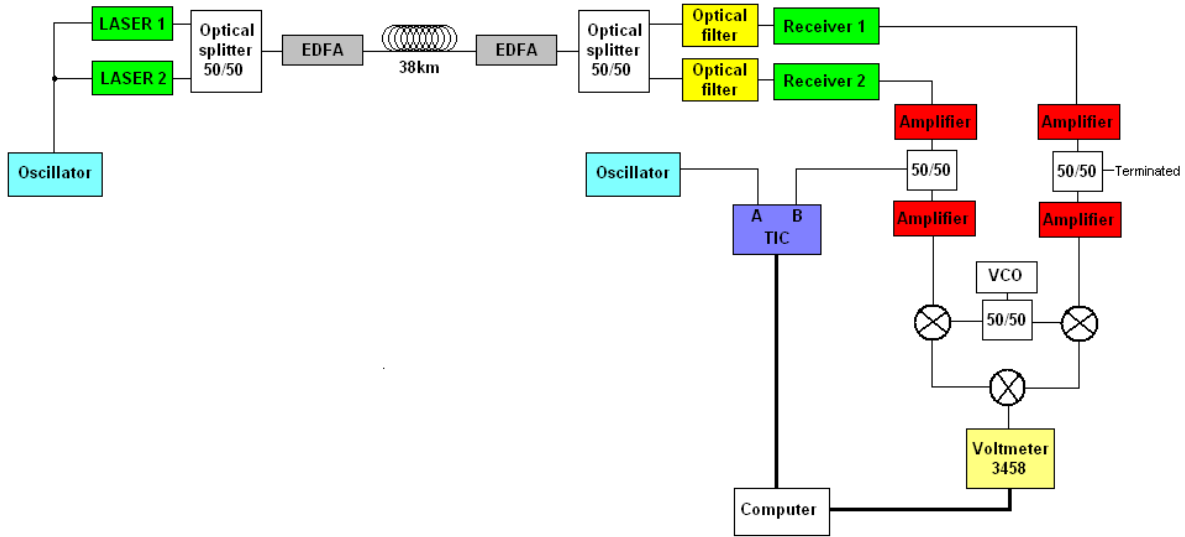


Figure 4. Experimental setup. Receiver 1 and Receiver 2 include optical pre-amplification, optical band pass filter, photodiode, and electrical trans-impedance amplifier. Amplifiers are electrical amplifiers, 3458 a digital voltmeter, and TIC is a time-interval counter.

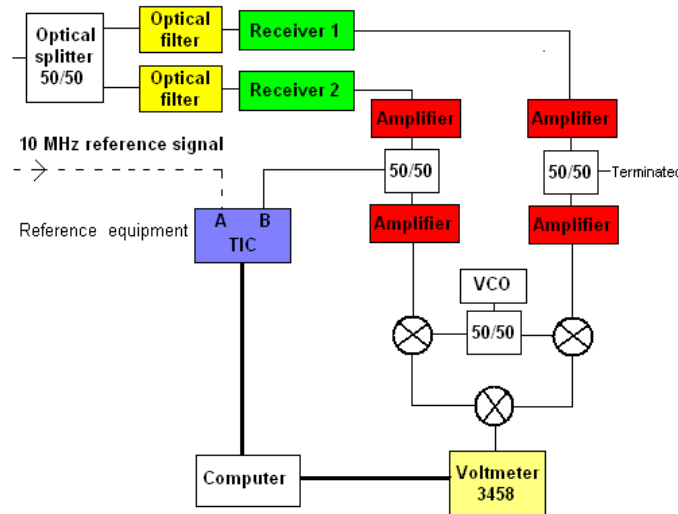


Figure 5. Schematics of the receiver and reference signal placed in the laboratory. The reference signal is compared to the information received from the transmitted wavelengths.

The output signals from the mixer connected to the voltmeter are calculated in equation (12) to (13) and low-pass filtered, which results in (14).

$$(12) \quad \omega = \omega_1 = \omega_2$$

$$(13) \quad M_v = \frac{A_1 A_2 A_L^2}{8} (\cos((\alpha_1 - \alpha_2)(t)) + \cos((2(\omega + \omega_L + \alpha_L) + \alpha_1 + \alpha_2)(t)))$$

Low-pass filtering,

$$(14) \quad M_v = \frac{A_1 A_2 A_L^2}{8} (\cos(\alpha_1(t) - \alpha_2(t)))$$

This means that the measured result from the voltmeter must be corrected for according to equation (14).

RESULTS

The data set is 7 days long and a time interval measurement is made for comparison and result verification. Measurements from the TIC are corrected for outliers and phase jumps, while the mixer solution is averaged over 1 hour to reduce the noise and then corrected for according to equation 14. Furthermore, the mixer solution is scaled to be able to be evaluated against the TIC measurements. A graph displaying the data from the TIC and 1-hour averaged values from the mixer voltage measurements during 7 days are shown in Figure 6. The mixer system is calibrated at the start to be able to calculate the fiber path parameters that would not be possible to measure in a system spread over a large distance. This calibration is presumed necessary for every individual system.

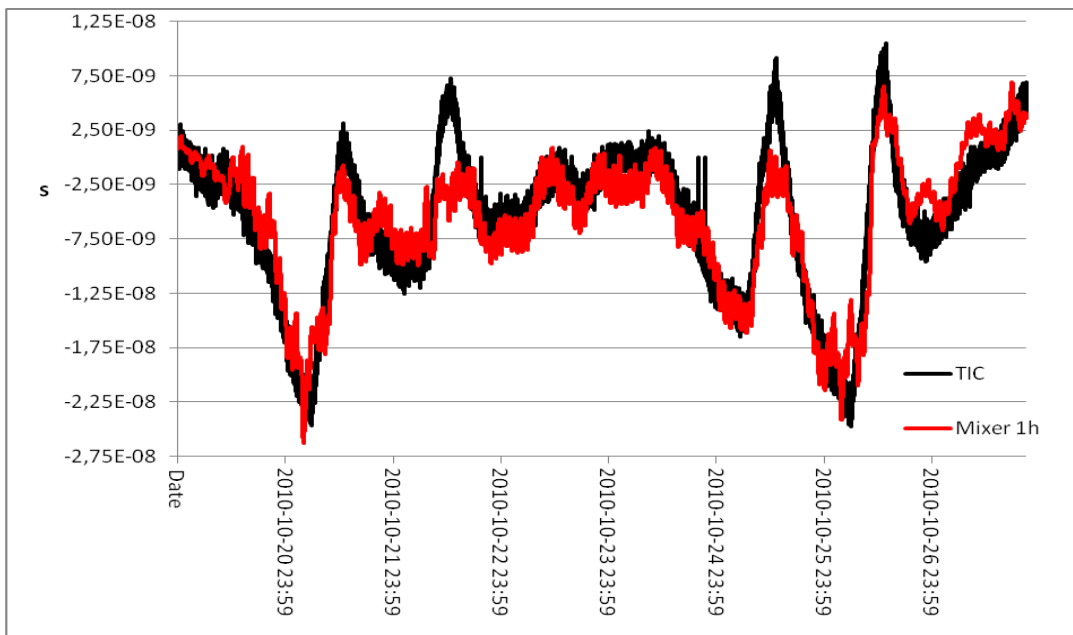


Figure 6. One-hour data averaged from the outputs of the mixer (red curve) and the time interval data represented by the reference TIC (black) are plotted from raw data during 7 days of measurement.

Data from the mixer system and the reference system TIC match well for the long-term variations, but some subsets with large gradients are apparent where the mixer solution does not match so well. This is to some extent explained by a lack of long-term stability in one of the laser sources.

The stability of the TIC data and the scaled compensated mixer solution for 3-hour averaging are plotted as the Modified Allan variance in Figure 7.

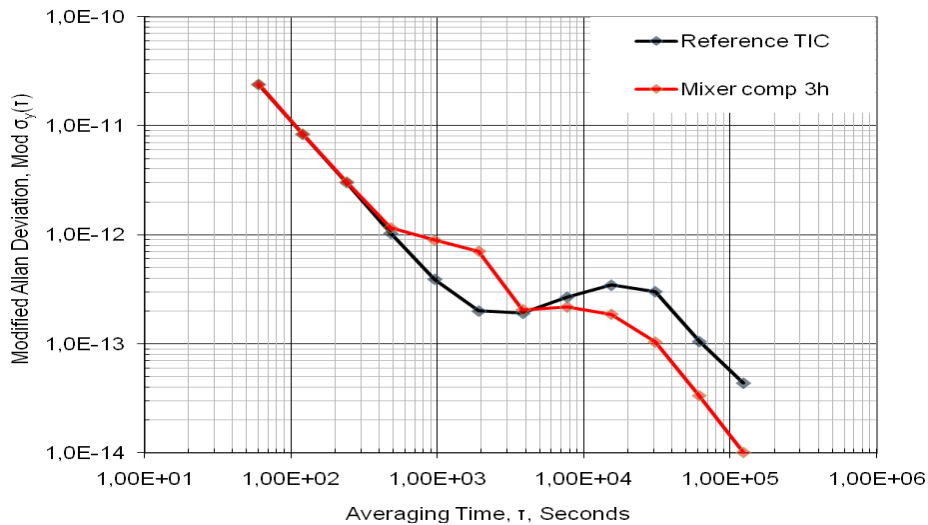


Figure 7. The stability of the reference TIC (black curve) and the scaled compensated mixer solution for 3-hour averaging (red curve).

One of the main goals with the new one-way method was to reduce the daily signature due to temperature variations in the time transfer. Figure 7 presents a result that has reduced these daily signatures and is more stable than an uncompensated fiber time transfer (as seen from the uncompensated TIC measurements). The whole system is affected by white phase noise in the short term and the bump between 500 s to almost 4000 s is probably added noise from the mixers, amplifiers, long coaxial cables, and the voltmeter, but also due to the simple correction algorithm, that has to be studied further. Figure 8 shows stability plots using shorter averaging windows as well (1-hour and 2-hour averaging).

This graph was plotted to evaluate which mathematical model that should be used. In this case, the 3-hour solution shows the best result, but further averaging will delay results in terms of real-time compensation.

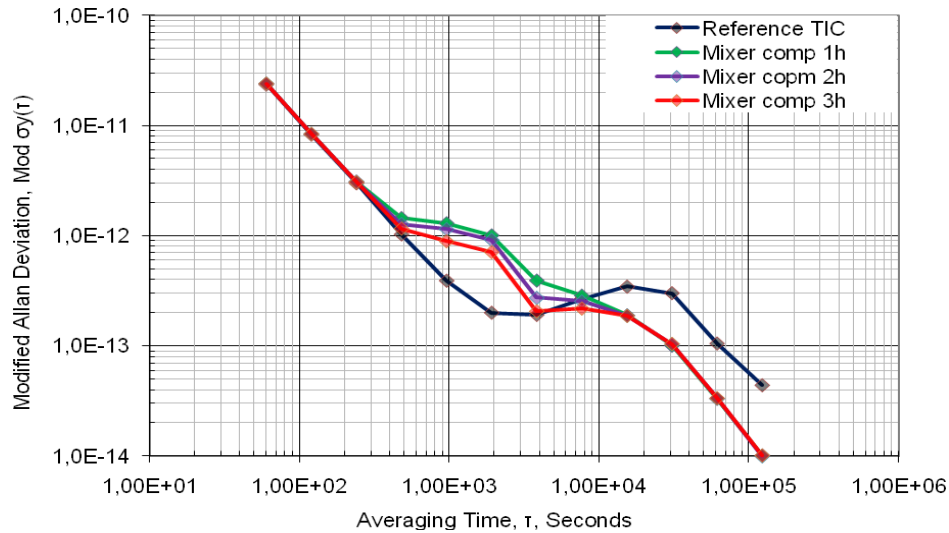


Figure 8. The stability of the reference TIC and scaled compensated mixer solution for 1-, 2-, and 3-hour averaging.

The filtering and smoothing of the short-term variations in the mixer solutions has in this paper been a simple averaging of in time nearby data. Further studies may involve a more optimum filtering using a Kalman filter.

CONCLUSION

It is experimentally verified that it is possible to perform a one-way time and frequency transfer of optical single mode fiber with continuous estimate of delay variations. The technique is based on transmission over two wavelengths, separated by 18 nm and, thus, both residing in the C-band of optical communication. By evaluating the phase difference between these two signals time transfer delay, a correction can be applied to compensate for the unwanted delay variations along the transmission path.

This experiment has shown proof of concept, and future work includes development of a physical real-time correction component at the end of the link that incorporates the steering signal based on the measured difference between the arriving signals at the two wavelengths. Also, there is a lot of work to be done in reducing the noise in the receiver as well as creating a new mathematical algorithm for the mixer solution. For the further work, the lasers must be replaced for such lasers that are incorporated in working WDM-systems and of course implement the whole system in a live WDM-network for evaluation.

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," in Proceedings of the 10th European Frequency and Time Forum (EFTF), 5-7 March, 1996, Brighton, England, UK, 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 Transactions on Instrumentation and Measurement**, **IM-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**, **34**, 914-916.
- [4] 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,” in Proceedings of the 2009 IEEE International Frequency Control Symposium Joint with the 23rd European Time and Frequency Forum (EFTF), 20-24 April 2009, Besançon, France (IEEE), pp. 1061-1064.
- [5] 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 Transactions on Instrumentation and Measurement**, **57**, 2495-2501.
- [6] S. C. Ebenhag, P. Jarlemark, R. Emardson, P. O. Hedekvist, K. Jaldehag, and P. Löthberg, 2008, “Time transfer over a 560 km fiber link,” in Proceedings of the 22nd European Frequency and Time Forum (EFTF), 22-25 April 2008, Toulouse, France, paper E5A04.
- [7] S. C. Ebenhag, P. O. Hedekvist, and K. Jaldehag, 2010, “Fiber based frequency distribution based on long haul communication laser,” in Proceedings of the 41st Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 16-19 November 2009, Santa Ana Pueblo, New Mexico, USA (U.S. Naval Observatory, Washington, D.C.), pp. 57-65.
- [8] S. C. Ebenhag, P. O. Hedekvist, and J. Johansson, 2010, “Fiber based one-way time transfer with enhanced accuracy,” in Proceedings of the 24th European Frequency and Time Forum (EFTF), 13-16 April 2010, Noordwijk, The Netherlands.
- [9] A. Walter and G. Schaefer, 2002, “Chromatic Dispersion Variations in Ultra-Long-haul Transmission Systems Arising from Seasonal Soil Temperature Variations,” in Proceedings of the Optical Fiber Communication (OFC) Conference, 17-22 March 2002, Atlanta, Georgia, USA (IEEE), pp. 332-333.
- [10] P. J. Vella, P. M. Garrel-Jones, and R. S. Lowe, “Measuring Chromatic Dispersion of Fibers,” US Patent 4551019, 5 November 1985.
- [11] W. H. Hatton and M. Nishimura, 1986, “Temperature dependence of chromatic dispersion in single mode fiber,” **Journal of Lightwave Technology**, **LT-4**, 1552-1555.
- [12] L. G. Cohen and J. W. Fleming, “Effect of temperature on transmission in lightguides,” 1979, **The Bell System Technical Journal**, **58**, 945-951.
- [13] L. A. Bergman, S. T. Eng, and A. R. Johnston, 1983, “Temperature stability of transit time delay for a single-mode fibre in a loose tube cable,” **Electronics Letters**, **19**, 865-866.
- [14] K. Cochrane, J. E. Bailey, P. Lake, and A. Carlson, 2001, “Wavelength-dependent measurements of optical-fiber transit time, material dispersion, and attenuation,” **Applied Optics**, **40**, 150-156.

- [15] W. Sellmeier, 1871, "*Zur Erklärung der abnormen Farbenfolge im Spectrum einiger Substanzen,*" **Annalen der Physik und Chemie**, **219**, 272-282.
- [16] G. Ghosh, M. Endo, and T. Iwasaki, 1994, "*Temperature-Dependent Sellmeier Coefficients and Chromatic Dispersions for Some Optical Fiber Glasses,*" **Journal of Lightwave Technology**, **12**, 1338-1342.
- [17] D. Gloge, 1971, "*Dispersion in weakly guided fibers,*" **Applied Optics**, **10**, 2442-2445.
- [18] G. Keiser, 1991, **Optical Fiber Communication** (2nd ed.; McGraw-Hill, New York).

