FIBER-BASED FREQUENCY DISTRIBUTION BASED ON LONG-HAUL COMMUNICATION LASERS

Sven-Christian Ebenhag[1], Per Olof Hedekvist[1], 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
E-mail: *sven-christian.ebenhag@sp.se*

Abstract

Recent research and development of optical clocks has increased the need and requirement of better performing time and frequency transfer over baselines longer than 100 km. This need has resulted in a lot of activities in transfer methods using optical fiber, some of them in dedicated fibers and others in already existing fiber networks. This study has focused on one-way transmission over a fiber-optic WDM network. The results show 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. This experiment has shown proof of concept, but further work is needed. Future work includes development of a physical correction component in the end of the link that incorporates the steering signal from the difference between the two wavelengths.

INTRODUCTION

Development and research of optical clocks has increased the need for and requirement of better performing time and frequency transfer over baselines longer than 100 km. Several time and frequency transfer methods using optical fibers have been developed or are under development **[1-8]**, some of these using dedicated fibers and others using already existing fiber networks. This study has resulted in one-way transmission over fiber-optic WDM network with detection of variation in transfer time. The results show 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.

The choice of method is often the limiting factor for the performance of a time and frequency transfer. 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 directions in the transfer should operate in the same transmission line to be able to cancel out transmission path delays. This paper focuses on a one-way method for time and frequency transfer in an optical WDM (Wavelength Division Multiplexing) link. It is, however, believed that the technique can be expanded to support a full network with frequency, corrected for any variation. By propagating two wavelengths in the same fiber, it is possible to measure the different characteristics for the two wavelengths and create a steering algorithm for compensating for path dependence, such as temperature and mechanical stress. This experiment has shown proof of concept, and opens a subject for further investigation.

BACKGROUND

Time and frequency transfer between two nodes with correction of any transmission time delay variations can be performed using several techniques. A common way is the two-way transfer, where the aim is to cancel out the path delays and other irregularities.

One-way transfer from node A to node B is described in equations (1) and (2). ΔC_{AA} is a time stamp of a pulse P_A compared to clock A (C_A). ΔC_{BA} is the time stamp when pulse P_A has arrived at node B and then compared to clock B (C_B) plus the transmission delay between Node A and B (ΔT_A). As mentioned above, the method should cancel the influence of ΔT_A by making a time transfer from Node B to A (3) and (4). ΔC_{BB} is a time stamp of a pulse P_B compared to clock B (C_B). ΔC_{AB} is the time stamp when pulse P_B has arrived at node A and then compared to clock A (C_A) plus the transmission delay Node B and A (ΔT_B).

(1) $\Delta C_{AA} = C_A - P_A$

(2) $\Delta C_{BA} = C_B - P_A + \Delta T_A$

(3) $\Delta C_{AB} = C_A - P_B + \Delta T_B$

(4) $\Delta C_{BB} = C_B - P_B$

The clock comparison equation (5) is the result from combining equations (1) to (4) with the addition of an asymmetry factor F (t) taking parameters such as unmodelled differential path delay and local equipment delays into account.

(5) $2(C_A - C_B) = (\Delta C_{AA} - \Delta C_{BA}) + (\Delta C_{AB} - \Delta C_{BB}) + F(t)$

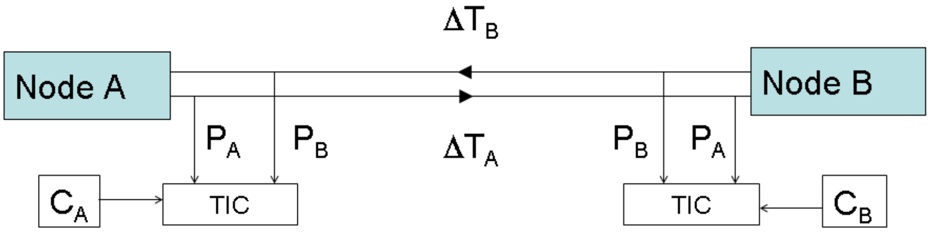

Figure 1. Two-way time-transfer between node A and node B.

This method is valid for all two way transfers performed in free space, coaxial or fiber cables.

In general, this is a good method for comparing clocks against 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 unmodelled asymmetry F (t) (equation 5) that can be difficult to make corrections for. This unmodelled asymmetry is due to many components, such as aging, connector connections, and different lengths 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 that will be able to circumvent previous mentioned disadvantages.

THEORY

The theory for the one-way WDM optical fiber frequency transfer is based on equations (6) to (10) below and **[10-15]**.

For a single mode to propagate a distance L at a wavelength λ, the transit time τ in a fiber is determined by the group velocity,

$$(6)\quad \tau = \frac{L}{c}\left(n - \lambda \frac{dn}{d\lambda}\right)$$

where *n* is the refractive index and *c* is the speed of light in vacuum. Transit time in a fiber is influenced by the refractive index and the wavelength according to (6). This means that two different wavelengths will propagate differently in the same fiber, since the material dispersion is defined as:

$$(7)\quad \frac{d\tau}{d\lambda} = -\lambda \frac{L}{c}\frac{d^2 n}{d\lambda^2}$$

Polarization mode dispersion is omitted, since it is small compared to chromatic dispersion over the wavelength span. A regular SMF28 fiber is temperature-dependent, which is the most important factor to include in the calculations. By calculating the derivative of the transit time (6) with respect to temperature, both wavelength and refractive index will be taken into account as follows:

$$(8)\quad \left.\frac{d\tau}{dT}\right|_{\lambda_N} = \frac{1}{c}\left(\frac{dL}{dT}\left(n - \lambda\frac{dn}{d\lambda}\right) + L\left(\frac{dn}{dT} - \lambda\frac{d^2 n}{d\lambda dT}\right)\right) \qquad \text{N} = 1, 2$$

Transit time as a function of temperature for two wavelengths can be calculated from (8), where N = 1, 2 represents the two wavelengths. If these two functions are subtracted from each other and the result still is separated from zero as

$$(9)\quad \left.\frac{d\tau}{dT}\right|_{\lambda_1-\lambda_2} \neq 0$$

it should be possible to calculate propagation delays and changes in an optical fiber path, as can be seen in following equation

$$(10)\quad \left.\frac{d\tau}{dT}\right|_{\lambda_1-\lambda_2} = \frac{1}{c}\left(\frac{dL}{dT}\left((n_{\lambda_1} - n_{\lambda_2}) + \lambda_2\frac{dn_{\lambda_2}}{d\lambda_2} - \lambda_1\frac{dn_{\lambda_1}}{d\lambda_1}\right) + L\frac{d}{dT}\left((n_{\lambda_1} - n_{\lambda_2}) + \lambda_2\frac{dn_{\lambda_2}}{d\lambda_2} - \lambda_1\frac{dn_{\lambda_1}}{d\lambda_1}\right)\right)$$

Expression (10) states that the two wavelength and refractive indexes are independently influenced by temperature. This statement is supported by the experimental results in this paper.

EXPERIMENTAL SETUP

The one-way transfer method for time and frequency is based on a single optical fiber SMF 28 connected between two WDM couplers. In this experimental setup, shown in Figure 2, two lasers (1310 nm and 1550 nm) are directly modulated from a 10-MHz reference oscillator. The oscillator is also used as reference to the measurement equipment in order to evaluate the link.

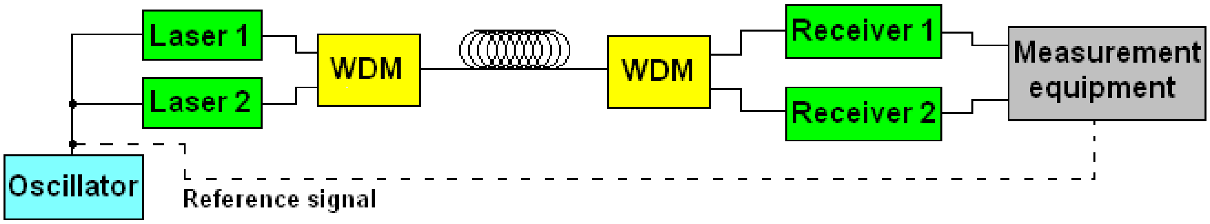

Figure 2. Schematics of the one-way frequency transfer. The dashed line indicates the reference system.

Most of the equipment is housed in a laboratory with controlled environment, except the spools of SMF28 fiber, which are placed outdoors with a temperature sensor for monitoring and comparison with link variations. The total sum of fiber length is measured with an OTDR (optical time-domain reflectometer**)** to be 12,761.5 m, as shown in Figure 3. Included in this length is 187.6 m of transfer fiber between the lab and the outdoor fiber spools. The fiber path, however, starts and ends in the laboratory for evaluation. The use of several fiber spools instead of one is to create a similar case to a commercial link in which there is no possibility to know the age or aging of all optical fiber along a link. An OTDR measurement also measures the attenuation in a link, shown as the slope of the trace, and the reflections at each connector, which appears as the peaks.

The WDM modules that are used can only separate two wavelengths (1310 nm and 1550 nm). Measurement equipment detects the frequency pulses after propagation through the WDM link. This equipment is divided into components according to Figure 4.

The measurement equipment after the receiving WDM link is the commercial 10-Gbit PIN receivers that convert the optical signal into an electrical one. Due to the rather weak amplitude of the signal, amplifiers must be inserted. At the output of each amplifier is the 10-MHz signal transmitted through the fiber, one propagated at 1310 nm and the other at 1550 nm. Since the 1550 nm signal is slightly more intense, it is divided and guided to the reference TIC and into the mixer. The 1310 nm signal is connected at the other input of the mixer. The output from the mixer is fed into a high-precision voltmeter (HP3458), and a computer connected to the TIC and voltmeter collects the data and time-stamps the measurements.

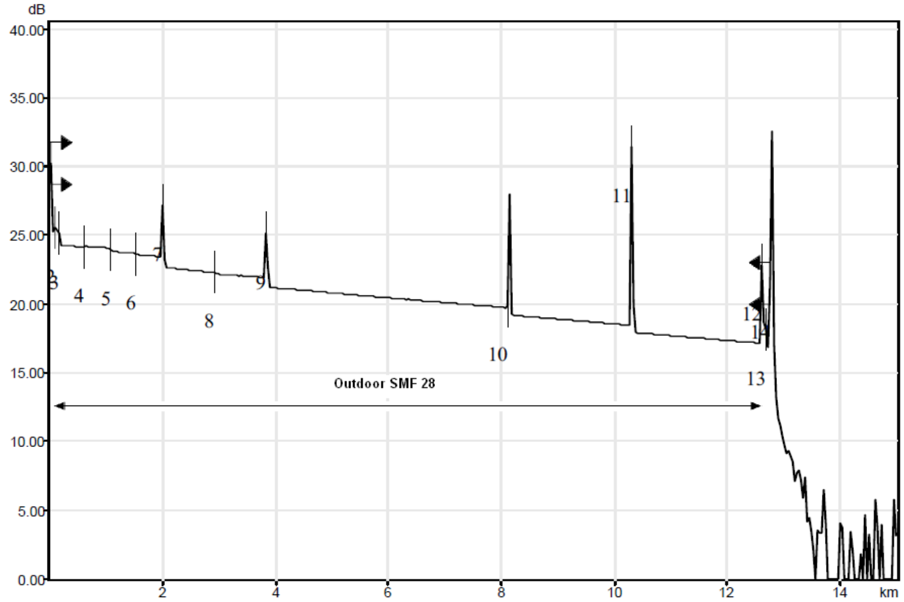

Figure 3. OTDR measurement of the whole fiber length, including transfer fiber between the laboratory and the outdoors spools.

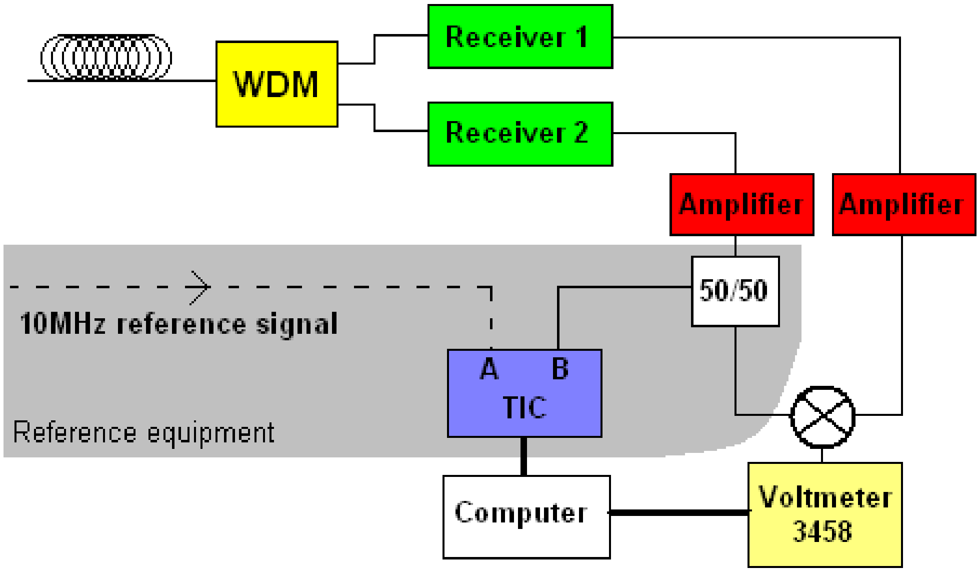

Figure 4. Schematics of the receiver and reference equipment (shown in the light gray area) placed in the laboratory. The reference equipment is used to evaluate the method.

RESULTS

Many papers **[9-12]** before this one have proven that standard single mode can be used as thermometers, but that assumption could not be made without validation of the whole fiber length. This is due to several fiber spools of different age and manufacturer. The result from that validation shows a clear relation to the surrounding temperature. The time interval curve in Figure 5 is plotted together with the temperature.

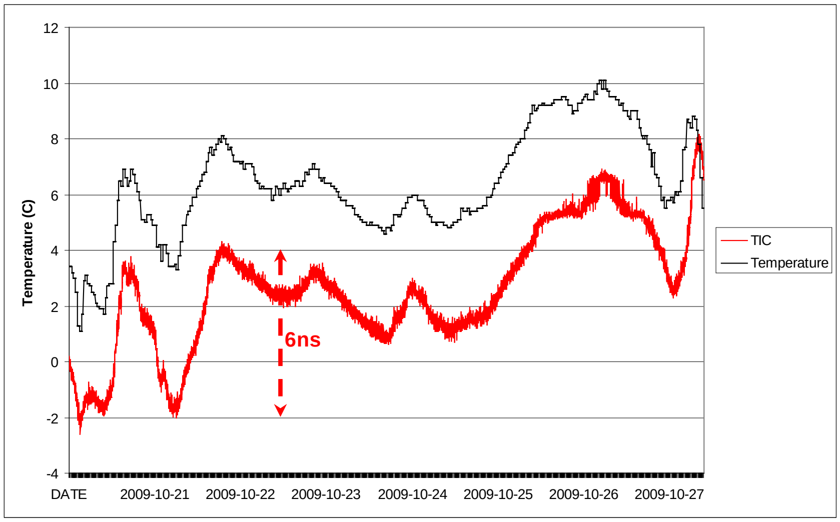

Figure 5. The black curve represents the measured outdoor temperure, while the red represents the fiber time change of the link during 6 days.

For each change in temperature of 1˚C, the propagation time will change 1.25 ns, according to Figure 5. This relatively large change in propagation time stresses the need for correction.

In Figure 6, the result from 1 week of measurement is plotted as a stacked line showing a value contributing trend over time with the one-way method and the reference time interval counter together with the temperature. The one-way method shows clear relations with the reference system (TIC). The choice of stacked line is due to the mixing process, where the output will depend on other parameters, but the stacked value shows the difference between previous and the correlation with transfer time becomes more apparent.

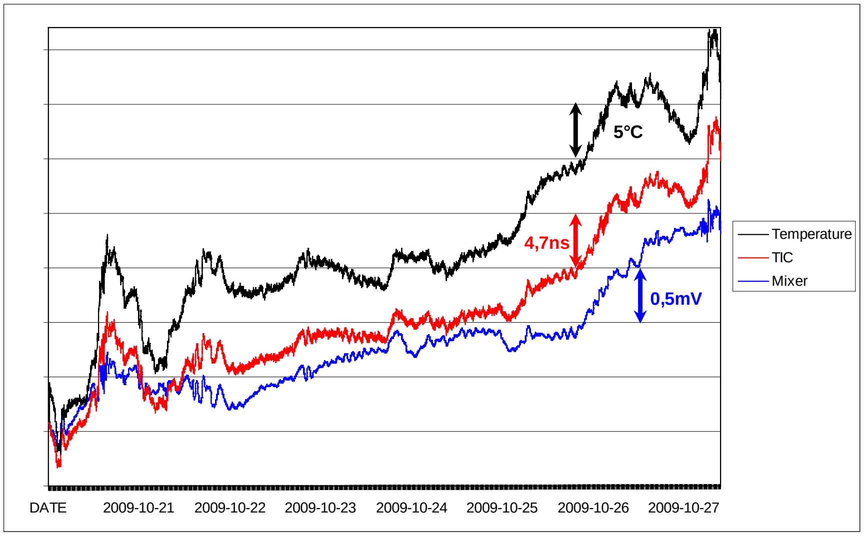

Figure 6. The result from 1 week of measurement plotted as a stacked line showing a value contributing trend over time with the one-way method and the reference time-interval counter together with the temperature.

CONCLUSION

The results in Figure 6 show 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 variations along the transmission path.

This experiment has shown proof of concept, and future work includes development of a physical correction component at the end of the link that incorporates the steering signal from the difference between the two wavelengths. For development of a final solution that can be implemented in a long-haul commercial system, it will be beneficial if the difference between the wavelengths can be included within the C-band. Furthermore, the effect of transmission equipment, such as EDFA (Erbium Doped Fiber Amplifiers) needs to be evaluated.

A possible future implementation will be a tree-structure as shown in Figure 7, where each user can access time and frequency through a passive connection and correct locally for any variations in transmission time, with no need for intermediate oscillators in the nodes.

This invention is patent pending.

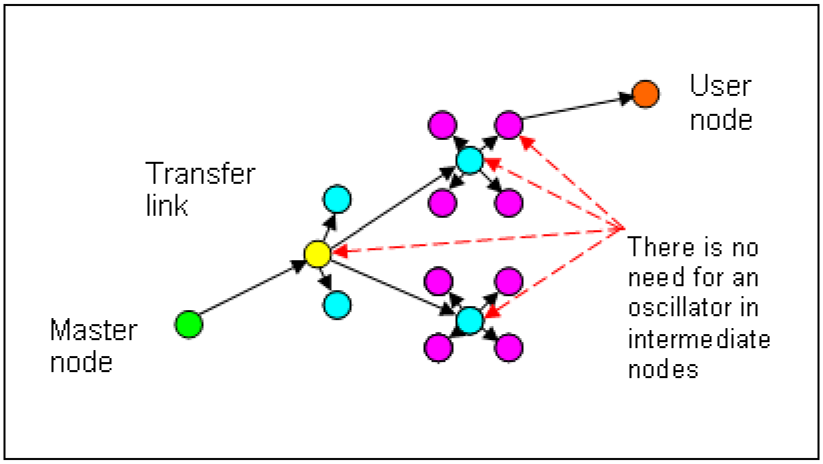

Figure 7. Possible method and proposal of transfer network tree.

REFERENCES

[1] R. Emardson, P. O. Hedekvist, M. Nilsson, S. C. Ebenhag, K. Jaldehag, P. Jarlemark, J. Johansson, L. Pendrill, C. Rieck, P. Löthberg, and H. Nilsson, 2005, "*Time and Frequency Transfer in an Asynchronous TCP/IP over SDH-network Utilizing Passive Listening,*" in Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, British Columbia, Canada (IEEE 05CH37664C), pp. 908-913.

[2] 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 Fibre,*" **IEEETransactions on Instrumentation and Measurement, 57,** 2495-2501.

[3] S. C. Ebenhag, K. Jaldehag, P. Jarlemark, P. O. Hedekvist, R. Emardson, and P Löthberg, 2008, "*Time transfer using an asynchronous computer network: Results from a 500 km baseline experiment*," in Proceedings of the 39th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 27-29 November 2007, Long Beach, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 477-487.

[4] 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.

[5] S. C. Ebenhag, P. O. Hedekvist, P. Jarlemark, R. Emardson, K. Jaldehag, C. Rieck, and P. Löthberg, 2009, "*Measurements and Error Sources in Time Transfer Using Asynchronous Fiber Network,*" **IEEETransactions on Instrumentation and Measurement,** in press.

[6] 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 European Frequency and Time Forum (EFTF), 5-7 March 1996, Brighton, UK (IEEE CP-418), pp. 461-464.

[7] M. Kihara, A. Imaoka, M. Imae, and K. Imamura, 2001, "*Two-Way Time Transfer through 2.4 Gb/s Optical SDH Systems,*" **IEEETransactions on Instrumentation and Measurement, 50,** 709-7151.

[8] 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.

[9] 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 23rd European Frequency and Time Forum (EFTF) joint with the IEEE International Frequency Control Symposium (FCS), 20-24 April 2009, Besançon, France, pp. 1061-1064.

[10] L. G. Cohen and J. W. Fleming, 1979, "*Effect of temperture on transmission in lightguides,*" **The Bell System Technical Journal, 58,** 945.

[11] L. A. Bergman, S. T. Eng, and A. R. Johnston, 1983, "*Temperture stability of transit time delay for a single-mode fibre in a loose tube cable,*" **Electronics Letters, 19,** 865-866.

[12] W. H. Hatton and M Nishimura, 1986, "*Temperature dependence of chromatic dispersion in single mode fiber,*" **Journal of Lightwave Technology, LT-4,** 1552-1555.

[13] D. N. Payne and A. H. Hartog, 1977, "*Determination of the wavelength of zero material dispersion in optical fibers by pulse-delay measurements,*" **Electronics Letters, 13,** 627-629.

[14] D. Marcuse, 1981, **Principles of Optical Fiber Measurements** (Academic Press, New York).

[15] 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.