TIME TRANSFER USING AN ASYNCHRONOUS COMPUTER NETWORK: RESULTS FROM A 500-KM BASELINE EXPERIMENT

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Abstract

SP Technical Research Institute of Sweden and STUPI have performed a time transfer experiment over a 500-km-long baseline between Borås and Stockholm. The time transfer technique passively utilizes the data bit stream generated in an optical fiber computer network based on the packet over SONET/SDH technique. A small fraction of the optical signal is monitored both at the transmitter and at the receiver. When an occurrence of a unique bit sequence of the SDH frames is detected, an electrical pulse is generated and compared with a resolution of 100 ps to a local clock. With data from all four positions of an optical bidirectional link, two-way time transfer can be achieved and any symmetrical variations in delay can potentially be cancelled. The results presented here have been obtained over OptoSUNET, the new Swedish University Network. In the experiment, 10 Gbit/s traffic from SP over OptoSUNET is extended in Stockholm to STUPI, a clock laboratory which is the second node in this setup. This reconnection enables that a communication channel is established between two nodes, with no intermediate jump. The time-transfer experiment includes more than 500 km of fiber transmission, of which several km is via air-lines. By comparing the results from a GPS carrier-phase link, a precision better than ± 1 ns is achieved over several months of measurements between two hydrogen-masers.

INTRODUCTION

A technique utilizing optical fiber networks for time and frequency transfer has previously been studied by SP for baselines extending up to about 7.5 km **[1-3]**. This paper presents results of a time transfer between two hydrogen masers separated by approximately 500 km. The technique is utilizing passive listening on existing data traffic in an optical fiber computer network based on packet over SONET/SDH (POS). In this technique, a small fraction of the optical signal is monitored at both the transmitter and the receiver. At the instant when a unique bit sequence of the transmitted SDH (Synchronous Digital Hierarchy) frames is detected, an electrical pulse is generated and compared with a resolution of 100 ps to a local clock. With data from all four positions of an optical bidirectional link, two-way time transfer can be achieved and any symmetrical variations in the delay can potentially be cancelled. The results presented in this paper have been obtained in an experiment using OptoSUNET, the new Swedish University Network (SUNET). In the experiment, 10 Gbit/s POS-based traffic transmitted from SP over OptoSUNET is extended in Stockholm to STUPI, a clock laboratory which is the second node in this setup. This reconnection enables a communication channel to be established between two nodes, with no intermediate node (see Fig. 1). At the same time, traffic from STUPI is received at SP. This is the first time this technique has been used to perform a time transfer between two hydrogen masers over a distance longer than 500 km, of which several km of the fiber transmission is through air-lines.

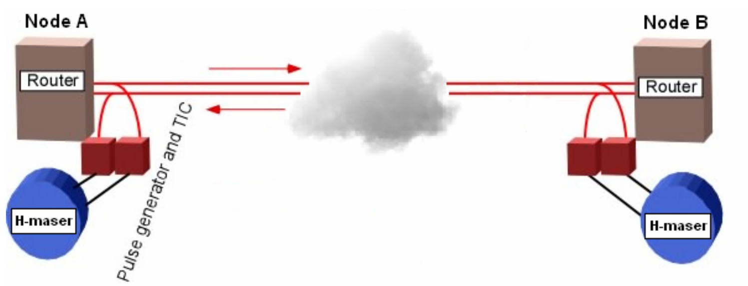

Figure 1. Clock comparison. The clocks in node A and node B can be compared using the bit stream going in both directions. The approximate distance between node A and B is 500 km.

The experiment is a part of a project with the purpose to develop and evaluate a method of comparing clocks over long distances as a supplement to existing and well established satellite-based time transfer methods, such as GPS and two-way time transfer over stationary satellites (TWSTFT) **[4]**. Other studies of time transfer over optical fiber networks have been presented earlier; see, e.g., **[5-7]**. These studies are, however, based on active transmission of data bits, which requires dedicated bandwidth for transmitting timing signals, or over dedicated networks. Implementation of those methods will require the inclusion of new devices in the transmitters and an allocation of bandwidth in the network. The system presented here has the desirable feature that it utilizes passive monitoring on already existing data traffic and, thus, influences the active data communication less.

SYSTEM STRUCTURE

As mentioned above, we are using an existing infrastructure as our time transfer platform (OptoSUNET, an optical fiber computer network based on packet over SONET/SDH). The network is based on dense wavelength division multiplexing (DWDM) with 50 GHz spacing. SONET/SDH was designed to have all clocks synchronized and traceable to UTC according to ITU-T G821. When operating IP routers over DWDM systems, no synchronization is required as the entire payload is terminated at each router and the payload data, which is IP packets, are transferred to the next link by a store and forward model. The frequency stability requirement is set by the lock range of the WDM transponders. Most high end IP routers implement the clock by using a local SDH stratum 3 OCXO, and that oscillator is used to drive the transmitter. The SONET/SDH framing and the rate of the bit stream in each router is driven by the local oscillator OCXO in each router.

OptoSUNET is constructed in a star topology with a central hub in Stockholm, such that each node, containing IP-routers, across the country communicates with the hub over a dedicated wavelength. The configuration necessitates that all communication passes through the central hub.

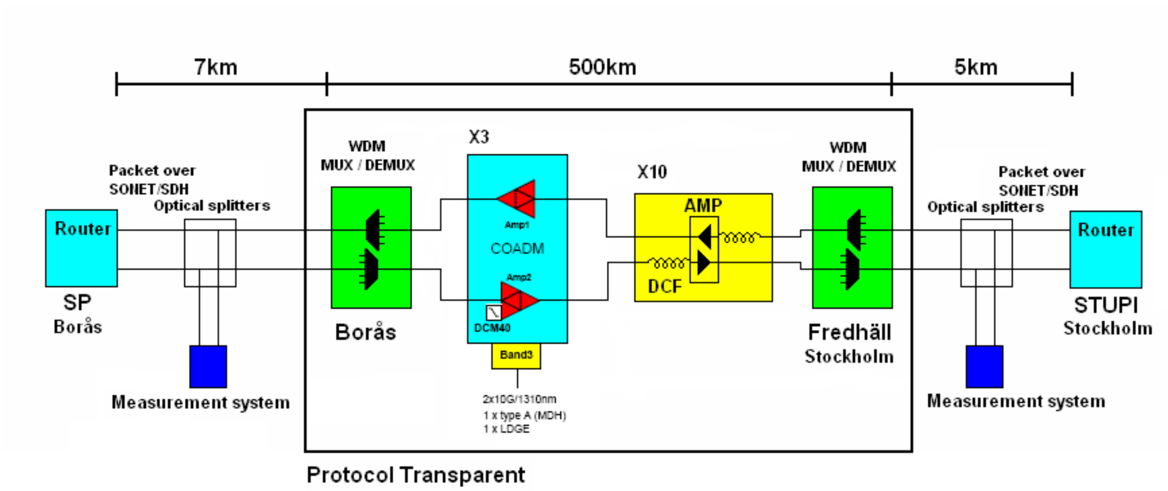

Figure 2. Protocol transparent WDM-network with ten stations of DCF and amplification.

Fig. 2 shows at typical link between two nodes in the network. Along the specific path between SP and STUPI, there are three filters and ten sites with amplification and dispersion compensations equipment. This path consists of 551 km of SMF28 fiber distributed over nine spans inside the DWDM system and 12 km of access fiber to the DWDM transponders. At almost every amplifier station, chromatic DCF (dispersion compensation fiber – a high negative dispersion fiber) are inserted in the amplifier mid stage.

Fig. 3 shows the transponders in each end, the nine optical amplifiers and the dispersion compensation modules in the path. The numbers in the boxes represent the equivalent length of SMF28 fiber positive compensation performed. Dispersion compensation fiber is approximately 14% of the corresponding SMF28 fiber. In some of the amplifier sites, the compensation fiber has different lengths for east-west versus west-east and this might introduce asymmetrical fiber delay changes due to temperature changes in the stations. Amplifier sites are not temperature stabilized.

The sites between SP and STUPI are Borås, Ulricehamn, Skövde, Mariestad, Laxå, Örebro, Arboga, Västerås, Bålstad, and Stockholm, and are marked in the map in Fig. 4.

The technique used for this experiment is applicable, with minor adjustments, to any packet-based data-transmission network, but for practical reasons it is developed for use with SDH as the physical layer, at the bit-rate STM-64 corresponding to 9 953 Mbit/s. SDH defines the transmission of packets of data in nominally 125 µs long frames, where each frame starts with a sequence that defines the beginning of a new frame. At STM-64, this sequence is 192 A1 bytes followed by 192 A2 bytes, where A1 is {11110110} and A2 is {01101000}. The A1A2 sequence is chosen in SDH, since it is extremely improbable that it occurs anywhere else in the bit stream, and therefore can be used as a reference marker for detection of the start of a new frame.

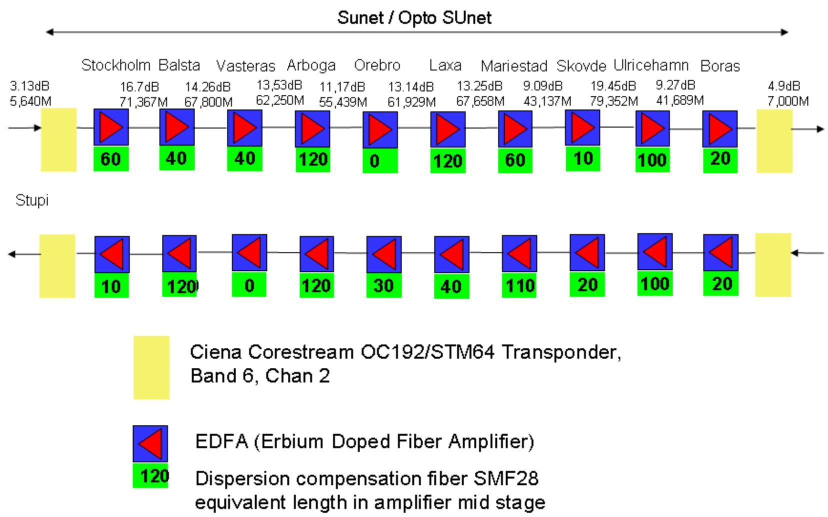

Figure 3. DCF-length and amplification of the sites between SP (Borås) to the right and STUPI (Stockholm) to the left.

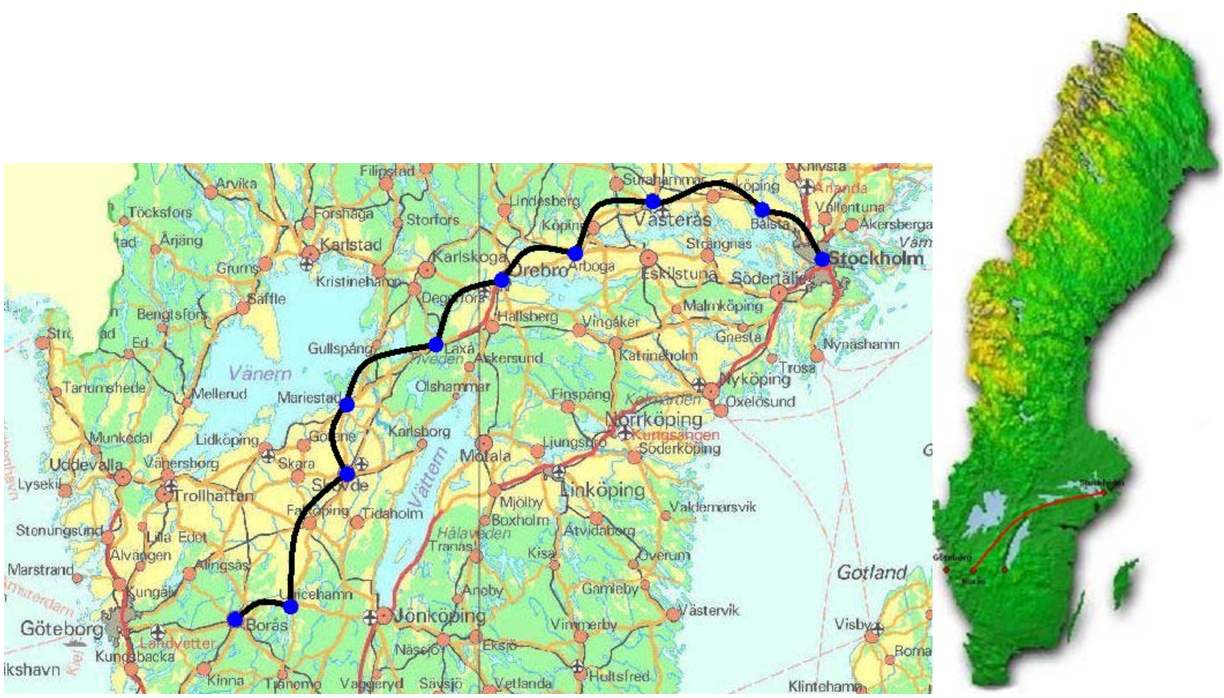

Figure 4. Amplification and DCF stations along the 500-km baseline between SP(Borås) and STUPI (Stockholm).

The reference marker is an electrical pulse generated at every detection of a full A1A2 sequence, as indicated in Fig. 5. To succeed in a time transfer, this operation must be performed both at the bit stream leaving the node, as well as the bit stream arriving to the node, i.e. in a two-way sense. The fundamental idea is to detect the time when this frame-start sequence is transmitted from a node in the network, in combination with the time when the same sequence arrives at the receiving node. Of course, both time stamps are relative to the respective local clock at that node. The frequency offset and stability of the OCXO clock source for the SONET/SDH framing do not affect the performance of the time transfer.

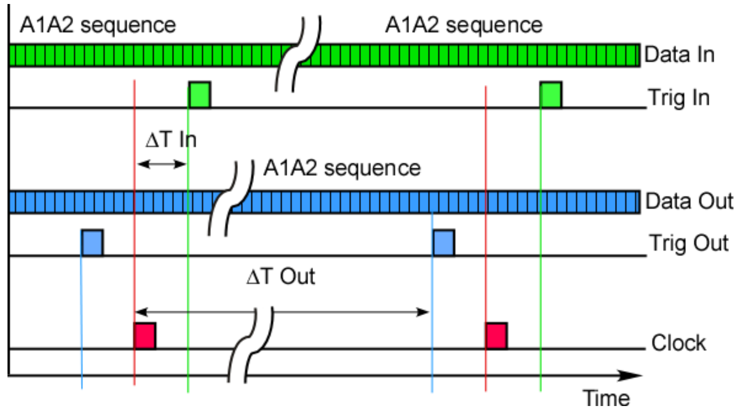

Figure 5. Schematic of pulse generation from SDH bit stream.

To implement the system in OptoSUNET, each fiber is equipped with two passive fiber-optic power-splitters (see Fig. 2). At the transmitter, where the power level is high, 1% of the light is connected to the time analysis circuits, and at the receiving end, where the power level is low, 10% is split-off to the circuits. The 11% added loss to the fiber transmission will decrease the power margin of the system, but it is anticipated that all systems are implemented with a far higher margin.

For a two-way time transfer, equipment is connected at all fiber ends of the incoming and outgoing traffic in order to generate measurable pulses. All pulses are compared with the local clock using a time-interval counter (TIC) and the measured time-interval data exchange will be used to evaluate the two-way time transfer. The setup of the experiment is shown in detail in Fig. 6. Each clock is connected to two distribution circuits, 10 MHz and 1pps. 10 MHz is used as the time base for the TICs, and 1pps is used for the reference pulse from the clock that starts the time-interval measurement. The set of boxes connected to both ends of each fiber consist of a photo-receiver that transforms the signal to the electrical domain, a Header Recognizer (HR), which analyses the bit stream and emits a pulse once a frame-start is detected, and, finally, a time-interval counter to measure the time interval between the pulses and the local reference clock.

The photo-receiver is a 10 GHz avalanche photodiode (APD) with integrated trans-impedance amplifier (TIA), with sensitivity as good as, or up to 10 times better than the sensitivity of the receivers in the router. Since the system can operate at very low power margin, the 10% available power is sufficient. The HR is the unit that continuously collects the bit stream transmitted over the fiber. At 10 Gbit/s, it searches for the sequence of bits that define the start of a new frame as described above. Every time this sequence is detected, the HR emits a 25-ns pulse with a well-defined delay and a sharp slope (25 ps rise-time). The HR is based on a Field Programmable Gate Array (FPGA) platform, specially developed for this project, in combination with 10 Gbit/s input and output circuits. Finally, the TIC is a commercial lab-bench unit with a resolution of 100ps. The accuracy and resolution of the TICs will influence the overall time transfer performance. In order to evaluate the system, we used a GPS link based on the carrier-phase observables **[8]**.

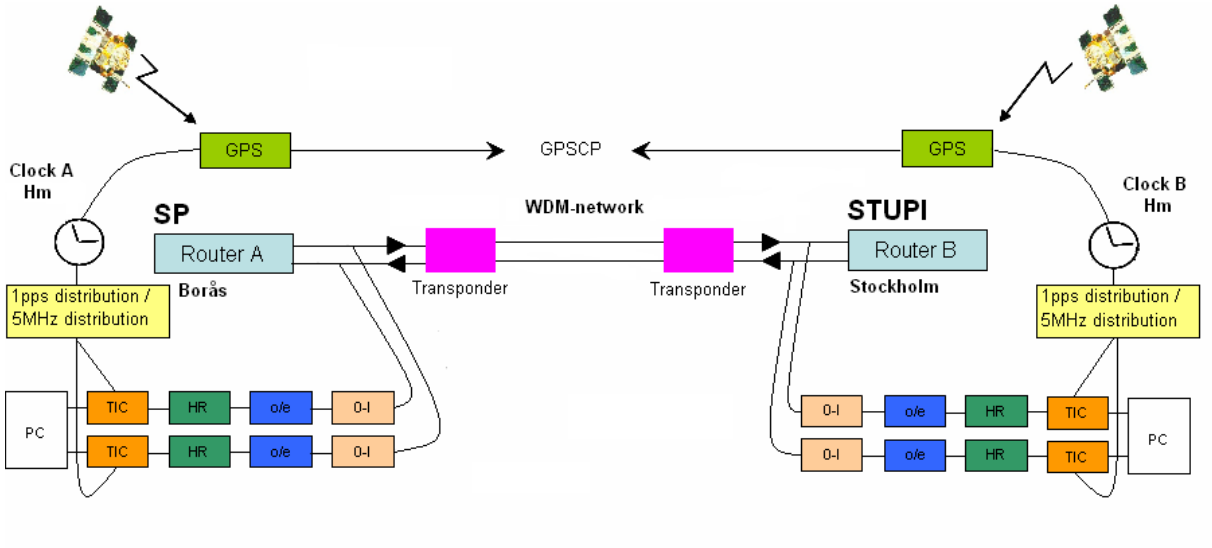

Figure 6. The setup for the 500-km baseline experiment of a fiber time transfer link with GPS carrier-phase link for comparison and evaluation.

EXPERIMENTAL RESULTS

The measured clock difference between the H-maser at SP (node A) and the H-maser at STUPI (node B) during the time transfer experiment (see Fig. 6) is shown in Fig. 7. The left graph shows the clock difference measured with the fiber link and the right shows the clock difference measured with the GPS link. During the experiment, some major problems occurred with one of the H-masers. These problems are expected to affect both links in a similar way.

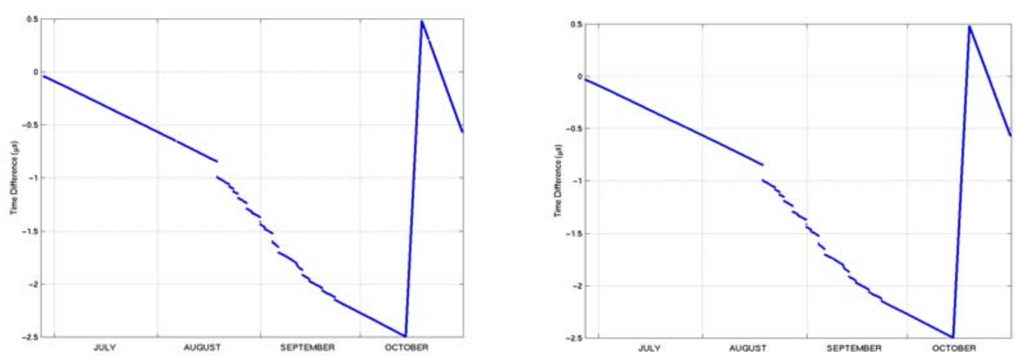

Figure 7. Measured time difference between node A (H-maser at SP) and a H-maser at node B (STUPI). The left graph shows the clock difference measured with the fiber link and the right graph shows the clock difference measured with the GPS link.

No obvious dissimilarity between the two links can be seen in Fig. 7. Fig. 8 shows the difference between the fiber link and the GPS link measurements during the first 4 months of the time transfer experiment. The rms difference between the fiber link and GPS link is less than 770 ps over the total period. In order to facilitate the study of the different characteristics of the results, we divide the measurements into three time periods. The first time period shows a difference of 320 ps rms and runs from 27 June to 16 August (see Fig. 9). These results are in agreement with previous results from similar measurements **[1-3]**. Time period 2 (Fig. 10) stretches from 18 August to 26 August and results in an rms difference of 210 ps. The third time period (Fig. 11) includes the dates 28 August to 31 October and has an rms difference of 860 ps.

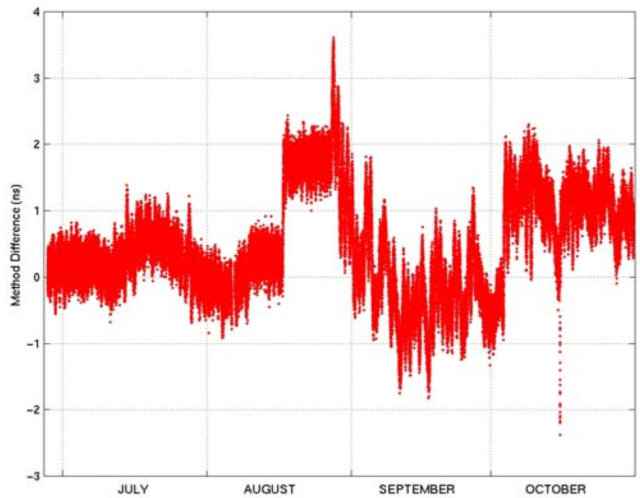

Figure 8. Difference between GPS link and Fiber link during 4 months. The rms difference is 770 ps. An arbitrary offset has been removed.

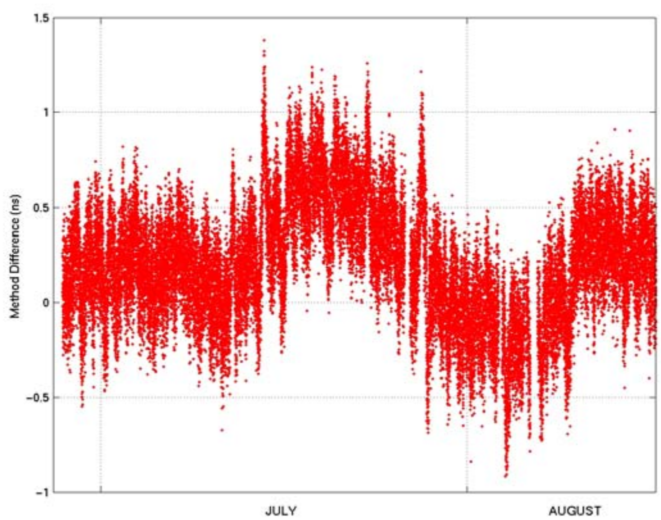

Figure 9. Difference between GPS link and fiber link during time period 1 (see text). The rms difference is 320 ps. An arbitrary offset has been removed.

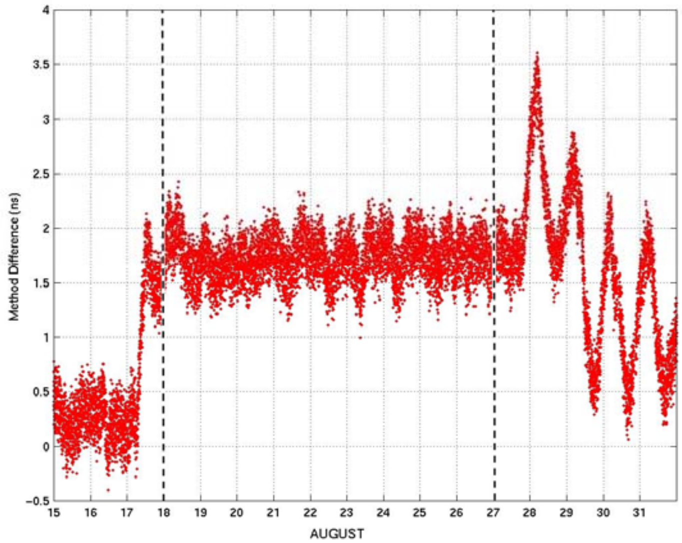

Figure 10. Difference between GPS link and Fiber link during time period 2 (see text). The rms difference is 210 ps. An arbitrary offset has been removed.

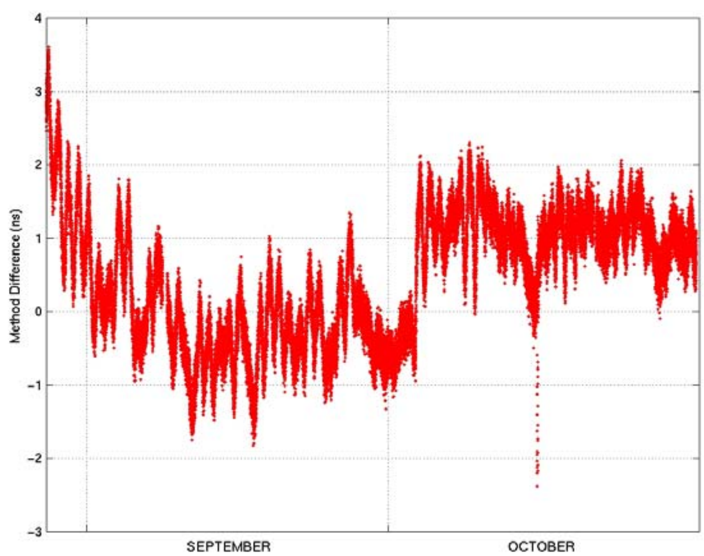

Figure 11. Difference between GPS link and fiber link during time period 3 (see text). The rms difference is 860 ps. An arbitrary offset has been removed.

In the measurement period (see Fig. 8), two major changes may be discussed. The first one is a step at 17 August and the second change is the onset of some oscillations at 27 August. In that region of time when the step occurred, a new climate control was installed at one site that contains DCF and amplification.

The periodical oscillations which can be observed in Fig. 11 started after this installation. Furthermore, in the beginning of November the malfunctioning H-maser and some other equipment were replaced at STUPI. The periodic variations disappeared after this restart. However, the measurement noise, as seen in the right graph in Fig. 12, increased somewhat. As a part of the future work, we will investigate the cause behind the observed oscillations and also try to explain why the measurement noise increased after the maser replacement. It is not at this writing obvious why the change of maser and other equipment affected the two links differently.

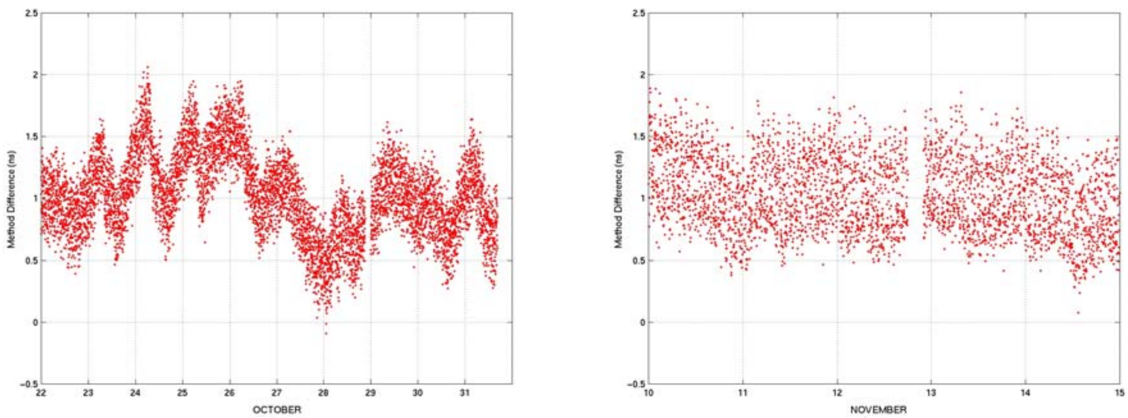

Figure 12. The graphs above shows the difference between GPS link and fiber link. The left graph shows perodic variations in October before change of H-maser and other equipmnet at STUPI. The right graph shows the difference between the systems after changes; the oscillations are gone, but the noise has been increased.

In comparison, the single-route fiber path delay variations are shown in Fig. 13. The link consists mainly of ground buried fiber, but also some aerial fiber, mounted along the power delivery lines. It is clear that the variations are at the magnitude of 100 ns, which proves that the two-way cancellation operates properly. In any case, as seen above, some oscillations still remain.

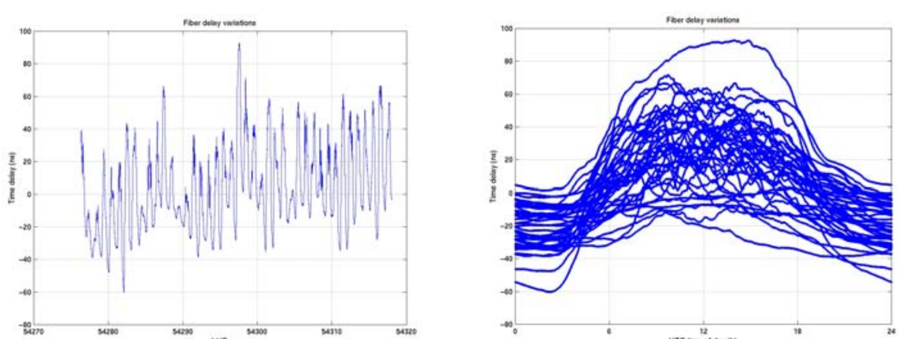

Figure 13. Single route fiber path delays variations over 43 days (left) and 24 hour overlay (right).

As a start to investigate if these oscillations are dependent on temperature, we started to measure the temperature in the amplifiers power supplies. We did not have temperature data from the amplifier sites to correlate with the oscillations during the first 4 months of the experiment. A big difference between the stations in behavior can been se in Fig. 14.

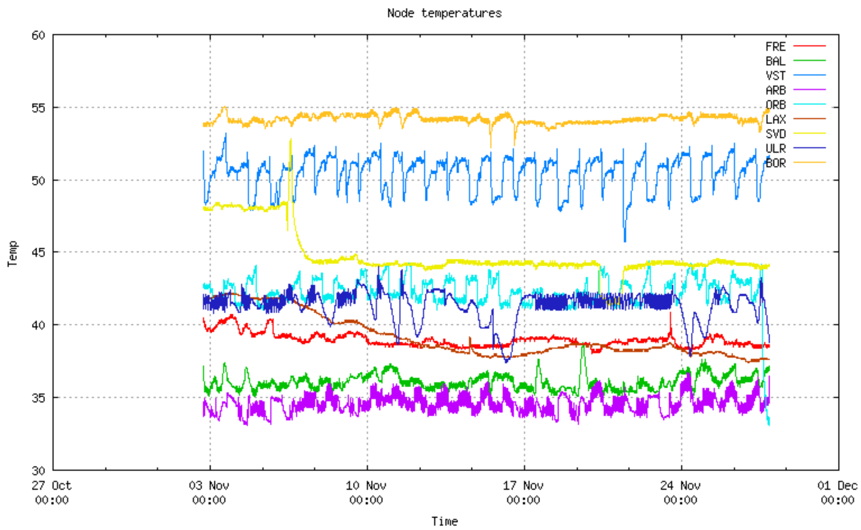

Figure 14. Temperature in amplifier power supply; 22-day view.

CONCLUSION

We have developed a demonstrator for time transfer using passive listening on existing traffic in optical-fiber computer networks based on Packet over SONET/SDH. Previous experiments **[1-3]** have shown good results on shorter baselines, and the result of this experiment shows that the technique also has a potential on baselines longer than 500 km. A precision relative to GPS carrier phase of < 1 ns was obtained, which is similar to previous experiments. The experiment indicates that there is no obvious linear degradation of the precision with distance.

More studies are needed especially on differential path delays in the optical fiber links (DCF) due to asymmetry and temperature dependence of the equipment.

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REFERENCES

[1] 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, "*Time Transfer by Passive Listening over a 10 Gb/s Optical Fiber,*" **IEEE Transactions on Instrumentation and Measurement,** in press.

[2] 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, Canada (IEEE Publication 05CH37664C), pp. 908-913.

[3] S. C. Ebenhag, K. Jaldehag, P. O. Hedekvist, R. Emardson, P. Jarlemark, C. Rieck, M. Nilsson, J. Johansson, L. Pendrill, P. Löthberg, and H. Nilsson, 2007, "*Time transfer using an asynchronous computer network: Results from three weeks of measurements,*" in Proceedings of TimeNav'07, the 21st European Frequency and Time Forum (EFTF) Joint with 2007 IEEE International Frequency Control Symposium (IEEE-FCS), 29 May-1 June 2007, Geneva, Switzerland (IEEE Publication CH37839), pp. 323-326.

[4] F. Arias, Z. Jiang, W. Lewandowski, and G. Petit, 2005, *"BIPM Comparison of Time Transfer Techniques,"* 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, Canada (IEEE Publication 05CH37664C), pp. 312-315.

[5] 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 (IEE Conference Publication 418), pp. 461-464.

[6] 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.

[7] A. Czubla, J. Konopka, M. Górnik, W. Adamowicz, J. Struś, T. Pawszak, J. Romsicki, M. Lipiński, P. Krehlik, Ł. Śliwczyński, and A. Wolczko, 2007, *"Comparison of precise time transfer with usage of multi-channel GPS CV receivers and optical fibers over distances of about 3 kilometers,"* in Proceedings of the 38th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 5-7 December 2006, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 337-346.

[8] C. Rieck, P. Jarlemark, and K. Jaldehag, 2006, "*The use of ambiguity resolution for continuos real-time frequency transfer by filtering GNSS carrier phase observations,*" in Proceedings of the 20th European Frequency and Time Forum (EFTF), 27-30 March 2006, Braunschweig, Germany.