Time Transfer Using Fiber Links

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ABSTRACT

This paper describes two-way time transfer over an optical network. The method is based on newly developed adapters utilizing channels in a DWDM (Dense Wavelength-Division Multiplexing) all-optical network. Results of several tests performed in real production network including the time transfer between atomic clocks in Prague and Vienna over more than 500 km long optical link are presented. In addition, the comparison of Common View GPS and optical time transfers is given.

KEYWORDS

Time and frequency transfer, optical network, fiber link, calibration, time scale comparison.

INTRODUCTION

Accurate time transfer between two geographically distant sites is dominated by GPS based systems, however the accuracy of GPS-based time transfer degrades at distances over 1000 km. There exists a request for an alternate technique and optical network is a medium that is predetermined for such applications: it can transfer signal to distance about 100 km without amplification and more than 2000 km (depending on the modulation) with optical amplification. Currently, several research teams are oriented at ultra-stable frequency transfer [1] but only few investigate methods of accurate, long distance time transfer [2], [3]. In recent years, fiber links are easier affordable than in past and backbone networks are being converted to DWDM (Dense Wavelength-Division Multiplexing) technology offering a lot of so called "lambda channels".

SYSTEM ARCHITECTURE

Our time transfer system is an instance of two-way transfer method that relies on symmetrical transport delay in both directions. Fig.1. shows the method and adapter interfaces. Two adapters are connected by a bidirectional optical link. Each adapter is provided by a 1PPS signal from local clock and each adapter has two outputs: T_{Ri} (i = **A**, **B**) is a 1PPS signal received via optical interface from the other adapter and T_{Si} represents epoch the encoded 1PPS signal was sent out. Both T_{Si} and T_{Ri} signals are connected to STOP inputs of two time interval counters (TIC). The first TIC measures interval x_i between T_i and T_{Ri} (i.e. the difference between local and remote 1PPS) and the second TIC measures adapter delay ε_{Si}, i.e. the time between T_i and T_{Si} signals.

1PPS pulse from a local clock arrives to adapter **A** in time t_A. It is transmitted by adapter **A** through the optical fiber to the remote site in time t_{SA} and the reception is signalized by adapter **B** in time t_{RB}. Analogically, 1PPS pulse from remote clock raised in time t_B is transmitted by adapter **B** in time t_{SB} and received by adapter **A** in time t_{RA}. Thus $\Theta_{AB} = t_B - t_A$ is the clock offset, $\varepsilon_{Si} = t_{Si} - t_i$; i = **A**, **B** is the delay of adapter i and $\delta_{AB} = t_{RB} - t_{SA}$ and $\delta_{BA} = t_{RA} - t_{SB}$ is the link delay from site **A** to site **B** and from site **B** to site **A** respectively.

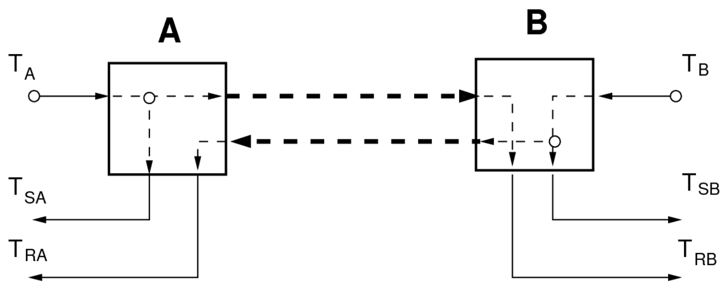

Fig. 1. Method of time transfer

Method of Measurement

Using a pair of time interval counters at both sites, it is possible to measure the adapter delays ε_{Si} and the time intervals

$$x_A = t_{RA} - t_A = \Theta_{AB} + \varepsilon_{SB} + \delta_{BA}, \quad (1)$$
$$x_B = t_{RB} - t_B = -\Theta_{AB} + \varepsilon_{SA} + \delta_{AB}. \quad (2)$$

On a symmetrical link, the delay in both directions equals $\delta = \delta_{AB} = \delta_{BA}$. In real network, the fiber length in both directions slightly differs (e.g. due to patch cords in switching board, fiber compensating the chromatic dispersion), introducing delay asymmetry Δ:

$$\Delta = \delta_{BA} - \delta_{AB}. \quad (3)$$

The clock offset Θ_{AB} may be then calculated as

$$\Theta_{AB} = ((x_A - x_B) + (\varepsilon_{SA} - \varepsilon_{SB}) - \Delta) / 2. \quad (4)$$

Knowing the clock offset Θ_{REF}, the link asymmetry Δ can be evaluated from

$$\Delta = (x_A - x_B) + (\varepsilon_{SA} - \varepsilon_{SB}) - 2\,\Theta_{REF}. \quad (5)$$

Adapter Description

Fig. 2. displays the adapter structure. It consists of two main components: the FPGA chip Virtex 5 and the SFP (Small Form-factor Pluggable) transceiver. The optical signal arrives at the receiver part of the SFP, where it is converted into electrical signal. The demodulator in FPGA regenerates the carrier frequency and demodulates the 1PPS, which is as T_R connected to the STOP input of TIC measuring the value x. The transmitter part contains oscillator generating the carrier frequency - 250 MHz in current prototype. The oscillator can be either locked to an external 10 MHz reference or can be free running. The carrier frequency is than modulated by the 1PPS signal from local clock. A delay up to 4 ns corresponding to the phase difference between 1PPS signal and the carrier is introduced in the modulator. The modulator output T_S is connected to the STOP input of the second TIC measuring the parameter ε. The adapter prototype is shown in Fig. 3.

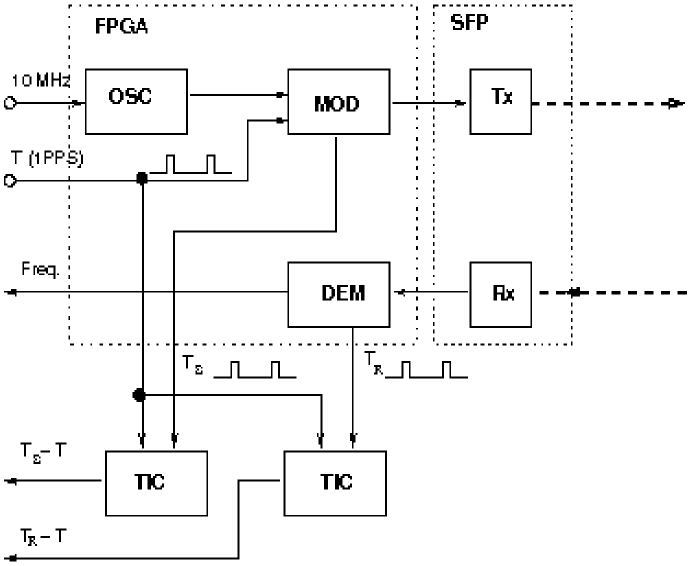

Fig. 2. Adapter structure

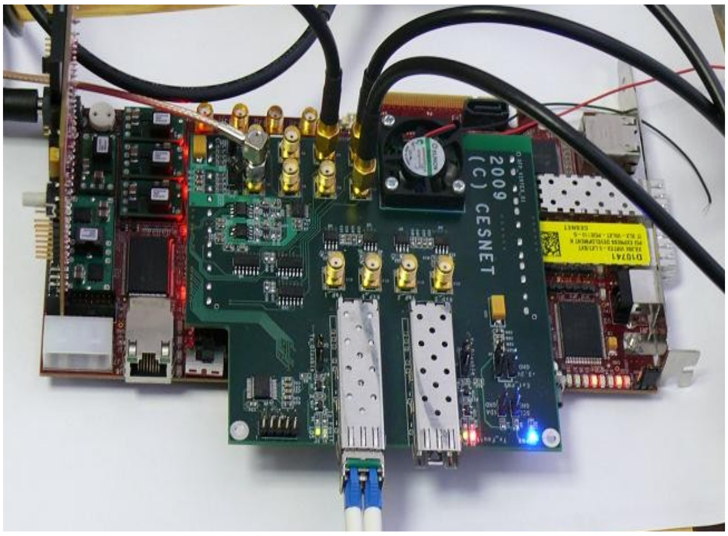

Fig. 3. Adapter prototype

OPTICAL NETWORK

All our experiments were performed using two unidirectional “lambda” (dedicated wavelength) channels in the Cesnet2 network and Prague metropolitan network PASNET. The Cesnet2 network is the Czech NREN (National Research and Educational Network) operated by the association CESNET. Fig. 4. shows DWDM backbone of the Cesnet2 network, including a ring providing two independent routes between the two main points of presence: Prague and Brno. The ring, which we used in one of experiments, is 744 km long (plus another about 80 km of fiber compensating the chromatic dispersion) and is equipped with 12 Erbium doped fiber amplifiers (EDFA).

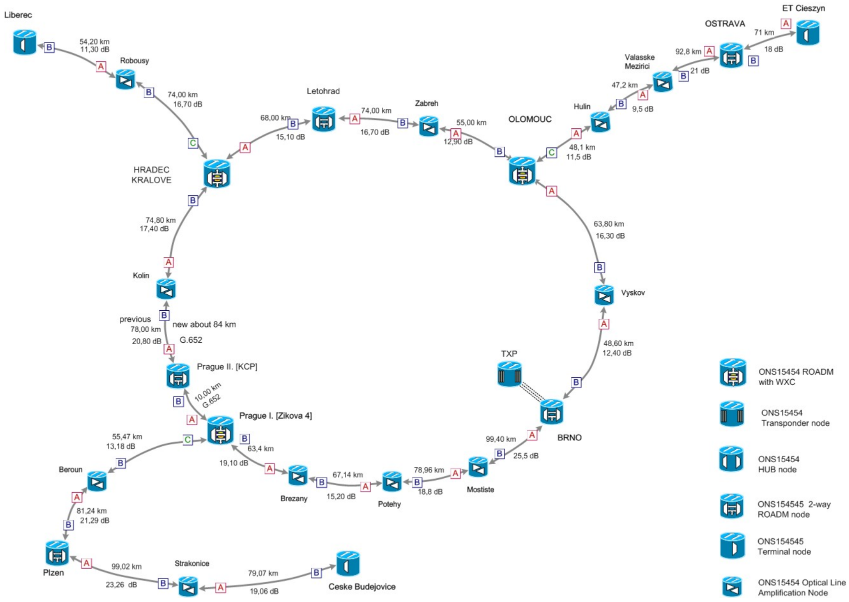

Fig. 4. Cesnet2 network backbone

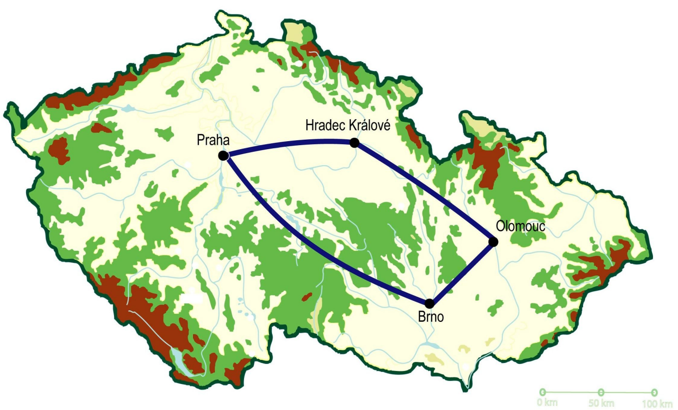

Fig. 5. Optical loop

EXPERIMENTS

We performed several experiments in order to verify the time transfer method and to assess developed adapters. Experiments focused on testing the method at long optical loop, comparing two atomic clocks and demonstrating long distance time transfer between Prague and Vienna.

Experiment 1 – Measurements on Optical Loop

The goal of this experiment was to measure the delay of a long optical path in order to predict the influence of the fiber thermal dilatation on changes of the asymmetry Δ defined in (3). 1PPS from a GPS-disciplined Rb clock was transmitted in both directions and using two time interval counters, the delays δ_{AB} and δ_{BA} were measured. Fig. 4. and 5. show the utilized 744 km long bidirectional optical loop – the route between cities Prague – Brno – Olomouc – Hradec Kralove – Prague. One segment of the loop consists of an optical cable installed on top of high-voltage poles, so its length is markedly affected by daily changes of temperature.

Fig. 6. displays one-way delays δ_{AB} and δ_{BA}. (Note: average value of Δ (3) is 7.378 µs but δ_{AB} is shifted for 7,36 µs in the graph for sake of clarity). Observed daily variations of ~130 ns in the link delays were apparently caused by thermal dilatation of the fiber. We expect that the main contribution to this dilatation came from the placement of optical cable on top of electricity distribution poles in the segment Hradec Kralove – Prague. Fortunately, the calculated time offset (4) does not depend on particular delays δ_{AB} and δ_{BA} but on the difference Δ, which is shown in Fig. 7. Ideally, Δ should be constant - its variations represent the accuracy of the time transfer.

Fig. 8. displays stability of the time transfer in terms of Time deviation denoted as TDEV or $\sigma_x(\tau)$ – we see that for averaging intervals up to 200 s, the white phase modulation $\sigma_x(\tau) \approx 100$ ps/√τ prevails. We assume this noise originates apparently in the modulation/demodulation of the carrier signal and in the output circuits of the adapters. The lowest value of ~8.1 ps for averaging time 500 s has been observed.

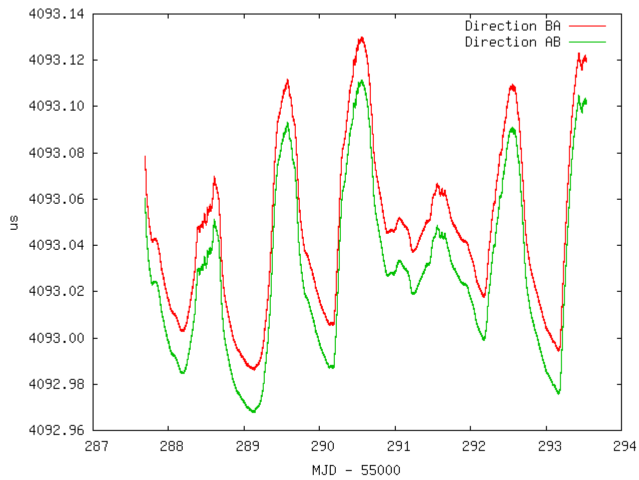

Fig. 6. One-way delays

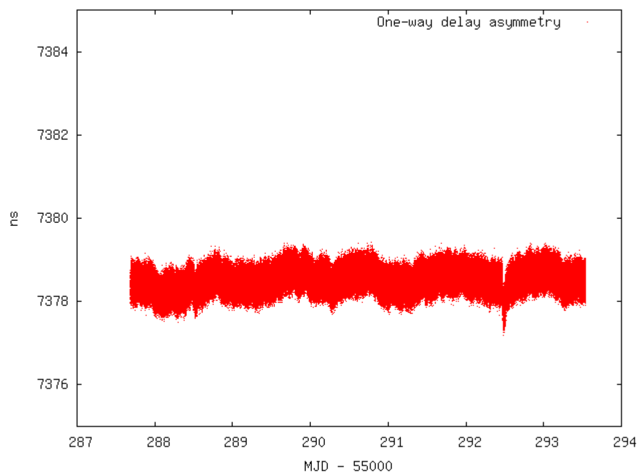

Fig. 7. Asymmetry of optical loop

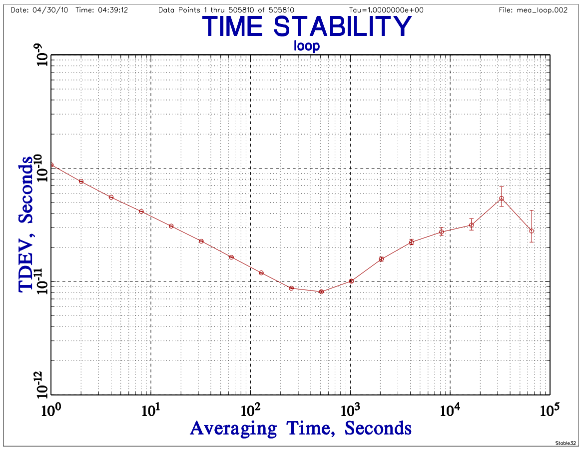

Fig. 8. Time stability of optical loop

Experiment 2 – Time Transfer between Cesnet and IPE

In this experiment, we compared UTC(TP) time scale generated from Cs clock HP5071A in the Laboratory of the National Time and Frequency Standard in IPE with time scale generated from Rb clock in Cesnet (GPS disciplined Rb clock PRS10 from Stanford Research Systems). The length of optical link between Cesnet and IPE is about 24 km and it is part of the Prague metropolitan network Pasnet. There is no optical amplifier installed in the path.

Both sites are equipped with GPS time transfer receiver GTR50 allowing us to make complementary Common View GPS (CV GPS) comparison. The clock comparison using both techniques is shown in Fig. 9. It should be mentioned that data from GTR50 have granularity 960s, while PRS10 control loop adjusts the frequency in steps of $1 * 10^{-12}$, therefore the time offset might change for 1 ns during one measurement cycle. Thus GTR50 results can not display fine and rapid changes of PRS10 time offset. Nevertheless, the standard deviation of the difference between both time transfers is about 500 ps. We expect that a comparison with higher precision could be done using more stable clock, either another Cs clock or at least a free running Rb clock.

Time stability of the clocks compared in this experiment in terms of Time deviation is displayed in Fig. 10. For averaging time up to 400 s, the noise of the optical link of ~100 ps in terms of TDEV is dominant while for longer averaging time, performance of Rb clock in Cesnet prevails.

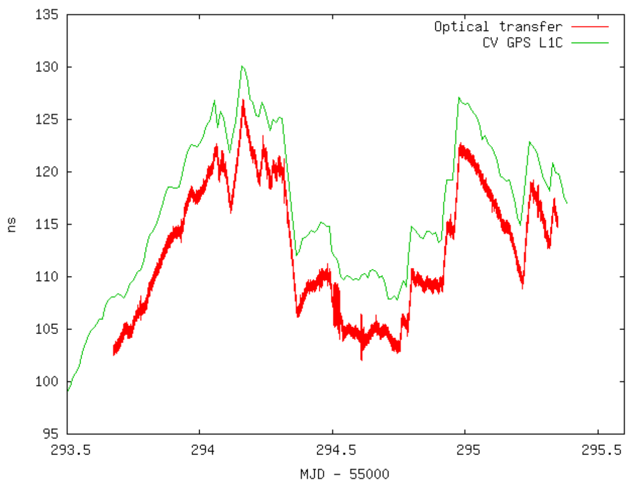

Fig. 9. Comparison of optical and GPS time transfer

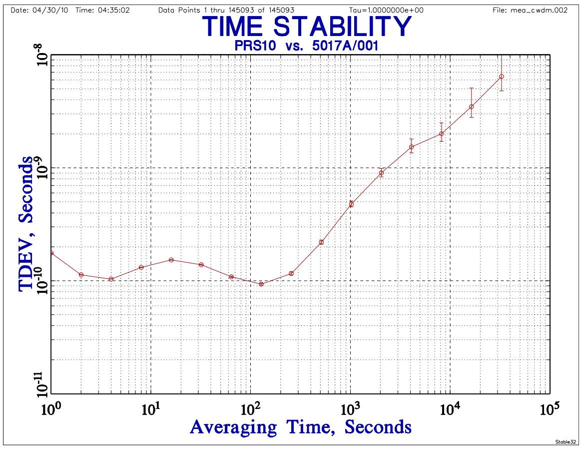

Fig. 10. Time stability of the optical time transfer between IPE and Cesnet

Experiment 3 – Time Transfer between Prague and Vienna

Cesnet operates also a DWDM fiber link from Brno to Vienna, where it ends in the premises of ACOnet (Austrian national research and education network) located in Vienna university campus. The length of this fiber link is 504 km excluding the fiber compensating chromatic dispersion.

This last experiment aimed at time transfer between Prague and Vienna. In Prague, we used the same GPS-disciplined Rb clock as in previous experiment. In Vienna, the situation was complicated by not yet operational fiber link between Vienna University and BEV. Therefore, BEV transported their Rb clock (Quartzlock LPRO) to ACOnet, where it was operated as free-running during the test.

Measured time offset between the clocks and corresponding time stability is shown in Fig. 11. and Fig. 12. As the clock in Prague was disciplined by GPS, we can conclude that free-running Rb clock in Vienna had a relative frequency offset of ~$8 * 10^{-12}$.

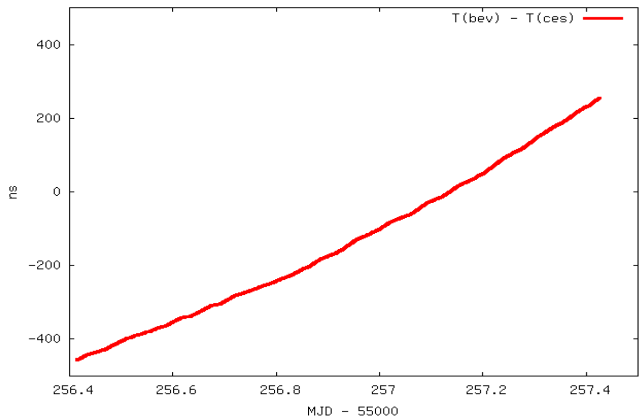

Fig. 11. – Time transfer between Rb clocks in Prague and Vienna

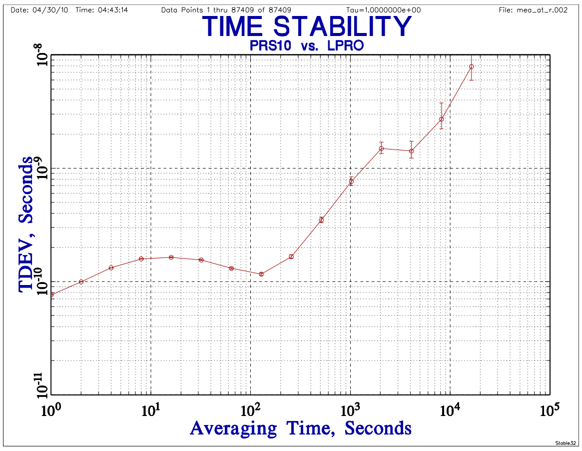

Fig. 12. – Time stability of the optical time transfer between Prague and Vienna

CONCLUSIONS

We successfully tested our adapters for time transfer on a 740 km link in real production network and we proved that the system is compatible with DWDM technology.

We measured time stability of the time transfer with minimum value of 8.7 ps in terms of TDEV at averaging time of 500 s. This value includes all sources of inaccuracy, i.e. the noise in transmission channel, SFP transceivers, signal modulator/demodulator etc. We also compared the accuracy of our method with the time transfer using common-view GPS.

Time stability of short distance (Experiment 2) and long distance (Experiment 3) time transfers are nearly identical for time intervals up to 300 s. We can conclude that the effect of fiber length and optical amplifiers is sub-dominant compared to other common effects like the method accuracy, noise in adapter prototypes and stability of the Rb clock.

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