Time transfer using an asynchronous computer network: Results from three weeks of measurements

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***Abstract*—We have performed a time transfer experiment between two atomic clocks, over a distance of approximately 75 km using an 10 Gbit/s asynchronous fiber-optic computer network. The time transfer was accomplished through passive listening on existing data traffic and a pilot sequence in the SDH bit stream. In order to assess the fiber-link clock comparison, we simultaneously compared the clocks using a GPS carrier phase link. The standard deviation of the difference between the two time transfer links over the three-week time period was 243 ps.**

I. INTRODUCTION

The Swedish National Time and Frequency laboratory, located at SP in Borås, has performed a time transfer, schematically shown in Fig. 1, between two clock locations SP (node A) and Gothenburg (node C) using a computer network based on communication over optical fiber. In this network, all communication between node A and node C passes Borås City (node B). Since the data transmission over every node is asynchronous, a third clock is used at node B in order to bridge the time step between the incoming and outgoing data transmission. In this field trial the clock at node A was the national time scale UTC(SP) based on a Cesium clock, whereas the two other were Rubidium atomic clocks. The network distance between node A and node C was approximately 75 km.

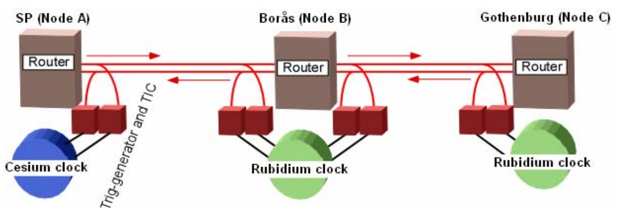

Figure 1. Clock comparison. The clocks in node A and node C can be compared using the signals going in both directions. Approximate distance between node A and B is 5 km, and between node B and C is 70 km.

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Mattias Nilsson†, deceased.

One of the goals with this project is to develop a method to compare 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). The proposition to utilize fiber-optic networks for accurate time transfer is not new [1,2]. However, previous and present alternative methods have used dedicated bandwidth for transmitting timing signals. Despite promising results, implementation with those methods will require the inclusion of new devices in the transmitters and an allocation of bandwidth in the network. Our system has the desirable features that it influences the active data communication less.

II. SYSTEM STRUCTURE

The time transfer technique proposed in this paper, see also [3], utilizes data communication in an existing fiber optic network to distribute time with comparable accuracy as present GPS-based time transfer technique, i.e. with an accuracy of a few ns. The benefits of the technique are twofold: first, there is no need for any infrastructure deployment, assuming that all clients have network access, and secondly, there is a minimum requirement of bandwidth in the backbone fiber-optic network.

The proposed technique is applicable, with minor adjustments, to any packet based data-transmission network, but for practical reasons it is developed for use with Synchronous Digital Hierarchy (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 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.

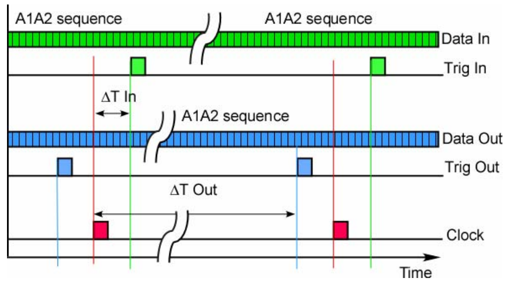

Figure 2. Schematic of pulse generation from SDH bit stream.

In the demonstrated time transfer system, at every instance a full A1A2 sequence is detected, an electrical pulse is generated, as indicated in Fig. 2. For a successful 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 local clock at that node.

In full implementation, every node in the nationwide network would operate as described above and, through an open access to all time measurements between the customer node and UTC(SP), an accurate time can be extracted at every node in the network. For a first, small-scale research implementation, the Swedish University Computer Network was used. During the trial, the network map was as shown in Fig. 3. This also corresponds to a typical backbone fiber optic computer network.

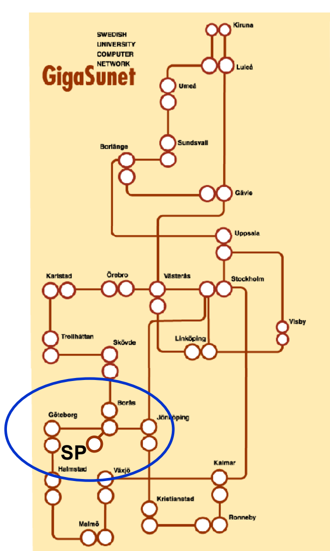

Figure 3. Network map of GigaSUNET, the Swedish University computer Network 2002 - 2007. The circle highlights the section that the field trial used.

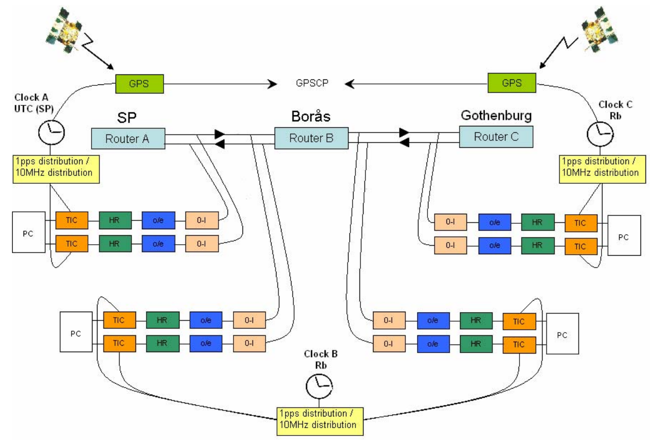

Figure 4. The setup for the three-week experiment of a fiber time transfer link with GPS-link for comparison and evaluation.

III. EXPERIMENTAL SETUP

To implement the system in SUNET, each fiber is equipped with two passive fiber-optic power-splitters. 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. 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. 4. 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 consists 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 (TIC) to measure the time interval between the pulses and a reference clock. The photo-receiver is a 10 GHz avalanche photodiode (APD) with an integrated trans-impedance amplifier (TIA), with sensitivity almost 10 times better than the sensitivity of a p-i-n photodiode operating at the thermal limit. 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. Every time this sequence is detected, the HR emits a 25 ns pulse with a well defined delay and a sharp steep 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. The last device is the TIC, which in the present measurement 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, since this is the digitalization [3]. Finally, in order to evaluate the system we used a GPS link based on carrier phase observables. This GPS link comparison is only needed between the outer nodes.

IV. EXPERIMENTAL RESULTS

The graph in fig. 5 shows the results of the clock comparison between UTC(SP) at node A and the Rubidium clock in node C using the two-way optical fiber time transfer method and the setup shown in Fig. 4.

The accuracy of the time transfer depends on the precision and accuracy in the evaluation of the transmission delay, which must be measured with a sampling frequency exceeding the fastest variation that has to be detected. Since this experiment is performed in an optical communication network, the main parameter is the transmission delay through the fiber. It is well known that the fiber delay varies with temperature, which is a slow process if the fiber is below ground, but any mechanical strain can also cause variations. Vibrations will appear as a fast fluctuation on the delay, but as this is presumed to appear as a zero-mean noise, it will not be a noticeable effect on the time transfer. Two-way measurements, schematically described in Figs. 1 and 4, were performed in order to compensate for changes in delay of the transmission in the optical fiber. The TIC measures one time interval every second, which will detect any variation slower than that. The derived, time-dependent delay is shown in Fig. 6, where it is apparent that the delay follows the slow day-by-day trends of the outdoor temperature, but not the fast variation during the sunny hours.

Data from the TIC-measurements are combined and used to calculate the transmission delay through the fiber optic links and the time difference between the two clocks. These results are compared with the GPS carrier phase technique and the difference between the two methods is shown in Fig. 7.

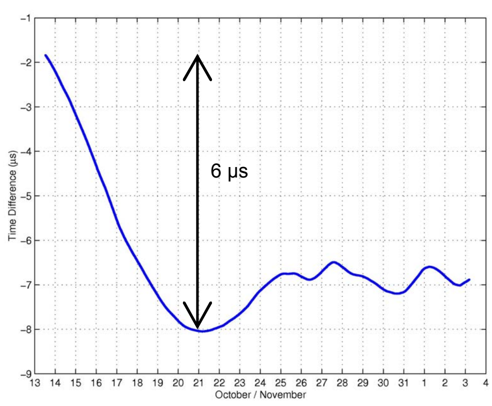

Figure 5. Measured time difference between UTC(SP) node A and Clock C (Rb) during the experiment. Evaluation through two-way optical fiber time transfer method.

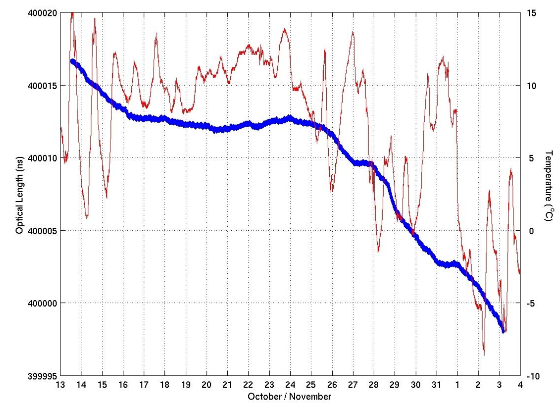

Figure 6. Optical length of the fiber between Borås City node B and Gothenburg node C. The outdoor temperature at Gothenburg is shown in red.

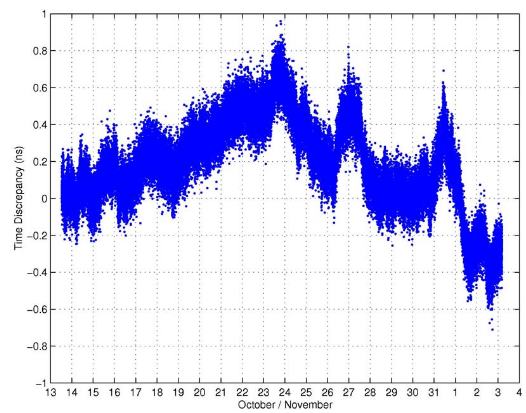

Figure 7. Difference between GPS-link and Fiber-link from 3 weeks of measurement. An arbitrary offset has been removed.

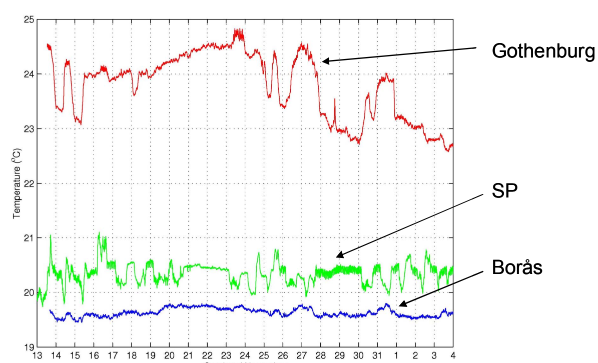

Figure 8. Indoor temperature in the clock nodes during 3 weeks of measurement.

The difference between the two methods has a standard deviation of 243 ps. Systematic variations are also evident. These are both correlated with (1) the temperature measured among the electronic cabinets and (2) the outside environmental conditions. Some of the variations are thus assumed to be dependent on the electronic components and instruments. Therefore we also performed measurements in a climate chamber to evaluate the environmental dependence of the electronic components individually [4]. The evaluation of the components has resulted in a decrease in the standard deviation of the difference between the fiber and GPS links to 184 ps, if the dependence on the indoor temperature is removed from the comparison shown in Fig. 7. The indoor temperatures in all three locations are shown in Fig. 8. The evaluation of the correlation with the outside environmental conditions will be analyzed in further detail and presented elsewhere.

V. CONCLUSION

We have experimentally verified the feasibility of time transfer utilizing passive listening on existing traffic in optical fiber computer networks based on Packet over SONET/SDH. This field-trial was completed over a distance of 75 km, during three weeks when the outdoor temperature varied almost 25°C. The stability of the time transfer was evaluated using a comparison with time transfer using the GPS carrier phase method. This resulted in a standard deviation of 184 ps between the two methods, taking temperature dependence of the local equipment into account. More studies are needed, especially on differential path delays in fiber links due to asymmetric installations as well as asymmetric delays caused by different indoor temperatures at different nodes. Therefore, time transfer on a longer baseline (about 500 km) with more stable clocks at both ends (hydrogen masers) in a controlled environment is planned. Integration of hardware and calibration of internal delays are future work.

VI. REFERENCES

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