Evaluation of Time Transfer Units for Time and Frequency Transfer in Optical Fibers Utilizing a Passive Technique Based on SONET/SDH

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Abstract—The time transfer method of using passive listening and detection of SDH frame headers in fiber-optical networks has been presented earlier. Previous results, using commercialized equipment and commercial fiber-links, have shown that time transfer with a precision of the order of a few nanoseconds is possible over links with network distances exceeding 1100 km. The motivation of the work has been to develop an alternative and complementary time transfer method using existing infrastructure and to make it accessible to regular users of time keeping equipment.

All previous reported experimental results were performed by SP Technical Research Institute of Sweden in commercial data communication networks in Sweden and Finland. This paper will report on the recent results from an experimental fiber test network implemented at the U.S. Naval Observatory. The fiber network is in a loop-back configuration with the two node elements in the same rack. The fiber link that connects the nodes is in an environmental chamber that allows a means to apply controlled fiber length fluctuations to the link. The performance of the Time Transfer Unit (TTU) was evaluated in this setting. This will be the first independent evaluation of the TTU equipment.

Key words: Two-way, fiber, passive frequency transfer

I. INTRODUCTION

The motivation of developing a fiber-based time transfer method using existing infrastructure is to have access to an alternative and complementary time transfer method. The goal is to make it accessible to regular time and frequency users with precision and accuracy comparable to readily used satellite-based methods. It is well known that time transfer methods using global positioning systems, such as GPS (see e.g. [1] and references therein), are used in a variety of time and frequency applications. For applications requiring extended robustness and reliability, it is often necessary that complementary, backup methods are available with similar precision and accuracy. For instance, in international time metrology, two-way satellite time and frequency transfer (TWSTFT) (see e.g. [1] and references therein) using geostationary satellites, has been used for many years. Also, in recent years, time transfer methods using optical networks have been extensively studied and developed; see for example [2-4]. The fact that optical and radio-based transmission differs in both signal frequency and used infrastructure, make the combination of both types of methods much less vulnerable to intentional or unintentional interruptions.

As a contribution to the robustness and reliability of time and frequency transfer, SP Technical Research Institute of Sweden has developed a novel time and frequency method based on passive listening and detection of SDH frame headers in fiber-optical networks. The method has been studied since 2005 (see e.g. [4-6]), and results based on prototype hardware implemented in experimental fiber-links have shown that time transfer with a precision of a few nanoseconds is achievable over links exceeding 500 km.

II. PRINCIPLES OF METHOD AND HARDWARE

The method is based on passive listening and detection of SDH frame headers, presently using an OC-192/STM-64 connection between core IP-routers at a nominal bit rate of 9953 Mbit/s, but is in practice with minor adjustments applicable to any STM line rate or packet-based data transmission network. SDH [8] defines the transmission of packets of data in nominally 125 microseconds long frames, where each frame starts with a well-defined sequence of A1 and A2 bytes that defines the beginning of a new frame, followed by packet information and finally the payload. The A1A2 sequence is chosen since it is extremely improbable that it occurs anywhere else in the bit stream and can therefore be used as a reference marker for the detection of the start of a new frame. At STM-64, this sequence is 192 A1 bytes followed by 192 A2 bytes.

In the time transfer setup, the reference marker is an electrical pulse which is generated at detections of a full A1A2 sequence. This marker is measured relative to the local and remote clocks to be compared. To succeed in an accurate 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 [4]. The transmission from a router is synchronized to a local oscillator (OCXO). The frequency offset and the stability of this clock source for the SONET/SDH framing do affect the performance of the time transfer by its jitter specification of less than 30 picoseconds. This jitter is probably not notable in the present measurements; however, router oscillators could become a limiting component in future systems with increased time resolution.

The transponders in the long haul system uses forward error correct (FEC) schemes, like G.709 or advanced FEC, so the clock from the SDH source, in our case the routers internal clock, will be used to phase lock a clock in the transponder of the higher order bit rate needed to carry the payload and the FEC data. Depending on FEC algorithm this can be 15 - 25% higher than the basic SDH/SONET rate. The transponders are also built to the 30 picoseconds requirements so improving the timing source might not improve the overall system performance.

Figure 1. The recently developed 2U (90 mm) time transfer unit hardware. Front panel and top view (without cover). See [7] for details.

Figure 1 shows pictures of the recently developed hardware, the Time Transfer Units (TTU) that is used for this time transfer study. Each TTU contains custom-made printed circuit board (PCB) cards with different tasks and a single-board computer. The unit is 2U high, which is approximately 90 mm. The TTU is described in detail in [7].

III. EXPERIMENTAL SETUP

In order to test the devices in a controlled manner, a test network was built that allowed for control of all pertinent parts. The network was constructed as shown in Figure 2. The intent was to create a simple network consisting of two routers connected to each other through a duplex pair of fibers. The first router was realized by a standard piece of network test equipment generating an OC-192 data stream. The duplex fiber pair consisted of two spools of fiber, both of which are approximately 31.5km long. The two spools were housed in an environmental chamber to allow for complete control of their surroundings. The chamber allowed for vibration isolation as well as control of the temperature. The far router consisted of a simple fiber loopback. As this was an idealized network for time transfer and data transfer was not the goal, passive elements sufficed as a router substitute. Both sides of the network resided in one rack for end-to-end comparisons of the link. By testing in this way, it was possible to remove the effects of the clocks used and measure the performance of the TTUs.

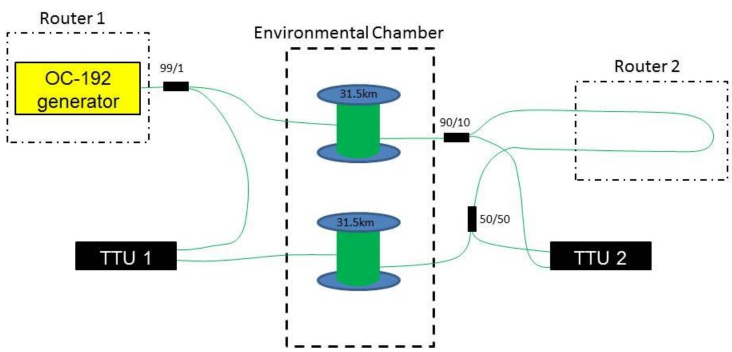

Figure 2. The experimental setup used for the evaluation. Two routers were linked via a duplex fiber pair 31.5km in length. The fiber spools were housed in an environmental chamber and the TTU boxes are situated near the routers for passive listening of the transmitted and received data.

The TTU devices were attached to the network as follows. At the first router, a splitter provided a 1% tap to the transmit port of the first TTU box. The return signal from the second router went directly to the receive port of the first TTU box. At the second router, a 10% splitter provided the signal to the receive port of the second TTU box. The transmit port for the second box came from a 50% splitter near the second router. To allow for simplified data analysis, the same time base was used for both boxes. The first TTU box supplied the master 10MHz signal and 1PPS signal that was then fed to the second box. In addition, the master 10MHz signal was supplied to the OC-192 test generator to remove relative drift between the generator and the TTUs. In this configuration the effects of the local oscillator at each TTU cancel out and the ability of the TTUs to accurately measure time transfer delays can be assessed.

Timing data was recorded in each box. As described above, when an A1A2 recognition pulse was generated, the time difference between it and the 1PPS from the local oscillator was recorded. This was done once a second both ports in both boxes and appropriately time tagged. By comparing the timing data between the two boxes it was possible to determine the one-way time delays for each fiber path of the link. The one-way data sets were then subtracted from one another to remove the fiber induced noise effects of the link as described in [4]. The stability of the transferred of time signal is reflected in this post-processed data set.

IV. RESULTS

The first experiment performed was a baseline test. The experiment was set for the most ideal conditions. The temperature in the environmental chamber was set at a constant 25C. The results of that test are shown in Figure 3. Two data sets are shown on the plot. The blue set is the round trip delay. As can be seen, the data set is quite constant due to the fact that the temperature is held steady. The second data set is the post-processed data set consisting of the difference between the two one-way data sets. This data set is also rather constant. A stability analysis of the phase data shows that the Allan deviation integrates down as 5e-10/τ. It should be noted that there is additional noise on the post-processed data, which is most likely due to a noisy counter in one of the boxes. It comprises only a small portion of the data and does not affect the stability significantly. This test provided a baseline of the best performance expected out of the boxes.

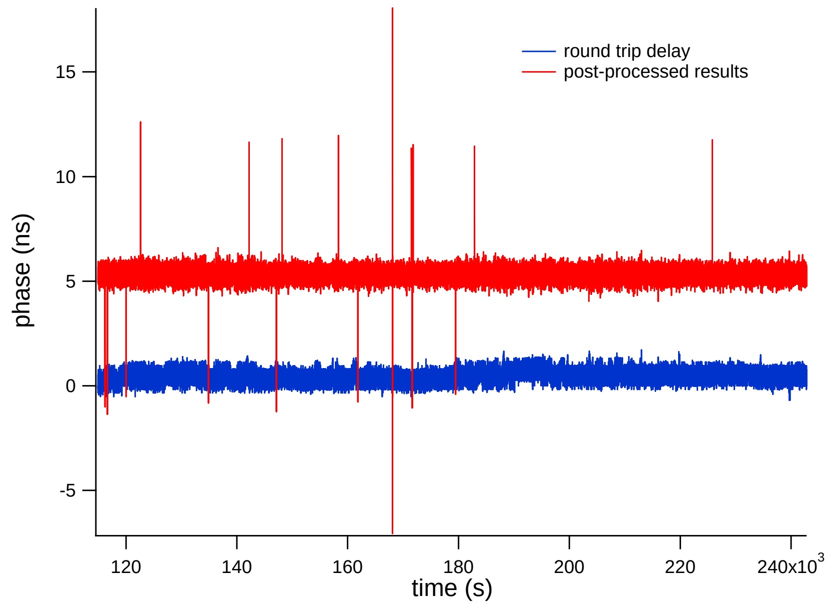

Figure 3. Results of the baseline test of the TTU boxes. The blue data corresponds to the round trip delay in a controlled environment. The red data, offset by 5 ns, is the post-processed data.

The next test performed involved operating the link in a more stressful environment. The environmental chamber that housed the fiber spools was programmed to cycle with various temperature swings, some up to 10C. Figure 4 shows a profile of the temperature cycle. Also shown in that figure are two data sets corresponding to the round trip delay and the post-processed data. The blue data shows the round trip delays brought about by temperature cycling. Delays of over 20ns were brought about by the temperature swings. The red data set shows the two-way post processed data. The temperature induced phase changes have clearly been suppressed. The Allan deviation of the post-processed data shows that the noise integrates down at 7e-10/τ which is only slightly worse than the baseline test. As before, there is some noise on the data sets, but this is believed to be due to a time slip between the two TTUs and is currently under investigation.

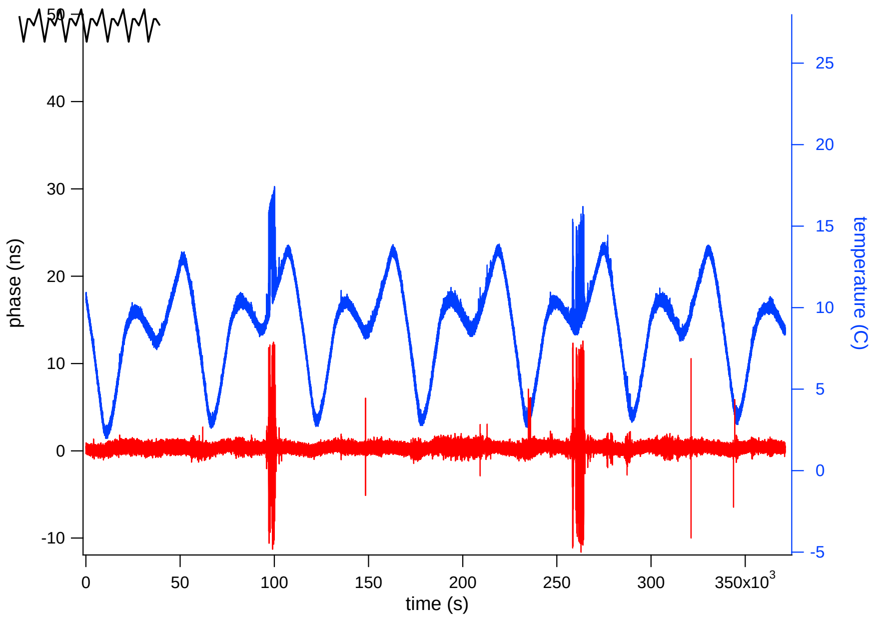

Figure 4. Results of the temperature cycling test of the TTU boxes. The black curve shows the temperature cycle profile. The blue data set shows the round trip time delay over the link. The red data set shows the post-processed data cancelling out the two one-way trip delays.

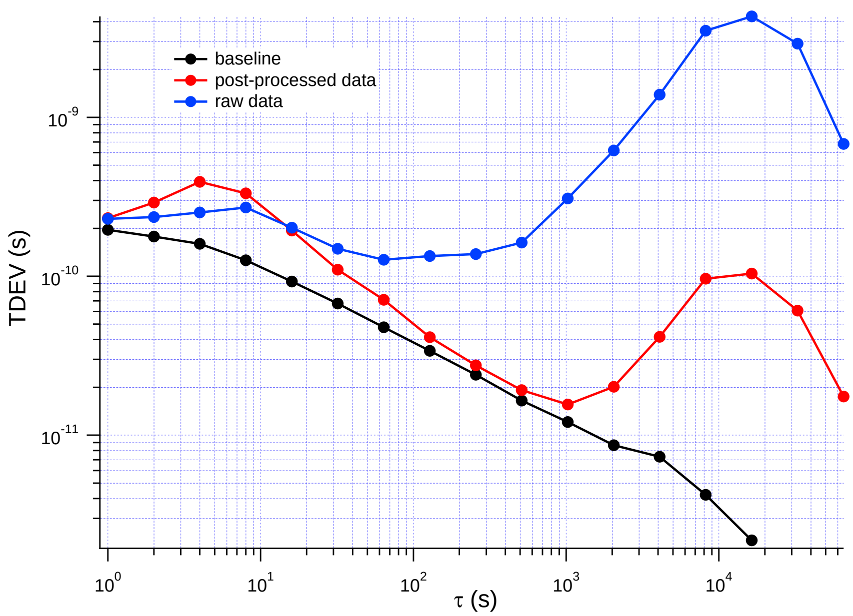

Figure 5. Analysis of the performance of the TTU boxes. The black data set represents the time deviation for thebaseline tests performed in ideal conditions. The blue data set represents the time deviation for the raw round trip phase deviations due to temperature cycling. The red data corresponds to the results of post processing the data showing the performance of the TTU boxes.

Using the post-processed data it is possible to evaluate the performance of the TTU boxes for time transfer. TDEV was calculated using the phase data for the different experimental runs. Figure 5 shows a plot of those results. As expressed earlier, the baseline test (shown in black on the plot) is the best that can be expected and acts likes a noise floor for the system. TDEV starts out at 2e-10 at one second and integrates down as approximately $1/\sqrt{\tau}$ which is indicative of white phase noise. The blue data set is TDEV for the raw round trip data. It also starts out at ~2e-10 and holds constant before growing to 4e-9 at ~20000 seconds. The red data shows the results for the post-processed data. As can be seen, there is a dramatic improvement from the raw round trip data. Again, the post-processed data starts at ~2e-10 at one second with a small bump up to 4e-10 most likely due to the previously mentioned noise. Then it integrates down similarly to the baseline data. Around 1000 seconds, it pulls away and climbs to ~100ps. This shows that there is a clear suppression of noise and over an order of magnitude improvement in TDEV gained through the use of the TTUs.

V. CONCLUSION

In conclusion, we have performed an independent evaluation of the Time Transfer Units based on passive listening of data traffic on a fiber optic link. A 31km test network was constructed and time transfer over that link using the TTU boxes was examined. The link was subjected to both ideal and harsh conditions. In both cases, the units transferred time quite well with the stability of the link integrating down as 7e-10/τ or better. TDEV for the link in a very harsh setting with temperature swings of 10 degrees Celsius was better than 100ps at one day. The results of the evaluation demonstrate that the units can act as a time transfer system that is complementary to other high quality systems such as TWSTFT and GPS.

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