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TWO-WAY TIME AND FREQUENCY TRANSFER IN SONET*

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Abstract

We have built a two-way time-transfer device which can use any currently unused byte in the SONET/SDH overhead to effect time transfer. The hardware should allow time transfer over short distances (km) with stabilities less than 10 ps for integration times greater than 1000 s. Accuracy at the same level in a dedicated fiber should also be possible. Time transfer though telecommunications network equipment has not yet been investigated.

Introduction

We have developed a system which allows us to measure the stability of time transfer over an optical fiber link using the standard transport format called Synchronous Optical Network (SONET) in North America, and called Synchronous Digital Hierarchy (SDH) in Europe and Japan. The SONET (SDH) protocol for data transmission is well established and, along with the growing need for improved synchronization in telecommunications systems, promises a vehicle by which improved synchronization through a terrestrial network can be achieved relatively inexpensively and robustly. Our measurements quantify some of the possibilities for using SONET equipment and optical fibers for time and frequency transfer in both a private network and a public telecommunications system. Work on this type of system was begun by Kihara and Imaoka [1] who reported on two-way time transfer via SDH/SONET over a baseline of greater than 1000 km. The system uses a single overhead byte in each SONET frame to transfer timing data from the remote clock, as well as providing an on-time marker (OTM) which is used to transfer the actual time. The system described here is suited for use in a private network, and should allow construction of a time scale with clocks separated by distances of kilometers. For use in a public network, the requirement of reciprocity of the paths may be problematic. However, the requirements of a public network may be no better than 100 ns for time transfer, many orders of magnitude less than the capabilities of this system.

Two-Way Time Transfer in SONET/SDH

Two-way time and frequency transfer is generally used to compare two geographically separated clocks. Each two-way system transmits the time of the local clock and receives the time of the remote clock. Each system then measures the difference between the local clock and the received signal from the remote clock. If the time difference data from the remote clock are differenced with the data from the local clock, then the path delay effects are removed, assuming that the delay in the path from the remote clock to the local clock is reciprocal with the path from the local clock to the remote clock. The time of the remote clock (clock 2) relative to the local clock (clock 1) can be written as [2]:

$$\begin{gathered}\mathrm{Time}(1)-\mathrm{Time}(2) = \\ 1/2\{(\mathrm{TIC}(1) - \mathrm{TIC}(2)) \\ + (T_{xdelay}(1) - R_{xdelay}(1)) \\ - (T_{xdelay}(2) - R_{xdelay}(2))\},\end{gathered}$$

where TIC(i) is the Time Interval Counter reading for system i, $T_{xdelay}(i)$ is the transmit delay for system i, $R_{xdelay}(i)$ is the receive delay for system i.

Accurate time transfer requires that the absolute magnitudes of the delays, T_{xdelay} and R_{xdelay}, associated with the hardware on each end of the link be known and that those delays be temporally invariant. Accurate frequency measurements, however, require only that the delays be stable; the magnitudes need not be known. In addition, the delays through the two paths need only be stable, not equal. In the present experiment we are attempting to measure the temporal stability of these delays, which in general is influenced by the environment (for example, temperature and power-supply voltage) as well as digital hardware delays which may differ from one reset cycle (turning power off and on) of the equipment to the next.

The SONET/SDH protocol involves an 8 KHz frame consisting of information payload and overhead. Communications links are categorized as sector, line and path. Path links are point-to-point, lines terminate at equipment such as multiplexors and cross-connects, and sectors are between repeators. The data rate depends on the synchronous transport signal level, STS-n, corresponding to the optical carrier level, OCn, where n = 1,3,12,24,48, etc, giving a data rate of n*51.84 Mbps. Our system used an STS-3 transport whose data frame is illustrated in Figure 1.

Two-way time transfer requires sending a time signal from one terminal to another. Since we also require path reciprocity it is natural to use the transport overhead to pass data as timing signals, since they are coherent with the 8 kHz timing. Note that any data in the payload can move relative to the 8 kHz timing, and thus can be problematic when requiring reciprocity in both directions for two-way. The 8 kHz signal provides a stable carrier for two-way, leading to the use of the line overhead for data transfer. A particular frame edge of the 8 kHz signal can be designated as the time of transmission from unit A. Thus, unit A starts a counter at that frame edge and stops when it receives the marked frame edge from unit B. The data that signals the timing frame edge is a particular byte in the transport overhead, called the on-time-marker (OTM). In the system used in this experiment we sent the OTM once per second and bytes with value 0 all other times.

For an operational system, data would be sent in addition to and coherent with the OTM to allow time and frequency transfer in the system without external analysis. Such data include the exact transmission time of the OTM and the TIC measurement from the previous cycle. In addition, in a hierarchical timing chain, control information would be sent from the master clock to the slave clock.

Results

The basic hardware is diagrammed in Figure 2. SONET overhead access is provided by the SONET Interface adapter [3]. This device, built around a framer chip [3] provides buffered access to both the received and transmitted SONET overhead. Start and stop commands for the time interval counter (TIC) are generated by the auxiliary timing board.

In the first test, the system was configured for loop-back tests, as shown in Figure 3. This configuration allows the measurement of the quantity $T_{xdelay} + R_{xdelay}$ combined with the delay associated with the fiber. The fiber used in this test is very short, about 15 cm, and is not expected to be a significant source of instability. The stability achieved using the configuration of Figure 3 is shown in Figure 4; the hardware stability exhibits an approximate flicker phase noise floor less than 10 ps, which is consistent with the flicker floor of the TIC used [4]. One of the two systems used in this experiment showed larger short-term noise. However, both systems had nearly identical long-term characteristics and exhibited similar results in this loop-back test.

A full two-way test using 30 m of twin lead fiber was also conducted. In this test, the two ends of the link were physically situated in the same environment, and the fiber was coiled between them. Further, the two SONET interfaces were driven from a common 155.52 MHz clock. The configuration is shown in Figure 5. The resulting data, Figure 6, exhibit instability of less than 10 ps at measurement periods greater than 1000 s, thereby allowing frequency transfer of 10^{-14} at times greater than 1000 s. The increase in short term noise in Figure 6 over that of Figure 4 is due to the higher short-term noise level in one of the two-way systems. Assuming the stability is not degraded by increasing distance, the observed stability should allow frequency transfer better than 1 part in 10^{15} at 1 d over distances of 10 km. This assumption will probably not, in general, be valid in a public telecommunications system, but should be possible in a private network, where path reciprocity can be engineered into the system.

A study of the stability of two-way time transfer vs. byte position in the overhead was also undertaken. The data show that the measured stability vs. byte position for the four byte positions 12, 17, 26 and 73 in the overhead frame does not seem to depend on the byte position for this particular hardware configuration. Byte 73 is of particular interest since it is the only byte tested in the line overhead. In particular it is the S1 byte, one nybble of which is currently used in SONET systems in North American networks for passing synchronization messages.

Preliminary study of the stability of the time-transfer process vs. temperature was also undertaken. Temperature coefficients measured in the loop-back mode of operation measure the quantity $T_{xdelay} + R_{xdelay}$, while temperature coefficients measured in the two-way mode are sensitive to the quantity $T_{xdelay} - R_{xdelay}$. The temperature coefficients for this equipment (not including the fiber) using the above technique are $\delta T_{xdelay}/\delta T \approx 3$ ps/°C and $\delta R_{xdelay}/\delta T \approx 44$ ps/°C.

The stability of the hardware delays as a function of power supply voltage was also studied using the same technique to separate the T_{xdelay} and R_{xdelay} coefficients. The results of this study, shown in Figure 7, give $\delta T_{xdelay}/\delta V \approx -6.2$ ns/V and $\delta R_{xdelay}/\delta V \approx 0$ ns/V.

Discussion

The ultimate accuracy attainable using this two-way system in SONET is limited by the long-term stability, if we can calibrate the delays. Temperature and line voltage will have to be controlled within the relevant ranges to match the time stability of the system. Our measurements here of 10 ps stability at 1000 s are actually an upper bound. Other studies have shown the flicker PM noise floor of the counters used in this study match closely with the measurements we obtain here [4]. Thus it is possible that the two-way SONET system is even more stable and we are only measuring the counter noise. Calibrating the delays should be possible also at the 10 ps level.

The equipment used by carriers for public telecommunications have multiple problems implementing this design for two-way time and frequency transfer between their timing signal sources. We mention three problems here. First, the optical fibers are maintained in a layer that is supposed to be transparent to higher-level functions such as synchronization transport. Hence it may be difficult to guarantee reciprocity between the two directions for any level of stability or accuracy. Buffering of digital signals may create unpredictable delays in SONET network elements such as among various lines in a multiplexor. A second problem is that the SONET overhead can be directed only as far as devices called "line" terminators. These include add-drop multiplexors and digital cross-connect equipment. Thus, comparing SONET timing signal generators (TSG's) using two-way timing would require that they be co-located with equipment separated by no more than a single line, unless a way can be found for passing the overhead bytes through a line terminator. A third problem with comparing clocks in a public network using two-way is that synchronization from the clocks currently does not use SONET to connect to the network. Instead a 1.544 MHz bi-polar signal (DS1) is derived from the SONET carrier and used to pass frequency to and from the TSG's. Time synchronization, called "time-of-day synchronization" in the telecommunications community, is not kept by the TSG's at this time. Framing bits in this DS1 signal are used to pass one of eight possible synchronization messages to and from the clocks in a format called an Enhanced Super Frame (ESF).

Thus, using two-way time and frequency transfer to link timing sources in existing public networks will require some system changes. Either the ESF data will have to be tightly locked to the SONET overhead data with some stable known delay, or the TSG's will have to pass synchronization to and from SONET overhead bits in a new way. One possibility is to use equipment much like the NIST system to read and write bytes in the SONET overhead and extract timing. This system would be timed using a frequency signal from the TSG, as well as a 1 pps if available, keeping time-of-day within the NIST-like system. In this scenario, the NIST two-way system would sit in the network ahead of the line terminating equipment, read and write bytes to the overhead, and pass the SONET signal to the line terminator in a transparent way.

Conclusions

We have shown that two-way time transfer over a SONET/SDH OC-3 link at 155.52 MHz of the order of 10 ps are acheivable. This system shows promise for allowing time-scales constructed from high-performance commercial Cs clocks to be used in situations where the clocks are separated by relatively large (≈km) distances. Hydrogen maser time-scales would, most likely, show some degradation of the short term stability of the maser caused by the time transfer process. Use of two-way time transfer in public telecommunications systems would require some re-design of the timing topology currently used in those systems.

Bibliography

[1] M Kihara and A. Imaoka, "SDH-Based Time and Frequency Transfer System", *Proc. of the 9th European Frequency and Time Forum*, Besançon 1995, pp. 317-322.

[2] C. Hackman, S. R. Jefferts and T. E. Parker, "Common-Clock Two-Way Satellite Time Transfer Experiments", *Proc. of the 49th Annual Symposium on Frequency Control*, 1995, pp. 275-281.

[3] SONET Interface Adaptor: Odetics Inc. LIMO SONET Interface Adaptor. Framer Chip: PC-Sierra Inc. The commercial equipment used has been identified for technical completeness only, to allow other researchers to duplicate the results contained herein. Other commercial equipment may perform differently, in particular it may be more or less suitable than the equipment described herein. Such identification implies neither recommendation nor endorsement by the National Institute of Standards and Technology.

[4] V.S. Zhang, D.D. Davis. M.A. Lombardi, "High Resolution Time Interval Counter," *Proc. of the 26th Annual Precise Time and Time Interval Applications and Planning Meeting*, Reston, VA, 1994, pp. 191-200.

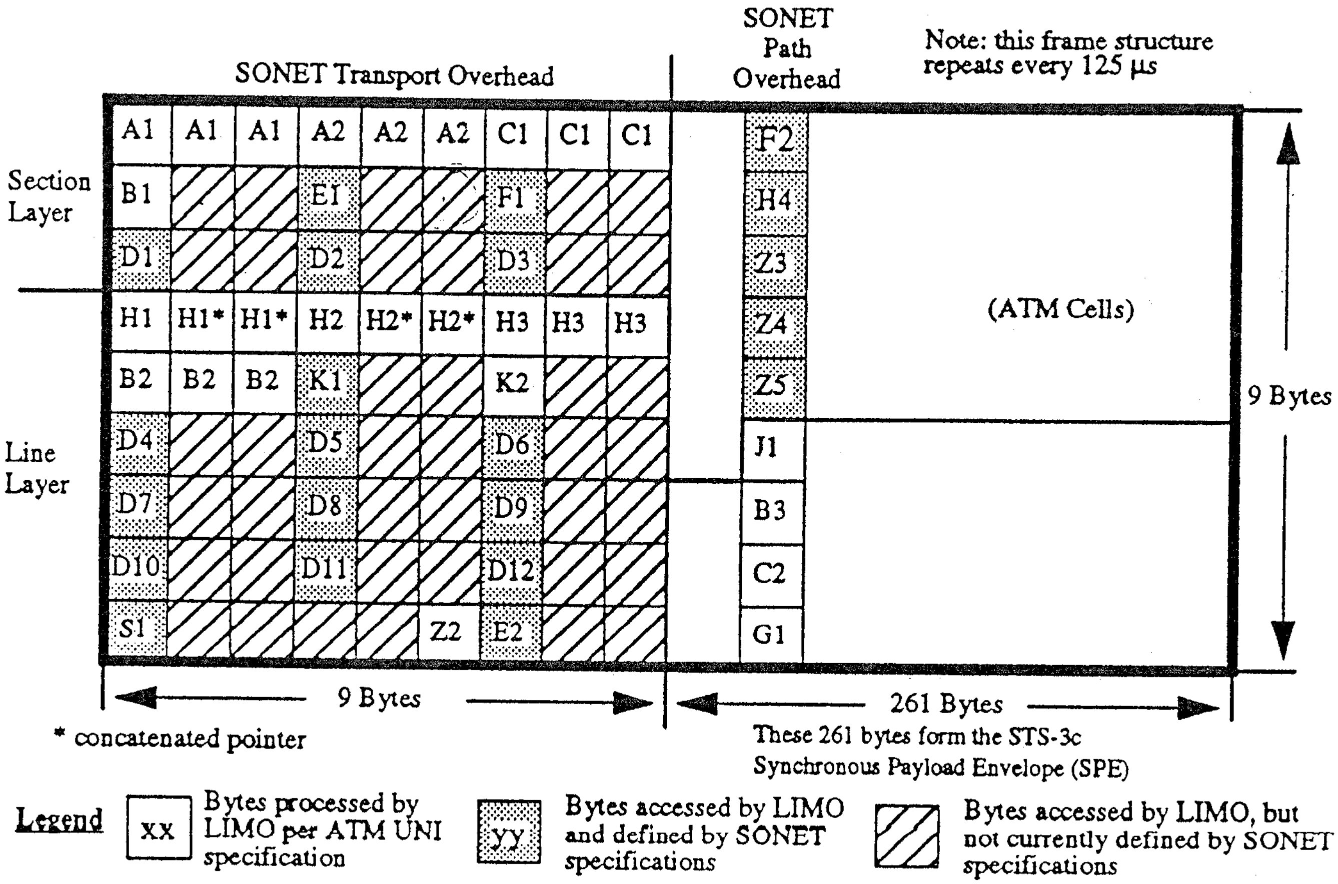

Figure 1. - SONET STS-3 overhead bytes.

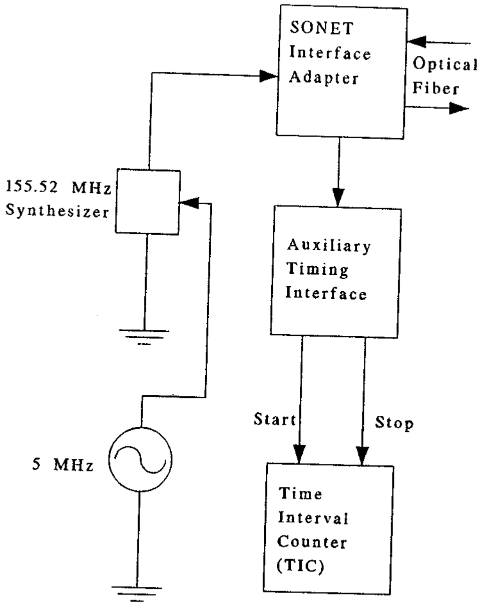

Figure 2. - Simplified block diagram of the SONET two-way time-transfer system.

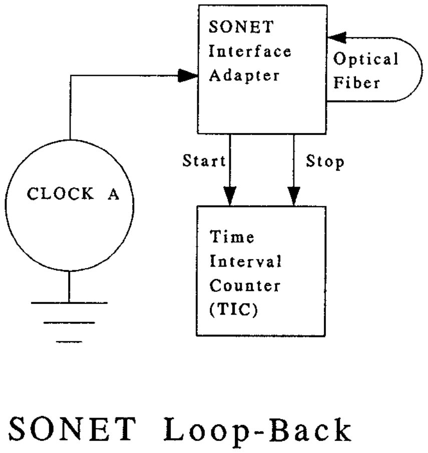

Figure 3. - SONET two-way time transfer system in loop-back mode. In this configuration the system measures the time between transmission and receipt of its own OTM.

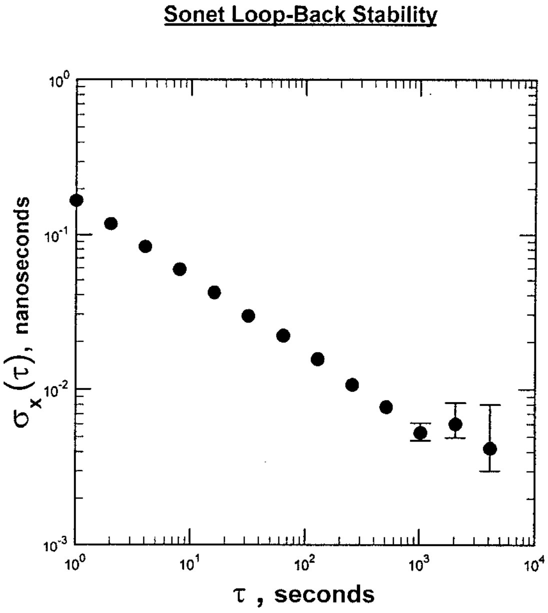

Figure 4. - Stability of the SONET two-way time transfer system in loop-back mode as described in Figure 3.

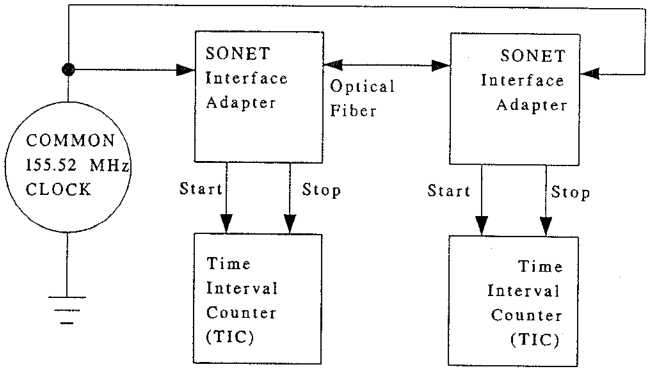

Figure 5. - Common clock two-way time transfer system designed to measure the stability of the hardware delays in the SONET two-way time-transfer system. The common clock arrangement removes clock noise from the measurement.

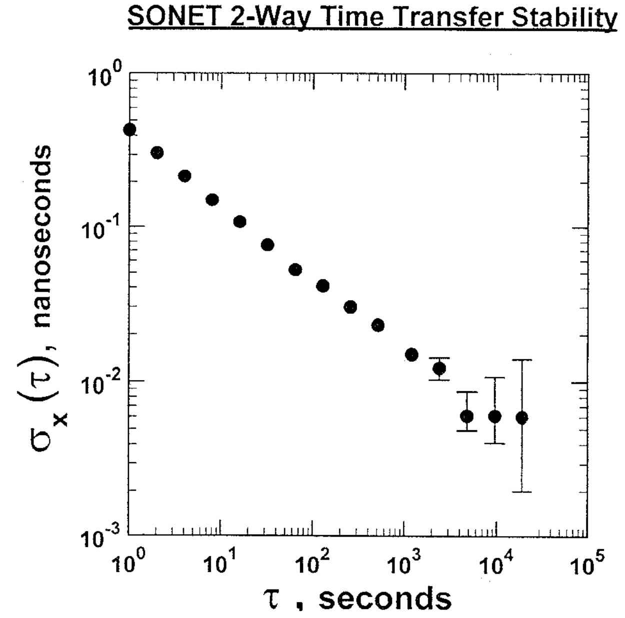
SONET 2-Way Time Transfer Stability

Figure 6. - The stability of the SONET two-way time transfer system in the common clock two-way mode described in Figure 5.

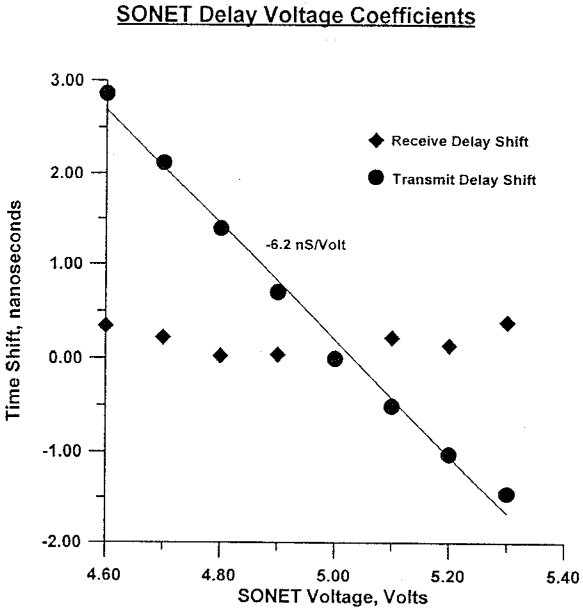
SONET Delay Voltage Coefficients

Figure 7. - The stability of the SONET two-way time transfer system as a function of power supply voltage.