Improving TWSTFT Short-Term Stability by Network Time Transfer

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***Abstract*—Two Way Satellite Time and Frequency Transfer (TWSTFT) is one of the major techniques to compare the atomic time scales between timing laboratories. As more and more TWSTFT measurements are performed, large numbers of point-to-point two-way time transfer links have grown to be a complex network. For a future improvement of the TWSTFT performance, it is getting important to reduce measurement noise of the TWSTFT results. One of the methods is using the TWSTFT network time transfer.**

The Asia-Pacific network is an exceptional case of simultaneous TWSTFT measurements. Some indirect links through relay stations show better short-term stability than the direct link because the measurement noise may be neutralized in a simultaneous measurement network. In this paper, the authors propose a practicable method to improve the short-term stability by combing the direct and indirect links in the network. Through the comparisons of time deviation (TDEV), the results of network time transfer show clear improved short-term stabilities. For the links based on H-maser, the average gain of TDEV at 1h averaging times is 20%. As TWSTFT short-term stability can be improved by network time transfer, the network may allow larger number of simultaneously transmitting stations.

I. INTRODUCTION

Two Way Satellite Time and Frequency Transfer (TWSTFT) is one of the major techniques to compare the atomic time scales between time keeping laboratories [1]. As more and more regular TWSTFT measurements are performed, large numbers of point-to-point two-way time transfer links have grown to be a complex network. However, most of the data in the network were not used effectively.

At the meanwhile, measurement noise in the TWSTFT network becomes an important matter as a lot of stations transmit simultaneously [2]. The stations should take care of their signals. For avoiding interference from some special strong signals, we usually check the clean carrier on the spectrum and make effort to keep all the stations at the same signal level. However, the C/N_0 value is not always the same as the signal level because it is also related to the background noise, affected by the elevation angle of antenna, the noise temperature of equipments, and so on. It is always important to achieve higher C/N_0 values for the TWSTFT performance. One unavoidable solution is limiting the number of transmitting stations. If one can employ the full potential of network to reduce the measurement noise, the network may allow larger number of simultaneously transmitted signals.

Jiang and Petit proposed the concept of network time transfer [3][4], which means that the time transfer between any two points through any links in the network gives exactly the same result with the same uncertainty. A global least square network adjustment was proposed to improve the time link stability by fully using the redundant links. Their studies focused on the data of European-American TWSTFT network.

The Asia-Pacific network comprises 6 laboratories. All TWSTFT measurements are performed simultaneously by using 8-RX-channel NICT modems [5][6]. Hourly data are available at the NICT's Web site. The analysis of the Asia-Pacific TWSTFT network has been done in previous study [7]. The links in this network meet closure to the 100 ps level, and there are several indirect links showing better quality than the direct link. These redundant links provide useful data that may allow us to improve the time transfer results.

This paper proposes a practicable method to employ the potential of the full network. We carried out more detailed data analysis and provided possible explanations for the reason of some high quality indirect links showing better quality than the direct link. The comparisons of time deviation (TDEV) are made to evaluate the improvement in the network time transfer.

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II. THEORETICAL BACKGROUND

The signal delays of time transfer via microwave links change with distance, ionosphere effect, environmental factors and so on. The two-way method is employed in canceling these influences due to the reciprocity of the signal path. The principle of two-way scheme is introduced in [8] and [9]. The accuracy of the result then depends on the residual incomplete reciprocity and measurement noises.

In this paper, the single baseline TWSTFT link is called as the direct link for distinguishing the indirect link, which is the combination of two or more links. The direct link and one of corresponding indirect links form a closure loop. The network time transfer is based on the closure analysis [10]. The similarities and dissimilarities between the direct and indirect links are discussed as follows.

TWSTFT between two stations A and C is obtained by combining two coincident measurements, $TW_{A,C}$ and $TW_{C,A}$, they are the time interval reading at stations A and C respectively. The measurement result is the observed information consisting of the difference between two clocks, (T_A–T_C), the combination of signal path delays and measurement noise, as in

$$\begin{aligned} \tfrac{1}{2}(TW_{A,C} - TW_{C,A}) = (T_A - T_C) & \\ - \tfrac{1}{2}[(TX_A - RX_{A,C}) - (TX_C - RX_{C,A})] & \\ - (SCD_C - SCD_A) & \\ + \tfrac{1}{2}(\delta_{A,C} - \delta_{C,A}). & \quad (1) \end{aligned}$$

The second term is the half difference of the differential delays of the transmission (TX) and receiving (RX) paths. The delay of RX path in station A receiving the signal from station C is expressed by mark the subscripts as $RX_{A,C}$. In the network, we have to distinguish the RX paths from different stations. The measurement noises are noted as $\delta_{A,C}$ and $\delta_{C,A}$ correlated to the measurements $TW_{A,C}$ and $TW_{C,A}$ respectively.

The indirect link via relay station B is obtained by combining two direct links (A-B) and (B-C). We gets

$$\begin{aligned} & \tfrac{1}{2}(TW_{A,B} - TW_{B,A}) + \tfrac{1}{2}(TW_{B,C} - TW_{C,B}) \\ & = (T_A - T_B) + (T_B - T_C) \\ & \quad - \tfrac{1}{2}[(TX_A - RX_{A,B}) - (TX_B - RX_{B,A})] \\ & \quad - \tfrac{1}{2}[(TX_B - RX_{B,C}) - (TX_C - RX_{C,B})] \\ & \quad - (SCD_B - SCD_A) - (SCD_C - SCD_B) \\ & \quad + \tfrac{1}{2}(\delta_{A,B} - \delta_{B,A}) + \tfrac{1}{2}(\delta_{B,C} - \delta_{C,B}). \quad (2) \end{aligned}$$

If the measurements are performed simultaneously, the relay station's time scale T_B, transmission path delay TX_B, and the Sagnac correction SCD_B are vanish. Then, (2) simplifies to

$$\begin{aligned} & \tfrac{1}{2}(TW_{A,B} - TW_{B,A}) + \tfrac{1}{2}(TW_{B,C} - TW_{C,B}) \\ & = (T_A - T_C) \\ & \quad - \tfrac{1}{2}[(TX_A - RX_{A,B}) - (TX_C - RX_{C,B}) + (RX_{B,A} - RX_{B,C})] \\ & \quad - (SCD_C - SCD_A) \\ & \quad + \tfrac{1}{2}(\delta_{A,B} - \delta_{B,A} + \delta_{B,C} - \delta_{C,B}). \quad (3) \end{aligned}$$

To compute (3) – (1), one can get the difference between the direct link (A-C) and the indirect link (A-B) + (B-C) via relay station B. We notice that the time scale differences, the TX path delays and Sagnac corrections vanish. The difference is thus written as

$$\begin{aligned} & \tfrac{1}{2}(TW_{A,B} - TW_{B,A}) + \tfrac{1}{2}(TW_{B,C} - TW_{C,B}) + \tfrac{1}{2}(TW_{C,A} - TW_{A,C}) \\ & = \tfrac{1}{2}(RX_{A,B} - RX_{A,C}) + \tfrac{1}{2}(RX_{B,C} - RX_{B,A}) + \tfrac{1}{2}(RX_{C,A} - RX_{C,B}) \\ & \quad + \tfrac{1}{2}[(\delta_{A,B} - \delta_{A,C}) + (\delta_{B,C} - \delta_{B,A}) + (\delta_{C,A} - \delta_{C,B})], \quad (4) \end{aligned}$$

which is the so-called closure sum.

In the part of RX path delays, if the path delay $RX_{A,B}$ may be different from the delay $RX_{A,C}$, the closure sum may be a small non-zero bias. Non-zero closure problems are discussed in [10]. The possible reasons are the interference from the simultaneous transmission from other stations, multiplication bandpass effect (MBE), and device biases due to the different RX modules in the multi-channel modem.

In the part of measurement noise, the indirect link is obtained by combining four coincident measurements, see (3). In a stochastic sense, its measurement noise will raise the noise level by $\sqrt{2}$ compared with the direct link. Fortunately, in the simultaneous TWSTFT measurements, the time signals of stations A and C are transmitted at the same instant. Both signals will pass through the same receiving path and the same instrumentations at the same time. Therefore they undergo the same background noise, which are mainly contributed by the antenna, LNB and receiver of station B. Consequently, the $\delta_{B,A}$ and $\delta_{B,C}$ are two highly correlated noise sources and their differential term may just contribute a very low residual noise to the indirect link. Finally, the terms of measurement noise for indirect link are reduced to ½ ($\delta_{A,B} - \delta_{C,B}$) adding possibly low residual noise. The measurement noise $\delta_{A,B}$ and $\delta_{C,B}$ are related to the C/N_0 values of signal from station B received by station A and C respectively. For some special cases of better C/N_0 combinations (result in small $\delta_{A,B}$ and $\delta_{C,B}$) and small residual noise in relay stations, the measurement noise of indirect link is possible lower than the direct link.

Finally, the non-zero closure sum may come from a combination of RX delay biases and residual measurement noise.

III. DATA ANALYSIS

Asia-Pacific TWSTFT data measured from MJD 54704 to MJD 54817 are used in this paper. During the period of data set, TWSTFT were only performed in 5 timing laboratories. Three stations, (NICT, KRIS, TL), employed H-maser as their reference, and two stations, (NTSC, SG), used cesium clocks as reference. There are 10 direct links in this network, see Fig. 1. Each direct link has 15 corresponding indirect links. For example, the NICT-TL link has 15 indirect links; they are 3 indirect links through 1 relay station, 6 links through 2 relay stations, and another 6 links through 3 relay stations. Some of them are shown in Fig. 2.

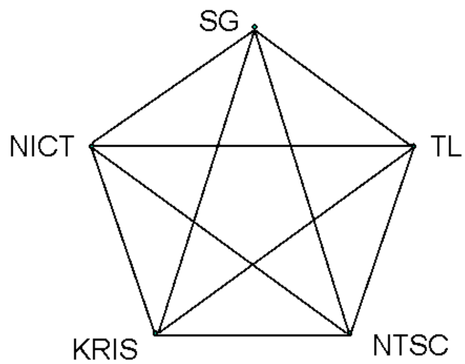

Figure 1. Asia-Pacific TWSTFT Network during MJD 54704 and MJD 54817. There are 10 direct link in the network.

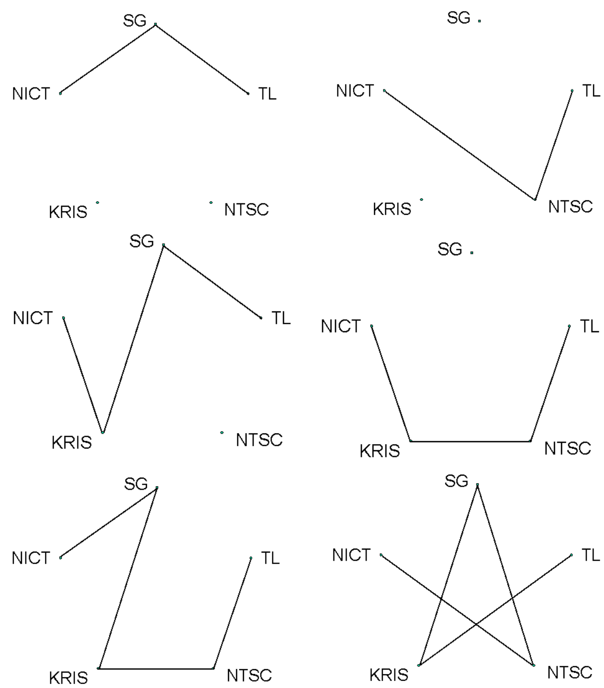

Figure 2. Some of indirect NICT-TL links. Top: links through 1 relay station; Middle: links through 2 relay stations; Bottom: links through 3 relay stations

Among those indirect NICT-TL links, two shows better short term stability than the direct link. We evaluate their short term stability by time deviation (TDEV) at averaging times of 1 h. Table I shows the TDEV and C/N_0 values of some high quality indirect NICT-TL links. The *C/N(nict,r)* means the C/N_0 of NICT receiving the signal from relay station. For the NICT-KRIS-SG-TL link as example, their C/N_0 combinations are *C/N(nict,kris)* and *C/N(tl,sg)*. There is an interesting coincidence between the high quality indirect links. They satisfy the conditions of better C/N_0 combinations. Among 150 indirect links in Asia-Pacific TWSTFT network, 40 indirect links show better quality than the direct link. There are 31 links satisfying the condition of better C/N_0 combinations. The ratio is about 77.5%.

TABLE I. C/N_0 COMBINATIONS OF HIGH QUALITY INDIRECT LINKS.

links	***TDEV(1h)***	***C/N(nict,r)***	***C/N(tl,r)*** [a]
	ps	**dBHz**	**dBHz**
NICT-TL (direct)	91	50	54.6
NICT-SG-TL	90.8	56.9	58.2
NICT-KRIS-SG-TL	82.4	53.6	58.2
NICT-SG-KRIS-TL	96	56.9	54.7

a. C/N(tl,r) means the C/N_0 of TL receiving the signal from relay station. For NICT-KRIS-SG-TL link, their C/N_0 combinations are C/N(nict,kris) and C/N(tl,sg).

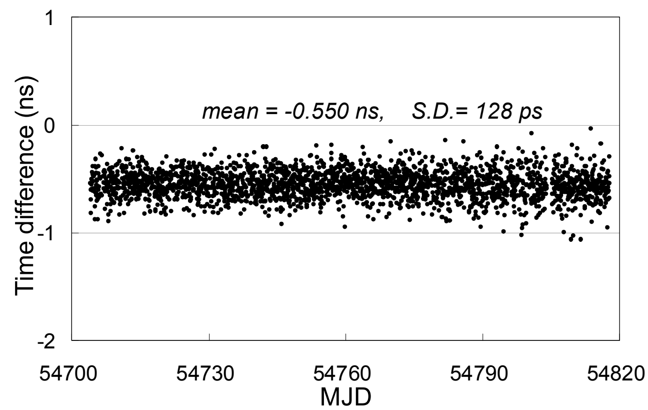

Figure 3. Closure sum of NICT-KRIS, KRIS-TL, and TL-NICT links. The calibration values are not taken into account here.

Closure results in Asia-Pacific network are concentrated on a constant bias. Fig. 3 shows the closure sum of NICT-KRIS, KRIS-TL, and TL-NICT links. Its standard deviation is only 128 ps.

IV. METHOD

Based on some high quality indirect links, we can obtain the result of network time transfer by averaging the direct link and redundant indirect links as the following steps.

A. *Treatment of closure errors and the missing data*

Before taking the average of the direct and indirect links, we face two problems. One is the non-zero closure sum, which has been discussed but not been well solved. To avoid dealing with the non-zero closure problem, we align the indirect links to the direct link by shifting the mean of their closure sums. The other is the missing data when not all data of involved links are available at the coincident time. For example, data of NICT-SG-NTSC-KRIS-TL link is missing when anyone of relay stations is not on-line. If either NICT or TL is fail to perform TWSTFT, all indirect links for NICT-TL link are failure at that time. Thus, the data points of indirect links are equal to or less than those of the direct link. During the period of data set, there are 2441 points in direct NICT-TL link while some indirect links has only 1850 data points. The average ratio of missing data for indirect links is 17%. We use the data of direct link to insert points where data is missing. Finally, the number of data points is always the same as that of direct link.

B. Weighting Strategy

The average method will preserve the useful information and neutralize the measurement noise if the weighting strategy is good enough and the total weight equals to 1. In this paper, weights are determined by

$$W_n = \frac{1/\sigma_n^2}{\sum_{i=1}^{16}\left(1/\sigma_i^2\right)}$$

$$\sigma_n = TDEV_n(1h) - 0.9 \cdot lowest[TDEV(1h)]. \qquad (5)$$

We give higher weights to the links whose TDEV are much close to the criterion. The criterion is set by the 90% value of the lowest TDEV among all links, as in (5). In order to judge the short-term stability of the links, we use the TDEV at averaging times of 1 h. Due to the inverse square exponent, the weights decrease rapidly for the links with worse short-term behavior. There are totally 16 links including 1 direct link and 15 indirect links here.

C. Higher order networks

Each link of Asia-Pacific network could be improved by the network time transfer. These improved links form a new time transfer network, called 2nd network in this paper. Again, each link may get benefit from the 2nd time transfer network by adjusting the criterion to 95% value of the lowest TDEV. The same process could be repeated until the improvement is no longer obtained. For sequence, we also name the original network as the 1st network.

V. RESULTS OF NETWORK TIME TRANSFER

Fig. 4 and 5 show the TDEV comparisons between the direct and network results for the NICT-TL and TL-KRIS link. In the short-term time stability, a clear improvement using the network time transfer is achieved. Compared with the time transfer result by 1st network, few gains are obtained by 2nd network. All time transfer results converge at the averaging times more than 4 hours.

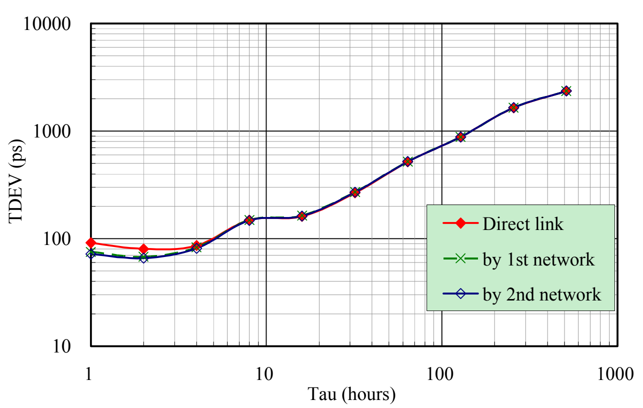

Figure 4. TDEV comparisons between the direct and network results for the NICT-TL link. Results of 1st and 2nd network are showed.

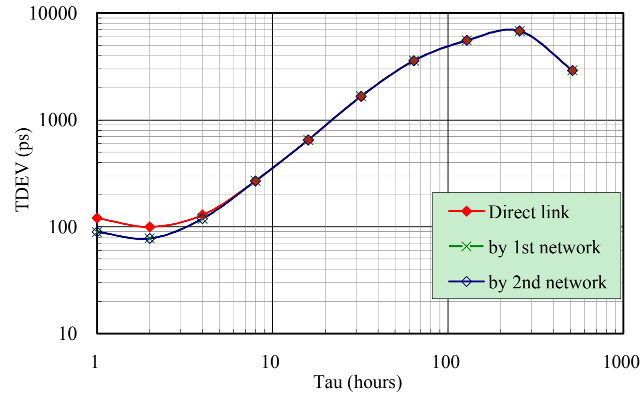

Figure 5. TDEV comparisons between the direct and network results for the TL-KRIS link. Results of 1st and 2nd network are showed.

Table II lists the TDEV of network time transfer results at averaging times of 1 h for all links. The gain is computed by

$$Gain = (TDEV_d - TDEV_n]/\ TDEV_n , \qquad (6)$$

where $TDEV_d$ is for direct link and $TDEV_n$ is for network result. For time transfer results obtained by 1st network, the range of gains is from -3% to 35%. There are negative gains for the NICT-SG and KRIS-SG links. The average of gains is 8%. After 2nd network calculation, additional improvements are obtained for the NICT-TL, NICT-KRIS, NICT-SG and KRIS-SG links. There are no negative gains by 2nd network. The average of gains is raised to 10%. Very few effective gains are obtained by network results for the order higher than 2nd.

Except for the NICT-KRIS link, which has an excellent direct link, it seems that the maser-maser links get more gains in the network time transfer. The average gain of three maser-maser links is 22%. It is likely because the clock noise of H-maser is much lower than the TWSTFT measurement noise. However, the behavior of cesium clock may start to dominate the stability of time transfer at the period of 1 h. Then, the improvement of reducing the measure noise may be unobvious shown on the TDEV. The average gain for maser-cesium links is 5%. The NTSC-SG link is a cesium-cesium link. Its gain is only 2%.

Figure 6 shows the closure sum of NICT-SG-KRIS-NTSC-TL link in the 1st, 2nd and 3rd network. The standard deviation of the closure is 153 ps in the 1st network, 98 ps in the 2nd network and 23 ps in the 3rd network. It reveals that the direct link and indirect links have very good agreement in high order networks. It follows the concept of network time transfer.

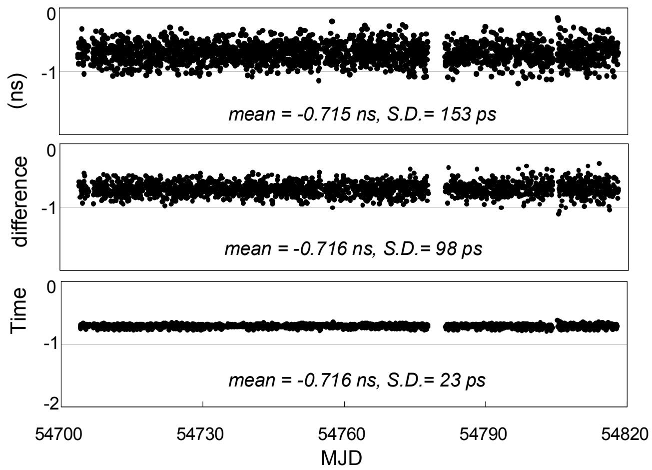

Figure 6. Closure sum for NICT-SG-KRIS-NTSC-TL link in 1st(top), 2nd(middle) and 3rd(bottom) networks.

TABLE II. TDEV COMPARISONS OF THE NETWORK TIME TRANSFER. *Gain = (TDEVd − TDEVn]/TDEVn; TDEVd is for direct link and TDEVn is for network result. Three stations (NICT, TL, KRIS) used H-masers as reference. Two stations (NTSC, SG) used cesium standards as reference.*

Link	**TDEV(1 h) (ps)**			**Gain**	
	Direct	***1st network***	***2nd network***	***1st network***	***2nd network***
NICT-TL	91	75.4	71.9	21%	27%
NICT-KRIS	88	87.4	84.8	1%	4%
TL-KRIS	121	89.4	89.7	35%	35%
NICT-NTSC	278	266	265	5%	5%
NICT-SG	249	258	250	-3%	0%
TL-NTSC	267	235	237	14%	13%
TL-SG	241	234	234	3%	3%
KRIS-NTSC	289	268	268	8%	8%
KRIS-SG	254	258	253	-2%	0%
NTSC-SG	350	343	343	2%	2%
Average	-	-	-	8%	10%

VI. CONCLUSION

All TWSTFT measurements in the Asia-Pacific network are performed simultaneously by using multi-channel modems. Some indirect links show better quality than the direct link. The most likely explanation is that such indirect links have better C/N_0 combinations and very low noise contribution of relay station.

Information of the indirect link is as value as the direct link. This paper proposed a practicable method to employ the potential of TWSTFT network. Results showed that the short-term stabilities can be improved, and the long-term stabilities, which are mainly dominated by clock behavior and path delay instability, have not been altered. The average gain of TDEV over 1 h is 10%. For the links based on H-masers, the gain is up to 22% in average.

Our method is useless to enhance the robustness of the network because once the data of direct link are unavailable; the indirect links are also invalid. The network time transfer is one possible solution to significantly reduce the measurement noise by getting the benefits from better C/N_0 combinations through the indirect links. However, the condition of better C/N_0 combinations is no guarantee of better stability. One should be careful of the existence of residual measurement noise, which may accumulate as more involved relay stations. The residual measurement noise of relay station must be as small as possible. As more and more stations transmit simultaneously, measurement noise in the TWSTFT network becomes an important matter. If the short-term stability can be considerably improved by employing the potential of network, the network may allow larger number of simultaneously transmitting stations.

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