Time and Frequency Transfer System for Synchronization Applications

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Abstract—**In this paper, we propose a new generation of time and frequency transfer system using Global Navigation Satellite System (GNSS) dual frequency receiver for the purpose of both time and frequency synchronization. The system can be used as a timing source, remote time and frequency calibration, and to monitor the characteristic of the telecommunication primary reference clocks (PRC). A series of experiments were conducted to evaluate the performance of the system. The common-view common-clock test was studied for the evaluation of the system noise level. The tests of short-baseline about 20 km between Chunghwa Telecommunication Laboratories (TL) and telecommunication facilities, and long-baseline around 10,000 km between TL and MSL (Measurement Standards Laboratory, New Zealand) were performed. Experimental results indicate that expanded time and frequency uncertainty of the proposed system (with a coverage factor of k=2) are less than 26 ns and 1.1 x10^{-13} (one day averaging), respectively, which can meet ITU-T G.811 standard approximately and requirements for the dominant telecommunication and power system synchronization applications.**

Keywords—Global Navigation Satellite System; Common-view method; All-in-view method; Synchronization; Syntonization;

I. INTRODUCTION

During the last three decades, there has been a rapid growth of Global Positioning System (GPS) applications for the civilian and military communities due to the development of precise positioning and navigations. The GPS has also proven itself to be valuable and important for distributing time and synchronizing clocks over large distance with a high degree of accuracy and precision[1][2]. Presently, GPS receivers are commonly used in many fields such as telecommunication networks, power system, industries, calibration and testing laboratories. They make it possible to control oscillators, to synchronize clocks and calibrate clocks of the facilities.

With the increasing demands of the reliable transmission of data and real-time service applications, synchronization is critical for telecommunication system performance. In particular, precise frequency and time synchronization have become more crucial for the mobile wireless and power system networks [3-6]. These networks require time or frequency synchronization in order to accurately send and receive traffic. For example, traditional GSM, WCDMA, WiMAX-FDD and LTE-FDD networks need frequency syntonization within 50 ppb of frequency error. CDMA, WIMAX-TDD, LTE-TDD and Smart Grid PMU (phasor measurement unit) systems all require microsecond level time synchronization. Table I summarizes the requirements of time and frequency accuracy for the dominant mobile wireless and power systems. Until recently, there are four preferred methods for synchronizing mobile base stations, which are TDM (time division multiplexing) link, GPS, SYNC-E (synchronous ethernet) link [7-8] and IEEE 1588 PTP [9]. The common ground of these methods is that they need a time source as primary reference clock for distributing time and frequency. However, due to the lack of the calibration and monitoring the characteristic of the PRC periodically in these methods, it is difficult to ensure the accuracy and stability of the system timing networks in the long term period. While a network is in a state of poor synchronization, the performance of the network will be degraded. In view of the preceding issues, a new generation of time and frequency transfer system using GNSS dual frequency receiver based on GPS common-view and all-in-view methods has been presented in this work.

TABLE I. REQUIREMENTS OF TIME AND FREQUENCY ACCURACY FOR THE DOMINANT WIRELESS AND POWER SYSTEMS

Application	Frequency Accuracy	Time accuracy
GSM [10]	5 x 10^{-8}	N/A
CDMA [11]	5 x 10^{-8}	1 μ s(10 μ s holdover)
WiMAX (FDD mode) [12]	2 x 10^{-6}	N/A
WiMAX (TDD mode) [12]	2x 10^{-6}	3 μ s(25 μ s holdover)
LTE (FDD mode)	5 x 10^{-8}	N/A
LTE (TDD mode)	5 x 10^{-8}	3 μ s inter-cell
Smart Grid DME	N/A	1ms
Smart Grid PMU	N/A	<1 μ s

II. SYSTEM ARCHITECTURE AND ITS TIME TRANSFER MODEL

The proposed time and frequency transfer system can provide timing reference signal, make time and frequency comparison and generate time transfer data format per day automatically. It integrates GNSS timing receiver, auto-measurement hardware, user interface (UI) and post-processing software. In the following sections, the detailed description of the proposed system architecture and its time transfer model is presented.

A. Proposed System Architecture

The architecture of proposed system is illustrated in Fig. 1. Its hardware includes a GNSS timing receiver, time interval counter, and data-processing unit.

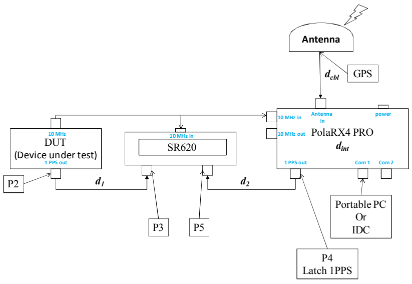

Figure 1. System architecture

B. GPS Time Transfer Model

The concept of the GPS common-view method is that the satellite transmits a time signal nearly received at station K1 and K2 as illustrating in Fig. 2.

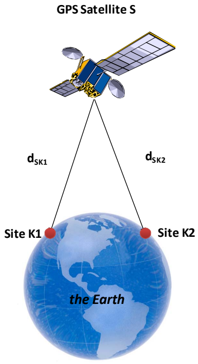

Figure 2. GPS common-view

However, the effects of the propagation delay from GPS satellite to receiver are a little different between two sites and thus it must be taken into consideration. The GPS observation models are described as following

$$\Gamma_{K1}^{S} = \frac{\rho_{K1}^{S}}{c} + I_{K1}^{S} + T_{K1}^{S} + \delta_{K1} - \delta^{S} + \varepsilon_{K1}^{S} \quad (1)$$

Here, Γ_{K1}^{S} is the time measurements from receiver K1 to satellite S (in units of seconds); ρ_{K1}^{S} is geometric distance between satellite and receiver; I_{K1}^{S} and T_{K1}^{S} are ionospheric and tropospheric delay, respectively; δ_{K1} and δ^{S} are the clock offsets of the receiver and the satellite, respectively; ε_{K1}^{S} is the measurement and unmodeled errors and c is the speed of light. The GPS common-view is that two local references are compared simultaneously with a common satellite and the difference of GPS observation between two sites as shown in the following

$$\Gamma_{K1-K2}^{S} = \frac{\rho_{K1-K2}^{S}}{c} + I_{K1-K2}^{S} + T_{K1-K2}^{S} + \delta_{K1-K2} + \varepsilon_{K1-K2}^{S} \quad (2)$$

Here, Γ_{K1-K2}^{S} is the common-view time difference between K1 receiver and K2 receiver with satellite S (in units of seconds). $\frac{\rho_{K1-K2}^{S}}{c}$, I_{K1-K2}^{S}, T_{K1-K2}^{S}, δ_{K1-K2} and ε_{K1-K2}^{S} are the geometric delay, ionospheric delay, tropospheric delay, receiver clock offsets, measurement and unmodeled errors difference respectively between K1 receiver and K2 receiver with satellite S due to asymmetric propagation delay between two receiving sites. The satellite clock offset is eliminated by the common-view effect.

The time difference between two references K1 and K2 by using GPS all-in-view method is expressed in (3).

$$\Gamma_{K1-K2}^{AV} = \left(\sum_{i} \omega_{K1}^{i} \Gamma_{K1}^{i} - \sum_{j} \omega_{K2}^{j} \Gamma_{K2}^{j}\right) = \Gamma_{K1}^{GPS} - \Gamma_{K2}^{GPS} \quad (3)$$

Here, the Γ_{K1}^{GPS} is time difference between K1 receiver and GPS satellite system time, and ω_{K1}^{i} is the weight of receiver K1 and satellite i.

III. EXPERIMENTAL RESULTS

In order to verify the performance of the proposed system, a series of experiments and uncertainty estimation were performed. The proposed system with GNSS timing receiver can provide 1PPS (one pulse per second) and 10 MHz signal disciplining by GPS signal. A directly phase comparison results between proposed system and reference standard at TL show that both the accuracy of GPS receiver timing output (-5.96×10^{-16}) and the time deviation (TDEV) are approximately to meet the ITU-T G.811 PRC requirements [13] as shown in Fig. 3.

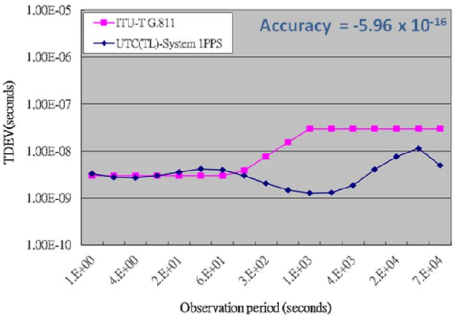

Figure 3. TDEV comparison between proposded system and ITU-T G.811 requirements.

Therefore, the system could be used as PRC independently for distributing time and frequency. The common-view common-clock calibration is used to evaluate systematic error of designed system as shown in Fig. 4. Two sets of proposed system, one is the reference system at TL and the other is prior to being tested on other site, are both measuring the same clock, a 1PPS signal from the UTC(TL) time scale. Fig. 5 shows measurement results of common clock calibration, where the one day average delay relative to the system at TL is equal to 43.6 fs, and the peak to peak variation is about 4.21 ns.

The short-baseline test was performed between reference site at TL and remote site at Fugo telecommunication facilities in Taoyuan with the distance of about 20 km between these two sites. The reference site and the remote site used UTC(TL) time scale and local cesium oscillator as its time reference, respectively. Fig. 6 shows time comparison results of short-baseline by using GPS common-view. The frequency stability $\sigma_y(\tau)$ at an averaging period of 1 day is about 1.4×10^{-14}. The time deviation $\sigma_x(\tau)$ at an averaging period of 1 day is about 0.65 ns. The long-baseline test was performed between reference site at TL and remote site at MSL in New Zealand with the distance of about 10,000 km between two sites. Fig. 7 shows time comparison results of long-baseline by using GPS common-view. The frequency stability $\sigma_y(\tau)$ at an averaging period of 1 day is about 3.5×10^{-14}. The time deviation $\sigma_x(\tau)$ at an averaging period of 1 day is about 1.73 ns. In estimating the uncertainty of the proposed system, both the Type A and Type B uncertainties evaluation must be made according to the guide of ISO standard [14]. For analysis of time uncertainty, we use time deviation $\sigma_x(\tau)$ value at an averaging period of 1 day as Type A time uncertainty. The long-baseline test result was chosen for conservative estimate of Type A time uncertainty (U_a=1.73 ns) and eleven components were taken into consideration as Type B evaluation, which potentially introduce systematic errors. The time uncertainties of Type A and Type B are summarized in table II. The combined Type B uncertainty (U_b) is estimated as 5.97 ns. The expanded time uncertainty U_c (with a coverage factor of k=2), where $U_c = k\sqrt{U_a^2 + U_b^2}$, is then equal to 25.44 ns.

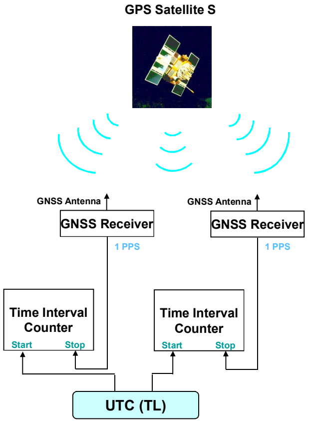

Figure 4. The diagram of common view common clock calibration

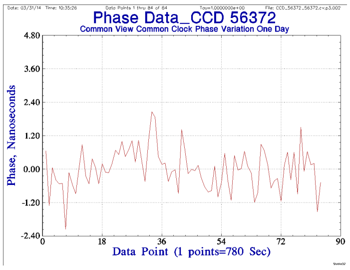

Figure 5. Common-view common-clock result

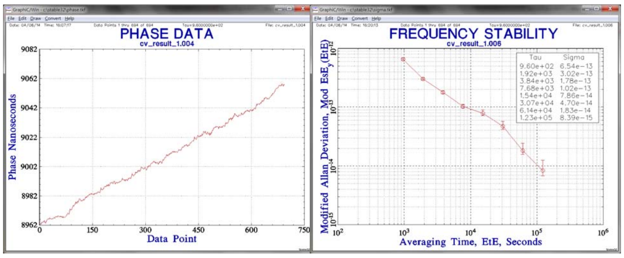

Figure 6. Time difference and frequency stability results of short-baseline.

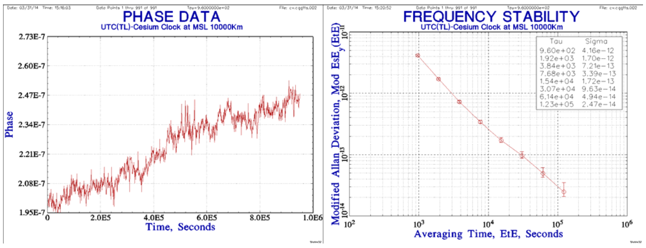

Figure 7. Time difference and frequency stability results of long-baseline.

TABLE II. THE EXPANDED TIME UNCERTAINTY OF THE PROPOSED SYSTEM

Type	Uncertainty component	Uncertainty (ns)	Coverage factor	Probability density distribution	Measurement uncertainty (ns)
B	Equipment resolution at TL	4.0	$\sqrt{3}$	rectangular	2.31
B	Equipment resolution at Remote	10.0	$\sqrt{3}$	rectangular	5.77
B	Ephemeris error	12.0	$\sqrt{3}$	rectangular	6.93
B	Common-View Common-Clock peak-to-peak variation	5.0	$\sqrt{3}$	rectangular	2.89
B	Antenna coordinate error	6.0	$\sqrt{3}$	rectangular	3.46
B	Environmental factor	3.0	$\sqrt{3}$	rectangular	1.73
B	Multipath	5.9	$\sqrt{3}$	rectangular	3.41
B	Delay error of Ionosphere	2.0	$\sqrt{3}$	rectangular	1.15
B	Delay error of Atmosphere	3.0	$\sqrt{3}$	rectangular	1.73

B	UTC-UTC(TL) 160 days measurement uncertainty	5.7	1	normal	5.7
B	Time interval counter	1.0	$\sqrt{3}$	rectangular	0.58
A	UTC(TL)-Cs between two sites	2.0	1	normal	1.73
Expanded time uncertainty (k=1)					12.72

For the analysis of frequency uncertainty, the frequency stability $\sigma_y(\tau)$ was used as Type A frequency uncertainty. The long-baseline test result was chosen for conservative estimate of Type A frequency uncertainty ($U_a=3.5\times10^{-14}$). Table III summarizes the frequency uncertainty components of Type A and Type B. The expanded frequency uncertainty (with a coverage factor of k=2) equals to 1.07×10^{-13}.

TABLE III. THE EXPANDED FREQUENCY UNCERTAINTY OF THE PROPOSED SYSTEM

Type	**Uncertainty component**	**Uncertainty (ns)**	**Coverage factor**	**Probability density distribution**	**Measurement uncertainty (ns)**
B	Frequency drift tracing back to BIPM	5.5 E-15 / 2	$\sqrt{3}$	rectangular	1.59E-15
B	Uncertainty tracing back to BIPM	1.6E-15	1	normal	1.60E-15
B	Hydrogen maser standard affected by temperature	2.0 E-14 / 2	$\sqrt{3}$	rectangular	5.77E-15
B	Stability of Hydrogen maser standard (1000s)	2.0E-15	1	normal	2.00E-15
B	AOG phase controller affected by temperature	1.0E-14/ 2	$\sqrt{3}$	rectangular	2.89E-15
B	Cable affected by temperature	5.0E-14/ 2	$\sqrt{3}$	rectangular	1.44E-14
B	SDI distributor (1)	3.0E-15/ 2	$\sqrt{3}$	rectangular	8.66E-16
B	SDI distributor (2)	3.0E-15/ 2	$\sqrt{3}$	rectangular	8.66E-16
B	Equipment at TL site	4.6E-14/ 2	$\sqrt{3}$	rectangular	1.33E-14
B	Equipment at Remote site	1.2E-13/ 2	$\sqrt{3}$	rectangular	3.46E-14
A	Frequency measurement between two sites	3.83E-14	1	normal	3.50E-14
Expanded frequency uncertainty (k=1)					5.35E-14

IV. CONCLUSION

In this paper, we present a new generation of time and frequency transfer system based on GPS common-view or all-in-view method for the purpose of time and frequency synchronization. The time and frequency uncertainty (k = 2) of the proposed system can be reached 25.44 ns and 1.07×10^{-13} respectively, which meets requirements for today's mobile wireless and power system applications. The performance indicates that the designed system could be used not only as primary reference clock independently but also as monitoring the characteristic of the primary reference clocks.

The present work enhances the mechanism of synchronization in the traditional closed telecommunication networks by providing the near-real time remote monitoring of time source, which could ensure long-term stability and improve efficiency as well as avoid impairments in networks. Moreover, the proposed system provides unbroken time and frequency link tracing back to SI through National Metrology Institute (NMI) TL in Taiwan.

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