URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

Clock Comparison with an ultra-stable optical fibre link utilizing White Rabbit Network

Neelam[1,2], Harish Rathore[1,2], Lakhi Sharma[1, 2], A. Roy[1,2], M. P. Olaniya[1], S. De[2, 3] and S. Panja[1, 2*]
[1]CSIR- National Physical Laboratory, Dr. K. S. Krishnan Marg, New Delhi 110012, India.
[2]Academy of Scientific and Innovative Research, CSIR-HRDC, Ghaziabad-201002, U.P., India
[3]Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune-411007, India
(*Email:panjas@nplindia.org)

Abstract

Precise time and frequency transfer as well as time synchronization among clocks have immense applications in different advanced technologies along with strategic applications. White Rabbit time synchronization protocol is one of the advanced technique and being utilized for precise time and frequency transfer in a large network. The present work describes establishment of a precise and stable optical fibre link for accurate time and frequency transfer utilizing White Rabbit Network. The link has been utilized for transferring time from an atomic clock in order to compare its performance with respect to another reference clock. The time deviation between the two clocks have been recorded over a long period of time and finally the fractional frequency offset between the two clocks has been derived.

1 Introduction

Over last two decades, optical fiber links have been studied with great importance and found to be one of the most reliable and precise medium for transferring time and frequency signals. As, the stability and accuracy of atomic frequency standards are increasing day by day, the precision and accuracy of time transfer techniques have also improved in parallel. Time transfer and clock comparison among remotely located atomic clocks had been started utilizing portable clock. After that satellite based methods like one-way Global Positioning System (GPS) time transfer method [1], GNSS common - view method and two way methods [2] have been utilized for long distance clock comparison. Satellite based methods are capable of transferring time within nanosecond accuracy but these methods are expansive as well as vulnerable to jamming and spoofing of satellite signals. Performance of these methods are also limited by different factors like ionospheric delay, atmospheric delay, multipath reflection, satellite orbit estimation error etc.
The accuracy and precision of network based time transfer techniques have also been improved remarkably from Network Time Protocol (NTP) [3], Precision Time protocol (PTP) [4] to White Rabbit Precision Time Protocol (WRPTP) [5,6]. WRPTP technique is capable of transferring time within sub-nanosecond accuracy through single mode optical fibres over a very long distances. Optical fibre based time and frequency transfer techniques emerged as an excellent alternative to satellite based methods and there are several techniques for accurate transfer of time and frequency signal through optical fibre [7, 8, 9]. WRPTP based optical fibre links can be utilized for disseminating accurate and secure time for different critical sectors, e.g., telecommunication, navigation, metrology, power and financial sectors etc. Establishment of long distance optical fibre links have been demonstrated utilizing White Rabbit Network [10, 11] for precise time and frequency transfer.
White Rabbit technique [12, 13] is an ethernet based two-way time transfer technique which solves the problem of limited bandwidth as well as impossibility of dynamically evaluation of link delay. It is capable of transferring time and frequency to hundreds of locations over a very long distances. Digital Dual Mixer Time Difference (DDMTD) [15] method has been implemented in WRPTP to convert the higher frequency signal into lower frequency signal without changing its phase. DDMTD is utilized to measure the fine delay among the oscillators by measuring phase difference between transmitted and recovered signal in loopback technique. WRPTP also includes Synchronous Ethernet (Sync E) [14] along with Precision Time Protocol (PTP) and utilize "Physical Layer" and "Data Link Layer" during communication within the WR network. Master sends reference clock frequency signal to the slave by encoding data through the physical layer. Slave separates clock signal from the data by utilizing clock - data recovery circuit and locks its oscillator to that reference. After locking its oscillator, slave sends data back to the master and also to other nodes (slaves), those are lower in hierarchical. In this way all the nodes (slaves) in the network are syntonized to the reference source frequency. After syntonization and link establishment between master and slave nodes, standard PTP messages are exchanged. The messages are 'Sync', 'Follow up', 'Delay request' and 'Delay response'. By exchanging these messages, slave node gets all the four timestamps those are required for estimating the link delays between master and slave nodes and eventually all slaves synchronize their time with the master.
We have used this technique for transferring time and frequency signals through optical fibres over a distance of several meters to kilometer. The optical fibre links also been utilized for comparing performance of a remotely located atomic clock (Cs beam frequency standard) with respect to a reference frequency standard (active Hydrogen Maser).

2 Experimental Setup

White Rabbit (WR) network has been established utilizing White Rabbit Lite Embedded Nodes (WRLEN, Seven Sol) and single mode optical fibres along with necessary devices. WRLEN has competence to be configured in Grandmaster (GM), Master or Slave mode. For GM mode, it requires reference frequency and time (10 MHz and 1PPS) signal from an external source *e.g.,* an atomic clock or GPS receiver for locking its internal oscillator. The schematic diagram of the experimental setup has been shown in Figure 1, and it has been used for synchronizing the remotely located node, *i.e.*, WRLEN2 and also for testing the stability of the optical fiber link between WRLEN1 and WRLEN2. WRLEN1 has been configured in GM mode by providing time and frequency signals from a high performance Cs clock (5071A, Microsemi) through a phase and frequency offset generator (HROG-10, Spectra Dynamics). Both WRLEN2 and WRLEN3 have been configured in slave mode. The nodes have been connected in sequence, as shown in Figure 1, with single mode optical fibres and all nodes have been syntonized as well as synchronized to the reference atomic clock.

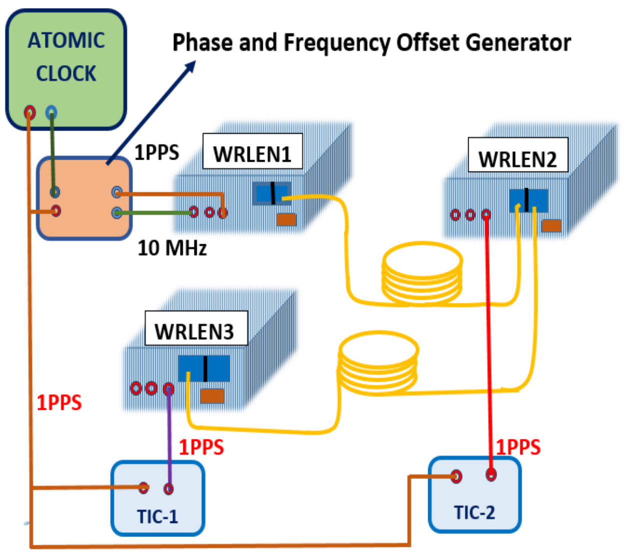

Figure 1. Schematic diagram of the experimental setup for testing the stability of the optical fibre link

The WRLEN3 has been included in this experimental setup for monitoring variation of time delays between the reference Cs Clock and WRLEN2. Commercial time interval counters (53230A, Keysight) have been utilized for measuring time delays among clocks.
After testing the stability of the optical fibre link between WRLEN1-WRLEN2, we have compared the performance of a high performance Cs atomic clock with respect to an active Hydrogen MASER (VCH-1003M) utilizing the same optical fibre link. The schematic depiction of the experimental setup for comparing performances of the clocks has been shown in Figure 2.

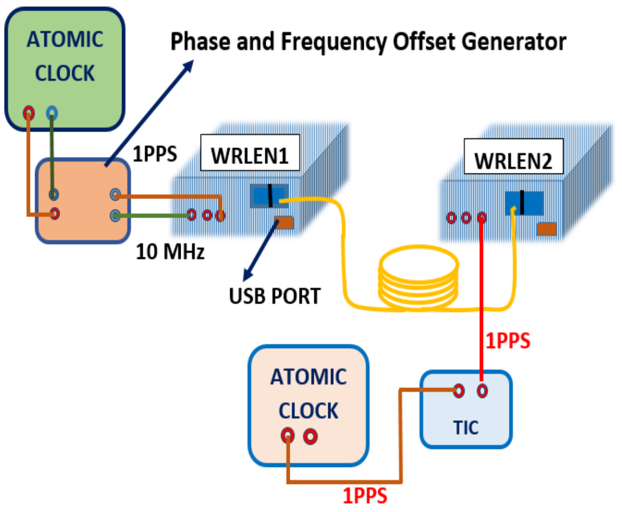

Figure 2. Schematic diagram of the experimental setup for comparing stability of atomic clocks.

3. Results and Discussion

In order to study the stability of the optical fiber link, variation of time delays between reference clock and the output of WRLEN2 have been recorded. Figure 3 shows variation of time delays between the reference clock and the output of WRLEN2 over a period about one day at ambient temperature.

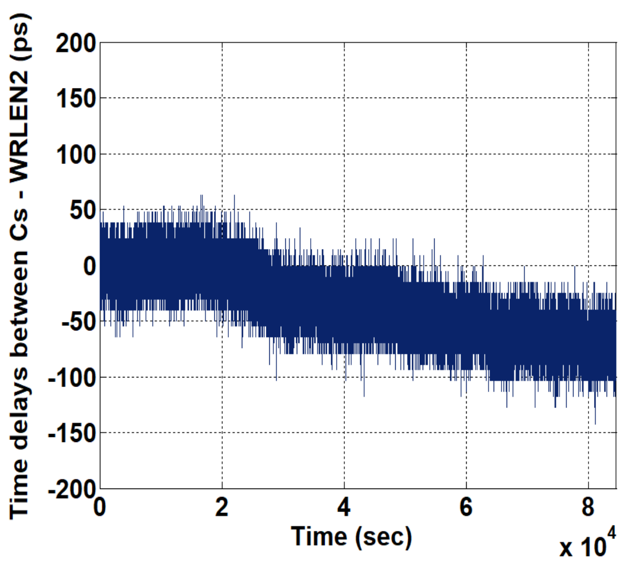

Figure 3. Time delays between Cs atomic clock and the WRLEN2 after compensating the fixed time offset at ambient temperature (19^0C-21^0C).

It has been observed that whenever the WRLEN1 is relocked to the reference clock, the time offset between the reference clock and WRLEN 2 varies by several nanoseconds. Once the GM, WRLEN1 locks its oscillator to the reference then time delays between the reference clock and WRLEN 2 does not vary much with elapsed time. There is no effect of relocking of WRLEN 1 and changing the length of optical fibres, up to 1km, on the time delay between the outputs of WRLEN2 and WRLEN3. It always remain same (1.4 ± 0.05 ns) in every condition. The initial time offset between Cs clock and WRLEN2 has been compensated by monitoring time delay between Cs clock and WRLEN3 and a precise time synchronization between the reference clock and WRLEN2 has been achieved. We also observed that the WRLEN1 which is in GM mode is more sensitive to any change of environmental condition compared to WRLEN2 and WRLEN3. So for better performance, temperature of the laboratories where those nodes have been kept should be maintained.

The effect of temperature variation of optical fibre on time delays has also been studied. Optical fibre between WRLEN1 and WRLEN2 has been heated by using a climate chamber from 20^0C to 45^0C in steps of 5^0C and time delays between the Cs atomic clock and WRLEN2 have been recorded. No significant change in time delays with the variation in temperature of the optical fibre have been noticed. It is evident from the Figure 4 that for temperature variation of 25^0C (from 20^0C to 45^0C), the time delay between the two nodes always fluctuates within a range of 100 ps.

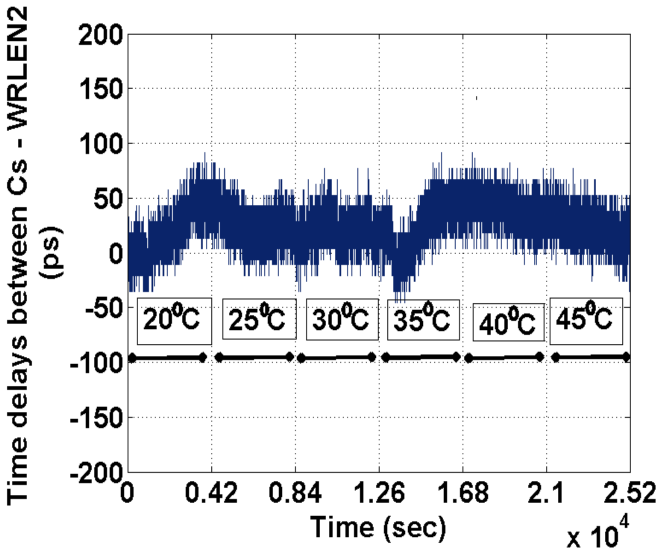

Figure 4. Variation of Time delays for different temperature [mentioned in boxes] of the optical fibre.

The stability of the time transfer link can be estimated from the variation of time delays between the reference clock and the output of WRLEN2. Figure 3 shows the variation of time delays between the reference clock and the output of WRLEN2 and the stability of the optical fibre link has been estimated in terms of modified Allan deviation (Figure 5). Time stability of the link has also been measured by estimating time deviation and the minimum value of time deviation has been estimated to be ~ 1.5 ps over an integration time ~ 500 sec. The modified Allan deviation of the optical fibre link reaches to ~ 3.9 e^{-16} within a day of integration time and such an ultra-stable link has been utilized for comparing performances of atomic clocks.

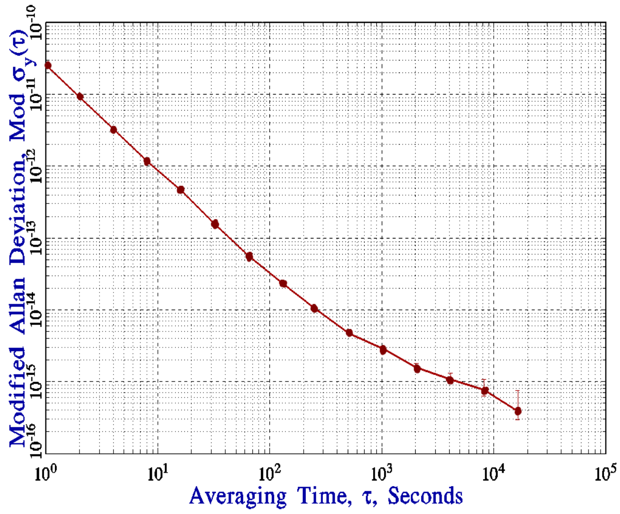

Figure 5. Modified Allan deviation for the time delay data between Cs clock - WRLEN2 at ambient temperature (19^0C-21^0C).

Our present experimental observation shows that through the optical fibre link, WRLEN2 remain synchronized to an atomic clock (reference source) within an uncertainty of ± 75 ps. So we recorded variation of time difference between an active Hydrogen Maser and WRLEN2, where the WRLEN2 is synchronized to the reference Cs clock through the same 400m long optical fibre link. Figure 7 depicts variation of time difference between the active Hydrogen Maser and the Cs clock, *i.e.,* the output of WRLEN2 over a period of 22 hours.

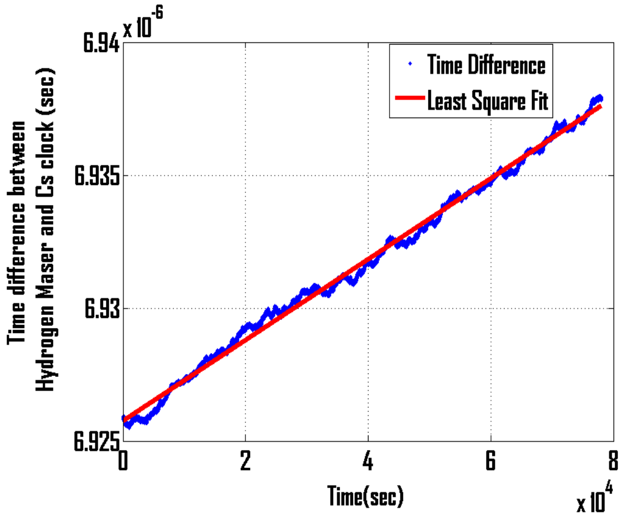

Figure 7. Variation of time difference between the active Hydrogen Maser and the Cs atomic clock. The red line shows the least square fitting of the time variation.

It has been observed that the time difference is increasing almost linearly, which indicates that there is a frequency offset between these two atomic clocks. The fractional frequency offset between the two atomic frequency standard estimated to be ~ $1.52e^{-13}$.

4 Conclusions

An ultra-stable optical fibre link has been established utilizing white rabbit network and the stability of that optical fibre link (~ 400m long) at ambient temperature (19^0C-21^0C) has been tested. The stability of that link, in terms of modified Allan deviation reaches to ~ 3.9 e^{-16} within a day of integration time which is quite suitable for comparing performance of highly stable atomic clocks. Performance of a Cs beam frequency standard has been compared with an Active Hydrogen Maser through this optical fibre link and the fractional frequency offset between these two frequency standard was derived from their time deviation over a period of several hours.

5 Acknowledgements

Neelam thanks to University Grants Commission (UGC) for providing Research Fellowship.

6 References

1. L. Sliwczynski et al. "Remote synchronization of atomic clocks" *21st International Conference on Microwave, Radar and Wireless Communications (MIKON),* May 2016, pp. 1–3, doi: 10.1109/MIKON.2016.7492092.

2. D.W. Hanson. "Fundamentals of two-way time transfers by satellite," *Proceedings of the 43rd Annual Symposium on Frequency Control*, May 1989, pp. 174–178, doi:10.1109/FREQ.1989.68861.

3. David L. Mills," Internet time synchronization: the Network Time Protocol," IEEE *Transactions on Communication*, **39**, 10, October 1991, pp. 1482- 1493, doi:10.1109/26.103043.

4. Steve T. Watt, Shankar Achanta, et al," Understanding and Applying Precision Time Protocol," *Saudi Arabia Smart Grid (SASG),* December 2015, pp. 1-7, doi:10.1109/SASG.2015.7449285

5. Erik F. Dierikx, Anders E. Wallin, et al, " White Rabbit Precision Time Protocol on Long - Distance Fiber Links," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* **63,** 7, July 2016, pp. 945-952, doi: 10.1109/TUFFC.2016.2518122.

6. Asia Derviskadic, Reza Razzaghi, et al, " The White Rabbit Time Synchronization protocol for Synchrophasor Networks," *IEEE Transactions on Smart Grid,* **11,** 1, January 2020, pp. 726-738, doi:10.1109/TSG.2019.2931655.

7. V. Smotlacha, A. Kuna and W. Mache, "Time transfer using fiber links," *EFTF-2010 24th European Frequency and Time Forum, Noordwijk*, April 2010, pp. 1-8, doi: 10.1109/EFTF.2010.6533650

8. Przemyslaw Krehlik, Lukasz Sliwczynski, Lukasz Buczek, Jacek Kolodziej and Marcin Lipinski, "Ultrastable long-distance fibre-optic time transfer: active compensation over a wide range of delays," *Metrologia*, **52,** 1**,** January 2015, pp. 82–88, doi: doi:10.1088/0026-1394/52/1/82

9. Lukasz Sliwczynski, Przemyslaw Krehlik, Albin Czubla, Lukasz Buczek and Marcin Lipinski," Dissemination of time and RF frequency via a stabilized fibre optic link over a distance of 420 km," *Metrologia*, **50**, January 2013, pp. 133-145, doi:10.1088/0026-1394/50/2/133.

10. N. Kaur et al, "Time and frequency transfer over a 500 km cascaded White Rabbit network," *Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium,* July 2017, pp. 86–90, doi: 10.1109/FCS.2017.8088808.

11. N. Kaur, P. Tuckey, et al, "Time transfer over a White Rabbit network," *European Frequency and Time Forum*, April 2016, pp. 1–4, doi: 10.1109/EFTF.2016.7477793.

12. White Rabbit. http:/www.ohwr.org/projects/white-rabbit.

13. E. Dierikx, et al, "Using white rabbit PTP for accurate time and frequency transfer in long haul optical fiber links," *Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium*, April 2015, doi:10.13140/RG.2.1.3543.9445.

14**.** T. Wlostowski, "Precise time and frequency transfer in a White Rabbit network," Master's thesis, Warsaw University of Technology, May 2011.

15. P. Moreira, et al, "Digital dual mixer time difference for sub-nanosecond time synchronization in Ethernet," *IEEE International Frequency Control Symposium*, June 2010, pp. 449-453, doi:10.1109/FREQ.2010.5556289