URSI - RCRS 2022, IIT (Indore), India, 1 - 4 December, 2022

Time transfer within 100ps uncertainty through 10 Km long optical fibre link

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Abstract

Precise time and frequency signal transfer over a long distance is one of the key activity in time and frequency metrology as precise time plays critical roles in many of the advanced technology as well as in scientific research. Since, last few decades optical fibre-based time and frequency signal transfer techniques has attracted immense importance as optical fibre-based methods show very low instability over long distances in various configurations.
This article presents the time synchronization of a remotely located clock with a reference atomic clock over a 10 km long optical fibre link within an uncertainty of 100 ps. Effect of ambient conditions mainly temperature variations on the White Rabbit (WR) based optical fibre link has been studied and a simple method to mitigate the effect of ambient variation on time synchronization accuracy has been presented. Stability of the phase compensated optical fibre link in terms of modified Allan deviation is reaching ~ 10^{-16} within one day of integration time and time deviation goes down to 2.2ps at 256 sec integration time.

1. Introduction

Requirements for precise and secure time is increasing day by day as time plays crucial role for many of the advanced scientific research as well as for modern technological applications, *e.g.,* navigation, power grid management, telecommunication, finance sectors etc. Different applications require different level of accurate time, and those requirements are fulfilled through various time transfer methods like, satellite-based methods (Global Navigation Satellite based methods, Two-way time and frequency transfer methods) [1-4], Internet or Intranet network-based method (Network Time Protocol and Precision Time Protocol) [5,6] etc. All these methods have their own advantages and limitations, *e. g.,* satellite-based methods are widely used to provide time synchronization within few nanoseconds accuracy, but it is vulnerable to jamming and spoofing of satellite signals. Similarly network based techniques are popularly used for synchronizing computer, server, devices but it is limited to provide time transfer accuracy within millisecond to microsecond due to asymmetric path delays within the network.

In recent years, optical fibres-based time dissemination methods are being used as a better alternative of satellite-based methods for transferring secure and accurate time [7,8]. Notable results have already been achieved with relatively long optical fibre links by incorporating different advanced techniques. Among them, White Rabbit time synchronization technique based optical fibre links are used for achieving time synchronization within few nanoseconds to sub nanosecond accuracy [9,10]. This technology was developed at CERN in collaboration with other laboratories and used in Large Hadron Collider experiment [11]. Currently, it is available as open source and commercialized in different forms like WR nodes and WR switches with its advanced time synchronization features. In our present studies we have used White Rabbit lite embedded node (WR-LEN, seven solutions) to establish WR network based optical fibre link. WR-LENs are compact and cost effective as well as easy to deploy to establish a WR network.
Performance of a WR-LENs based optical fibre link has been examined over 10 Km long optical fibre under variant ambient conditions (mainly at varying temperature temperature). A real time phase compensating method has been adopted to minimize the effect of varying ambient conditions on time synchronization accuracy.
This section presents a brief description of the working principle of WR time synchronization technique. WR time synchronization technique uses two-way communication through a single strand of optical fibre at different transmitting and receiving wavelengths. It overcomes the limitation of symmetric path delays consideration of precision time protocol (PTP) and introduces asymmetric path delays factor to compensate the unequal time delays between transmitting and receiving paths. In addition to PTP, it includes synchronous ethernet (Sync E) and digital dual mixture time difference (DDMTD) techniques. Synchronous ethernet technique enables all the WR nodes within the network to syntonize (frequency synchronization) their oscillators with the reference clock. DDMTD circuits measure fine delays between master and slaves and enhances the precision of time stamping done through PTP to estimate delay between the ‘master’ and ‘slave’ clock. After estimating and compensating total link delay, time synchronization with nanoseconds to sub-nanosecond accuracy is achieved [12].

2. Experimental Set-up

WR network based optical fibre link has been established to synchronize a remotely located clock to a reference atomic clock. WR-LENs and single mode optical fibres of core diameter 10 micrometer are the key component of this network. A pair of 10 km long optical fibre spool and three WR-LENs have been used to establish the network and the schematic diagram of experimental setup has been shown in figure 1. A high-performance cesium (Cs) atomic clock (5071A, Microsemi) act as reference clock within the network. High resolution phase and frequency offset generator (HROG-10, Spectra dynamics) is used for compensating frequency or time/phase offset. Time interval counters (53230A, Keysight) have been used for measuring time offset between the clocks. A LabVIEW based program has been developed for remote access and automatic operation of the HROG-10 and the TIC.

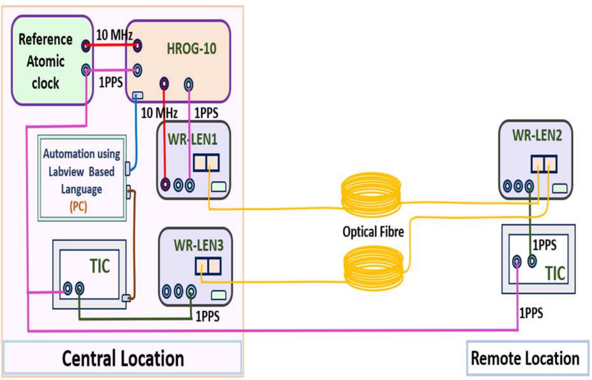

Figure 1. Schematic diagram of experimental setup for synchronizing remotely located clock (WR-LEN2) over 10 Km long optical fibre link

WR-LEN have potential that it can be configured in Grandmaster (GM), Master or Slave modes. It is necessary to provide an external reference signal, *i.e.,* 10 MHz frequency and 1PPS time signals to the WR-LENs in order to configure it in GM mode. In fig.-1, WR-LEN1 has been configured in GM mode using reference signals (10 MHz and 1PPS signal) from the reference atomic clock (Cs atomic clock) through HROG-10 while WR-LEN2 and WR-LEN3 are in their default mode *i.e.,* in Slave mode and follow their master nodes. Bidirectional small form factor pluggable (SFP) transceivers, operating at communication wavelength 1490/1310 nm, have been used to establish bidirectional (two way) communication between the WR-LENs through a single strand optical fibre. Following WR synchronization protocol, all the WR nodes within the network are synchronized to the reference Cs clock. WR-LEN1 and WRLEN3 are collocated in the central position and through the optical fibre link between WR-LEN2 to WR-LEN3, remotely located WR-LEN2 is monitored and controlled from the central location to keep it synchronized to the reference atomic clock. In order to study the synchronization capability of the WR network based optical fibre link, time offset between Cs atomic clock and remotely located WR-LEN2 as well as between Cs atomic clock and WR-LEN3 has been recorded.

Firstly, data have been recorded at ambient temperature (22^{O}C±1^{O}C) after that data have been recorded by varying temperature around optical fibres by 33^{O}C (22^{O}C to 55^{O}C).

3. Results and Discussion

It has been observed that time synchronization accuracy is affected due to variation in ambient conditions. A real time phase compensating scheme has been incorporated within the WR network by utilizing the HROG-10, TIC, and LABVIEW based program, to minimize the effect of varying ambient condition on time transfer accuracy. In this section, measurements, and observations on time delay variation through the optical fibre link in both conditions *i.e.,* without introducing any phase corrections and after introducing phase corrections though the automated HROG-10 have been explained.

3.1. Time synchronization without introducing phase corrections

Time offset variation between the Cs atomic clock and WR-LEN2 has been recorded for several hours in varying ambient conditions, *i.e., at varying* temperature around the optical fibre spool. At first, time offset variations have been recorded at ambient temperature (22^{O}C±1^{O}C) for 16 hours and after that temperature around the optical fibres have been changed by 33^{O}C over a time about 6 hours.

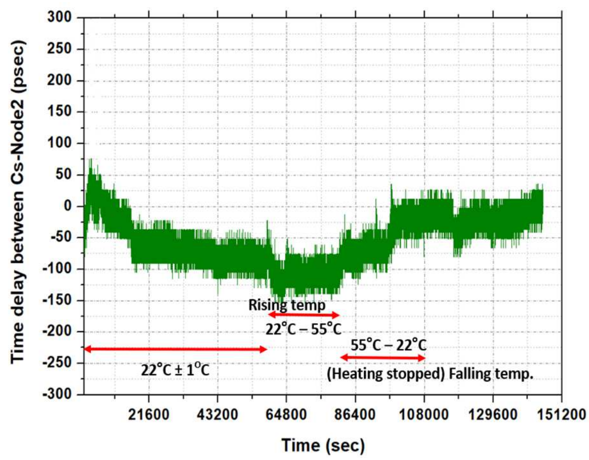

Figure 2. Time offset variation between the Cs atomic clock and the WR-LEN2 under varying temperature condition

Figure 2 depicts the time offset variation recorded due to change of temperature around the optical fibre link. It has been found that WRLENs are very sensitive to temperature variations when they are configured in GM mode [13]. So, during first 16 hours of recorded data (figure 2), temperature sensitivity of GM node (WRLEN1) is responsible for variations in time offset at room temperature (22^{O}C±1^{O}C, 16 hours) while during next 6 hours, while temperature around optical fibres are increased by 33^{O}C, temperature variations around optical fibres is also contributing for variation in time offset between Cs atomic clock and WRLEN2 (figure 2). Similarly, after 22 hours, falling temperature by 33^{O}C around optical fibres is also causing variation in time offset between the Cs atomic clock and remotely located WR-LEN2 (figure 2). The total variation in time offset for several hours of recorded data in varying temperature condition lies within 200 ps.

3.2. Time synchronization after introducing phase corrections

An algorithm has been developed to estimate and compensate time offset variation between the reference Cs atomic clock and the remotely located WR-LEN2, arises due to temperature variations around the optical fibre or due to temperature sensitivity of GM (WR-LEN1). This algorithm uses the data obtained through feedback optical fibre link, *i.e.,* the link between the Cs atomic clock and WR-LEN3, to synchronize the remotely located WRLEN2 with reference Cs clock.

A LabVIEW based program has been developed to automate the TIC and HROG-10 as represented in figure 1. In this way, required amount of phase correction is introduced automatically to the remotely located WR-LEN2 from the central location to mitigate the phase variation arises due to ambient temperature variations.

This phase correction is introduced continuously at a desired interval of time to keep the clock synchronized within sudden limit. Figure-3(b) depicts the dynamics of phase correction introduced at different times over a period about 30 hours to keep remotely located WRLEN2 synchronized to the reference atomic clock.

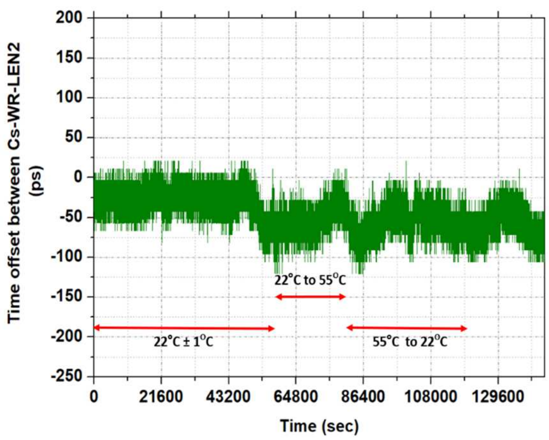

Figure 3(a). Time synchronization of WR-LEN2 with reference atomic clock (Cs atomic clock)

With the introduction of active phase corrections, time offset variation between reference clock (Cs atomic clock) and remotely located WR-LEN2 has been recorded and shown in figure 3(a). The remotely located WR-LEN2 remains synchronized with the reference clock within 100 ps uncertainty.

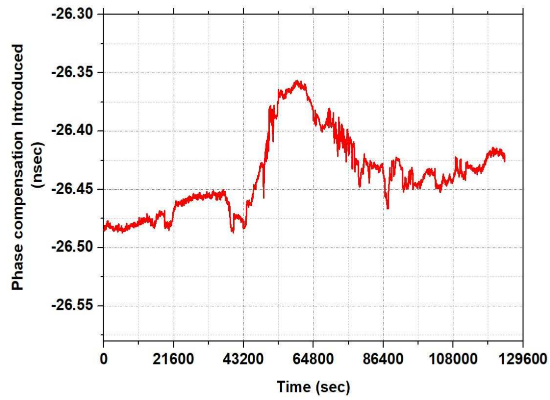

Figure 3(b). Amount of phase correction introduced during the period of time synchronization

The frequency and time instability of the optical fibre link after phase stabilization has been estimated in terms of modified Allan deviation and time deviation.

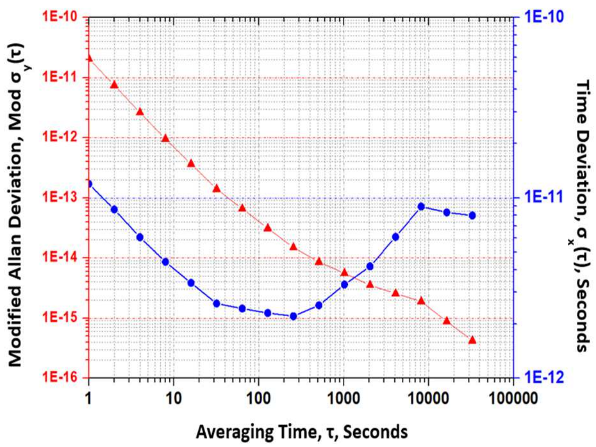

Figure 4(a). Stability of the phase compensated optical fibre link

The modified Allan deviation is reaching ~ 10^{-16} within one day of integration time while the minimum value of time deviation is 2.2ps at integration time of 256 sec [Figure 4(a)].

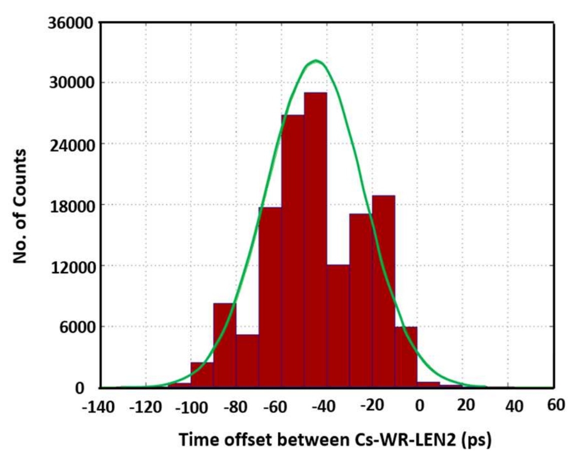

Figure 4(b). Histogram of time offset variation between the reference Cs atomic clock and phase compensated time of remotely located WR-LEN2

Histogram of the several hours measurement of time offset variation between reference atomic clock (Cs atomic clock) and WR-LEN2 [figure 4(b)], shows that WR-LEN2 is synchronized to the reference Cs atomic clock within an uncertainty of 100 ps at 3σ.

4. Conclusion

The effect of temperature variations on the time synchronization accuracy over a 10 Km long WR network based optical fibre link has been studied. Local variations in time offset, arises due to temperature variations, between reference clock and remotely located WR-LEN2 has been estimated through an additional fibre link and the dynamic phase variation has been compensated. The remotely located WR-LEN2 has been synchronized to the reference clock (Cs atomic clock) within 100 ps uncertainty. The instability of the optical fibre link is reaching ~ 10^{-16} within one day of integration time.

5. Acknowledgements

Subhasis Panja acknowledges to DlRL, DRDO, Hyderabad for the research grant and Neelam thanks to University Grants Commission (UGC) for providing research fellowship.

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