Published by IOP Publishing for Sissa Medialab

Received: *October 28, 2019*
Revised: *January 30, 2020*
Accepted: *February 4, 2020*
Published: *March 2, 2020*

Synchronization system with symmetric optical fiber links

2020 JINST 15 P03001

Y. Ye, H. Li, J. Li and G. Gong[1]

Key Laboratory of Particle & Radiation Imaging, Ministry of Education,
Qinghuayuan Street No. 1, Beijing, China
Department of Engineering Physics, Tsinghua University,
Qinghuayuan Street No. 1, Beijing, China

E-mail: ggh@mail.tsinghua.edu.cn

Abstract: In most synchronization schemes based on fiber, the compensation on fiber link asymmetry significantly affects the synchronization accuracy, thus complicated calibration may be needed to achieve high performance synchronization. Moreover, as the fiber temperature varies, fiber link asymmetry is not fixed, leading to synchronization deterioration, especially in long distance applications. This paper proposes a new synchronization scheme named LBSYNC, which achieves complete symmetry fiber link with new loopback structure. LBSYNC is based on White Rabbit system, a high performance synchronization technology with sub-nanosecond accuracy and tens of picoseconds precision, but adopts customized protocol. Theoretical analysis and experiments show that LBSYNC can achieve better synchronization performance than White Rabbit system in the fiber interconnection situation or the fiber temperature fluctuation situation, which is expected to have wider applicability in actual deployment environment.

Keywords: Hardware and accelerator control systems; Trigger concepts and systems (hardware and software); Instrumentation and methods for time-of-flight (TOF) spectroscopy

[1]Corresponding author.

https://doi.org/10.1088/1748-0221/15/03/P03001

Contents

1 Introduction

Synchronization is important in large scale distributed systems for data acquisition and action synergism, such as large particle accelerator [1], distributed cosmic ray observatory [2], etc. The normal strategy of synchronization technologies is to measure the roundtrip delay between master node and slave node, calculate the one-way delay and clock offset, then adjust the clock of slave node according the clock offset to achieve synchronization. In most practical synchronization scheme based on fiber, there is asymmetry between the fiber uplink and the fiber downlink, which affects the calculation accuracy of the one-way delay. In order to achieve high performance clock synchronization, the fiber asymmetry needs to be calibrated accurately.

White Rabbit (WR) [3] is a high performance synchronization technology with sub-nanosecond accuracy and tens of picoseconds precision. With Wavelength Division Multiplexing (WDM) technology, WR implements clock synchronization and bidirectional data transmission through a single fiber, avoiding the link asymmetry problem brought by two fibers with unequal length. Thus the asymmetry in WR includes two parts, the fixed delay asymmetry and the fiber propagation delay asymmetry. The fixed delay asymmetry is caused by the circuits and electronic components, which can be relatively calibrated. The fiber propagation asymmetry results from the chromatic dispersion: the uplink and downlink work at different wavelengths, resulting in different fiber propagation delays. WR considers that the ratio of uplink and downlink fiber propagation delays is fixed, which is defined as asymmetry parameter. Normally asymmetry paramter is determined by signal wavelengths and fiber categories, remaining unchanged within a certain fiber temperature range. Calibration procedure is needed to measure this asymmetry parameter before network deployment [4]. However, the fiber temperature variation does deteriorate the synchronization performance, especially in long distance applications. Research [5] has showed that the influence of fiber temperature change on WR synchronization is about -0.21 ps/(km·°C). Previous research [6] uses two SFPs of the same nominal wavelength to reduce the fiber asymmetry influence. However, the asymmetry is hard to be eliminated due to the wavelength difference among SFPs of the same model.

In this paper, we propose the Loopback Synchronization System (LBSYNC) based on WR. With a new loopback structure and customized protocol introduced in section 2, LBSYNC can achieve complete symmetry fiber link, thus avoiding the complicated calibration, as well as synchronization deterioration caused by fiber temperature variation. Preliminary tests, including synchronization test, fiber interconnection test and fiber temperature test, have been carried out in section 3 to verify the feasibility of this scheme, compared with WR system. In section 4, we will discuss the advantages and disadvantages of this scheme. This major drawback of this structure is the inability of bidirectional communication, which can be addressed by additional communication channel or ring-topology communication. Finally, the conclusion is given in section 5.

2 The implementation of loopback synchronization system

This section provides a brief introduction of hadrware and firmware of LBSYNC system. It then goes on to the loopback structure and customized protocol. Finally, the synchronization control procedure is described .

2.1 Hardware and firmware of LBSYNC

The LBSYNC system is based on CUTE-WR-DP hardware platform, which is a standalone WR node implemented on a FPGA Mezzanine Card for synchronous DAQ frontends and other applications. The LBSYNC node inherits the hardware and firmware from WR system for frequency transfer, fine timestamp function and clock phase adjustment.

The figure 1 shows hardware of CUTE-WR-DP boards. A XILINX Spartan-6 series FPGA is used as main processor. Two White Rabbit compatible SFP sockets are integrated, which support cascade mode WR system. Two lemo connectors are used to output clock signal for synchronization measurement.

The structure of CUTE-WR-DP firamware is illustrated in figure 2. Compared with other designs of WR node, the firmware of CUTE-WR-DP adds extra data transmission channel. Both channels support frequency transfer and fine timestamp function. An embedded microprocessor LM32 is implemented in FPGA to handle the data packets and synchronization issues. Notably, the user data packets form on channel can be transfer to the other channel directly without the intervention of LM32.

Relevant materials about this borad including PCB design and code are open source and can be found in the OHWR website [7]. LBSYNC is based on the hardware and firmware of CUTE-WR-DP, with new structure of optical connection and corresponding customized protocol implemented in LM32 .

2020 JINST 15 P03001

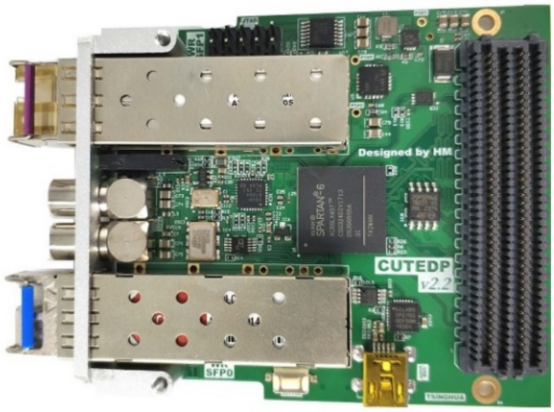

Figure 1. The CUTE-WR-DP Board [7].

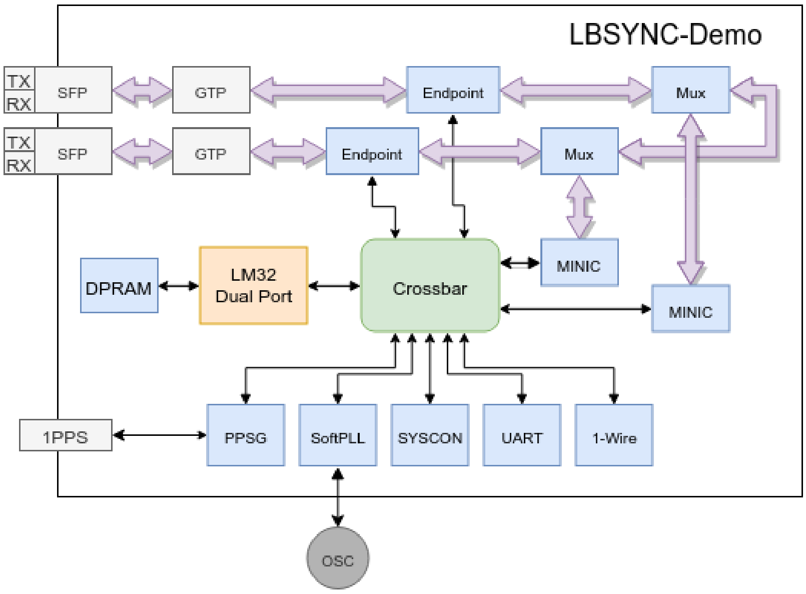

Figure 2. The structure of CUTE-DP-WR firmware.

2.2 Structure and protocol of LBSYNC

To solve the asymmetry problem, special optical connection structure and customized protocol are proposed.

LBSYNC uses two simplex SFPs, two optical circulators and one optical splitter to construct the optical connection. The schematic diagram of the LBSYNC system is shown in the figure 3. The optical circulators allow the optical signal passing in only one direction as the black arrows shown. And the optical splitter can duplicate the input signal to dual output. Under this structure, the packet transmitted from master can be received by slave via first optical splitter output, so that the slave can recover the reference clock from the data stream and get the time information for clock adjustment. The master can receive the copied packet return from the second splitter output. By recoding the timestamps when master transmits and receives the same packet, the round-trip delay

2020 JINST 15 P03001

between two LBSYNC devices can be got. In this process, all light signals are generated by the laser module in SFP of master, achieving complete symmetry fiber link. As the fiber propagated latencies in uplink and downlink are equal, then the one-way delay calculation could be easy calculated.

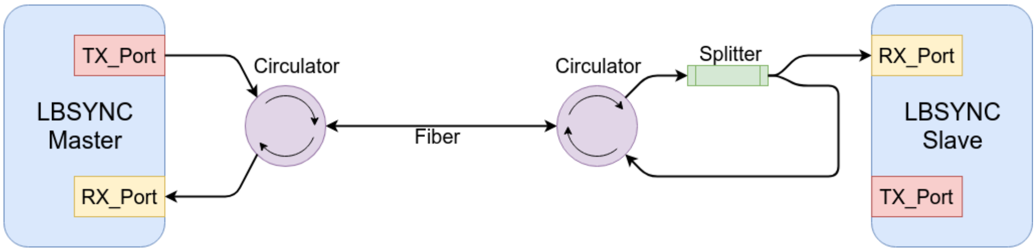

Figure 3. The LBSYNC schematic diagram.

The new protocol is shown in figure 4. Two kinds of packets, the 'Sync' packet and the 'Resp' packet, are designed for round-trip delay measurement. When the 'Sync' packet is transmitted from the master, timestamp generated by master named t_1 will be recorded. The slave generates the timestamp called t_2 when it receives the 'Sync' packet. When the 'Sync' packet comebacks to master, it will be timestamped as t_3. The t_1 and t_3 are timestamped in the referent clock domain of master, and the t_2 is in the local clock domain of slave. Then the 'Resp' packet will carry the t_1 and t_3 to the slave for clock offset calculation. In current design, this process happens once per second.

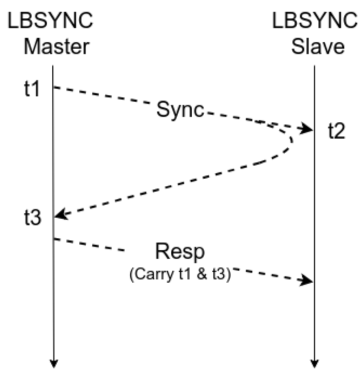

Figure 4. LBSYNC protocol.

2.3 Delay model

To elaborate the clock offset calculation, the delay model is shown in figure 5. It illustrates the messages transmission latencies in all links of LBSYNC system. The Δ_{txm}, Δ_{rxm}, Δ_{txs} and Δ_{rxs} are the transmission and reception delay caused by the SFPs, PCB circuitry, electronic components and FPGA. The bitslide values ε_m and ε_s are generated by aligning recovered clock signal to the inter-symbol boundaries of data stream. The δ is one-way fiber propagated latency. Due to symmetry of uplink and down link, the fiber propagated latency in uplink and downlink are equal. And the other latencies are transmission delay caused by the fiber circulator and optical splitter.

2020 JINST 15 P03001

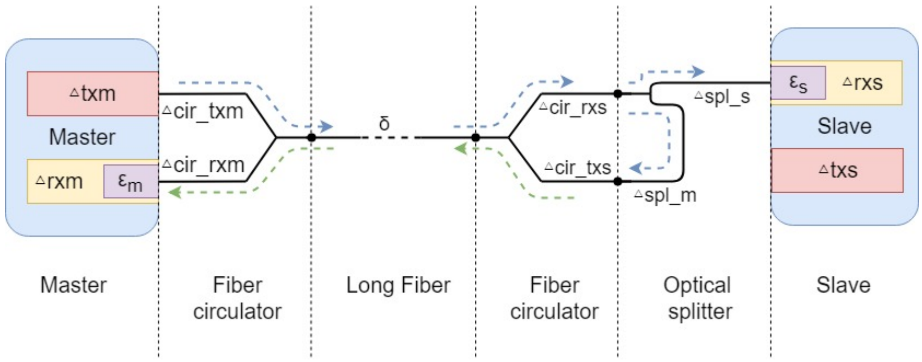

Figure 5. The delay model of LBSYNC.

To make the slave synchronizing to the master, we regard the clock of master as reference clock. There is clock offset existing between master's clock and slave's clock:

$$t_m = t_s + \text{offset} \tag{2.1}$$

By transmitting the 'Sync' packet, the round-trip delay can be got by:

$$\text{Delay}_{MM} = t_3 - t_1 \tag{2.2}$$

The Delay_{MM} includes several parts:

$$\begin{aligned}\text{Delay}_{MM} = {} & 2\delta + \Delta_{txm} + \Delta_{cir-txm} + \Delta_{cir-rxs} + \Delta_{spl-m} + \Delta_{cir-txs} \\ & + \Delta_{cir-rxm} + \varepsilon_m + \Delta_{rxm}\end{aligned} \tag{2.3}$$

Mark the reference time when slave receives the 'Sync' message as $t_2{}'$. The relation between $t_2{}'$ and t_2 is:

$$t_2' = t_2 + \text{offset} \tag{2.4}$$

The one-way delay can be got by:

$$\text{Delay}_{MS} = t_2{}' - t_1 = \Delta_{txm} + \Delta_{cir-txm} + \delta + \Delta_{cir-rxs} + \Delta_{spl-s} + \Delta_{rxs} + \varepsilon_s \tag{2.5}$$

Combine formula (2.3), formula (2.5) and eliminate the δ:

$$\text{Delay}_{MS} = \frac{t_3 - t_1}{2} - C_{\text{delay}-m} + C_{\text{delay}-s} \tag{2.6}$$

$$C_{\text{delay}-m} = \frac{\Delta_{rxm} + \Delta_{cir-rxm} + \varepsilon_m - \Delta_{txm} - \Delta_{cir-txm}}{2} \tag{2.7}$$

$$C_{\text{delay}-s} = \frac{\Delta_{cir-rxs} - \Delta_{cir-txs}}{2} + \frac{2\Delta_{spl-s} - \Delta_{spl-m}}{2} + \Delta_{rxs} + \varepsilon_s \tag{2.8}$$

$C_{\text{delay}-s}$ and $C_{\text{delay}-m}$ are constants when the link is established. They can be relatively calibrated with the time interval measurement equipment and be configured through the serial port. We connect one Cute-WR board with a SFP and a fiber circulator, regarding them as the LBSYNC master node. And the LBSYNC slave includes one Cute-WR board with a SFP, a fiber circulator and an optical splitter. The $C_{\text{delay}-s}$ and $C_{\text{delay}-m}$ can be fixed in the master node and slave node respectively if we do not replace those components.

The clock offset is:

$$\text{offset} = t_1 - t_2 + \text{Delay}_{MS} = \frac{t_1 + t_3}{2} - C_{\text{delay}-m} + C_{\text{delay}-s} - t_2 \tag{2.9}$$

The slave adjusts its local clock by the value of offset, then it will synchronize to the master.

3 Performance test

To verify the feasibility and performance of LBSYNC system, preliminary tests have been carried out. The tests include the synchronization performance test, long distance test and temperature test. The experimental setups and results are described in this section.

3.1 Test setup

For comparison, four CUTE-WR-DP boards are prepared. Two of them are programed with LBSYNC firmware and the other boards are programed with normal WR firmware. Mark them as LBSYNC-M, LBSYNC-S, WR-M and WR-S. Each WR node or LBSYNC node outputs one pulse per second (1PPS) signal. The offset between two 1PPS signals reflects the synchronization performance between two devices. Oscilloscope with 1 GHz Bandwidth and 10GS/s sample rate (Teledyne Leroy HDO8108A) is used to measure the 1PPS offset between two synchronized nodes and store the measurement data. The fibers used in these tests are produced by three manufacturers. The details are shown in table 1.

Table 1. Manufactures of prepared fibers.

Length of Fiber	2m	1km, 2km_1,2km_2	10km_1,10km_2
Manufactures	Fei Su	YOFC	Bao Gang

Before the tests, warm up four CUTE-WR-DP boards for about 20 minutes, and then calibrate the fixed delay parameters. The asymmetry parameter of the Fiber-10km-1 is calibrated according to the official manual [8, 9] as well, which is regarded as default value in following WR tests. The test setups are illustrated in figure 6.

In synchronization performance test, shown in figure 6(a) and figure 6(b), two LBSYNC nodes or two WR nodes are connected with 20 km fiber (Fiber_10km_1 and Fiber_10km_2) and all devices are put in temperature stable environment. The 1PPS offset is measured for 100 minutes to test the synchronization performance.

The setup of long distance test is to verify that LBSYNC system is free from the interference of fiber asymmetry parameter. This test is similar to synchronization performance test except that two LBSYNC nodes are connected with fiber of different lengths. Some lengths that are not listed in table 1, such as 15 km, are composed of short fibers. 500 1PPS offsets are recorded in each test.

The setup of temperature test is illustrated in figure 6(c) and figure 6(d). The Fiber_10km_1 is put in a climate chamber to test the synchronization performance of LBSYNC system and WR system when fiber temperature varies. The climate chamber is set to be stable at -10 °C for half

2020 JINST 15 P03001

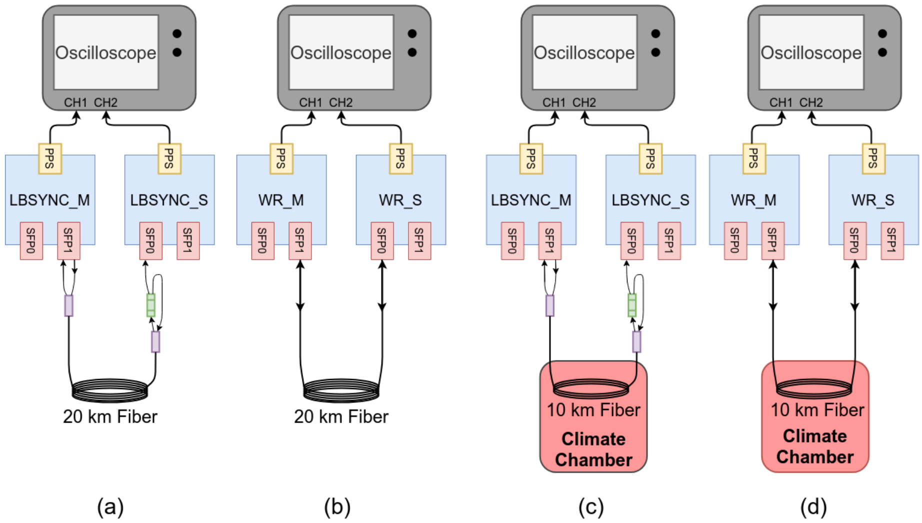

Figure 6. Diagram of performance test.

an hour, and then rise uniformly from -10 °C to 40 °C during 6 hours. The LBSYNC/WR nodes and oscilloscope are placed in temperature stable environment to reduce the effect of temperature on measurement.

3.2 Test results

3.2.1 Synchronization performance test

Figure 7 shows the synchronization performance test results. There are 6000 samples in each synchronization performance test. Synchronization accuracy could be defined as the mean value of all samples, while synchronization precision could be defined as the standard deviation of all samples. As the asymmetry parameter used in WR is calibrated based on Fiber_10km_1 and asymmetry parameters of Fiber_10km_1 and Fiber_10km_2 are slightly different, there are about -436 ps offset in WR system when the combined 20 kilometers fiber is used. Test results show the standard deviation of LBSYNC system and WR system are almost the same, which means LBSYNC and WR could achieve the same synchronization precision in temperature stable environment.

3.2.2 Long distance test

Test results are recorded in table 2. Each value is averaged over 500 measurements and the standard deviations are all less than 15 ps. In short distance tests, the 1PPS offset in LBSYNC and WR are less than 30 ps, which could mean that the fixed delay asymmetry is compensated precisely. Due to the power limitation of SFPs used in WR system, the test data is unavailable when the fiber length is beyond 25km.

Since the asymmetry parameter in WR is measured base on the Fiber_10km_1, the WR system synchronized well when Fiber_10km_1 is used. But as fibers produced by different manufactures have different asymmetry parameters, 1PPS offset or synchronization accuracy of WR system in 1km, 2km, 3km and 5km are deteriorated. Tests also confirm that even the fibers produced by

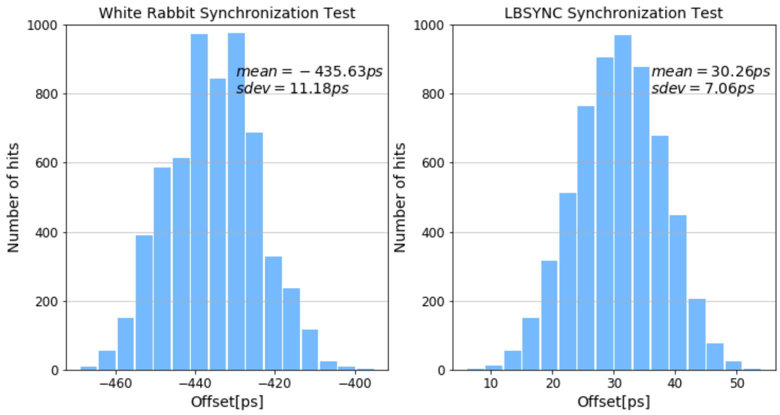

Figure 7. Result of synchronization performance test (6000 measurements).

Table 2. The result of long distance test (Unit: ps).

Types of Fiber		2m	1km	2km	3km	5km	10km-1	10km-2	15km	20km	25km
1PPS offset (Sync. Accuracy)	LBSYNC	24.6	21.2	16.6	42.5	19.6	-38	-30	61.8	21.3	9.6
	WR	27.4	-61.9	-122.3	-150.4	-314.7	41.7	-445.3	-306.4	-434	-683.6

the same manufacture with the same model, the asymmetry parameter could be slight different, according to the results of Fiber-10km-1 and Fiber-10km-2.

On the other hand, the 1PPS offset between two LBSYNC nodes keeps stable as the fiber length increases. The little synchronization accuracy fluctuation may be caused by the uncertain of fixed delay asymmetry when system restart, which exists in White Rabbit as well.

The tests show that LBSYNC system could have stable synchronization performance in different fiber interconnections than normal WR system.

3.2.3 Temperature effect test

Figure 8 and figure 9 show the result of temperature effect test. The clock offset in White Rabbit increases as the fiber temperature raises. The distribution of clock offset in LBSYNC is more concentrated and has no tendency to fiber temperature change.

As the fiber temperature varies, the fiber's length and refractive index changes. Variation in the refractive index will cause inaccuracy asymmetry parameter, which will affect the synchronization between the WR nodes. With the symmetric loopback structure, LBSYNC can avoid those problems and keep the synchronization performance.

4 Discussion

In this section, we will discuss the advantages and limitations of LBSYNC.

The preliminary tests verify the feasibility and performance of the LBSYNC. According to the test results, LBSYNC can achieve the same synchronization performance with WR system when WR system compensates the fiber asymmetry precisely and the fiber temperature is stable. In the

2020 JINST 15 P03001

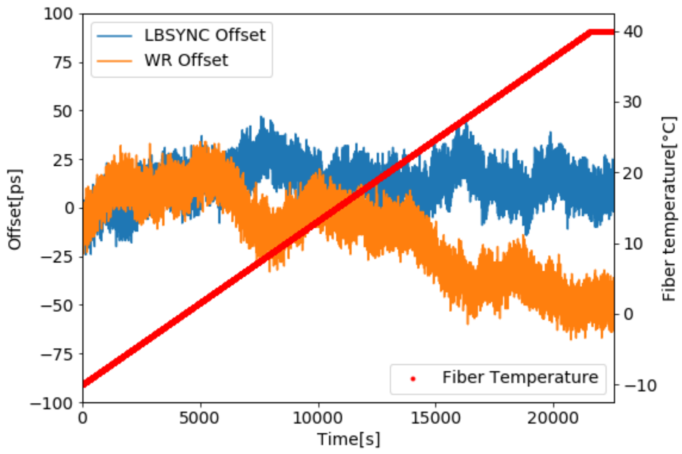

Figure 8. Curve of clock offset with uniform temperature change.

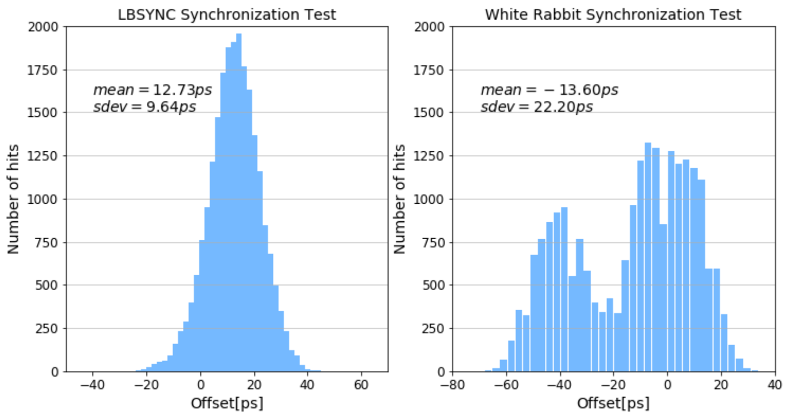

Figure 9. Distribution of clock offset with uniform temperature change.

fiber interconnected case and fiber temperature fluctuation case, the synchronization performance of LBSYNC keeps stable, which is much better than WR system. Thanks to the complete symmetry fiber link, the deployment of LBSYNC is easier without the requirement for fiber calibration. Furthermore, LBSYNC can also support the complex fiber conditions, such as interconnection of different fibers and fiber temperature variation. The light loopback structure also brings better environmental adaptability for LBSYNC.

However, there are two limitations on LBSYNC system.

The first limitation is that this loopback structure sacrifices the ability of bidirectional communication. Since the uplink is occupied by the loopback light signal, the slave can't transmit signal to master through the same fiber. In other words, data can only be transferred from master to slave in a single fiber. Using additional communication channel to transfer the slave's synchronization state and user data could solve this problem. Ring topology is compatible to this loopback structure of LBSYNC, but a special grandmaster node is needed in the ring network to keep the clock hierarchical system. Time multiplex is another solution to overcome this drawback. Firstly, master node and slave node is synchronized with LBSYNC. Then after the synchronization is built, these two nodes are changed to normal WR scheme by controlling the fiber switch. Alternate LBSYNC scheme and WR scheme periodically to compensate the fiber temperature variation.

The second limitation is the interference during the data bidirectional transmission with the same wavelength. The Backward Rayleigh scattering and Fresnel reflection of forward signal may overlap the backward signal, leading to the poor signal-to-noise ratio in data transmission, especially when the same wavelength is used for uplink and downlink in s single fiber. This may cause high bit error rate, making the communication fiber link out of work. However, the interference is not observed during the tests with fiber less than 25km. Further tests on the interference in longer fiber should be done in future.

5 Conclusion

This paper proposes a new synchronization scheme named LBSYNC which could achieve high performance synchronization with sub-nanosecond accuracy and several picoseconds precision. LBSYNC is accomplished based on off-the-shelf WR devices, but with new light loopback structure and customized protocol, realizing a complete symmetry fiber link. Theoretical analysis and preliminary tests have shown that LBSYNC has several prominent advantages comparing to normal WR system thanks to the complete symmetry fiber link feature. This feature not only allows user to get high accuracy synchronization without the need of fiber link calibration, but also brings the advantage of keeping high performance synchronization with several picoseconds precision when fiber temperature changes.

However, as an old saying goes, every coin has two sides. The loopback structure of LBSYNC makes it impossible to achieve bidirectional communication in a single fiber link. Additional communication channel may be implemented for user to transmit data and monitor the synchronization state. Physical ring topology is compatible in LBSYNC, but the clock hierarchical system should be kept. Another limitation of LBSYNC is caused by the interference during the data bidirectional transmission with the same wavelength. The signal-to-noise ratio of data transmission in LBSYNC may be influenced by Backward Rayleigh scattering and Fresnel reflection, which needs further test.

In conclusion, although the limitations exist, LBSYNC system brings more deployment convenience and higher synchronization precision comparing to normal WR system. LBSYNC is expected to have wider applicability in actual deployment fiber environment.

References

[1] P. Loschmidt, G. Gaderer, N. Simanic, A. Hussain and P. Moreira, *White rabbit — sensor/actuator protocol for the CERN LHC particle accelerator*, in *IEEE sensors*, IEEE, October 2009.

[2] H. Li, G. Gong and J. Li, *Portable calibration node for LHAASO-KM2a detector array*, *IEEE Trans. Nucl. Sci.* **64** (2017) 1363.

[3] P. Moreira, J. Serrano, T. Włostowski, P. Loschmidt and G. Gaderer, *White rabbit: sub-nanosecond timing distribution over ethernet*, in *International symposium on precision clock synchronization for measurement, control and communication*, IEEE, October 2009.

2020 JINST 15 P03001

[4] T. Włostowski, *Precise time and frequency transfer in a white rabbit network*, Master dissertation, Institute of Radioelectronics, Warsaw University of Technology, Warsaw, Poland (2011).

[5] H. Li, G. Gong, W. Pan, Q. Du and J. Li, *Temperature effect on white rabbit timing link*, *IEEE Trans. Nucl. Sci.* **62** (2015) 1021.

[6] X. Yuan and B. Wang, *Using single wavelength light to improve the synchronization accuracy of the white rabbit system*, *Chin. Opt. Lett.* **15** (2017) 101202.

[7] *Cute-WR-DP (Compact Universal Timing Endpoint based on White Rabbit with Dual Ports) webpage*, https://www.ohwr.org/project/cute-wr-dp/wikis/home.

[8] E. Dierikx and Y. Xie, *WR good practice guide*, 15SIP04_TIMEFUNC_D3, (2019).

[9] G. Daniluk, *White rabbit calibration procedure*, CERN, Geneva, Switzerland (2015).