SUB-NANOSECOND TIMING SYSTEM DESIGN AND DEVELOPMENT FOR LHAASO PROJECT*

Guanghua Gong#, Shaomin Chen, Qiang Du, Jianming Li, Yinong Liu
Department of Engineering Physics, Tsinghua University, Beijing, China
Huihai He, Institute of High Energy Physics, Beijing, China

Abstract

The Large High Altitude Air Shower Observatory (LHAASO) project is designed to trace galactic cosmic ray sources by approximately 10,000 different types of ground air shower detectors. Reconstruction of cosmic ray arrival directions requires a precision of synchronization down to sub-nanosecond, a novel design of the LHAASO timing system by means of packet-based frequency distribution and time synchronization over Ethernet is proposed. The White Rabbit Protocol (WR) is applied as the infrastructure of the timing system, which implements a distributed adaptive phase tracking technology based on Synchronous Ethernet to lock all local clocks, and a real time delay calibration method based on the Precision Time Protocol to keep all local time synchronized within a nanosecond. We also demonstrate the development and test status on prototype WR switches and nodes.

INTRODUCTION

Gamma ray source detection above 30TeV is an encouraging approach for finding galactic cosmic ray sources. All sky surveys for gamma ray sources using a wide field of view detector is essential for population accumulation for various types of sources above 100GeV.

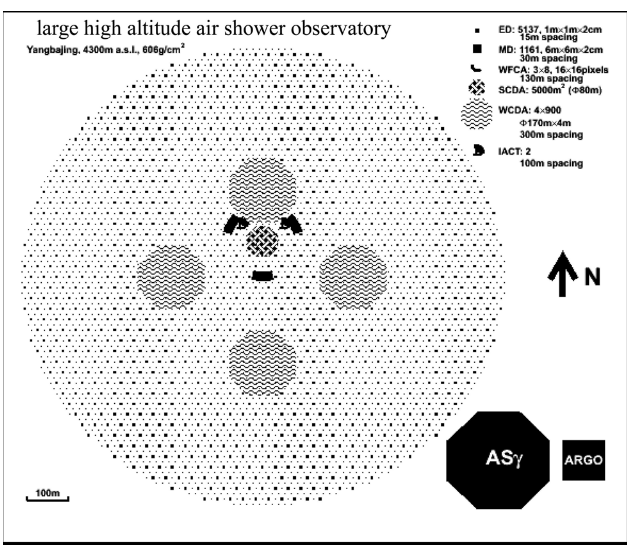

Figure 1: Layout of LHAASO observatory.

In order to target those objects, a large air shower particle detector array of $1Km^2$ (the LHAASO project [1]) at 4,300 m a.s.l. is proposed, which is designed to cover a wide energy region from 30TeV to few EeV by combining together with many air shower detection techniques. The layout of the LHAASO observatory is shown in Fig. 1.

- KM2A: particle detector array with an effective area of $1km^2$, including 5,137 scintillator detector ($1m^2$ each) to measure arrival direction and total energies of showers; 1,200 μ detectors to suppress hadronic shower background.
- WCDA: water Cherenkov detector array with a total active area of $90{,}000m^2$ for gamma ray source surveys.
- WFCTA: 24 wide FOV Cherenkov telescope array
- SCDA: $5{,}000m^2$ high threshold core-detector array.

To reconstruct the direction of cosmic rays, the arrival time difference of shower particles to each individual detector is measured using a uniform clock frequency. Differing from the classical structure which uses a central trigger as a common stop for measuring arrival time difference [2], a readout scheme without the central trigger is expected which means each individual detector will be self-triggered and the event must be precisely time tagged with a common time stamp reference.

Considering the pointing accuracy in reconstruction and the dimension of the detector array, a clock and time system is required to distribute time and clock to 10,000 nodes within 1 square Km area. Each node must have a local clock which is locked to a primary reference clock and have a local time with an accuracy of less than 1ns relative to the common reference.

There are also other considerations for this time and clock distribution system. Since it is neither practical nor realistic to manually calibrate the cable length of thousands of detectors, the system must have the capability to automatically calibrate and compensate the propagation delay caused by different cable length, temperature and mechanical stresses variation. The system should also be low cost, high reliable and low power consumptive.

EXISTING TECHNOLOGIES

Certain technologies exist for military, industry and commercial purposes with different features and performances:

- Radio/satellite navigation systems: like radio station, Global Positioning System (GPS), Global Navigations Satellite System (GLONASS), Galileo and Beidou.

*Work supported by Tsinghua University under collaboration with White Rabbit project (CERN) and National Science Foundation of China (No.11005065)
#ggh@tsinghua.edu.cn

- Wireless telecommunication: the commercial wireless telecommunications like CDMA, WCDMA, WiMAX/LTE also provide a time distribution.
- Physical Layer (Layer 1) synchronisation: like SONET/SDH, Gigabit Passive Optical Network (GPON), and Synchronous Ethernet.
- Packet-based synchronisation: like NTP, IEEE1588-2008 PTP, Circuit Emulation Services (CES) encapsulation and the future UTI J.211 from ITU-T.
- Ethernet based real-time network: like ProfiNet, EtherCAT, SERCOS III, INTERBUS and etc.

Method	Ability	Accuracy jitter	Medium	Layer	Complexity	Manageability
Radio Clock	Time	10ms	Wireless	Layer 1	Simple	No
NTP	Time	1ms	Wireless	Layer 3	Complex	No
CDMA	Time/Freq	10μs	Wireless	Layer 2	Complex	?
WCDMA	Time/Freq	3μs	Wireless	Layer 2	Complex	?
WiMAX/ LTE	Time/Freq	1μs	Wireless	Layer 2	Complex	?
GPS	Time/Freq	14ns	Sat – earth	Layer 1	Simple	No
PTPv2	Time	~ns	Ethernet	Layer 2	Complex	Yes
UTI J.211	Time/Freq	1ns	Cable	Layer 1	Simple	Yes
SDH/SyncE	Freq	10ps	Ethernet	Layer 1	Simple	No
White Rabbit	Time/Freq	<1ns	Fiber GBE	Layer 1, 2	Complex	Yes
Optical carrier sync	Freq	<50fs	Fiber	Layer 1	Ultra complex	Yes
Optical Frequency Comb distribution	Time/Freq	<10fs	Fiber	Layer 1	Ultra complex	Yes

Figure 2: Existing time distribution technologies.

Figure 2 lists the major features of several existing technologies. The PTPv2 and SDH/SyncE show the potential capability to be applied for the time and clock distribution in LHASSO project.

Facing the requirement of controlling thousands of nodes over few kilo-meters around large particle accelerate instruments, a novel technology, White Rabbit [3][4][5], has been developed in the frame of CERN's (and GSI's) renovation projects.

The White Rabbit technology shows a great applicability for LHAASO project:

- It can distribute clock and time with required accuracy
- It is possible to extend to 10,000 nodes.
- It has the feature of automatic link delay measurement and compensation.
- It has high reliability to support plug&play, no further tuning needed.
- It is an enhancement of existing data transmission links; does not need dedicated fiber or cable, which is cost effective.

WHITE RABBIT

White Rabbit is a combination and improvement of several technologies including synchronous Ethernet, precision time protocol, DMTD phase tracking and deterministic routing protocol.

Synchronous Ethernet

Synchronous Ethernet is a special extension of standard IEEE802.3 Ethernet standard where the recovered RX clock from its master is used as its own TX clock, making the whole system synchronous. With Synchronous Ethernet technology, the entire network can share a common clock to avoid any clock rate difference between nodes. This is done in hardware and is the basis for the PTP fine measurements.

Precision Time Protocol (IEEE1588)

The PTP [6][7] protocol synchronizes local time with the master time by measuring and compensating the delay introduced by the link. Link delay is measured by exchanging packets with precise hardware transmit & receipt timestamps which is explained in Fig. 3.

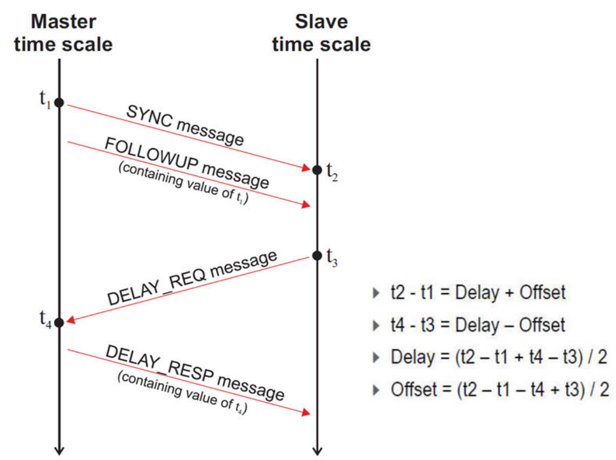

Figure 3: PTP timing process.

The Synchronous Ethernet technology provides the same clock frequency to the whole network which simplifies the PTP calculation that there is no clock rate difference but only time delay.

DMTD Phase Tracking

The measurement of standard PTP is limited by the clock frequency, a fine delay measurement of less than one clock cycle can be achieved by detecting the phase shift between transmit and receive clock on the master side.

A digital Dual Mixer Time Difference [8] (DMTD) clock measuring logic is shown in Fig. 4, which is easy to implement in a modern FPGA device.

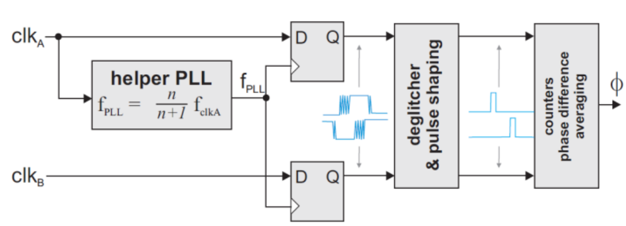

Figure 4: Digital DMTD.

DEMONSTRATION SETUP AND TEST

To evaluate the performance of Write Rabbit technology, a test system has been setup, including one WR switch and one receiver node, as shown in Fig. 5.

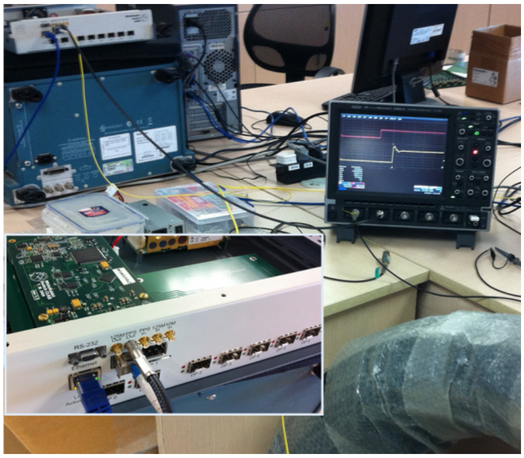

Figure 5: Demonstration setup.

The White Rabbit switch is a standalone device, the receive node is provided as an IP core and is tested on a PCI-E FMC carrier board, as shown in Fig. 6.

Figure 6: Slave node (SPEC).

The delay between the PPS of the switch and the receiver node is measured with a oscilloscope. The results are listed in table 1, which shows that the fiber length difference is transparently measured and compensated.

Table 1: Fiber Length Compensation Measurement

Fiber Length	PPS delay	
	Mean[1]	Sdev[2]
30cm	121.02ns	115.49ps
1km	125.72ns	110.66ps
5km	127.62ns	105.14ps

Note 1: the delay mainly comes from the length difference of the coaxial cables used for measurement.

Note 2: the deviation mainly comes from the test signal drive circuit.

The link was forced to re-establish to verify the stability of the time reconstruction. As presented in table 2, the peak-peak deviation among different runs is less than 100ps. The average shows a slight linear relation with the length of the fiber which is caused by the asymmetric delay factor of the 1550nm and 1390nm lights used for upstream and downstream respectively. This effect can be further reduced by calibrating and tuning a corresponding parameter in the delay calculation, which can be specific for certain optical fiber and transceiver.

WHITE RABBIT DEPLOYMENT IN LHAASO

Since the LHAASO project has around 10,000 nodes to be synchronized, a hierarchical structure of up to 3 levels must be implemented. The synchronization accuracy across multi-level switches is essential for this structure and a test for this purpose will be carried out soon.

Table 2: Repeatability of Recovered PPS (Unit: ns)

#Run	30cm	1km	2km	3km	4km	5km
Run 1	16.05	15.89	15.82	15.78	15.67	15.57
Run 2	16.05	15.92	15.89	15.76	15.64	15.65
Run 3	16.02	15.93	15.86	15.72	15.67	15.65
Average	16.04	15.91	15.86	15.75	15.66	15.62
Peak-Peak	0.03	0.04	0.07	0.06	0.03	0.08
Link delay	473	10305	20145	29969	39801	49641

A Rubidium/Caesium module provides a high accurate clock source as the external reference of the top switch, all the nodes will then trace this clock to recover a local clock; a high-precise GPS receive module provides a UTC time information as well as a Pulse per Second (PPS) signal to the top switch, all detector nodes will follow to re-establish a local time with an accuracy of less than 1ns.

Each type of detector in LHAASO project has its dedicated readout electronics to resolve the specific design issues. To save the cost and man-power of implementing the synchronized clock and time function among all detectors, a LHAASO wide clock and time mezzanine (CTM) will be developed to handle all the delicate details of white rabbit technology, each detector electronics will carry one CTM through a simple and straightforward interface.

The block diagram of CTM is shown in Fig. 7.

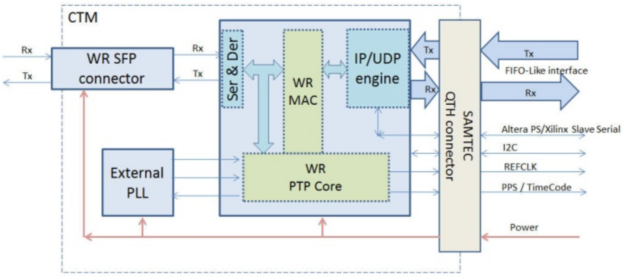

Figure 7: block diagram of CTM.

The CTM contains few major components:

- SFP connector: perform the O/E and E/O conversion.
- External PLL: to improve the precision of clock phase adjustment.
- FPGA: to implement the White Rabbit PTP core IP; it will also include a small IP packet process engine to simplify the interface to external logic as a FIFO. The engine can also provide a FPGA reconfiguration link for dynamic updating of external FPGA.
- Connector: a high-speed type from SAMTEC.

The recovered clock is directly feed to external logic, the time information will be encoded into a wide used format like IRIG-B such that the external logic will treat the CTM as a standard UTC device.

SUMMARY

The future LHAASO project requires high precise time and clock synchronization among thousands of detectors nodes. A novel design based on the White Rabbit protocol that could provide sub-nanosecond precision clock and time stamp distribution over the DAQ Ethernet fiber has been proposed. A preliminary test between a pair of master/slave nodes is presented and shows <0.4 ns rms time jitter between recovered master/slave PPS signals over different fiber lengths.

REFERENCES

[1] CAO Zhen, "A future project at Tibet: the large high altitude air shower observatory", Chinese Physics C, CPC(HEP & NP), 2010, 34(2): 249-252

[2] P.Allison, "Timing Calibration and Synchronization of Surface and Fluorescence Detectors of the Pierre Auger Observatory", 29th international Cosmic Ray Conference Pune (2005) 8,307-310.

[3] J.Serrano, "The White Rabbit Project", BE-CO Hardware and Timing section, CERN, Feb.7,2011

[4] J. Serrano, "THE WHITE RABBIT PROJECT", TUC4, ICALEPS2009, Kobe, Japan, Oct 2009

[5] Tomasz Wlostowski, "Precise time and frequency transfer in a White Rabbit network", master of science thesis, 2011, Warsaw University of Technology.

[6] "IEEE Std. 1588-2002 IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems" IEEE Std 1588-2002, pp. i–144, Nov. 2002, replaced by 61588-2004.

[7] J. Eidson, J. Mackay, G. M. Garner, V. Skendzic, "Provision of Precise Timing via IEEE 1588 Application Interfaces," in Proc. IEEE International Symposium on Precision Clock Synchronization for Measurement.

[8] G.Brida, "High resolution frequency stability measurement system", Review of Scientific instruments, Vol73, Number 5, May 2002