White Rabbit Protocol Enhanced TDM-PON with Nanoseconds Clock and Data Recovery and Picoseconds Time Synchronization Accuracy

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Abstract: White Rabbit protocol enhanced TDM-PON is proposed first time for fast clock and data recovery (CDR) and accurate time synchronization. Experimental results validate 38ns CDR time without cost-high burst-mode receiver and 390ps average time skew. © 2022 The Author(s)

1. Introduction

With the emerging of 5G related services, the incremental access devices significantly increase the Access Network (AN) traffic, which therefore requires higher bandwidth rate and utilization rate. In the widely deployed time-division multiplexing passive optical network (TDM-PON), the time-slot will align precisely according to the results after time synchronization. Although the coarse-grained (nanoseconds) time synchronization precision can be compensated by sized interval between packets, it however reduces the bandwidth utilization. Moreover, with the different deployed places of optical network units (ONUs), the uplink transmission from ONUs to optical line terminal (OLT) will be in different clock frequency and phase [1]. The receiver module at the OLT side, thus, is required to recover the clock first and then to recover the packet data. The longer time of clock and data recovery (CDR) process takes, the lower bandwidth utilization gets. Confronting to these issues, one of the latest solutions whereby IEEE 802.1AS protocol with precision time protocol (PTP) can only achieve tens nanoseconds precision, which is inadequate for the high-speed (e.g., 10Gbps upstream) network [2]. The traditional CDR techniques either based on oversampling or gated oscillator with tens nanoseconds recovery time are cost-high and technique-complicated [3]. Moreover, these techniques only solve a certainly aforementioned challenge, but introduce other issues. A concerted approach is accordingly required to overcome both challenges for the high-speed TDM-PON in next-generation.

In this paper, we deploy for the first time of white rabbit (WR) protocol in TDM-PON system to implement fast CDR and accurate time synchronization. It precisely synchronizes the time and reduce the CDR time cost, simultaneously. In the experimental assessment, the results achieve 38ns average CDR time at the OLT side. With the economic-feasible CDR enhanced, the average time synchronization skew is 390ps to afford the high-precision time-slot transmission. The sub-nanosecond time synchronization skew is further potential for the reduced packet interval to nanoseconds.

2. WR enhanced TDM-PON

As illustrated in Fig. 1, the CDR process is necessitated to recover the frequency for extracting the valid data in the point-to-point topology. Nevertheless, the tracking of frequency in the voltage-controlled oscillator (VCO) occupies the most CDR time. The unified frequency, accordingly, becomes a feasible scheme to diminish the CDR time. Confronting to the time-slot mechanism in TDM-PON, the precise time synchronization will reduce the interval to improve the bandwidth utilization. The time-slot will transmit precisely based on the timestamp stipulated by the OLT. The precise timestamp measurement will versus become the necessary factors for the high-speed TDM-PON.

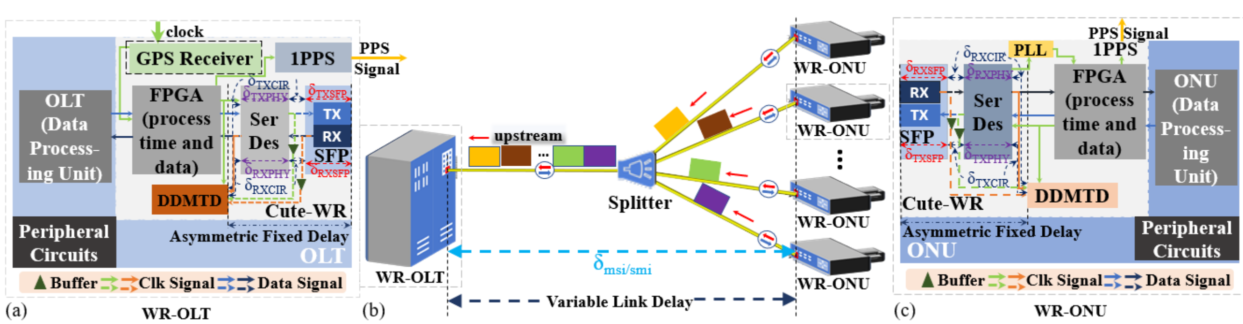

Fig. 1. (a) Concise structure of WR-OLT, (b) TDM-PON system, (c) Concise structure of WR-ONU.

To achieve the high-precision frequency syntonization and time synchronization, we implement the WR protocol in the TDM-PON system. The WR protocol is proposed by the workgroup of European Organization for Nuclear Research (CERN) and some commercial corporations [4]. It can execute the precise frequency and time synchronization simultaneously. In the sequence flow of WR protocol, the precise delay measurements will enhance the compensation firstly at ONUs to obtain the picosecond timestamps. In the system, the delay is divided in two parts: fixed delay and variable delay. As shown in Fig.1 (a) and (c), fixed delay is the composition of propagation delays of electronic components and PCB traces (δ_{TX/RX_CIR}), the asymmetry of the optical transceivers (δ_{TX/RX_SFP}) and internal PHY (serializer and deserializer chips) delay (δ_{TX/RX_PHY}) [4]. The fixed delays are measured at all devices implemented WR protocol, which are defined as WR-OLT and WR-ONUs. And the different propagation delay induced by the chromatic dispersion for different wavelengths is compensated in the upstream and downstream of the fiber. The fixed delays and fiber asymmetry coefficient are presented as equation (Eq.) (1) and Eq. (2):

$$\Delta_{TX/RX} = \delta_{TX/RX\_PHY} + \delta_{TX/RX\_CIR} + \delta_{TX/RX\_SFP} \tag{1}$$

$$\alpha = \frac{\delta_{ms}}{\delta_{sm}} - 1 \tag{2}$$

Where the δ_{ms} is the one-way fiber delay M-to-S, and the δ_{sm} is the one-way fiber delay S-to-M. After the precise fixed delay measured, we start the link setup, frequency syntonization and time synchronization process orderly. The WR-OLT will be set in master mode to broadcast the ANNOUNCE messages. With the WR-ONUs in slave mode active in the network, the replied SLAVE_PRESENT will afford the identified clk_id to guarantee the consecutive link setup process [5].

In virtue of synchronous ethernet (Sync-E), the WR-OLT will transmit the reference frequency in M_LOCK messages to the WR-ONUs. The phase locked loop (PLL) of WR-ONUs will extract the reference frequency for the slave node. The counter in receiver will recorded the number of pulses after the reference pulse per second (1PPS) rising edge to generate the reference frequency to complete the process of frequency synchronization. Subsequently, the WR-ONU will response a M_LOCKED message to manifest the accomplishment of frequency syntonization. To enhance the precision of offset measurement between WR-OLT and WR-ONUs, the transmission (Tx) and reception (Rx) delays are measured in the calibration pattern. The delays are regarded as the circuit latency between the Digital Dual Mixer Time Difference (DDMTD) phase detectors and clock generators.

With the WR link setup determinate, the PTP request-response mechanism is started to get the precise timestamp from WR-OLT to WR-ONUs [6]. The resolution of timestamp is confined by the operating frequency in transmission, and thus the picosecond part beneath the frequency period is measured by the DDMTD phase detector. The DDMTD phase detector deploys two parallel D-type flip-flops. With the converting frequency from two flip-flops passing through the low-pass filters, it is efficient to count the rising edges for the difference between the incoming clock signals. The low-frequency counter is affordable to the TDM-PON system. For different WR-ONUs, the delays will be compensated with their own measured round-trip delay $delay_{MM}$ according to the clk_id as Eq. (3) and Eq. (4):

$$delay_{MM} = (t_{4p} - t_1) - (t_3 - t_{2p}) = \Delta_{TXM} + \Delta_{RXS} + \Delta_{TXS} + \Delta_{RXM} + \delta_{ms} + \delta_{sm} \tag{1}$$

$$delay_{MS} = \frac{1+\alpha}{2+\alpha}(delay_{MM} - \Delta) + \Delta_{TXM} + \Delta_{RXS} \tag{2}$$

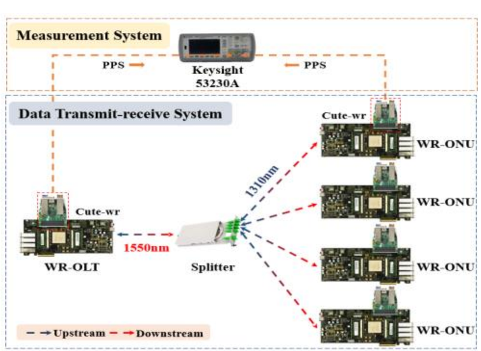

Fig. 2. Architecture of the experimental TDM-PON system

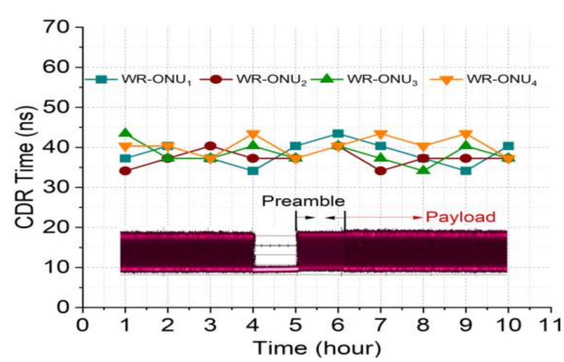

Fig. 3. The CDR time experimental results for four WR-ONUs

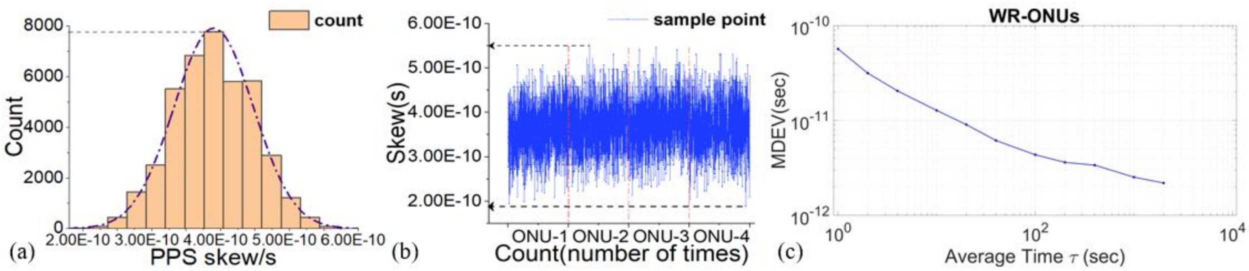

Fig. 4. (a) Distribution level of all experimental data, (b) Time synchronization skew statistics of four WR-ONUs, (c) MDEV plots for WR-ONUs as slaves.

Where the t_{2p} , t_{4p} are the enhanced received timestamps in WR-ONU and WR-OLT, separately. The Δ_{TXS} and Δ_{RXS} manifests the different Tx and Rx fixed delays of WR-ONUs with the Δ_{TXM} and Δ_{RXM} corresponding to the Tx and Rx delays of the only master WR-OLT.

3. Experiment setup and results analysis

The experimental setup is shown in Fig.2. The WR protocol is implemented on the Field Programmable Gate Array (FPGA) boards called cute-wr. The cute-wr cards are connected by a 1:4 splitter and single mode fiber with bidirectional small form pluggable plus (Bidi-SFP+) optical modules. The Xilinx VC709 boards are deployed to process data for WR-OLT and WR-ONUs. We evaluated the time synchronization performance with the comparison to the PPS from both sides by Keysight 53230A. We measured the preamble symbols received in WR-OLT as the CDR time for different WR-ONUs to demonstrate the performance of frequency syntonization.

After recording the CDR time separately, the experimental results of optical packets transmission per hour confirms the effective CDR with the average 38.6323ns among the WR-ONUs. As the Fig 3 depicted, the average CDR time values for every WR-ONU are 38.4772ns, 37.236ns, 38.4772ns and 40.339ns. The frequency syntonization is demonstrated as an economic-feasible scheme with no burst-mode receivers deployed.

In this experiment, the quality of time synchronization is evaluated from two aspects: PPS skew and stability. As shown in Fig. 4(a), its median is 389ps, with average 390ps. After one day operation, we selected the first 1200 sample points of every WR-ONU to depict the performance of time synchronization. The experimental results of PPS skew from four WR-ONUs are 362ps, 370ps, 377ps, 367ps in average, respectively. Just shown in Fig. 4(b), the worst case is 550ps in WR-ONU$_2$ while the best case is 189ps in WR-ONU$_4$.

The stability is estimated by the tool of Modified Allan deviation (MDEV). The Fig.4 (c) is the MDEV assessment result. The diminishing curve represent the maintained working stability over time. The results of MDEV demonstrate the most stable situation of 2.17e-12s corresponding to the average time τ=2000s in WR-ONUs. With the evaluation of 2000s, the stability of time synchronization demonstrates the potential of the WR protocol implementation in high-speed TDM-PON.

4. Conclusions

Confronting the explosively increased IP traffic, we propose the implementation of WR protocol in TDM-PON system first time to afford the challenges in the evolution to the high-speed. We implemented the frequency syntonization and time synchronization simultaneously. With the results analysis, it successfully achieved average 390ps PPS skew in the time synchronization process and 38ns CDR time in average at WR-OLT side. The results indicate that the proposed scheme is an economic-feasible and stable method to improve the bandwidth utilization in high-speed TDM-PON system with high-precision.

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