White Rabbit: High Precision PTP

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***Abstract*—White Rabbit is a time synchronization technology based on the Precision Time Protocol. It is used to synchronize clocks between different entities on an Ethernet network. Promising sub-nanosecond accuracy it is well suited for time and latency sensitive distributed applications. This paper gives an overview of the functionality, performance and application domains of White Rabbit.**

***Index Terms*—White Rabbit, Precise Time Protocol, Synchronous Ethernet, Time Synchronization**

1. Introduction

In 2008 development begun at CERN to replace its old timing infrastructure. The result of this work was White Rabbit (*WR*) – inspired by the habitually late rabbit of Alice in Wonderland. A requirement for the new implementation was compatibility with existing infrastructure. As a result an Ethernet-based application was chosen, adding enhancements to the Precision Time Protocol (*PTP*). PTP is a sub-microsecond accuracy time synchronization protocol for network devices, using a master-slave architecture [1]. As an improvement White Rabbit synchronizes the master and slave's clock frequencies using Synchronous Ethernet (*Sync-E*). This reduces the problem of determining latencies in the synchronization procedure to one of detecting phase offsets, enabling sub-nanosecond accuracy [2]. In 2020, after 12 years of development White Rabbit was included into the latest PTP release as High-Accuracy profile [3].

White Rabbit is used at CERN and other scientific institutions, helping to synchronize telescope arrays and distributed measurement units. It has also gained traction in the financial sector where time synchronization is important to manage stock transactions.

In this paper we will introduce the building blocks of White Rabbit: PTP (Section 2.1) and Sync-E (Section 2.2). We will continue with an overview of the components and topology of WR (Section 3.1), its time synchronization procedure (Section 3.2), applications (Section 3.4) and performance (Section 3.5). We provide further reading material in Section 4 and end with a short summary in Section 5.

2. Background

White Rabbit is mainly based on on two technologies: The (1) Precision Time Protocol which, as the name suggests, attends to precise time synchronization. And (2) Synchronous Ethernet which enables synchronization on the physical layer.

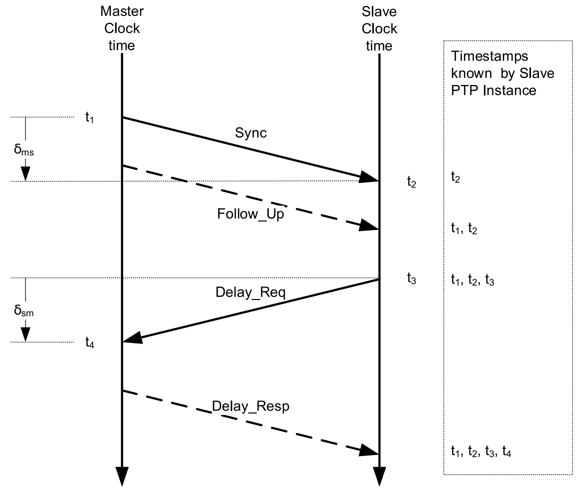

Figure 1: PTP synchronization sequence diagram [4]

2.1. Precision Time Protocol

The Precision Time Protocol is defined in its latest version v2.1 by IEEE Standard 1588-2019 [4]. It is used to synchronize clocks in networks with sub-microsecond accuracy. PTP makes use of a master-slave architecture. Its benefits are that the protocol supports heterogeneous clocks, has low latency and minimal resource usage. The protocol can be enhanced with profiles to meet use case specific requirements. One of these profiles is White Rabbit [4, Annex M] which enables PTP to synchronize clocks with sub-nanosecond precision.

The PTP procedure is shown in Figure 1. A PTP master node sends a `Sync` message to one of its slave node, signaling it to listen for a `Follow_Up` message. In the `Follow_Up` the master includes its egress timestamp t_1 of the `Sync` message. To account for communication latency δ_{ms} the slave sends a `Delay_Req` request to the master which returns a `Delay_Resp`, containing the timestamp t_4 of the message reception. With timestamps t_1, t_2, t_3, t_4 known by the slave, it can estimate the roundtrip time $\delta_{mm} := \delta_{ms} + \delta_{sm}$, the sum of message delays from master to slave and vice versa, see Equation (1). Under the assumption that communication delay is symmetrical, then one-way delay $\delta = \delta_{ms} = \delta_{sm}$ is half of the roundtrip time, which we can estimate using Equation (2).

$$\hat{\delta}_{mm} = (t_2 - t_1) + (t_4 - t_3) \tag{1}$$

$$\hat{\delta} = \frac{\hat{\delta}_{mm}}{2} \tag{2}$$

doi: 10.2313/NET-2021-05-1_14

The slave updates its local time t with the estimated clock offset $\hat{o}_{ms}$, see Equations (3) and (4).

$$\hat{o}_{ms} := \left(t_2 - t_1 + \hat{\delta}\right) \quad (3)$$

$$t := t - \hat{o}_{ms} \quad (4)$$

PTP provides accuracy in the sub-microsecond range [1]. Problems in accuracy stem from the assumption of symmetrical delay, which when violated invalidates the one-way delay computation seen Equation (2). Another source for low synchronization accuracy are imprecise timestamps, where errors propagate into the roundtrip delay, given in Equation (1).

2.2. Synchronous Ethernet

Synchronous Ethernet is a standard defined by the ITU-T (International Telecommunication Union - Telecommunication Standardization Sector) [5]. Sync-E enables clock frequency synchronization – also called syntonization – between a master and a slave node. In standard Ethernet, clock oscillators are free running, introducing clock drift and diminishing the ability to synchronize clocks accurately. Synchronous Ethernet operates on the physical layer with little overhead.

Sync-E syntonization functions as following [5]: the grandmaster node is connected to a precise reference clock, similar to Figure 3. The reference clock input is passed to a central timing card on the network interface which calibrates and handles the input accordingly. With the reference clock signal the master synchronizes its physical layer line code frequencies. A slave can recover the reference clock by extracting the frequency via a clock data recovery unit from the line codes. This is possible because the medium in Ethernet is never idle [2], thus line codes are sent with a constant frequency.

3. White Rabbit

Building upon PTP and Synchronous Ethernet, a White Rabbit network enables sub-nanosecond accuracy time synchronization.

WR uses special hardware to provide its high accuracy. Fortunately, it is an open hardware initiative, firmware and hardware designs are open sourced and freely available [6]. Several commercial implementations for WR switches and nodes are available.

In the following sections we will focus on WR as presented in its specification [7]. The specification focuses on Gigabit Ethernet over fiber, thus we will too.

3.1. Topology

Like PTP and Sync-E, White Rabbit networks use a master-slave architecture. The main component of White Rabbit is the WR switch which functions as time synchronization source and sink. A White Rabbit node is only a synchronization sink [8].

One or more WR switches can be connected to a reference clock or GPS, with one grandmaster and possibly several backup grandmasters [9]. WR nodes and switches connected to a downlink port are slaves to the switch. White Rabbit networks must have a tree topology in order for time synchronization to function properly. However, additional connections can be established to ensure redundancy. This layout is exemplarily displayed in Figure 2.

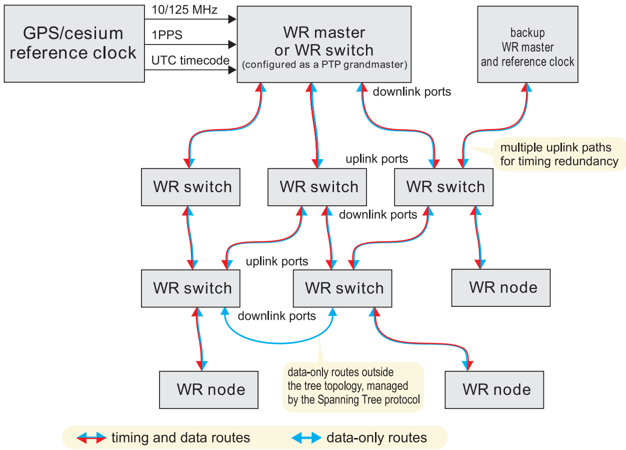

Figure 2: Exemplary White Rabbit network topology [8]

In general, White Rabbit functions transparently, working alongside non-compatible hardware. During link detection, a White Rabbit master determines if a node is compatible by sending a `ANNOUNCE` message. If a node responds with a `SLAVE_PRESENT` message, White Rabbit synchronization is enabled.

3.2. Time Synchronization

The main source of errors in PTP are the inaccuracies in time-stamping and delay measurement. Using syntonization both time-stamping and delay measurement can be reduced to a problem of phase detection. In Figure 3 a connection between a master and a slave node is shown. The master and slave clocks are running with the same frequency. Additionally, the slave node adds an estimate $phase_s$ offset to its network clock to compensate for the phase introduced between master and slave. This corrected frequency is used to transmit data to the master and for clock correction. From the loopback from master to slave and back, the master can measure a roundtrip phase offset $phase_{mm}$ [7, Sec. B.1].

White Rabbit's initial time synchronization procedure is as follows [7, Sec. B.1]:

1) Syntonization.
2) Calibration.
3) Roundtrip delay.
4) Phase measurement.
5) Fine delay.
6) Determine link asymmetry.
7) One-way delay computation.

Syntonization. Using Sync-E, clock frequencies of the master and the slave are synchronized and locked [7, Sec. 5.1].

Calibration. Constant delays, shown in Figure 3 as $\Delta_{\{txm,txs,rxm,rxs\}}$, are measured. Depending on requirements, different calibration techniques can be employed:

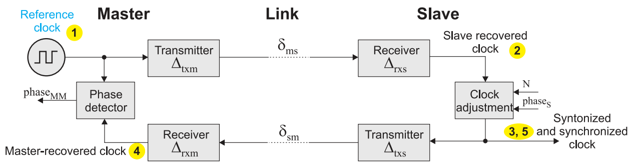

Figure 3: WR link connection [7, Fig. 11]

First, factory calibration and measurements can be used to compensate constant delays by physical latencies. Secondly, compensate active interference sources, e.g. temperature with a model of the interference's influence on the delay. Lastly, ensure similar operation conditions and setup between master and slave to minimize the delay asymmetry between nodes [7, Sec. B.6.1].

Roundtrip delay. The slave obtains $t_1, t_2, t_3, t_4, \hat{\delta}_{mm}, \hat{\delta}$ using standard PTP. To minimize timestamp errors due to clock jitter, timestamps are obtained via specialized hardware. This enables timestamp accuracy of one clock cycle [7, Sec. B.5]. Additionally, rising and falling edges of the timestamp trigger event are captured, for further precision.

Phase measurement. The roundtrip phase offset from master to slave and back is extracted on the master node [7, Sec. B.1]. Shown as $phase_{mm}$ in Figure 3.

Fine delay. PTP roundtrip time $\hat{\delta}_{mm}$ is refined using the established phase difference $phase_{mm}$.

The timestamps t_2 and t_4 are further calibrated, due to the fact that these incoming timestamps come from a different frequency domain. Either the rising or falling edge timestamp of the timestamp trigger event is used as new timestamp basis. This rising or falling edge timestamp is then adjusted using a simple algorithm to take phase offset into account [7, Sec. B.5]. For t_2 and respectively t_4, $phase_s$ / $phase_{mm}$ is incorporated to obtain t_{2p} / t_{4p}. Using these new precise timestamps t_{2p} and t_{4p} the new roundtrip delay is computed with the standard PTP roundtrip delay formula [7, Eq. (20)]:

$$\hat{\delta}_{mm} := (t_{2p} - t_1) - (t_{4p} - t_3) \tag{5}$$

Determine link asymmetry. White Rabbit loosens the assumptions of standard PTP that $\delta_{ms} = \delta_{sm}$. To transmit and receive data different wavelengths, with different refractive indexes, are used. This results in different propagation delays between the master-slave connection and the slave-master connection in the link medium. White Rabbit uses a delay asymmetry coefficient α defined as [7, Eq. (23)]:

$$\alpha := \frac{\delta_{ms}}{\delta_{sm}} - 1 = \frac{n_{1550}}{n_{1310}} - 1 \tag{6}$$

Here, n_{1550} and n_{1310} would be the refractive indexes of the transmitting wavelength of 1550 nm and receiving wavelength of 1310 nm over fiber. The delay asymmetry coefficient can be expressed in relation to δ_{mm} and the master and slave clock offset o_{ms} [7, Eqs. (8, 24, 25)]:

$$\Delta := \Delta_{txm} + \Delta_{txs} + \Delta_{rxm} + \Delta_{rxs} \tag{7}$$

$$\delta_{mm} := \Delta + \delta_{ms} + \delta_{sm} \tag{8}$$

$$o_{ms} := \frac{\delta_{ms} - \delta_{sm}}{2} \tag{9}$$

$$\alpha = \frac{\delta_{mm} - \Delta + 2 * o_{ms}}{\delta_{mm} - \Delta - 2 * o_{ms}} \tag{10}$$

One-way delay computation. With the dependency of α on δ_{mm}, as seen in Equation (10), one-way delay and offset can be computed [7, Eqs. (30,31)]:

$$\hat{\delta}_{ms} := \frac{1+\alpha}{2+\alpha}(\hat{\delta}_{mm} - \Delta) + \Delta_{txm} + \Delta_{rxs} \tag{11}$$

$$\hat{o}_{ms} := t_1 - t_{2p} - \hat{\delta}_{ms} \tag{12}$$

Multiple offset correction terms are computed [7, Eqs. (32–34)]:

$$corr_{UTC} = \left\lfloor \frac{\hat{o}_{ms}}{1\,\mathrm{s}} \right\rfloor \tag{13}$$

$$corr_{CNT} = \left\lfloor \frac{\hat{o}_{ms} - corr_{UTC}}{T_{ref}} \right\rfloor \tag{14}$$

$$corr_{PHASE} = \hat{o}_{ms} - \lfloor \hat{o}_{ms} \rfloor \tag{15}$$

$corr_{UTC}$ for the UTC time, $corr_{CNT}$ for the clock counter, $corr_{PHASE}$ for the estimated offset $phase_s$, T_{ref} is the duration of one reference clock cycle (8 ns for Gigabit Ethernet over fiber).

The corrective terms are used for the following:

1) The slave updates its UTC time counter to: $t_{UTC} := t_{UTC} + corr_{UTC}$.
2) Updates its reference clock counter: $t_{CLOCK} := t_{CLOCK} + corr_{CNT}$.
3) And its phase offset: $phase_s := phase_s + corr_{PHASE}$.

In subsequent synchronizations not all synchronization steps have to be performed. It is sufficient to recalculate phase differences.

3.3. PTP Extension

After twelve years of development [10] White Rabbit was added as High-Accuracy profile to the latest PTP version, IEEE Standard 1588-2019, in 2020 [4, Annex M]. For the integration the WR protocol was split into multiple features which are described separately in the standard [11]:

- How layer 1 syntonization shall be used within PTP [4, Annex L].
- Asymmetric delay estimation and correction for PTP [4, Clause 16.7f].
- Hardware calibration and delay asymmetry coefficient estimation [4, Annex N].
- Master-Slave assignment [4, Clause 8.2.15.5.2, 9.2.2.2 & 17.6].
- High-Accuracy delay request-response default PTP profile [4, Annex I.5].
- High-Accuracy profile for sub-nanosecond accuracy [4, Annex M].

doi: 10.2313/NET-2021-05-1_14

Overall the PTP High-Accuracy profile is a generalization of White Rabbit offering more configuration options [4, Annex L].

3.4. Applications

Initially developed to replace CERN's old timing infrastructure, White Rabbit has gained traction in other scientific projects. While CERN is still one of the main users of White Rabbit [12], many other research organizations adapted the technology. Some examples are [12]: KM3NET, a deep-sea neutrino telescope, where undersea detection units use White Rabbit. LHAASO, an air shower detection unit, consisting of 10000 detectors which are synchronized by 583 WR switches.

Another domain where White Rabbit has been gaining traction is the financial sector. The Deutsche Börse Group has been using White Rabbit to synchronize their trading network [13], [14]. Stock trading is highly dependent on accurate timing, as the trade execution order is based on bid price and time [15]. Stock exchanges also started offering timing as a service [14], [16], offering market participants to gain access to high precision timestamps for order executions. This enables insight into the strategies of other market participants trading strategies.

3.5. Performance

The first real-world application of White Rabbit was at the CERN Neutrino to Gran Sasso *CNGS* project [17], where a first WR performance survey was conducted. The experimental setup consisted of two timing devices, one of which was connected via Gigabit Ethernet over fiber to a WR grandmaster switch and the reference clock. The other was connected to a second WR switch and the reference clock. Total distance from the second timing device and the grandmaster switch was 16 km. Timestamps were taken for 31 d and the influence of temperature fluctuations of approximately 3.5 °C where taken into account. The average time difference between the two nodes was 0.517 ns with a standard deviation of 0.119 ns. Temperature fluctuations introduced only a small long-term timing drift.

Lipinski et al. [3] gives an overview of the performance of multiple WR installations, accuracy ranges from 150 ps to 8 ns. White Rabbit performance depends on the communication medium, achieving its highest performance when used with Ethernet over fiber. Using Ethernet over copper cable enables an accuracy of around 30 ns [9]. Experiments [18] to use WR over wireless bands showed that sub-nanosecond accuracy could be preserved, with slightly worse precision. Comparing this with standard PTP, where studies [1], [19] show an accuracy ranging from 1 ns to 800 ns, we see a performance improvement of 1 to 2 orders of magnitude. However, these comparisons should be taken with a grain of salt as experimental setup differs between these studies.

4. Related work

White Rabbit is an open hardware collaboration from CERN aiming to make hardware design, software and specification freely available. More information on WR can be found at the open hardware repository [6] where presentations, papers, information about hardware vendors and users, etc. are freely available.

A recent paper by Lipinski et al. [3] gives an overview of possible performance enhancements, benchmarks and users of the technology. Furthermore, he lists possible advanced use cases, for example using White Rabbit for low-latency event trigger distribution, fixed-latency data transfer or radio-frequency transfer.

5. Conclusion

In an evermore distributed world where time distribution becomes increasingly critical even at the network edges, White Rabbit is a technology particularly suited for this task. Based on existing technologies it enables fast and low-latency time synchronization. Additionally, the inclusion into the official PTP standard, promises an increasingly large adoption. Its transparent functionality enables easy integration into already existing networks.

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