Introduction to White Rabbit

Greg Daniluk

CERN

SKA meeting on High Precision Timing and Frequency Transfer
12 March 2020
## Outline

1. Introduction
2. Technology
3. Equipment
4. Standardisation
5. Ongoing Work
6. Summary
What is White Rabbit?

- CERN and GSI initiative for control & timing
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- Based on well-established standards
  - Ethernet (IEEE 802.3)
  - Bridged Local Area Network (IEEE 802.1Q)
  - Precision Time Protocol (IEEE 1588)
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  - Sub-ns synchronisation
  - Deterministic data transfer
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- Initial specs: links $\leq 10$ km & $\leq 2000$ nodes
- Open Source and commercially available
Many users worldwide, including metrology labs...

- CERN and GSI
Many users worldwide, including metrology labs...

- CERN and GSI
- The Large High Altitude Air Shower Observatory
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See user page: http://www.ohwr.org/projects/white-rabbit/wiki/WRUUsers
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White Rabbit technology - sub-ns synchronisation

Based on

- Gigabit Ethernet over fibre
- IEEE 1588 Precision Time Protocol
White Rabbit technology - sub-ns synchronisation

Based on
- Gigabit Ethernet over fibre
- IEEE 1588 Precision Time Protocol

Enhanced with
- Layer 1 syntonisation
- Digital Dual Mixer Time Difference (DDMTD)
- Link delay model
Ethernet network in a nutshell

Ethernet Switch

PC 1
MAC: 00-1B-C5-00-00-01

PC 2
MAC: 00-1B-C5-00-00-02

PC 3
MAC: 00-1B-C5-00-00-03

D: 00-1B-C5-00-00-02
S: 00-1B-C5-00-00-01
Ethernet network in a nutshell

1. PC1 → PC2
2. Ethernet Switch
3. MAC: 00-1B-C5-00-00-01
4. D: 00-1B-C5-00-00-
5. S: 00-1B-C5-00-00-01
6. MAC: 00-1B-C5-00-00-02
7. MAC: 00-1B-C5-00-00-03
8. PC1 → PC2
9. PC 1: MAC: 00-1B-C5-00-00-01
10. PC 2: MAC: 00-1B-C5-00-00-02
11. PC 3: MAC: 00-1B-C5-00-00-03
Ethernet network in a nutshell

Ethernet Switch

PC1 → PC3

PC1
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PC3
MAC: 00-1B-C5-00-00-03

D: 00-1B-C5-00-00-03
S: 00-1B-C5-00-00-01
Ethernet network in a nutshell

### Diagram

- **PC 1**: MAC: 00-1B-C5-00-00-01
- **PC 2**: MAC: 00-1B-C5-00-00-02
- **PC 3**: MAC: 00-1B-C5-00-00-03

### Ethernet Switch

- Ports 1 to 8

### Example Traffic Route

- **Source (S)**: 00-1B-C5-00-00-01
- **Destination (D)**: 00-1B-C5-00-00-02

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*Introduction to White Rabbit*
Precision Time Protocol (IEEE 1588)

- Frame-based synchronisation protocol
- Simple calculations:
  - link delay: \( \delta_{ms} = \frac{(t_4 - t_1) - (t_3 - t_2)}{2} \)
  - offset from master: \( OFM = t_2 - (t_1 + \delta_{ms}) \)
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- Hierarchical network
Precision Time Protocol (IEEE 1588)

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- Hierarchical network
- Shortcomings:
  - devices have free-running oscillators
  - frequency drift compensation vs. message exchange traffic
  - assumes symmetry of medium
  - timestamps resolution
Layer 1 Syntonisation

- Clock is encoded in the Ethernet carrier and recovered by the receiver chip
- All network devices use the same physical layer clock
- Clock loopback allows phase detection to enhance precision of timestamps
Precise phase measurements in FPGA

WR parameters:
- \( \text{clk}_{\text{in}} = 62.5 \text{ MHz} \)
- \( \text{clk}_{\text{DDMTD}} = 62.496185 \text{ MHz} \) (N=14)
- \( \text{clk}_{\text{out}} = 3.814 \text{ kHz} \)

Theoretical resolution of 0.977 ps
Link delay model

- Correction of RTT for asymmetries
Link delay model

- Correction of RTT for asymmetries
- Asymmetry sources: FPGA, PCB, SFP electrics/optics, chromatic dispersion

**Sources of asymmetry:**

- Fiber (single strand)
  - $\lambda_M = 1490\text{nm}$
  - $\lambda_S = 1310\text{nm}$

**Equations:**

- RTT = $(t_4 - t_1) - (t_3 - t_2)$

**Calibration procedure to find fixed delays and $\alpha$:**

- $\delta_{ms} = 1 + \alpha^2 + \alpha (\text{RTT} - \sum \Delta - \sum \epsilon)$

- $\text{OFM} = t_2 - (t_1 + \delta_{ms} + \Delta_{txm} + \Delta_{rxs} + \epsilon_S)$
Link delay model

- Correction of RTT for asymmetries
- Asymmetry sources: FPGA, PCB, SFP electrics/optics, chromatic dispersion
- Link delay model:
  - Fixed delays – FPGA, PCB, SFP
  - Variable delays – fiber:
    \[ \alpha = \frac{\nu_g(\lambda_s)}{\nu_g(\lambda_m)} - 1 = \frac{\delta_{ms} - \delta_{sm}}{\delta_{sm}} \]
  - Calibration procedure to find fixed delays and \( \alpha \)
Link delay model

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- Link delay model:
  - **Fixed delays** – FPGA, PCB, SFP
  - **Variable delays** – fiber:
    \[
    \alpha = \frac{\nu_g(\lambda_s)}{\nu_g(\lambda_m)} - 1 = \frac{\delta_{ms} - \delta_{sm}}{\delta_{sm}}
    \]
  - Calibration procedure to find fixed delays and \( \alpha \)
  - Accurate offset from master (OFM):
    \[
    \delta_{ms} = \frac{1+\alpha}{2+\alpha} \left( RTT - \sum \Delta - \sum \epsilon \right) 
    \]
    \[
    OFM = t_2 - (t_1 + \delta_{ms} + \Delta_{txm} + \Delta_{rxs} + \epsilon_S)
    \]
Out-of-the-box performance

Stable oscillator

Cesium beam clock

10 MHz 1 PPS

WR Switch (master)

5 km

Oscilloscope

CH1 CH2 CH3 CH4

1 PPS

WR Switch (slave 1)

5 km

WR Switch (slave 2)

5 km

WR Switch (slave 3)
Out-of-the-box performance

Histogram of offsets between master and each slave

Master (CH1)

Slave 1 (CH2)
mean = 161.86 ps
sdev = 5.45 ps

Slave 2 (CH3)
mean = 24.67 ps
sdev = 5.30 ps

Slave 3 (CH4)
mean = -135.25 ps
sdev = 6.14 ps
Management of WR networks: monitoring & config

- White Rabbit is an extension of Ethernet
White Rabbit is an extension of Ethernet

It can be managed using standard protocols and tools:
- Simple Network Management Protocol (SNMP)
- Syslog
- Link Layer Discovery Protocol (LLDP)
- Kerberos-based authentication
White Rabbit is an extension of Ethernet

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It can be debugged using standard tools:
- Wireshark
- Tcpdump
- Professional Ethernet testers
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Typical WR network
WR Switch

- Central element of WR network
- 18 port gigabit Ethernet switch with WR features
- Default optical transceivers: up to 10km, single-mode fiber
- Fully open, commercially available from 4 companies
WR Switch: hardware block diagram

- **Xilinx Virtex6 FPGA**
- **ARM CPU**
- **64MB DDR2**
- **256MB NAND**
- **8MB boot flash**
- **Power supply 12V DC 80W**
- **Cooling FANs**
- **Debug ports**
- **18 SFP cages**
- **Power supply 12V DC 80W**
- **10 MHz in/out**
- **1-PPS in/out**
- **Management ports**
- **Front panel**
- **Back panel**

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Introduction to White Rabbit
18/28
WR Node: carriers + mezzanines

- All carrier cards are equipped with a White Rabbit port
- All carrier cards instantiate WR PTP Core
- Mezzanines can use the accurate clock signal and timecode (synchronous sampling clock, trigger time tag, ...)

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19/28
WR PTP Core

WR Node Device

WR Node IP Core

Example WR Node Design

SPEC

FPGA

user core

WHISPONE

time

EtherBone

WR PTP core

SFP

Network

FMC-base CARD

WR PTP Core

external oscillators

CLK_FER

CLK_FEM

adjust

EEPROM

PC

source

sink

MAC I/F

pipelined WB Slave I/F

1-PPS Timecode

frequency

timing I/F

control/status pins

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Introduction to White Rabbit

20/28
Open and commercially available off-the-shelf

Companies selling White Rabbit:
www.ohwr.org/projects/white-rabbit/wiki/wrcompanies
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Introduction to White Rabbit
WR standardisation in IEEE 1588

- IEEE 1588 revision started in 2013 & targeted "...support for synchronisation to better than 1 nanosecond"
- Working Group with 5 sub-committees
- High Accuracy sub-committee
  - Focus on White Rabbit
  - Experts from industry and academia
  - Division of WR into self-contained parts
  - Definition of Optional Features and PTP Profile that allow WR-like implementation and WR performance
- Revised IEEE 1588 approved on 7 Nov 2019
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Ongoing work

- Improve accuracy (<10 ps) and jitter (<100 fs)
- New WR Switch hardware
- White Rabbit over 10 Gb Ethernet
- WR PTP Core support for new FPGA families
- Support for building WR applications
Summary

- Ethernet-based synchronization
- <1 ns accuracy and <10 ps precision out-of-the-box
- Open with commercial support
- Standard-based and standard-extending
- Included in the revised IEEE 1588
Summary

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- A versatile solution for general control and data acquisition
- Showcase of technology transfer
Thank you!

WR Project page: http://www.ohwr.org/projects/white-rabbit/wiki
Applications
WR applications in science and beyond

- Time & frequency transfer
- Time-based control
- Precise timestamping
- Trigger distribution
- Fixed-latency data transfer
- Radio-frequency transfer
Time & frequency transfer

- Widely used/evaluated by National Time Labs (5 countries)
- Evaluated by Deutsche Telecom

High Accuracy Time Dissemination
4. Application of Time Transfer Methods and Network Sync Level

ISPCS keynote *Highly Accurate Time Dissemination & Network Synchronisation*, Helmut Imlau, Deutsche Telekom
Time-based control
Time-based control

<table>
<thead>
<tr>
<th>Event ID</th>
<th>Hh:mm:ss:nanoseconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID = 1</td>
<td>00:00:10:0000000000</td>
</tr>
<tr>
<td>ID = 2</td>
<td>00:00:10:0000000010</td>
</tr>
<tr>
<td>ID = 3</td>
<td>00:00:10:0000001000</td>
</tr>
</tbody>
</table>

Control Message (CM)
Time-based control

### Event ID and Time Information

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</tr>
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<td>ID = 3</td>
<td>00:00:10:000000100</td>
</tr>
</tbody>
</table>

### Control Message (CM)

- **Data Master (Controller)**
- **Magnet SPS**
- **Actuator**
- **Magnet in PS**
- **Sensor**

### Timeline

- **Send CM**
  - 00:00:09:999000000

- **Receive CM**
  - 00:00:10:0000000000

- **Execute Events**
  - 00:00:10:000000100

### Event Sequence

1. **Tip**
2. **Pause**
3. **Stop Measure**
Time-based control

**Event ID** | **Hh:mm:ss:nanoseconds**
--- | ---
ID = 1 | 00:00:10:0000000000
ID = 2 | 00:00:10:0000000100
ID = 3 | 00:00:10:0000001000

**Control Message (CM)**

![Diagram of time-based control](image)
Time-based control - example application

- GSI Helmholtz Centre for Heavy Ion Research in Germany
GSI Helmholtz Centre for Heavy Ion Research in Germany
1-5 ns accuracy and 10 ps precision
Time-based control - example application

- GSI Helmholtz Centre for Heavy Ion Research in Germany
- 1-5 ns accuracy and 10 ps precision
- WR network at GSI:
  - Operational since June 2018: 134 nodes & 32 switches
  - Final: 2000 WR nodes & 300 switches in 5 layers
Precise timestamping

- Association of time with
  - an event
  - a sample (measured value)
Precise timestamping

- Association of time with
  - an event
  - a sample (measured value)
- The most widely used WR application

![Time-to-digital converter (TDC)](image)

![Digitizer](image)
Precise timestamping

- Association of time with
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- The most widely used WR application
  - Time-of-flight measurement
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    - Speed of neutrinos - CNGS
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- The most widely used WR application
  - Time-of-flight measurement
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  - Cosmic ray and neutrino detection
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    - Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy
Precise timestamping

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    - Cubic Kilometre Neutrino Telescope
    - Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy
  - High Frequency Trade monitoring
    - German Stock Exchange
Trigger distribution

- Trigger pulse
  - Time-to-Digital Converter (TDC)
    - TAI Timestamp: 12:34:56 + 111.5 ns
    - TAI time
      - White Rabbit network
        - Fixed delay (e.g., 300 us)
          - Output timestamp: 12:34:56 + 300,111.5 ns
        - 300 us
          - Programmable pulse generator
            - trigger pulse
              - trigger pulse
Trigger distribution - example applications

LHC trigger distribution to measure beam instabilities - since 2016

OB Observation instrument (OB)
Trigger distribution - example applications

LHC trigger distribution to measure beam instabilities - since 2016

WRTD - White Rabbit Trigger Distribution- to be used for CERN’s Open Analog Signals Information System (OASIS)
Fixed-latency data transfer

**Diagram Description:**

- **User** sends a word to the FPGA.
- **Timestamp data & transmit** is processed by the FPGA.
- **MAC** processes the data.
- **Ethernet Frame** with **Header** is transmitted with delay **$t_{Tx}$**.
- **Receive data & delay** is processed in the FPGA.
- **User** receives the word with delay **$t_{Rx}$**.
- The fixed latency is **$(t_{Tx} + \Delta) - t_{Rx}$**.

**Note:**

- **$t_{Tx}$** is the transmit time.
- **$t_{Rx}$** is the receive time.
- **$\Delta$** represents the fixed latency delay between the transmit and receive times.
Fixed-latency data transfer- example application

Distribution of magnetic field in CERN accelerators

Accelerating RF cavity

$f_{\text{rev}}(t)$

Bending magnet

$B(t)$

Magnets power converter

$I(t)$
Radio-frequency transfer

Feedback frequency (equal to RF input when locked)

RF input

Phase detector → PI control → DDS

Encode packets

125 MHz reference
TAI time

White Rabbit network

Decode packets
Apply control words

125 MHz reference
TAI time

DDS tune

RF output
Radio-frequency transfer

Feedback frequency (equal to RF input when locked)

RF input -> Phase detector -> PI control -> DDS

Encode packets

125 MHz reference TAI time

Address counter -> Waveform lookup table -> Digital to analog converter

Direct digital synthesis (DDS)

Master

White Rabbit network

125 MHz reference TAI time

Decoder packets
Apply control words

DDS

RF output
Radio-frequency transfer - example application

- RF over WR at European Synchrotron Radiation Facility (ESRF)
  - A prototype tested in operation: <10 ps jitter

- RF over WR at CERN
  - A prototype: <100 fs jitter and <10 ps reproducibility over reboots