White Rabbit: an accurate time and frequency transfer over Ethernet networks

Maciej Lipiński

CERN CEM-EDL
Electronics Design & Low-Level Software section

Open Compute Forum
5 May 2021
Outline

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

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

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- The Large High Altitude Air Shower Observatory
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See user page: http://www.ohwr.org/projects/white-rabbit/wiki/WRUsers
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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
Gigabit Ethernet Local Area Network over fibre

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

D: 00-1B-C5-00-00-01
S: 00-1B-C5-00-00-03
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: \( OFM = t_2 - (t_1 + \delta_{ms}) \)
Precision Time Protocol (IEEE 1588)

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- Hierarchical network
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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.

Diagram:
- Reference clock & PPS
- System Timing Master
- Ethernet link
- Uplink port
- Switch fabric
- Other nodes or switches
- Cesium
- Rx
- Tx
- Transmitter
- Receiver
- Downlink 1
- Downlink 2
- Downlink N
- Clock loopback

Note: Diagram shows a network configuration with various nodes and links, including a reference clock, system timing master, and Cs 132.91.
Digital Dual Mixer Time Difference (DDMTD)

- 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

\[
\text{RTT} = (t_4 - t_1) - (t_3 - t_2)
\]

PTP message exchange
Link delay model

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

**Sources of asymmetry:**

- Fiber (single strand)

\[ \lambda_M = 1490\text{nm} \]
\[ \lambda_S = 1310\text{nm} \]
**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 \(\alpha\)
Correction of RTT for asymmetries

Asymmetry sources: FPGA, PCB, SFP electrics/optics, chromatic dispersion

Link delay model:
- **Fixed delays** – FPGA, PCB, SFP
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  \]
- Calibration procedure to find fixed delays and \(\alpha\)

Accurate offset from master (OFM):
\[
\delta_{ms} = \frac{1 + \alpha}{2 + \alpha} (RTT - \sum \Delta - \sum \epsilon)
\]

\[
OFM = t_2 - (t_1 + \delta_{ms} + \Delta_{txm} + \Delta_{rxs} + \epsilon_S)
\]
Out-of-the-box performance

Stable oscillator

Cesium beam clock

10 MHz 1 PPS

WR Switch (master)

5 km

Oscilloscope

WR Switch (slave 1)

5 km

WR Switch (slave 2)

5 km

WR Switch (slave 3)

1 PPS

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White Rabbit
Out-of-the-box performance

"White Rabbit: a PTP Application for Robust Sub-nanosecond Synchronization", M.Lipinski et al, ISPCS 2011
State of the art performance

- **Accuracy:** <10 ps
- **Jitter:** <100 fs RMS 10 Hz–10 MHz
Typical WR network
WR Switch v3 - current

- 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 v4 - under development

- Up to 24 port, 1 and 10 Gbps, with WR features
- Redundant & hot-swappable power supply and fans
- Expansion board
- Fully open design
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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WR PTP Core

WR Node Device

SPEC

FPGA

user core

WHISBONE

time

EtherBone

WR PTP core

FMC-base CARD

Network

SFP

Example
WR Node Design

WR Node IP Core

Tx Ethernet Rx

external PHY

time

external oscillators

CLKref

CLKlaser adjust

EEPROM

WR PTP Core

1PPS Timecode frequency

MAC I/F

timed WB Slave I/F

source

sink

timing I/F

control/status pins

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White Rabbit

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Open and commercially available off-the-shelf

Companies selling White Rabbit:
www.ohwr.org/projects/white-rabbit/wiki/wrcompanies
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)
## 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

![Diagram of time dissemination network](image)

- **UTC(k) level**
  - UTC(x)
  - UTC(PTB) Braunschweig
  - UTC(DTAG) Frankfurt

- **CORE Network level**
  - Cs
  - PTP-FTS

- **Aggregation Network level**
  - Bi-di over single fiber/sync only

- **Access level**
  - w/o T-BC
  - T-BC Cl. D
  - Fiber pair/together with traffic

---

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

4.3 km

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White Rabbit
Time-based control

<table>
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<th>Event ID</th>
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<td>ID = 1</td>
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<td>ID = 2</td>
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<td>00:00:10:000000100</td>
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</table>

Control Message (CM)

- Data Master (Controller)
- Magnet
- SPS
- actuator
- Magnet in PS
- sensor

- send
- receive
- execute events

00:00:09:999000000
00:00:10:000000000
00:00:10:000001000
00:00:10:00000010

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Time-based control

Event ID  Hh:mm:ss:nanoseconds
ID = 1  00:00:10:000000000
ID = 2  00:00:10:000000010
ID = 3  00:00:10:000000100

Control Message (CM)

Max latency

send

receive

execute events

00:00:09:999000000
time

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### Time-based control - example application

- **GSI Helmholtz Centre for Heavy Ion Research in Germany**

![GSI Helmholtz Centre for Heavy Ion Research in Germany](image_url)
Time-based control - example application

- 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)**

**Digitizer**

- Voltage
- Time
- Timestamp
- Threshold
- Time

- Voltage
- Time
- Timestamp & Measurement
Precise timestamping

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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
Precise timestamping

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    - Large High Altitude Air Shower Observatory
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    - 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
- White Rabbit network
  - Fixed delay (e.g., 300 us)
  - Output timestamp: 12:34:56 + 300,111.5 ns
- Programmable pulse generator
  - Trigger pulse

300 us delay
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

WR Node
FPGA
WR Port
WR Network
WR Node
FPGA
WR Port

User
word 1
Timestamp data & transmit
MAC
Ethernet Frame
word 1 $t_{Tx}$ Header
MAC
Receive data & delay
User
word 1

$\Delta$ Fixed latency
$t_{Tx}$
$t_{Rx}$
$t_{Use}$

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Fixed-latency data transfer - example application

Distribution of magnetic field in CERN accelerators
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

Master

White Rabbit network

Receiver

Decode packets
Apply control words

125 MHz reference
TAI time

DDS

RF output

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Radio-frequency transfer

Feedback frequency (equal to RF input when locked)

RF input

Phase detector

PI control

DDS tune

Encode packets

125 MHz reference

TAI time

125 MHz reference

TAI time

Decode packets

Apply control words

DDS tune

RF output

Direct digital synthesis (DDS)

Address counter

Waveform lookup table

Digital to analog converter

RF signal

Master

Receiver

White Rabbit network
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
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IEEE standards are revised periodically
WR standardisation in IEEE 1588 (1)

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- IEEE 1588 revision started in 2013 & targeted
  "...support for synchronisation to better than 1 nanosecond"
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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
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- Revised IEEE 1588 approved on 7 Nov 2019
White Rabbit integration into IEEE 1588 as High Accuracy: 
https://www.ohwr.org/projects/wr-std/wiki/wrin1588
WR standardisation in IEEE 1588 (2)

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WR standardisation in IEEE 1588 (2)

- HA-specific optional features (active by default):
  - Calculation of the \textit{<delayAsymmetry>}
  - Configurable correction of timestamps

- L1 Sync

Changes to IEEE1588 "Core"

Modify BMCA

- Generic optional features (inactive by default):
  - Mechanism for external configuration
  - Master Only mode

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WR standardisation in IEEE 1588 (2)

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Summary

- Ethernet-based synchronization
Summary

- Ethernet-based synchronization
- \(<1\) ns accuracy and \(<10\) ps precision out-of-the-box
Summary

- Ethernet-based synchronization
- <1 ns accuracy and <10 ps precision out-of-the-box
- Sub-10 ps accuracy and sub-100 fs precision achievable
Summary

- Ethernet-based synchronization
- $< 1$ ns accuracy and $< 10$ ps precision out-of-the-box
- Sub-10 ps accuracy and sub-100 fs precision achievable
- Open with commercial support
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- Standard-based and standard-extending
Summary

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- $< 1 \text{ ns accuracy and } < 10 \text{ ps precision out-of-the-box}$
- Sub-10 ps accuracy and sub-100 fs precision achievable
- Open with commercial support
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- Included in the revised IEEE 1588
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- A versatile solution for general control and data acquisition
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- A versatile solution for general control and data acquisition
- Showcase of technology transfer
Questions?

WR Project page: http://www.ohwr.org/projects/white-rabbit/wiki
Outline

7 Management

8 WR Performance in Long Chain

9 WR Performance Improvements

10 WR networks at CERN

11 Determinism in WR
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
Management of WR networks: monitoring & config

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- It can be managed using standard protocols and tools:
  - Simple Network Management Protocol (SNMP)
  - Syslog
  - Link Layer Discovery Protocol (LLDP)
  - Kerberos-based authentication
- It can be debugged using standard tools:
  - Wireshark
  - Tcpdump
  - Professional Ethernet testers
WR performance in a long chain

Oscilloscope

Accuracy vs. distance from the Grandmaster

Precision vs. distance from the Grandmaster
Outline

7. Management

8. WR Performance in Long Chain

9. WR Performance Improvements

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11. Determinism in WR
Time transfer: out-of-the-box

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

Reported in 2011
Frequency transfer: out-of-the-box and improved

Measurement device: Microsemi/Microchip 3120A Phase Noise Test Probe
Frequency transfer: out-of-the-box and improved

Out-of-the-box performance:
- **GM-in to GM-out**: jitter of **9 ps** RMS 1 Hz–100 kHz and MDEV of **2E-12** \(\tau=1\) s ENBW 50 Hz
- **GM-in to Slave-out**: jitter of **11 ps** RMS 1 Hz–100 kHz and MDEV of **4E-12** \(\tau=1\) s ENBW 50 Hz
**Frequency transfer: out-of-the-box and improved**

- **Out-of-the-box performance:**
  - **GM-in to GM-out:** jitter of 9 ps RMS 1 Hz–100 kHz and MDEV of $2E$-$12$ $\tau$=1 s ENBW 50 Hz
  - **GM-in to Slave-out:** jitter of 11 ps RMS 1 Hz–100 kHz and MDEV of $4E$-$12$ $\tau$=1 s ENBW 50 Hz

- **WR Switches improved with Low Jitter Daughterboard (LJD):**
  - **GM-in to GM-out:** jitter of 1 ps RMS 1 Hz–100 kHz and MDEV of $<5E$-$13$ $\tau$=1 s ENBW 50 Hz
  - **GM-in to Slave-out:** jitter of $<2$ ps RMS 1 Hz–100 kHz and MDEV of $<7E$-$13$ $\tau$=1 s ENBW 50 Hz
GM-out to end-node-out: accuracy of <10 ps
GM-out to end-node-out: jitter of <100 fs RMS 10 Hz–10 MHz
Outline

7 Management
8 WR Performance in Long Chain
9 WR Performance Improvements
10 WR networks at CERN
11 Determinism in WR
**Determinism**

A deterministic system is predictable: it provides calculable and consistent characteristics of operation that are required by the application, e.g. network latency of data transmission.

**Network latency**

![Diagram of network latency](image)

**Deterministic network** is a network in which we can calculate the maximum latency.
Network Latency Contributors

- Cables: 5us/km – we cannot do much about this
- Switch operation
- Other traffic

We can do something about this
"White Box" design of WR switch - allows thorough analysis
Backward-compatible extension of the IEEE 802.1Q std
Priorities

Min frame: 0.672us

Max frame: 12.336us

MAC: 00-1B-C5-00-00-02
Priorities

- Assignment of priorities – standard option

Min frame: 0.672us
Max frame: 12.336us

VID: 0
Prio: 5

D: 00-1B-C5-00-00-02
S: 00-1B-C5-00-00-01

VID: 0
Prio: 7

D: 00-1B-C5-00-00-02
S: 00-1B-C5-00-00-03
Priorities

- Assignment of priorities – standard option
- Two problem remain:
  - Memory resources
  - Frames being transmitted
High Priority traffic in White Rabbit:
- Concerns priorities selected by configuration
- By default: separate memory resources

Min frame: 0.672us
Max frame: 12.336us
High Priority

High Priority traffic in White Rabbit:
- Concerns priorities selected by configuration
- By default: separate memory resources
- Drop non-HP frames
WR Switch Latency

<table>
<thead>
<tr>
<th>Intervening traffic</th>
<th>Latency [us]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>One switch</td>
</tr>
<tr>
<td></td>
<td>Max</td>
</tr>
<tr>
<td>No</td>
<td>3.1</td>
</tr>
<tr>
<td>WR-PTP</td>
<td>5.6</td>
</tr>
<tr>
<td>Non-HP traffic</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Maximum latency for 10 streams between 4 ports (no PTP traffic)