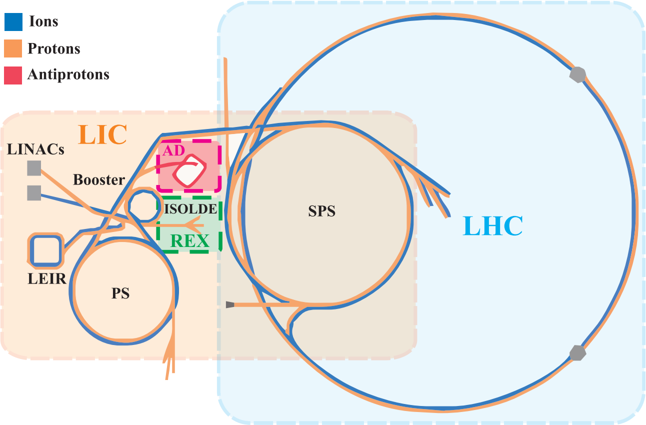
White Rabbit Overview

Maciej Lipiński

Hardware and Timing Section
European Organization for Nuclear Research, CERN

24 November 2017

CERN accelerator complex

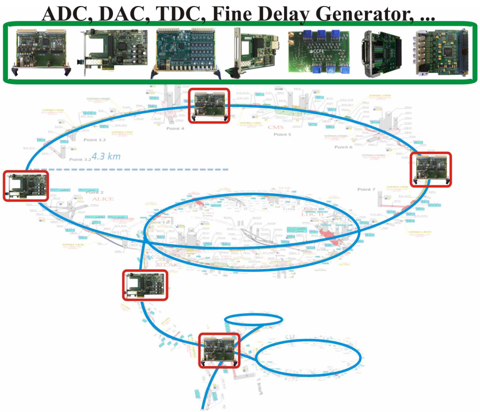


LHC : **L**arge **H**adron **C**ollider
LINAC : **LIN**ear **AC**celerator
PS : **P**roton **S**ynchrotron
SPS : **S**uper **P**roton **S**ynchrotron

LIC : **L**HC **I**njection **C**hain
AD : **A**ntiproton **D**ecelerator
ISOLDE : **I**sotrope **S**eparator **O**n**L**ine **DE**vice
REX : The **R**adioactive beam **Ex**periment@ISOLDE

Time-triggered distributed system

- Each accelerator consist of hundreds of subsystems



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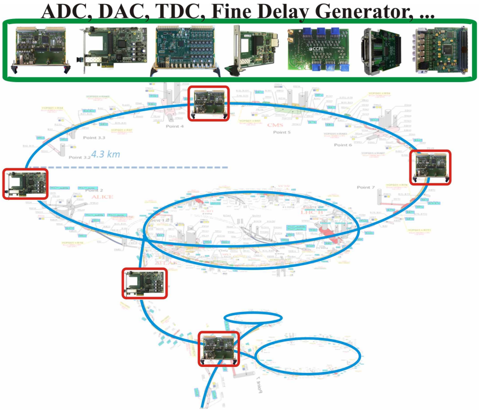

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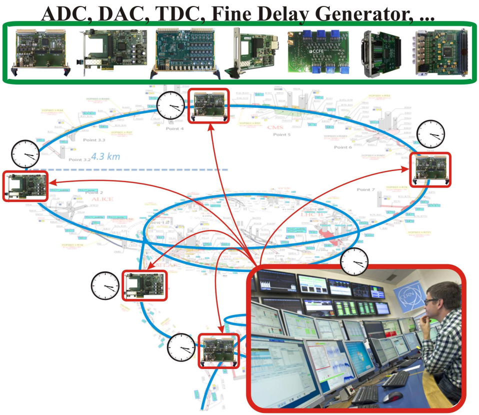
- All actions are orchestrated by the **General Machine Timing**:
  - UTC time
  - Actions for next milisecond



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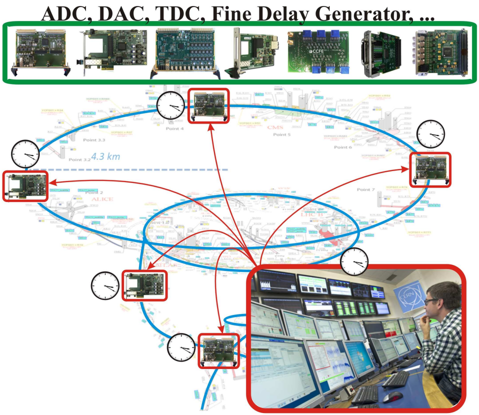
- Accelerator control is based on:
  - Accurate device synchronization
  - Deterministic data transmission



General Machine Timing renovation – White Rabbit

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- Stringent requirements

Requirement	Value(s)
Network size:	10km & 2000
Accuracy	sub-ns
Message size	1.2–5 kB
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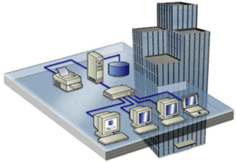

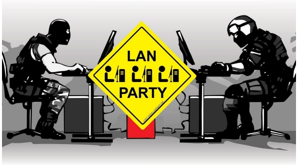

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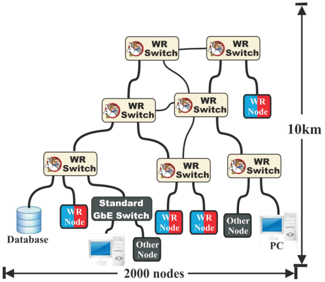

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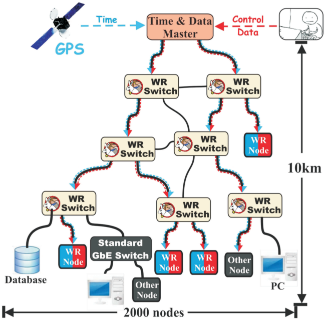

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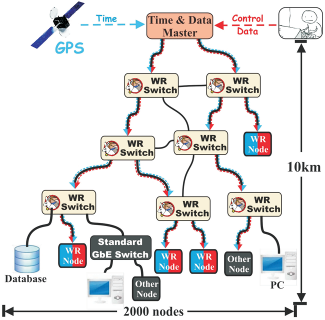

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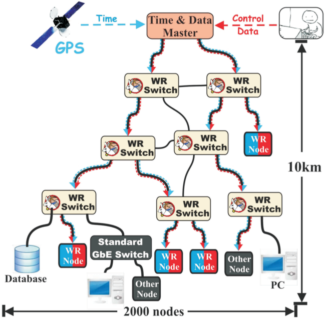

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- Foreseen for non-radiation areas
  (in radiation: WorldFIP – now, Powerlink – in future)

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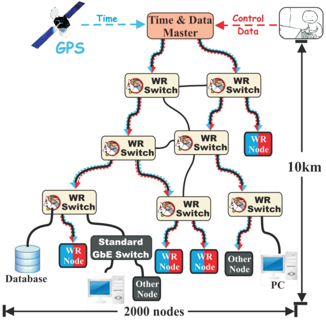

White Rabbit applications

- Particle accelerators
  - CERN
  - GSI (Germany)
  - JINR Dubna (Russia)

European Organization for Nuclear Research, CERN

All users: `www.ohwr.org/projects/white-rabbit/wiki/WRUsers`

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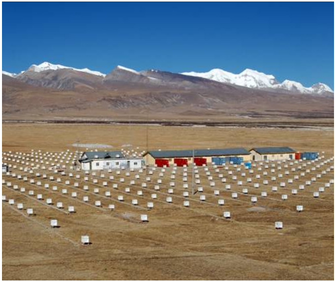
The Large High Altitude Air Shower Observation



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- National Metrology Institutes
  - MIKES (Finland)
  - VSL (Netherlands)
  - LNE-SYRTE (France)

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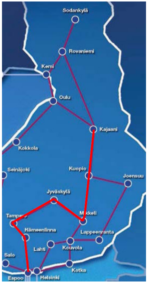

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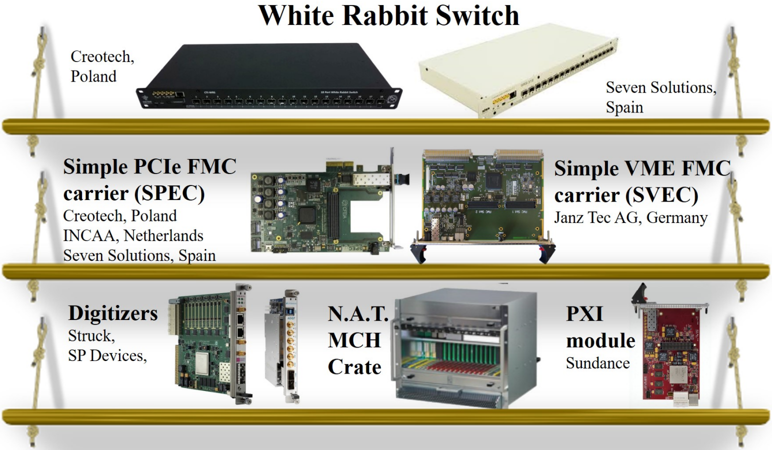
Open **and** commercially available off-the-shelf



Companies selling White Rabbit:

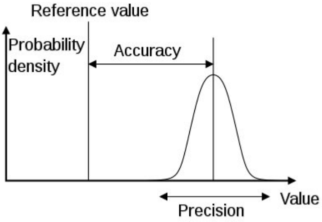
www.ohwr.org/projects/white-rabbit/wiki/wrcompanies

Outline

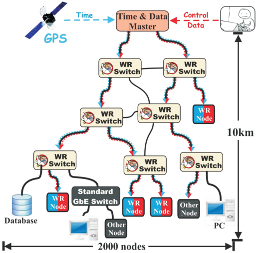
Outline

Sub-ns synchronization

- Synchronization performance:
  - **Sub-ns** accuracy: $max(|TE|) < 1ns$
  - **Sub-50 ps** precision: $sdev(TE) < 50ps$



Value = Time Error (TE)



Sub-ns synchronization

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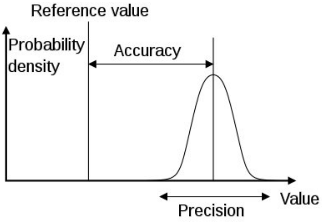
- Building blocks:
  - Precision Time Protocol (PTP, IEEE1588)
  - Layer 1 syntonization
  - Digital Dual Mixer Time Difference
  - Link delay model



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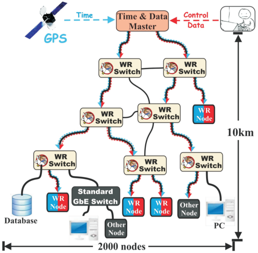

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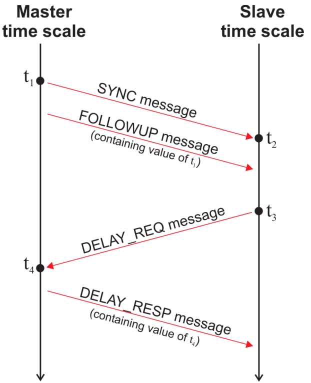
Precision Time Protocol (PTP, IEEE1588)



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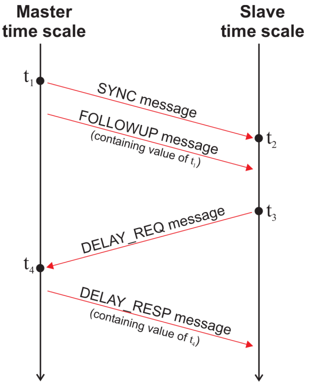

- Packet-based synchronization protocol
- Simple calculations:
  - Link *delay*$_{ms}$ $\delta_{ms} = \frac{(t_4 - t_1) - (t_3 - t_2)}{2}$
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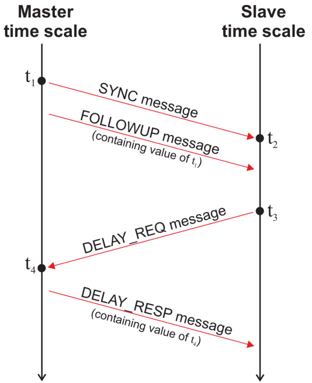

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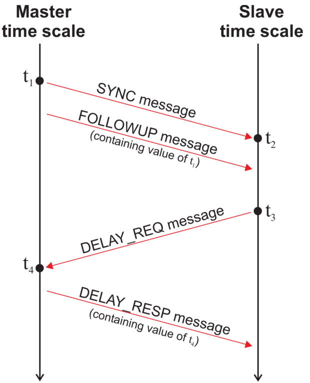

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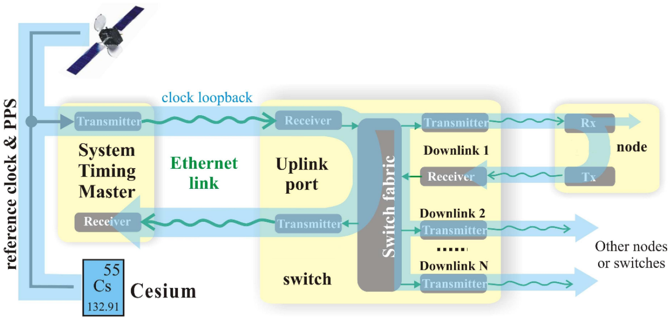
- Sub-μs synchronisation
- Limitations:
  - Free-running oscillators
  - Timestamping precision
  - Medium asymmetry

Outline

Layer 1 Syntonization

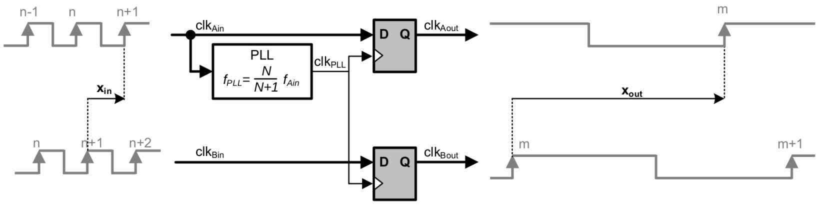
- All network devices use the same physical layer clock
- Clock is encoded in data by master and recovered by slave
- Clock loopback and phase detection allow precise timestamps



Outline

Digital Dual Mixer Time Difference (DDMTD)

- Clever implementation of a phase detector in an FPGA
- Uses D-flip-flops to zoom-in phase offset
- Allows for phase measurements at picosecond level

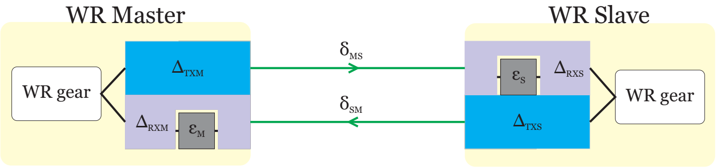


www.cern.ch/white-rabbit/documents/DDMTD_for_Sub-ns_Synchronization.pdf

Outline

Link delay model

- Hardware delays:
- Link asymmetry:



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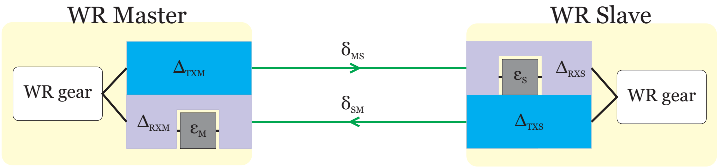

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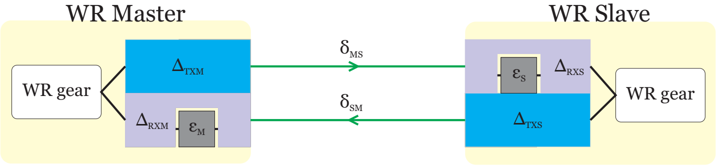
  - Single fibre for two-way communication
  - Fibre asymmetry coefficient: $\alpha = \frac{\delta_{MS} - \delta_{SM}}{\delta_{SM}}$



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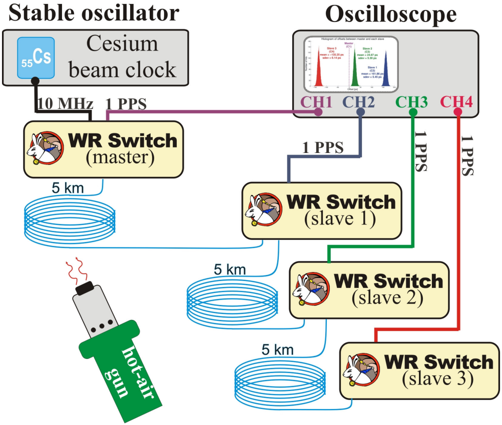
WR Synchronization performance



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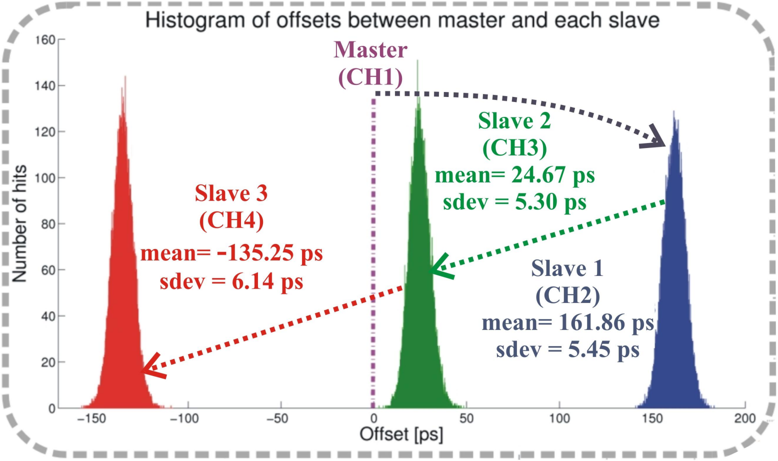

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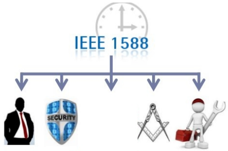

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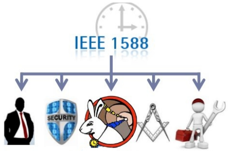

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Determinism and network latency

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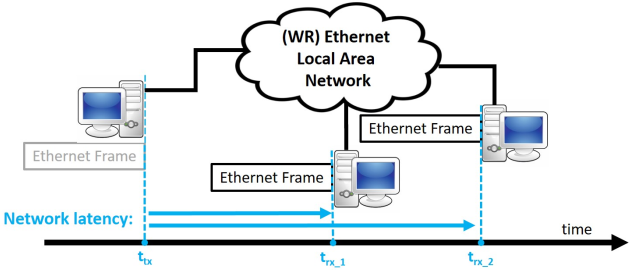

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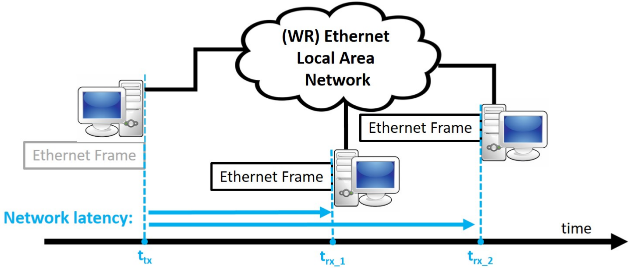

Deterministic network is a network in which we can calculate the maximum latency

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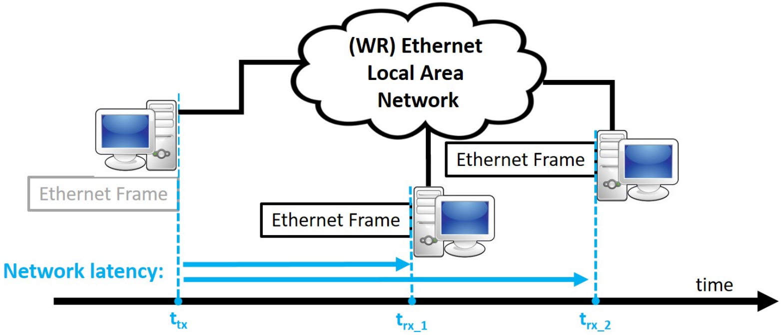
Network latency contributors



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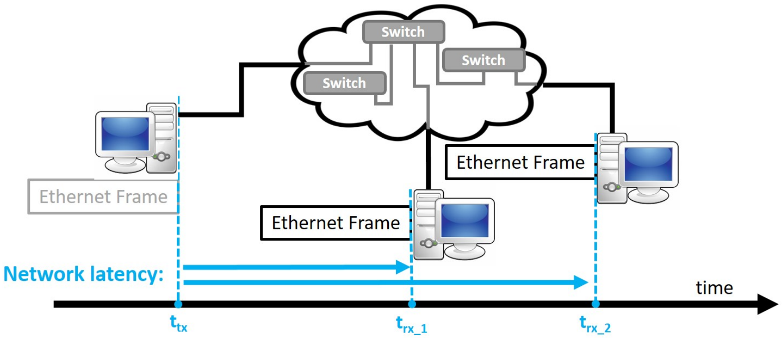
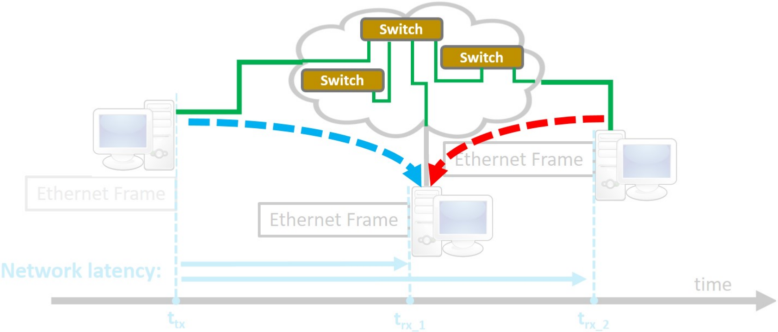


Network latency contributors

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

We can do something about this



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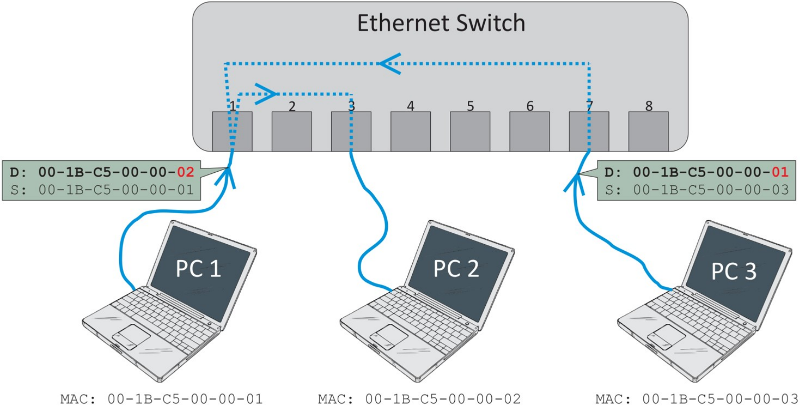
Switch in a nutshell



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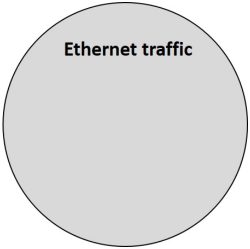

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  - **Fast Forward (FF)**:
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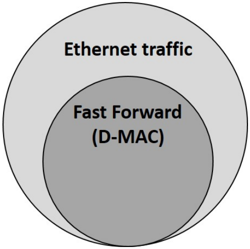

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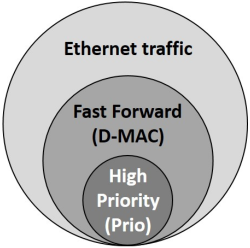

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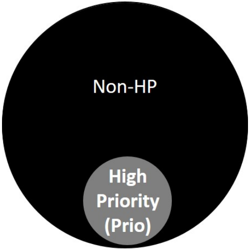

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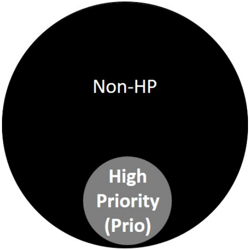
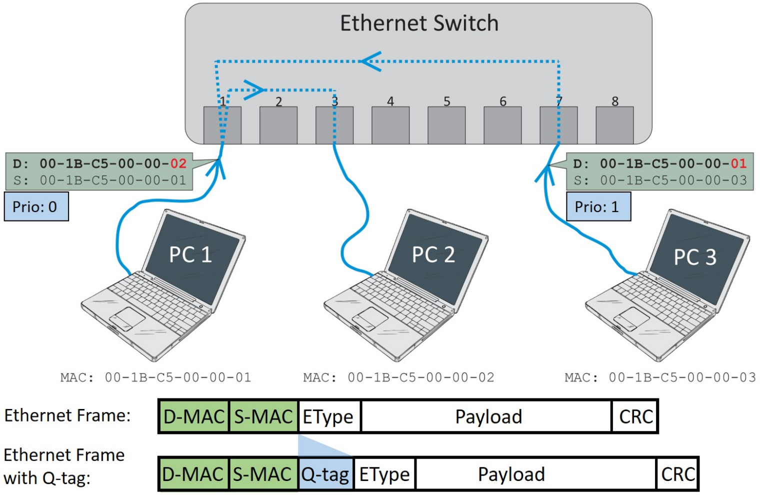
- And what on Earth are priorities...?



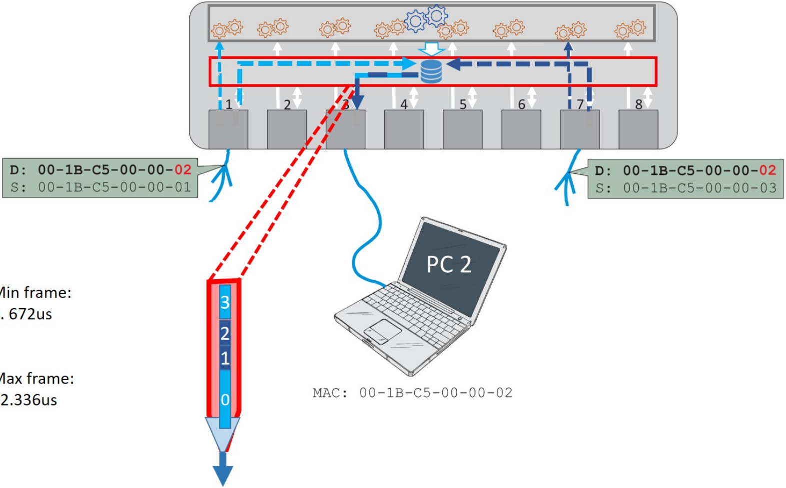
Outline

Priorities - standard extension of Ethernet Frame



Standard and optional extension of Ethernet Frame (IEEE802.1Q)

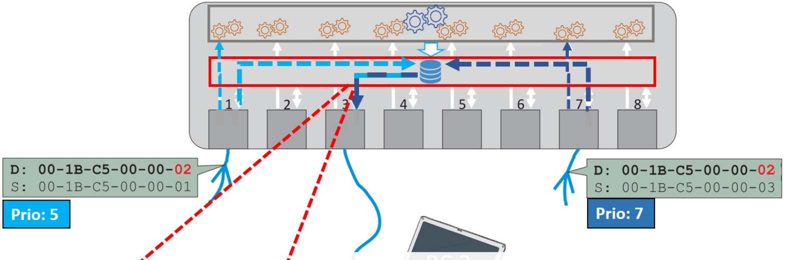
WR Switch Not Using priorities



Min frame:
0. 672us

Max frame:
12.336us

WR Switch Using Standard Priorities



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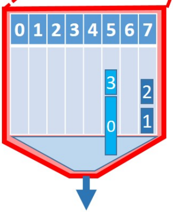
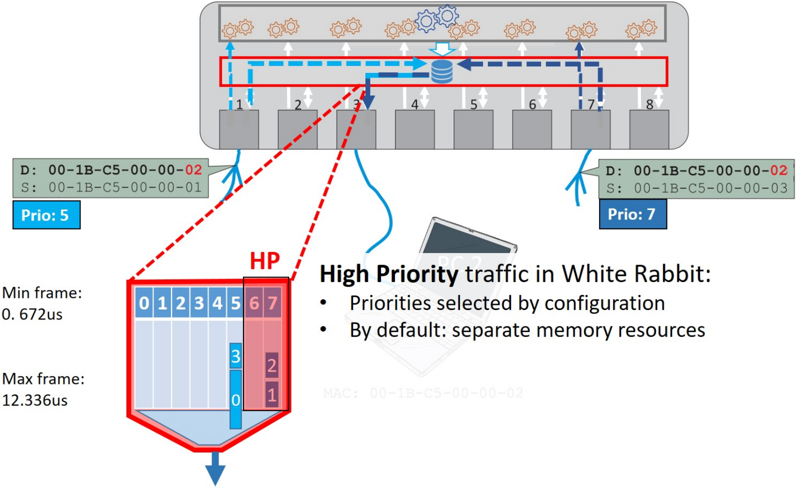


- Assignment of priorities – standard option
- Two problem remain:
  - Memory resources
  - Frames being transmitted

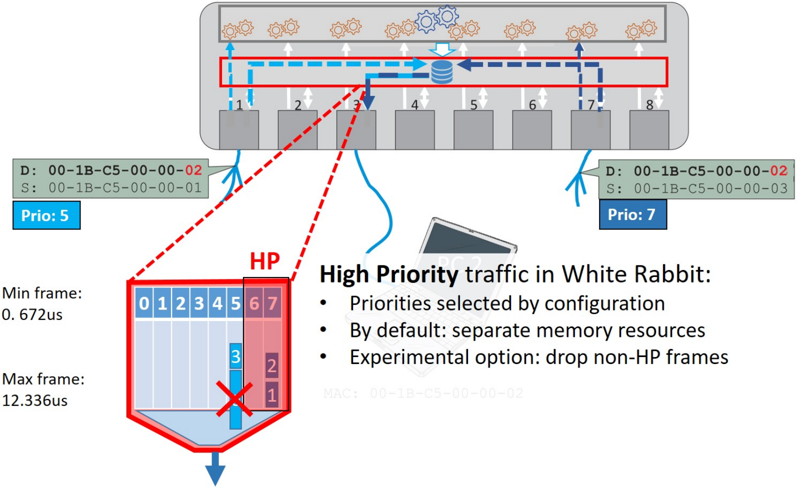
WR Switch Using Standard Priorities



High Priority traffic in White Rabbit:

- Priorities selected by configuration
- By default: separate memory resources

High Priority



High Priority traffic in White Rabbit:

- Priorities selected by configuration
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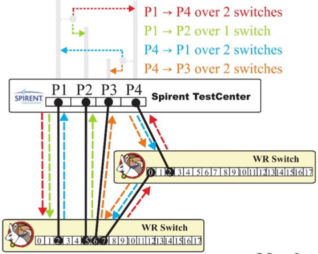
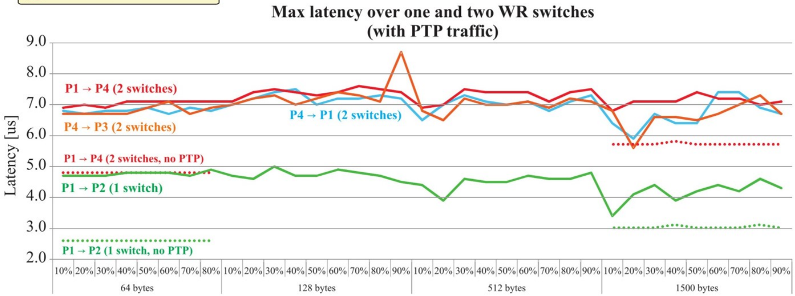
- Experimental option: drop non-HP frames

Outline

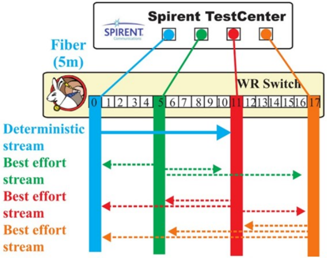
Latency of WR Switch for Fast Forward



Intervening traffic	Latency [us]			
	One switch		Two switches	
	Max	Pk-pk	Max	Pk-pk
No	3.1	0.3	5.8	0.5
WR-PTP	5.6	2.8	8.7	3.9
Non-HP traffic	3.1	0.2	N/A	N/A



Latency of WR Switch for High Priority



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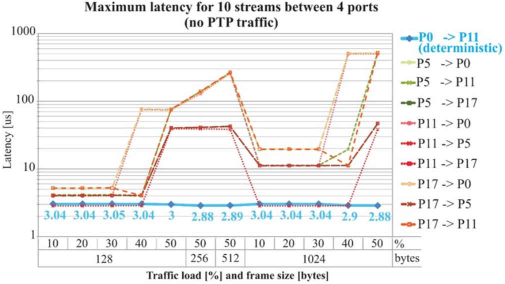
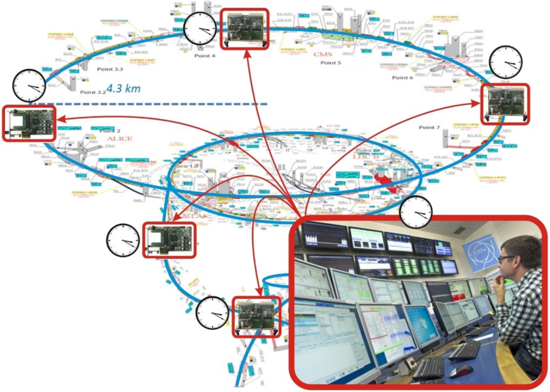


Outline

Outline

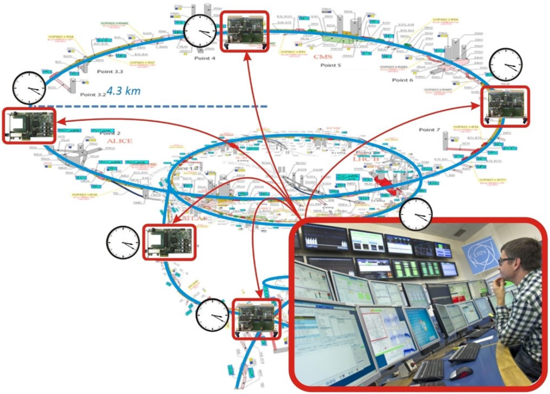
Using synchronization and determinism



Using synchronization and determinism

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)



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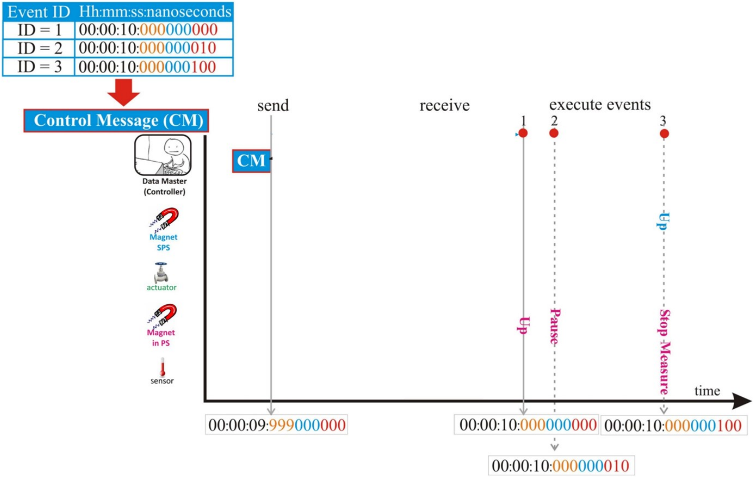

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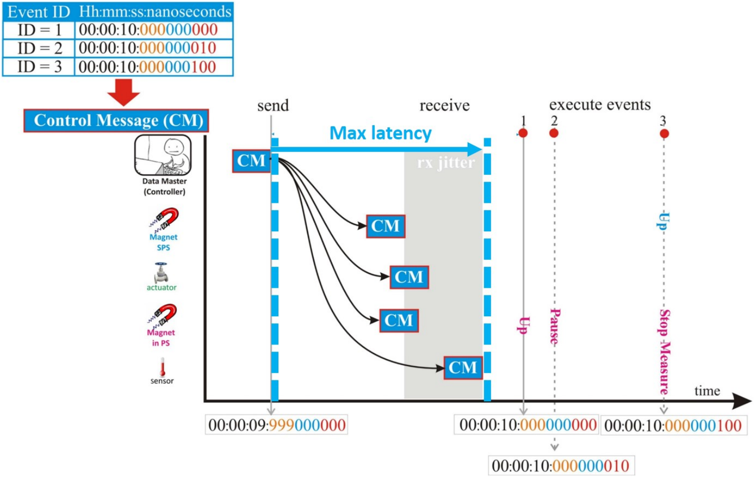

Outline

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- Future plans
  - Mechanisms to increase reliability
    (`http://cds.cern.ch/record/2261452`)
  - 10 Gbit Ethernet

Thank you

Thank you !

www.cern.ch/white-rabbit

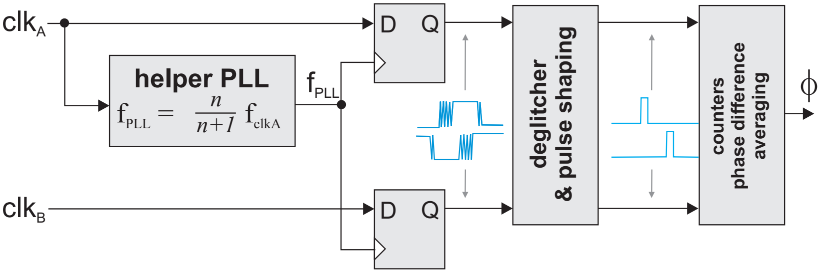
Extras

Extras

Outline

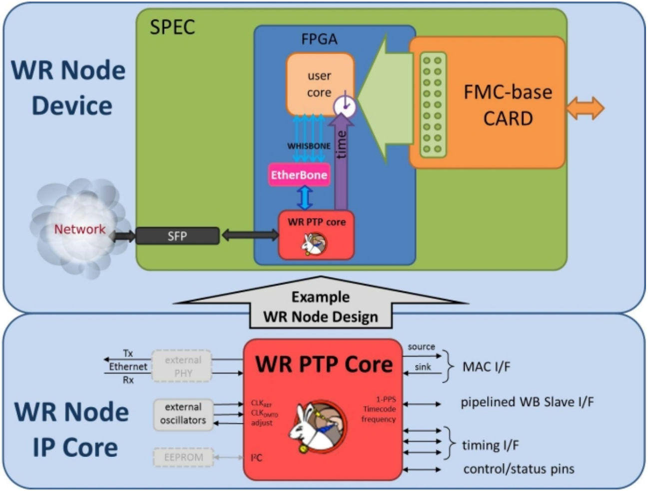
Digital Dual Mixer Time Difference (DDMTD)

- Used for precise phase measurements
- Implemented in FPGA and SoftPLL
- 62.5MHz WR clock and N=14 results in 3.814kHz output signals



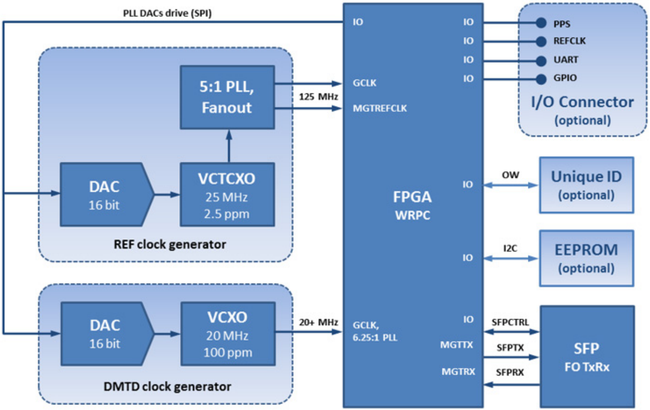
Outline

WR Node IP Core



www.ohwr.org/projects/white-rabbit/wiki/node

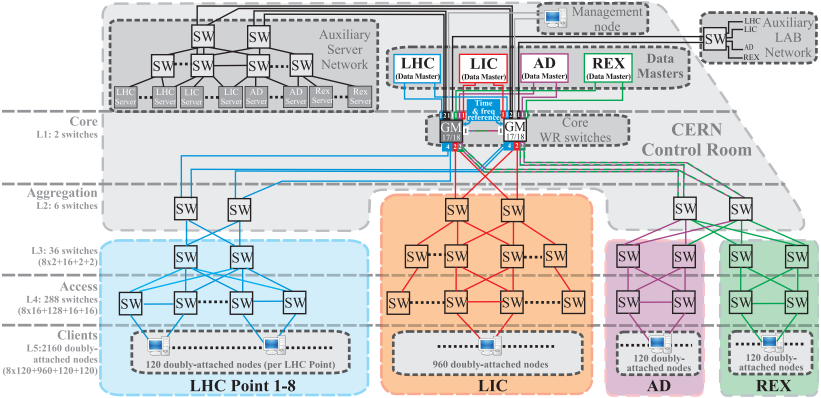
WR Node Reference Design for Hardware



www.ohwr.org/projects/white-rabbit/wiki/wrreferencedesign

Outline

WR Reference Network



Explanation:

SW – White Rabbit **SW**itch
GM – **G**rand**m**aster SW
LHC – **L**arge **H**adron **C**ollider
LIC – **L**HC **I**njection **C**hain
—— – Fiber link

AD – **A**ntiproton **D**ecelerator
ISOLDE – **I**sotrope **S**eparator **O**n**L**ine **DE**vice
REX – The **R**adioactive beam **Ex**periment @ ISOLDE
(arrow) – 10MHz, PPS and UTC

Performance of the Reference Network

Name	Requirement	In the reference WR network
Network size:	10 km & 2000 nodes	10 km & 2160 nodes
Synchronization : - accuracy over a year: - accuracy in transient: - precision: Control message - allowed size - max lost per year	 sub-ns sub-ns sub-50 ps 1200–6000 bytes 1	 0.41 *ns* 1.19 *ns* 31 *ps* 1200–6000 bytes 1 with probability R(t)
Upper-bound network latency	$< 500\ \mu s$ (derived from 1 ms)	$\leq$ 78 μs for network $\leq$ 150 μs for control message
Total reliability $R(t)$	≥ 0.98	0.9854 for $MTBF_{switch} = 40\,000\ h$ 0.9967 for $MTBF_{switch} = 100\,000\ h$ 0.9997 for $MTBF_{switch} = 650\,000\ h$