White Rabbit Applications and Enhancements

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5 October 2018

Outline

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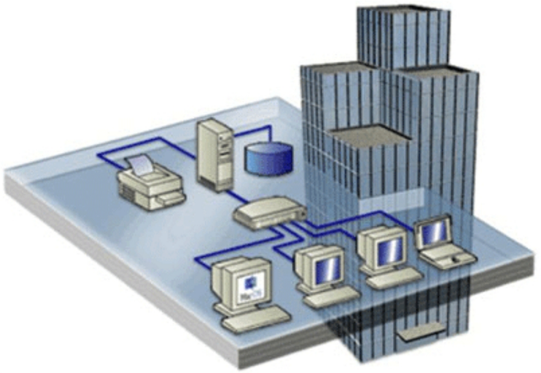
White Rabbit

- Based on well-established standards
  - Bridged Local Area Network
  - Ethernet
  - Precision Time Protocol



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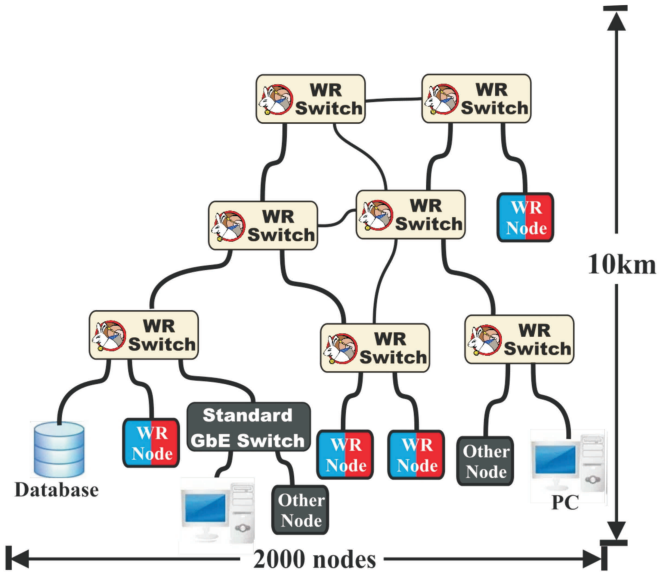
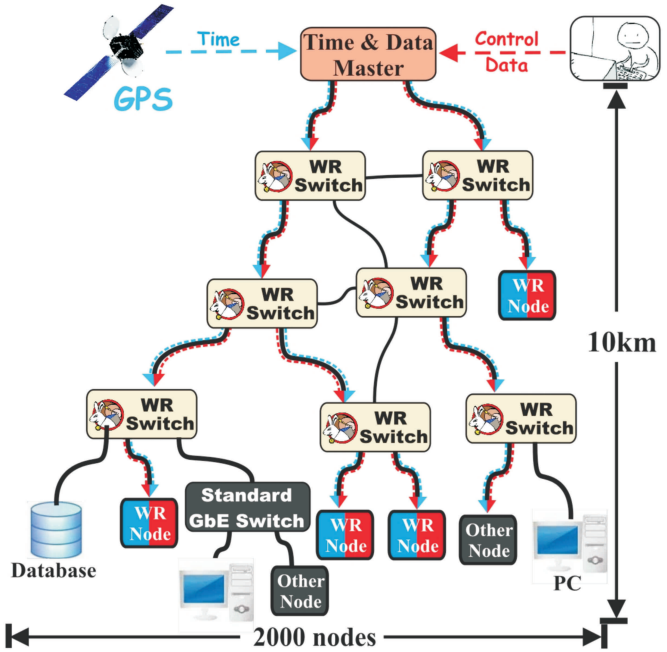


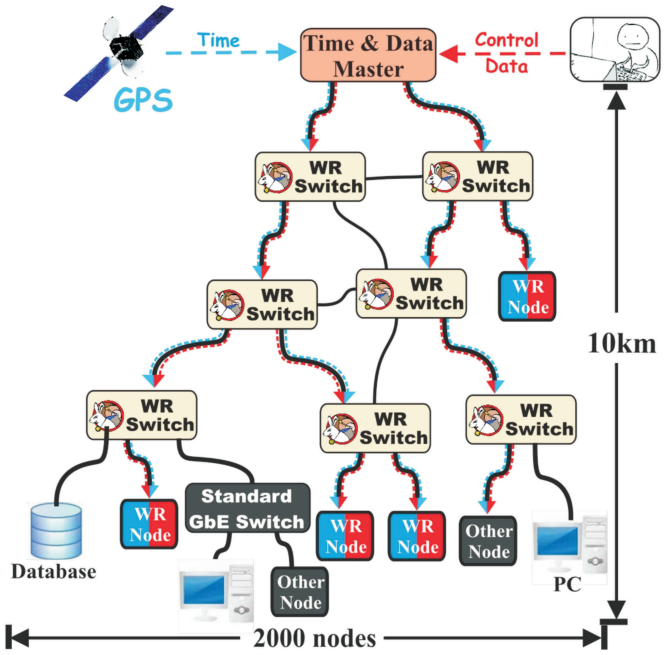
White Rabbit

- Based on well-established standards
  - Bridged Local Area Network
  - Ethernet
  - Precision Time Protocol
- Extends standards to meet CERN requirements and provides
  1. **Sub-ns synchronization**
  2. **Deterministic data transfer**



White Rabbit

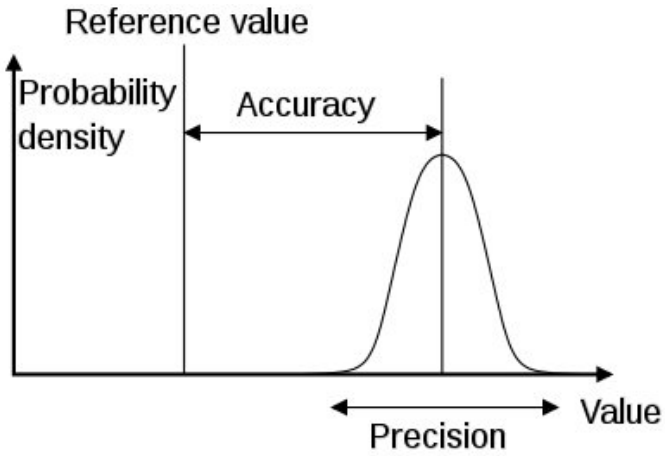
- Based on well-established standards
  - Bridged Local Area Network
  - Ethernet
  - Precision Time Protocol
- Extends standards to meet CERN requirements and provides
  1. **Sub-ns synchronization**
  2. **Deterministic data transfer**
- Non-exhaustive list of worldwide applications
  - **2018:** 564 nodes and 106 switches
  - **2020:** 17592 nodes and 1532 switches



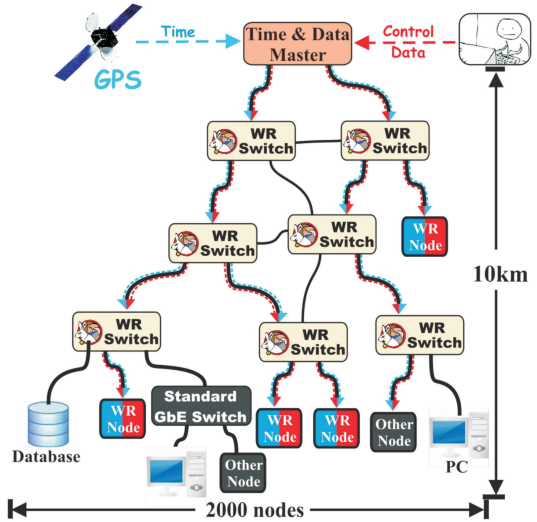
www.ohwr.org/projects/white-rabbit/wiki/newsletter-2018-09

Sub-ns synchronization

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

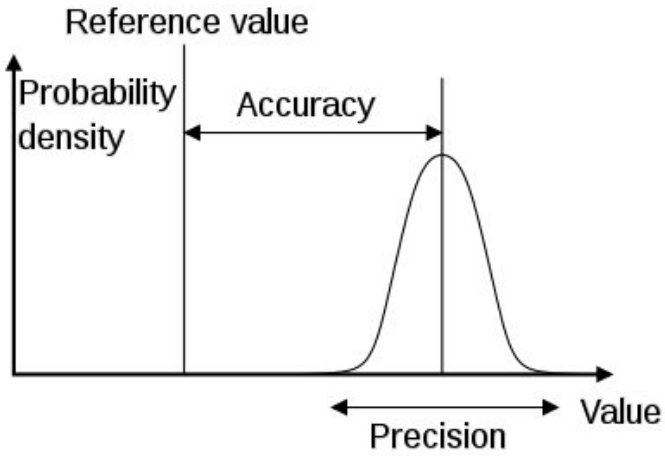


Value = Time Error (TE)



Sub-ns synchronization

- Synchronization performance:
  - **Sub-ns** accuracy:
    $avg(TE) < 1ns$
  - **Sub-50 ps** precision:
    $sdev(TE) < 50ps$
- Building blocks:
  - Precision Time Protocol (PTP, IEEE1588)
  - Layer 1 syntonization
  - Phase measurement
  - Link delay model to compensate asymmetries



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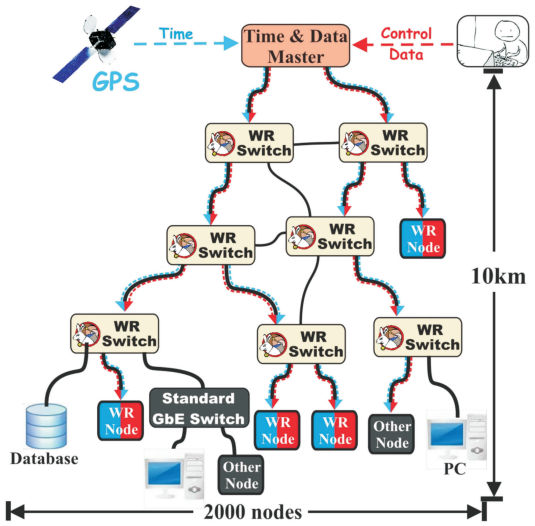
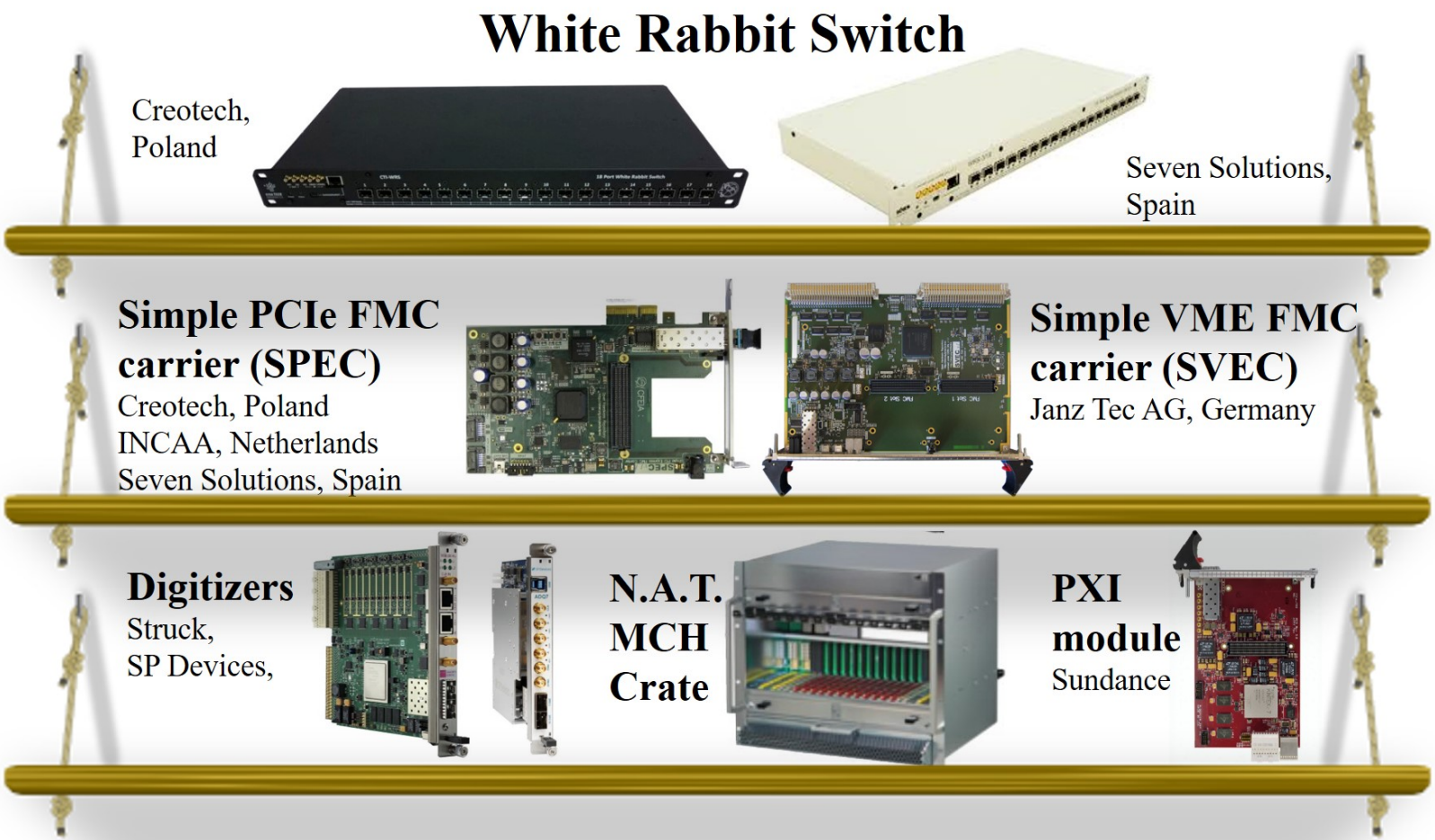


Open **and** commercially available off-the-shelf



Companies selling White Rabbit:

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

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Time and frequency transfer

- T&F transfer from Grandmaster to switches/nodes

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- National Time Laboratories using WR:

Time Lab	Country	Link Length	Time Error
VTT MIKES	Finland	950 km	$\pm$2ns
		50 km	$<$1ns
VSL	Netherlands	2x137 km	$\approx$8ns
LNE-SYRTE	France	25 km	150ps
		125 km	2.5ns
		4x125 km	2.5ns
NIST	USA	$<$10 km	$<$200ps
NLP	UK	2x80 km	$<$1ns
INRIM	Italy	50 km	800ps $\pm$56ps
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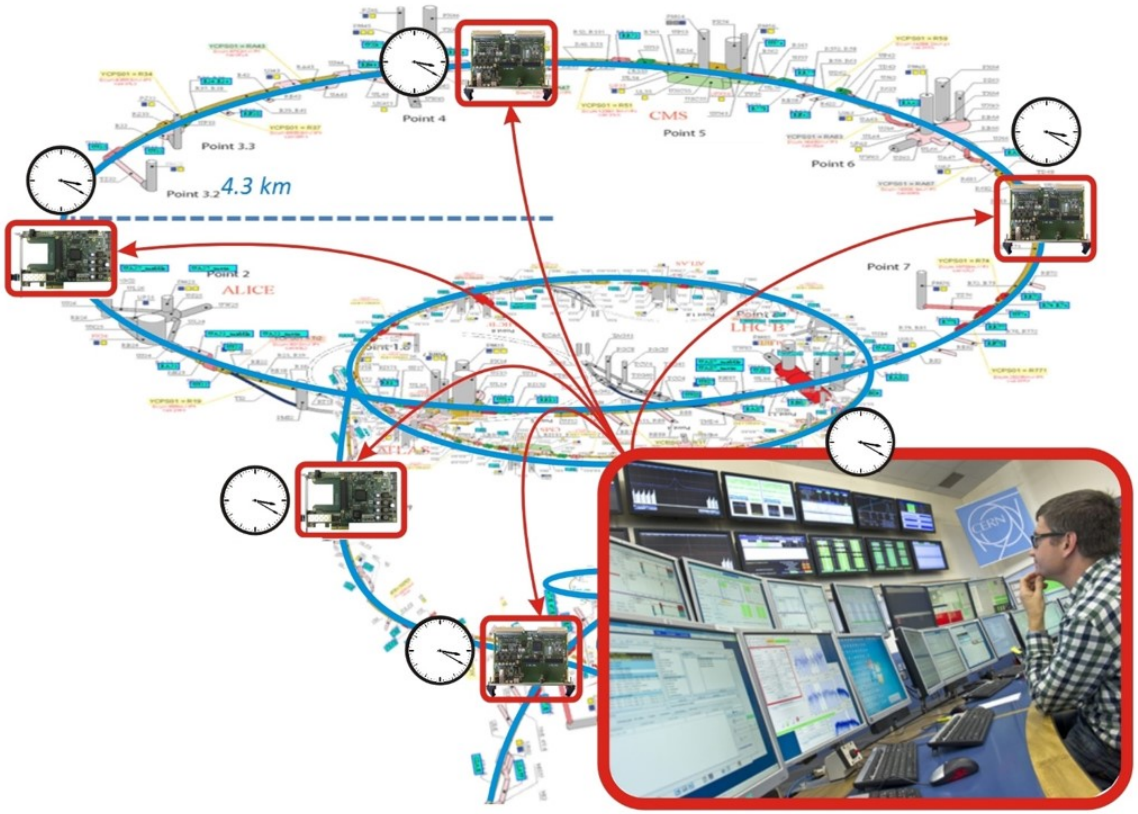
- WR used operationally by MIKES, NLP & INRIM
- INRIM, NLP, LNE-SYRTE, MIKES, VSL work within EU-funded ”White Rabbit Industrial Timing Enhancement” (WRITE) project

Outline

Time-based control

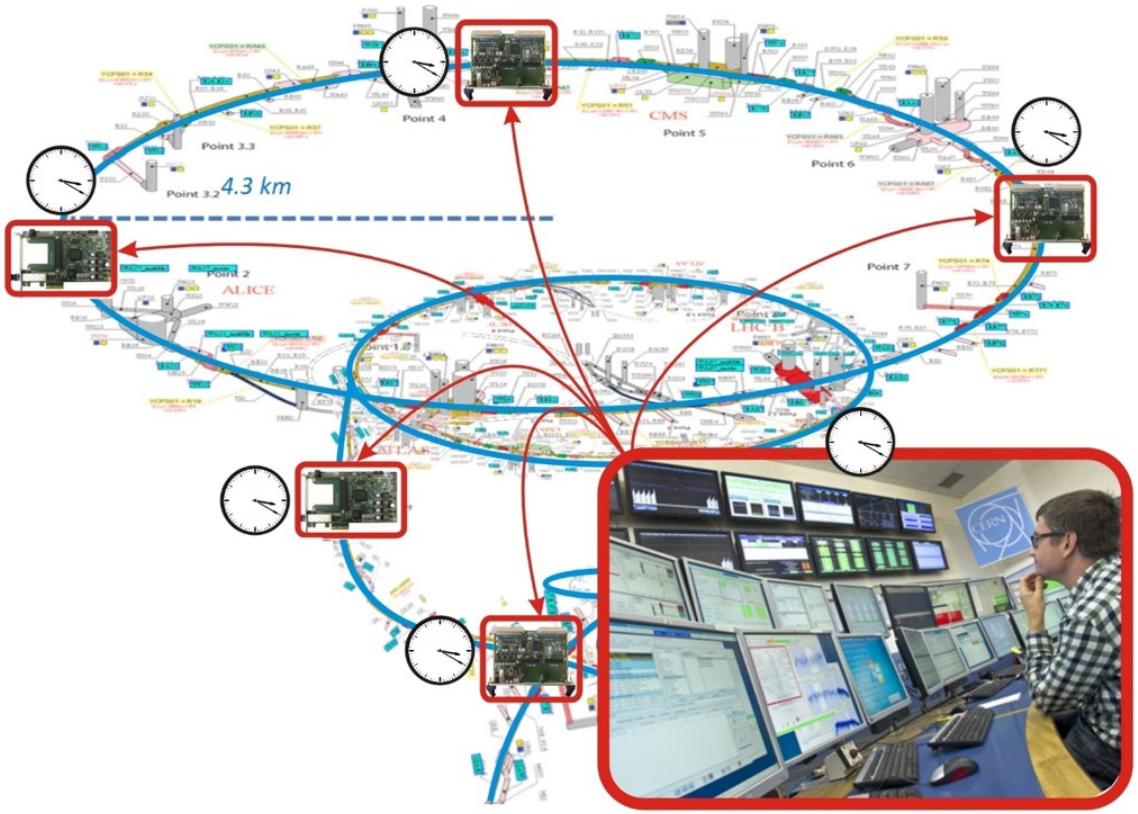


Time-based control

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)

Data Master (Controller)



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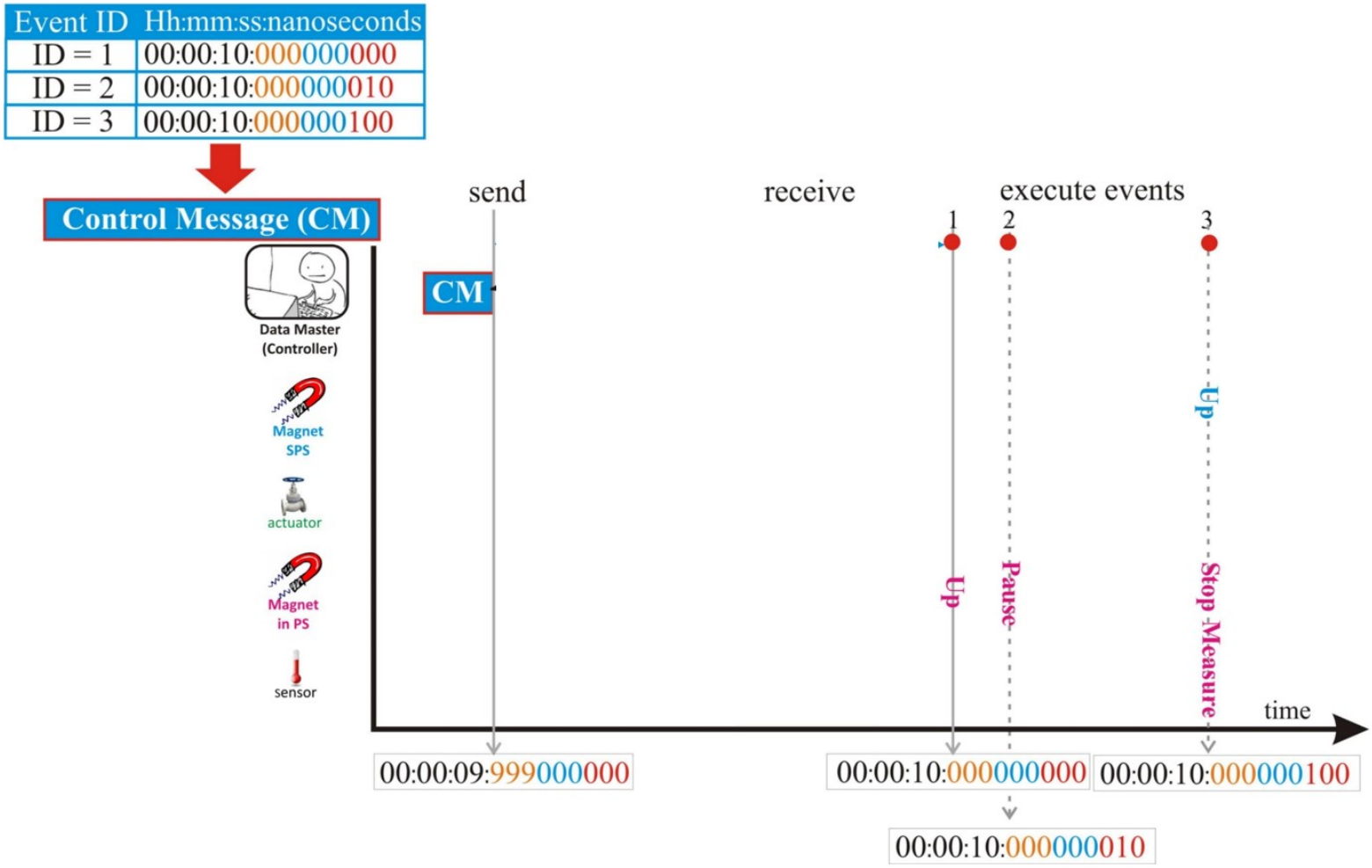

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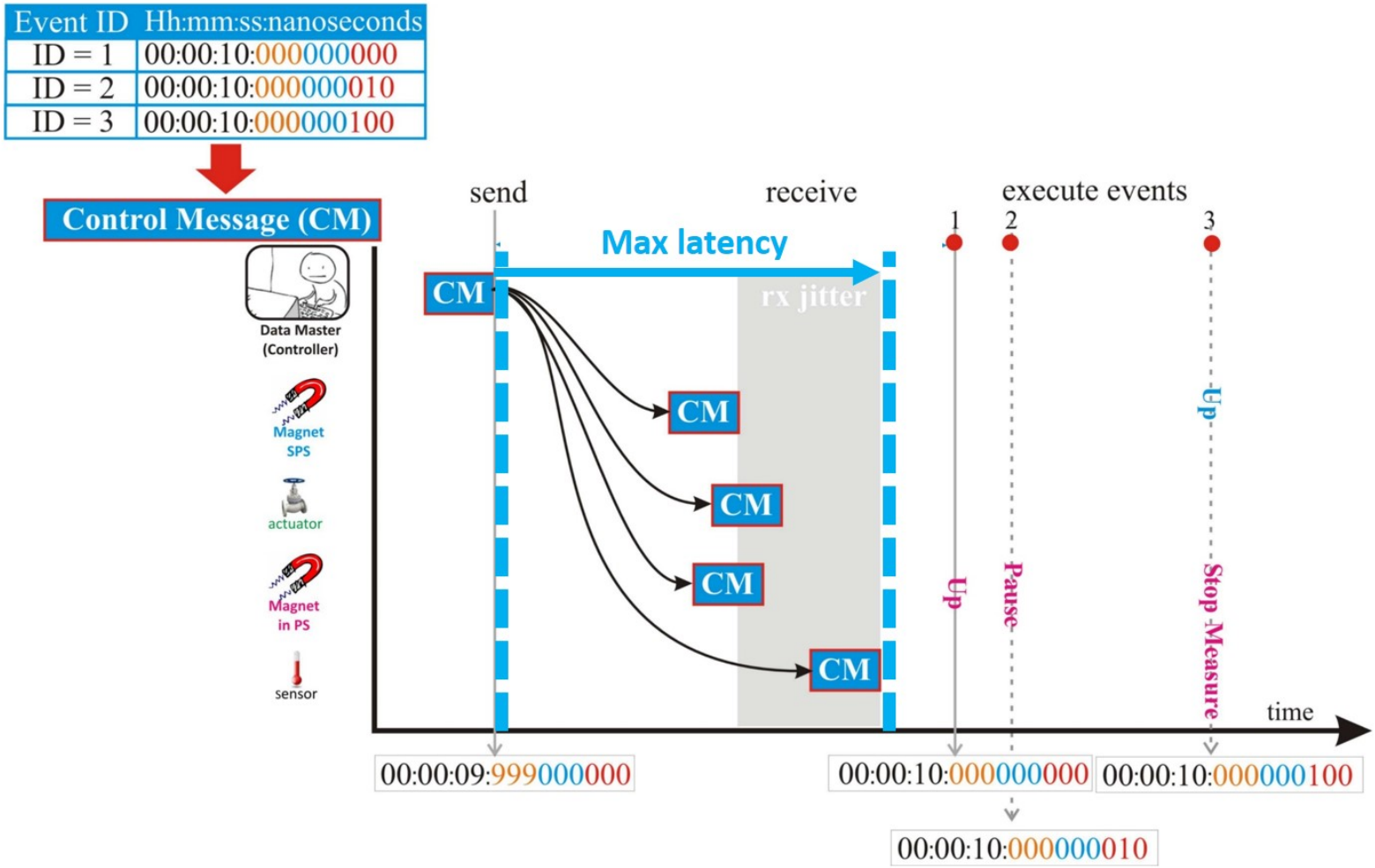
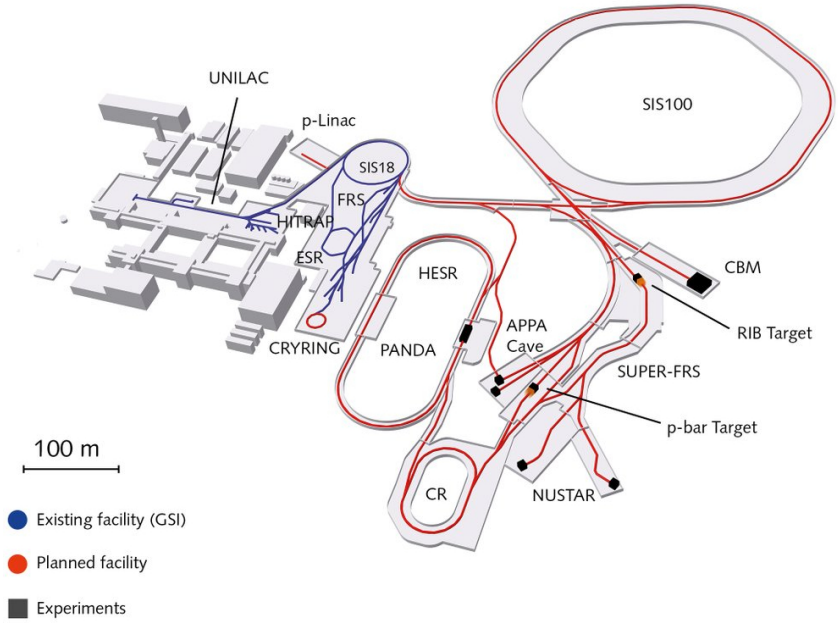


Time-based control - example applicatoin

- GSI Helmholtz Centre for Heavy Ion Research in Germany



Time-based control - example applicatoin

- GSI Helmholtz Centre for Heavy Ion Research in Germany
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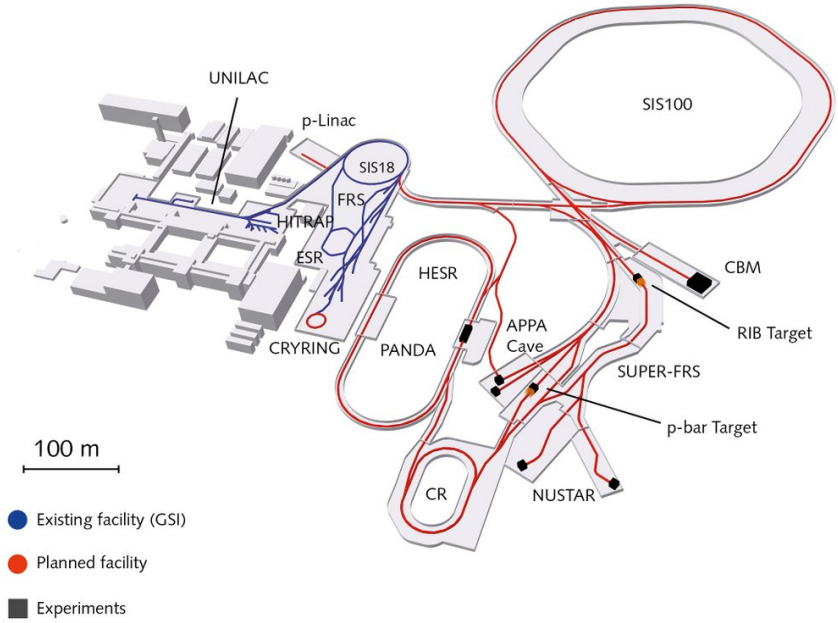
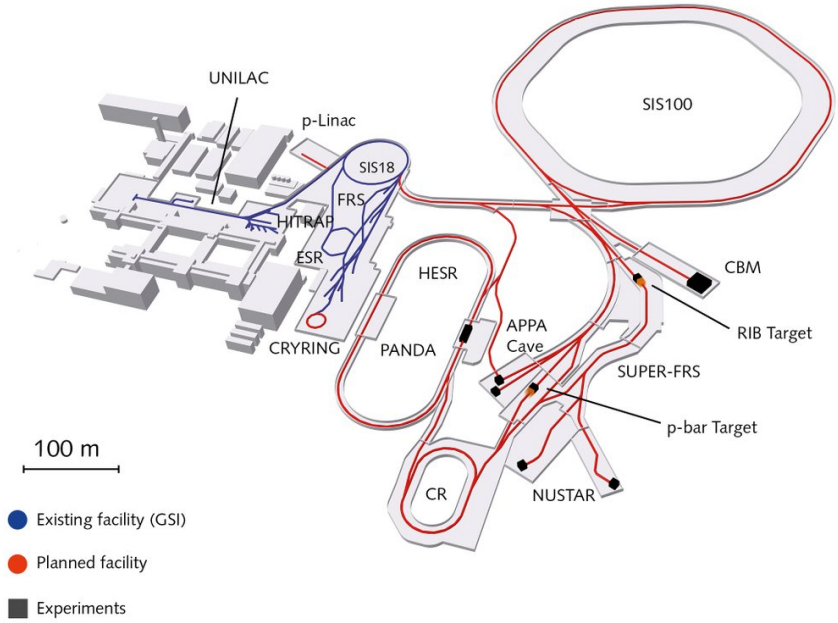


Time-based control - example applicatoin

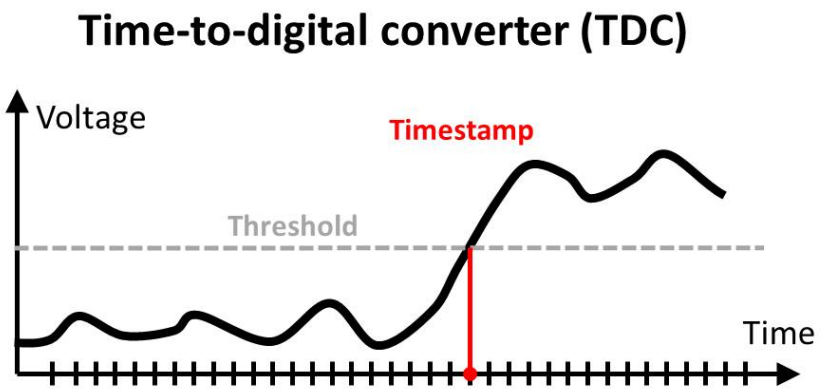
- GSI Helmholtz Centre for Heavy Ion Research in Germany
- 1-5 ns accuracy and 10 ps precision
- WR network at GSI:
  - Current: 134 nodes and 32 switches (operational since June 2018)
  - Final: 2000 WR nodes and 300 switches in 5 layers

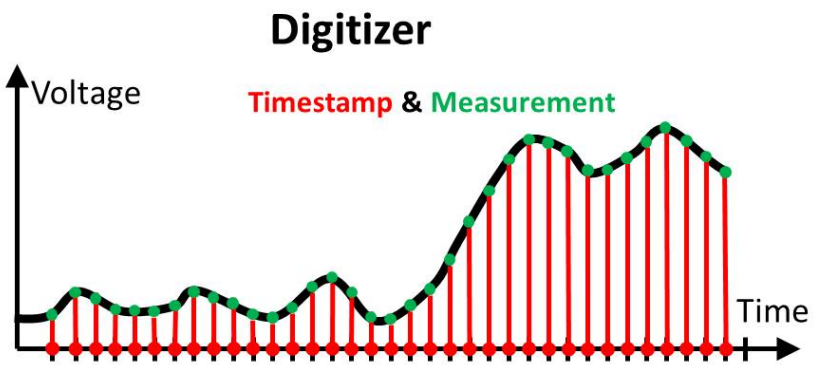


Outline

Precise timestamping

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





Precise timestamping

- Association of time with
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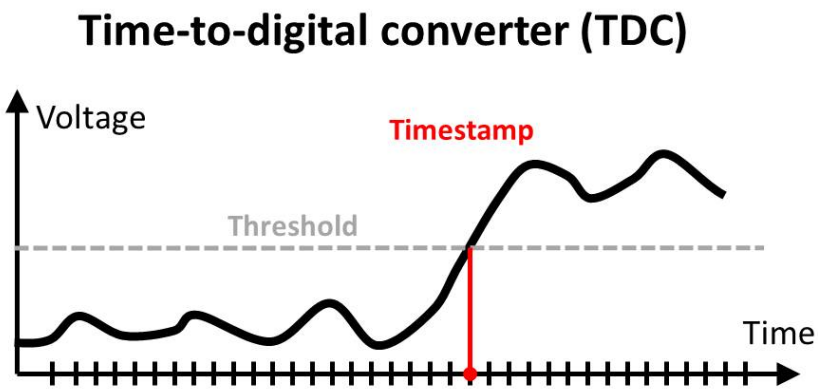
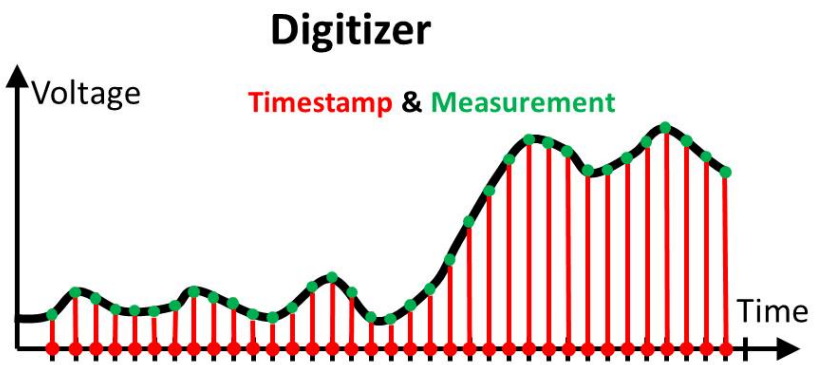
- The most widely used WR application





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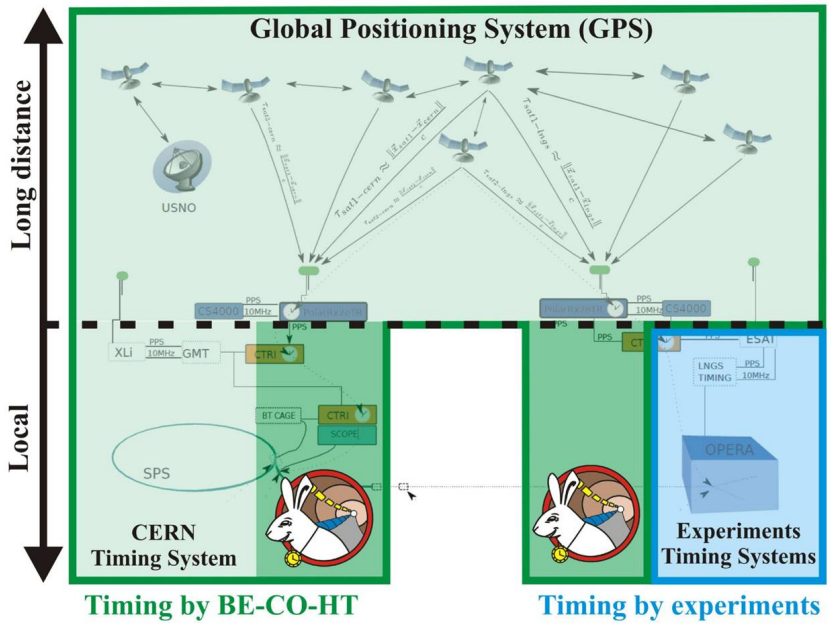
  - Time-of-flight measurement
    - Speed of neutrinos - CNGS



10 nodes and 4 switches

Precise timestamping

- Association of time with
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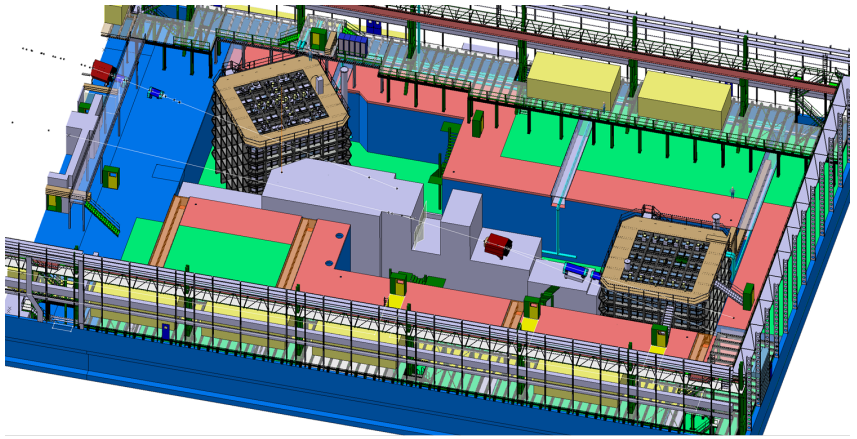
- The most widely used WR application
  - Time-of-flight measurement
    - Speed of neutrinos - CNGS
    - Types of particles - ProtoDUNE



CERN, later Fermi Lab in USA
2018: 14 nodes and 5 switches
2020: 36 nodes and 5 switches

Precise timestamping

- Association of time with
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  - a sample (measured value)
- The most widely used WR application
  - Time-of-flight measurement
    - Speed of neutrinos - CNGS
    - Types of particles - ProtoDUNE
  - Cosmic ray and neutrino detection

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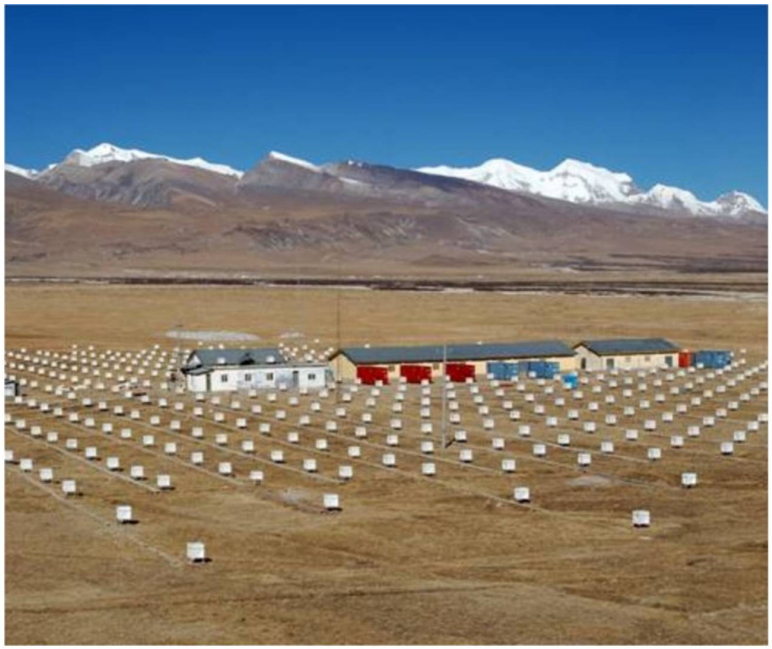
  - Cosmic ray and neutrino detection
    - Large High Altitude Air Shower Observatory



China, 4410 m above sea level
2018: 40 nodes and 4 switches
2020: 6734 nodes and 564 switches

Precise timestamping

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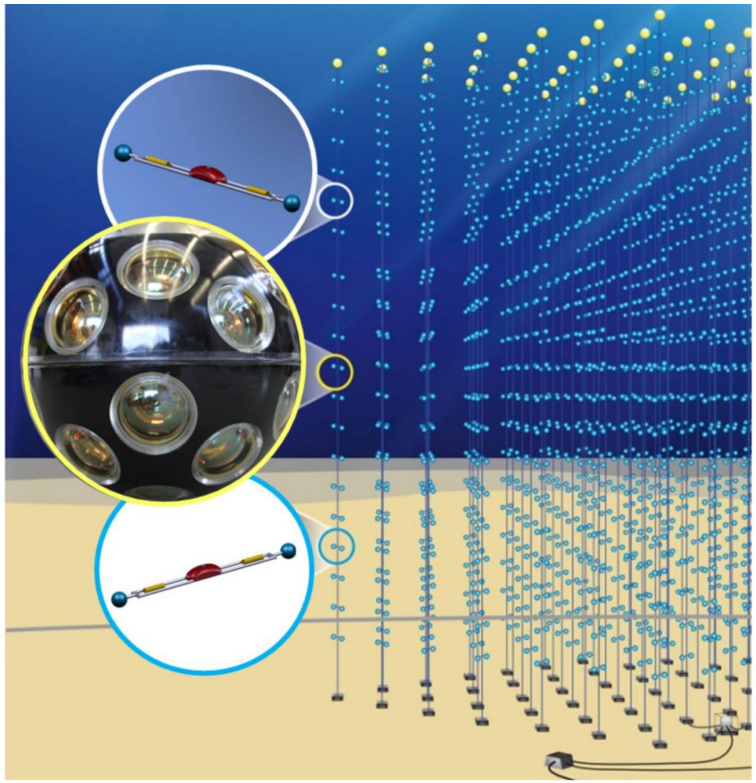
  - Time-of-flight measurement
    - Speed of neutrinos - CNGS
    - Types of particles - ProtoDUNE
  - Cosmic ray and neutrino detection
    - Large High Altitude Air Shower Observatory
    - Cubic Kilometre Neutrino Telescope



Mediterranean Sea, ~3000m depth
2018: 36 nodes and 2 switches
2020: 6140 nodes and 400 switches

Precise timestamping

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  - Time-of-flight measurement
    - Speed of neutrinos - CNGS
    - Types of particles - ProtoDUNE
  - Cosmic ray and neutrino detection
    - Large High Altitude Air Shower Observatory
    - Cubic Kilometre Neutrino Telescope
    - Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy

Siberia, Russia
2018: 20 nodes and 4 switches
2020: 1100 nodes and 90 switches

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  - a sample (measured value)
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  - Cosmic ray and neutrino detection
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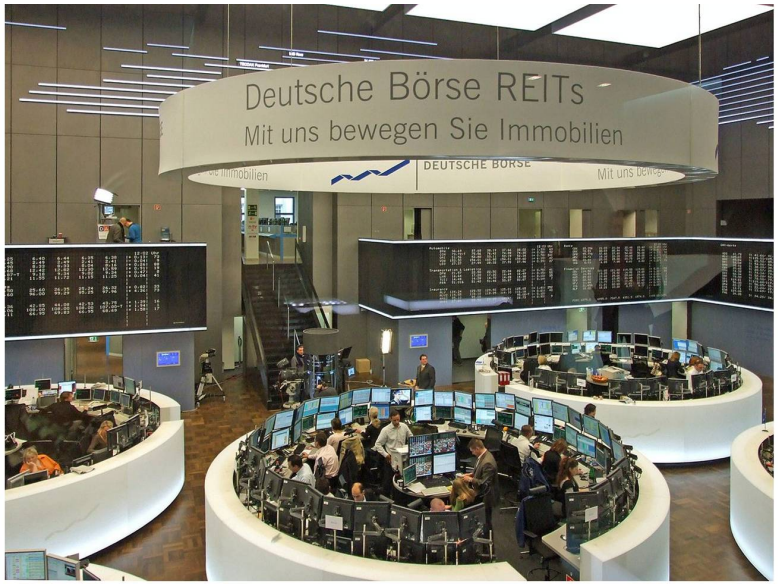
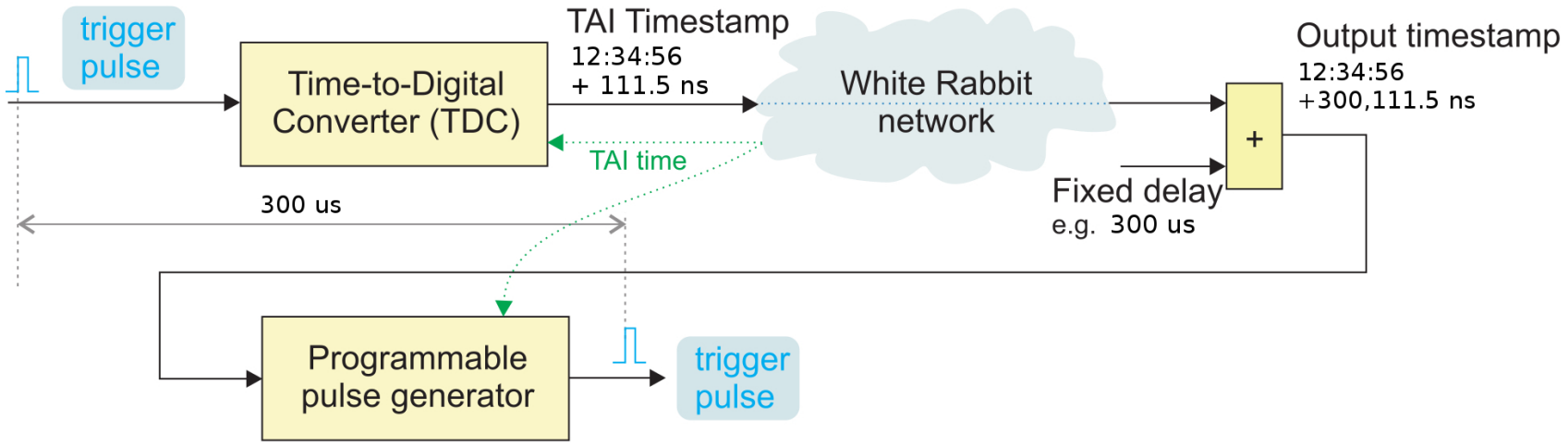
    - Cubic Kilometre Neutrino Telescope
    - Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy
  - German Stock Exchange



Frankfurt, Germany
2018: 7+ nodes and 4 switches

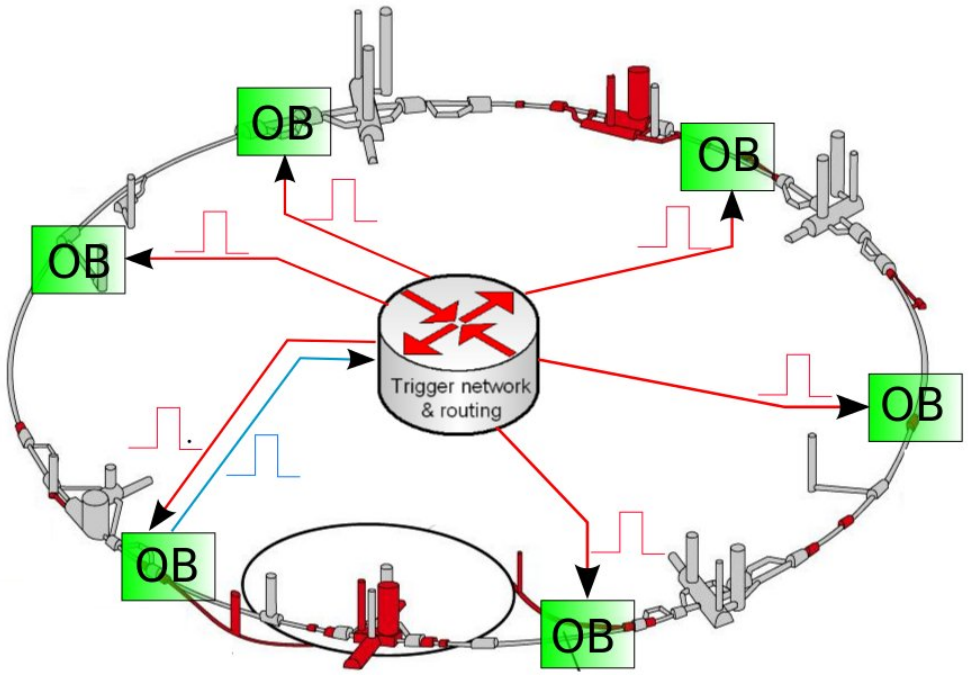
Outline

Trigger distribution



Trigger distribution - example applications

LHC trigger distribution to measure beam instabilities - since 2016



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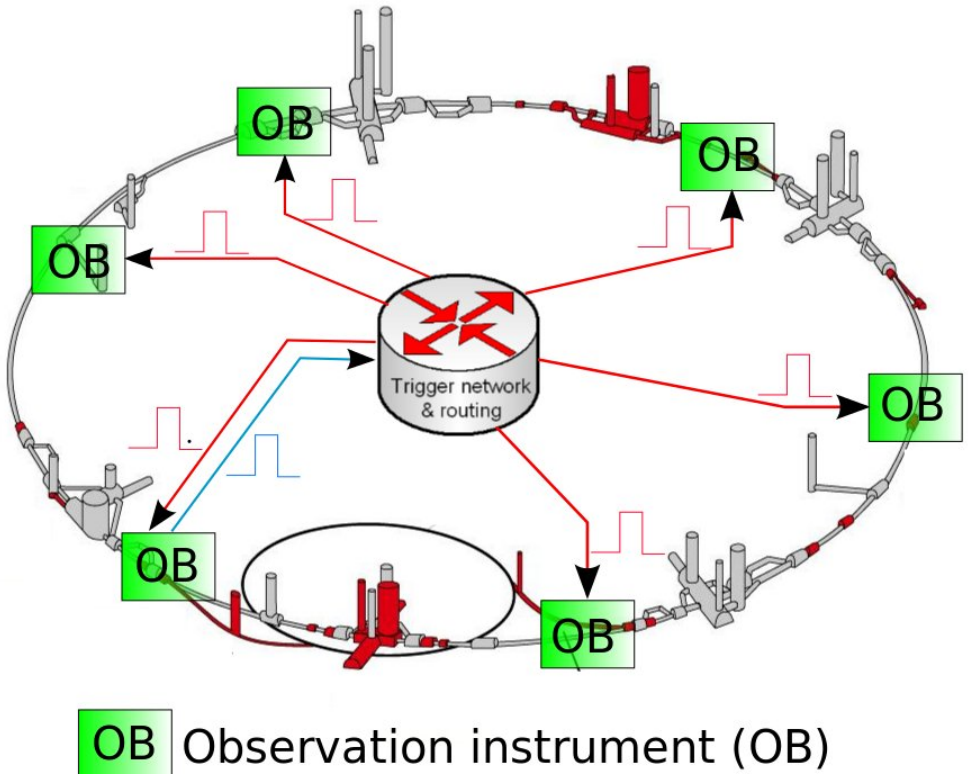
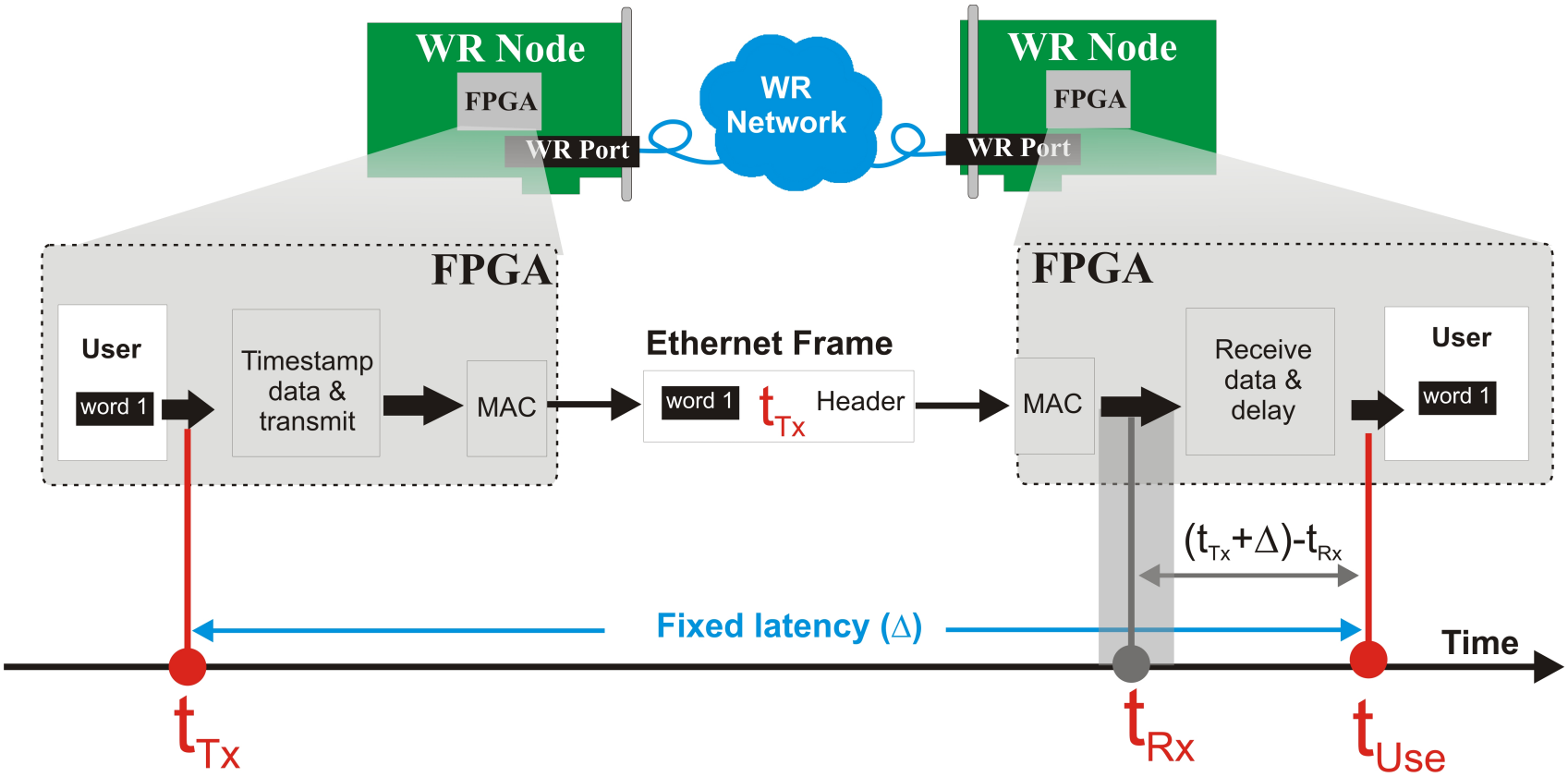


WRXI - White Rabbit eXtensions for Instrumentation - to replace CERN's Open Analog Signals Information System (OASIS)

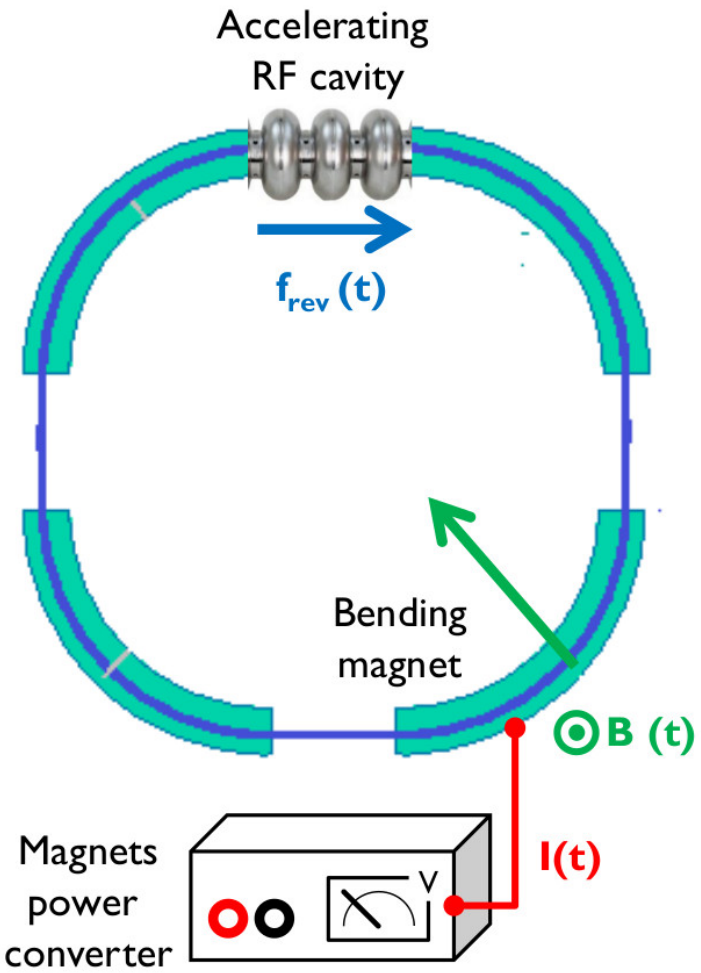
Outline

Fixed-latency data transfer



Fixed-latency data transfer- example application

Distribution of magnetic field in CERN accelerators



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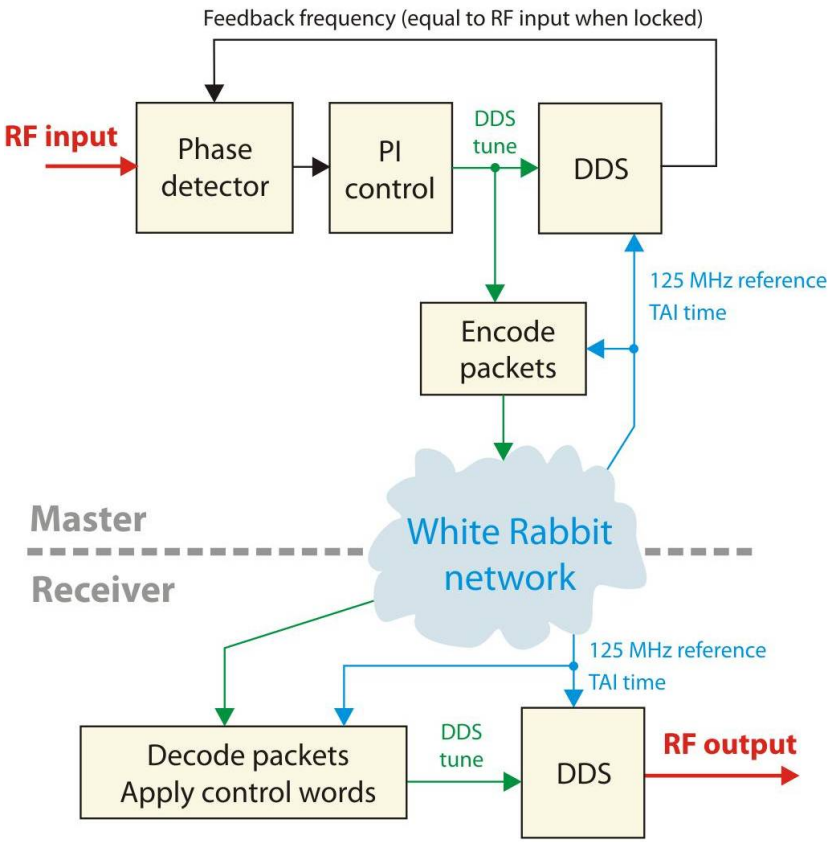
Radio-frequency transfer



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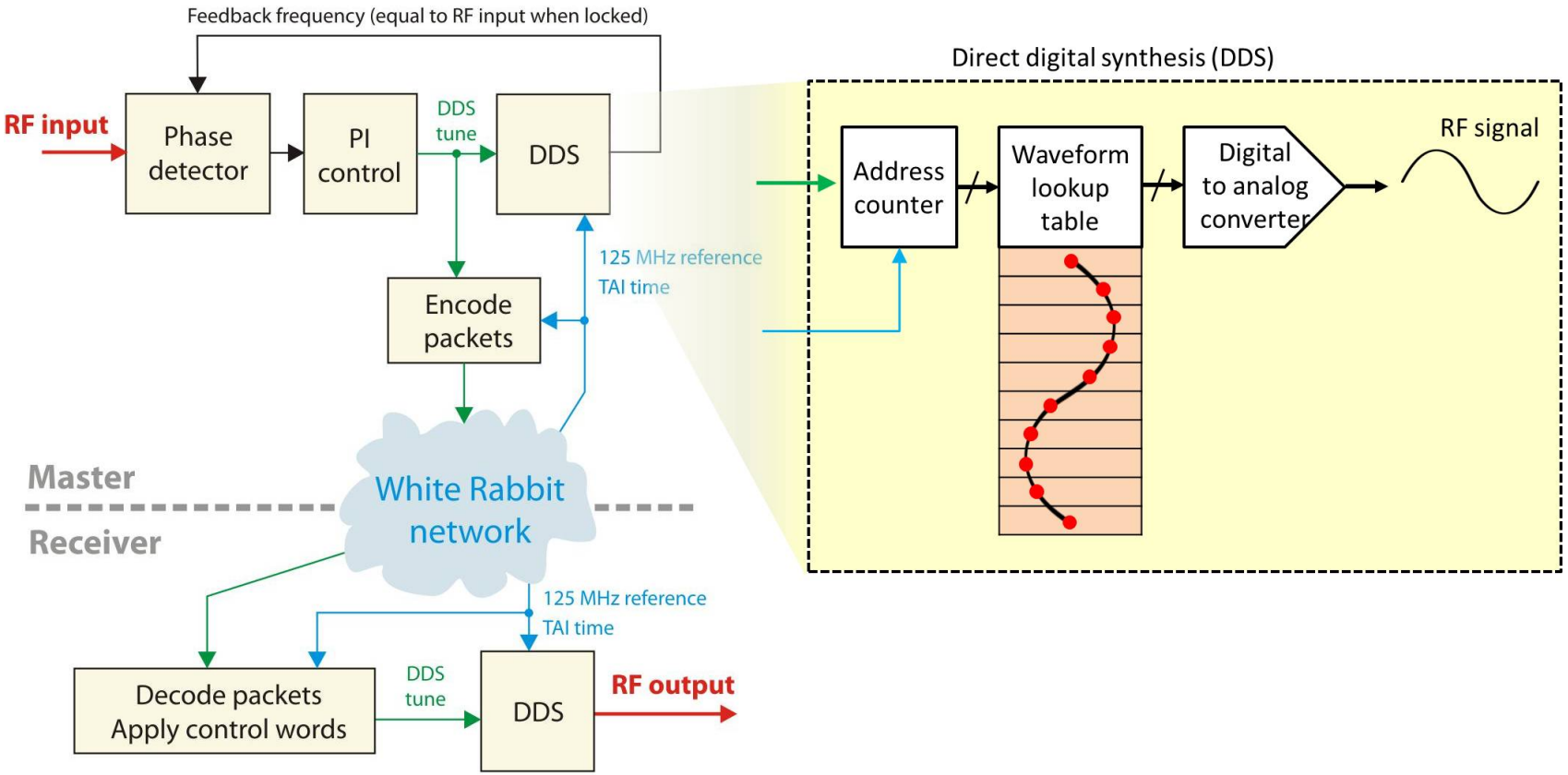

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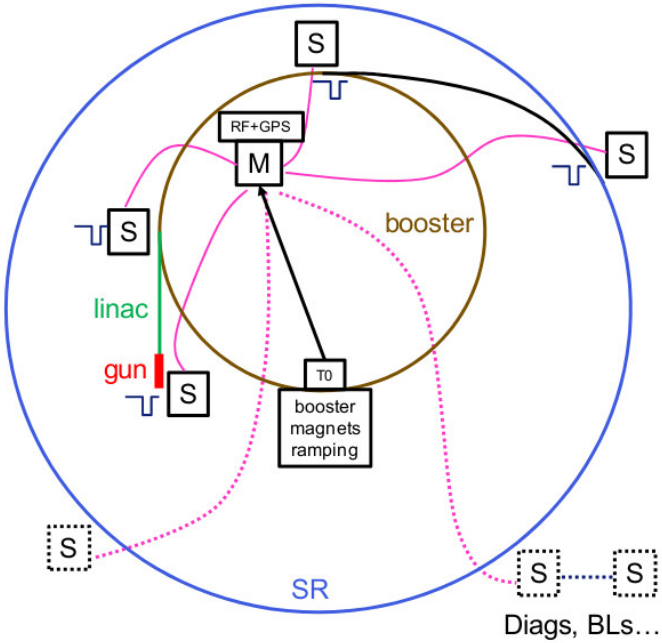

RF over WR at European Synchrotron Radiation Facility (ESRF)

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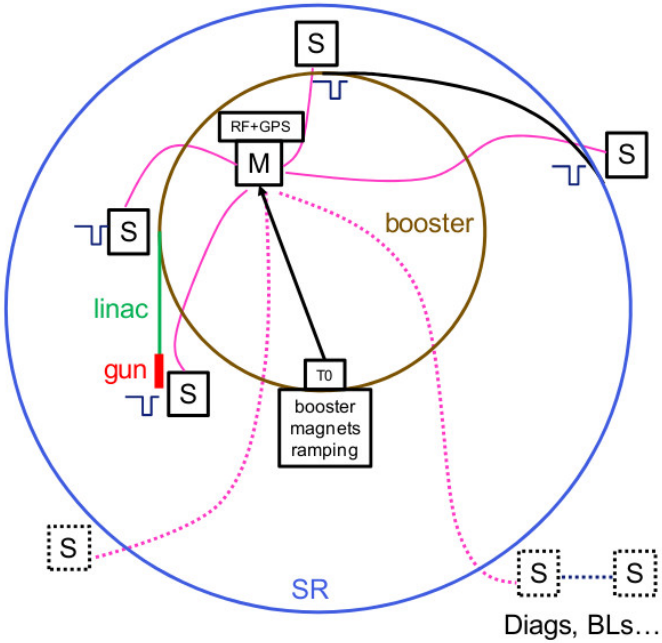

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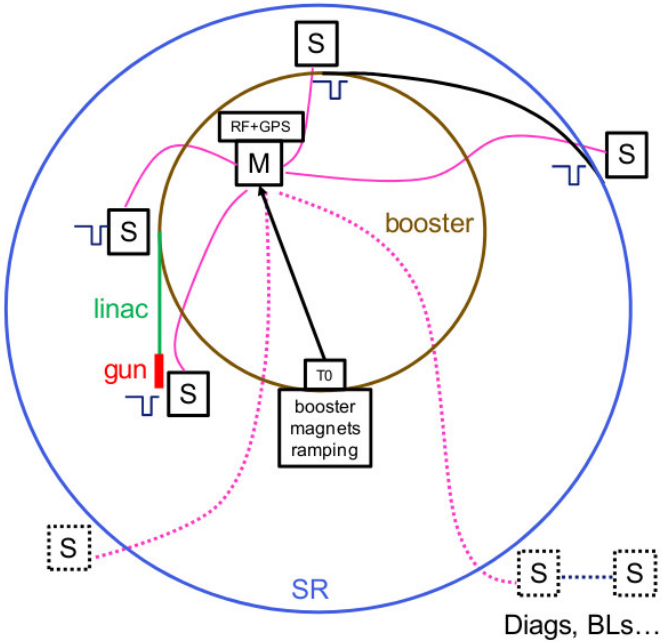

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- Currently operational with 1 WR switch and 8 WR nodes

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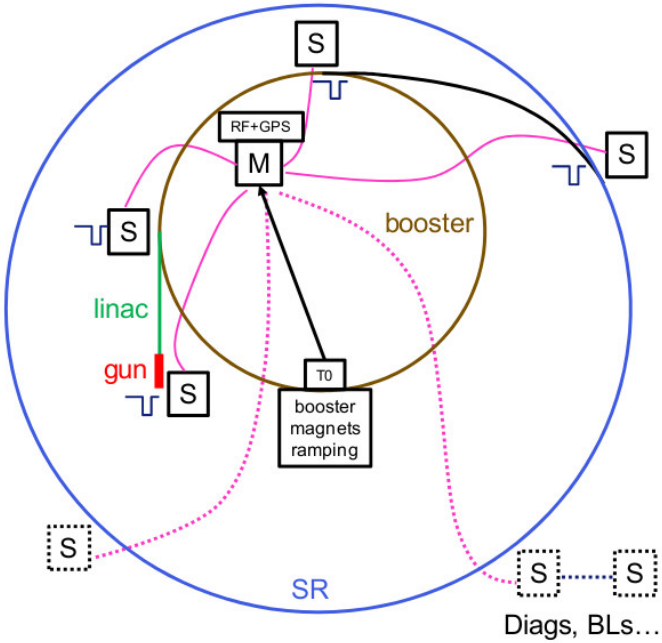

RF over WR at European Synchrotron Radiation Facility (ESRF)

- A prototype system provided $<$10 ps jitter
- Currently operational with 1 WR switch and 8 WR nodes
- In 2020: 5 WR switches and 41 WR nodes

Outline

Performance Enhancements

- Jitter and clock stability
  - Triggered by National Laboratories and RF distribution
  - Allan deviation (ADEV) from 1e-11 to **1e-12** over 1s
  - Random jitter from 11 to **1.1ps RMS** (1 Hz to 100kHz)
  - Ongong work to achieve jitter of **sub-100fs RMS** (100Hz to 20MHz)

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  - Triggered by cosmic ray detectors
  - Active correction of hardware temperature variation
  - Pk-pk variation from 700 ps to $<$**150 ps with sdev** $<$**50ps (-10 to 50^{o}C)**

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- Long-haul link
  - Triggered by National Time Labs and Radio Telescope
  - **Sub-ns** is achievable on links on **up to 80km**
  - **Ns on 137km** bidirectional & $\pm$**2.5ns on 950km** unidirectional links

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  - Pk-pk variation from 700 ps to $<$**150 ps with sdev** $<$**50ps (-10 to 50^{o}C)**
- Long-haul link
  - Triggered by National Time Labs and Radio Telescope
  - **Sub-ns** is achievable on links on **up to 80km**
  - **Ns on 137km** bidirectional & $\pm$**2.5ns on 950km** unidirectional links
- Link asymmetry correction
  - Triggered by radio telescope (Square Kilometre Array)
  - At 1310/1490nm, temp variation -0.12 ps/km/K (3ns for 80km over 50^{o}C)
  - **Sub-ns for 80km over 50^{o}C** using DWDM SFP on ITU channels C21/C22 (1560.61/1558.98 nm)

Performance Enhancements

- Jitter and clock stability
  - Triggered by National Laboratories and RF distribution
  - Allan deviation (ADEV) from 1e-11 to **1e-12** over 1s
  - Random jitter from 11 to **1.1ps RMS** (1 Hz to 100kHz)
  - Ongong work to achieve jitter of **sub-100fs RMS** (100Hz to 20MHz)
- Compensation of hardware temperature variation
  - Triggered by cosmic ray detectors
  - Active correction of hardware temperature variation
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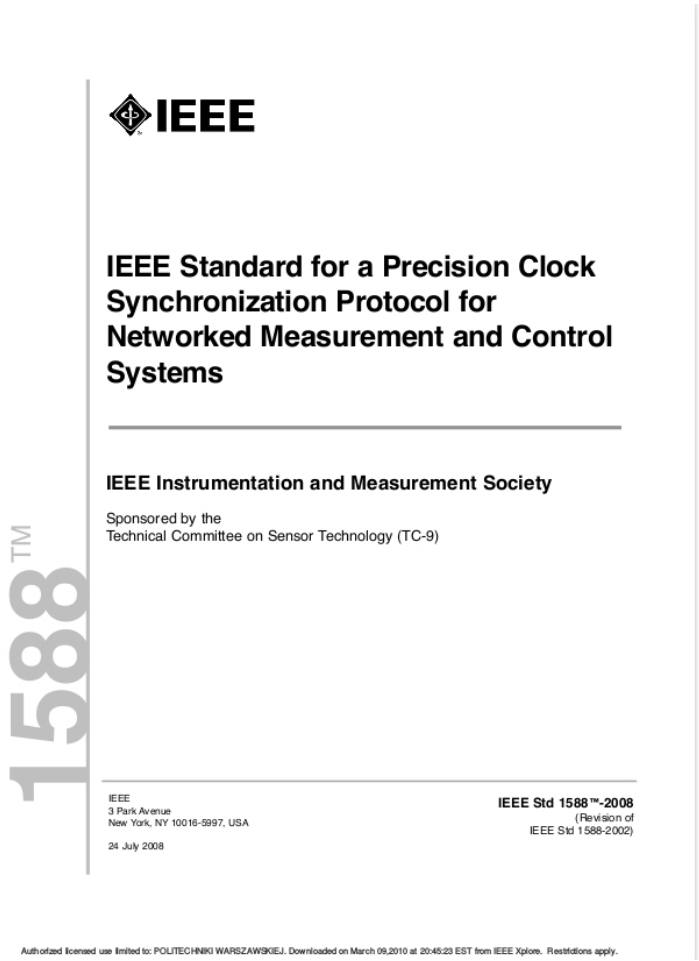
- Absolute calibration - next presentation

Outline

WR standardization in IEEE1588



IEEE

IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems

IEEE Instrumentation and Measurement Society

Sponsored by the
Technical Committee on Sensor Technology (TC-9)

1588™

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3 Park Avenue
New York, NY 10016-5997, USA

24 July 2008

IEEE Std 1588™-2008
(Revision of
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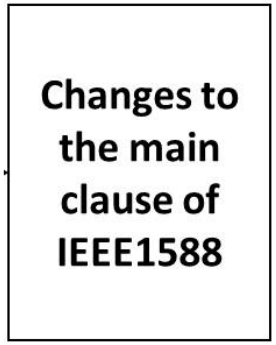
White Rabbit integration into IEEE1588-20XX as High Accuracy:

`https://www.ohwr.org/projects/wr-std/wiki/wrin1588`

WR standardization in IEEE1588



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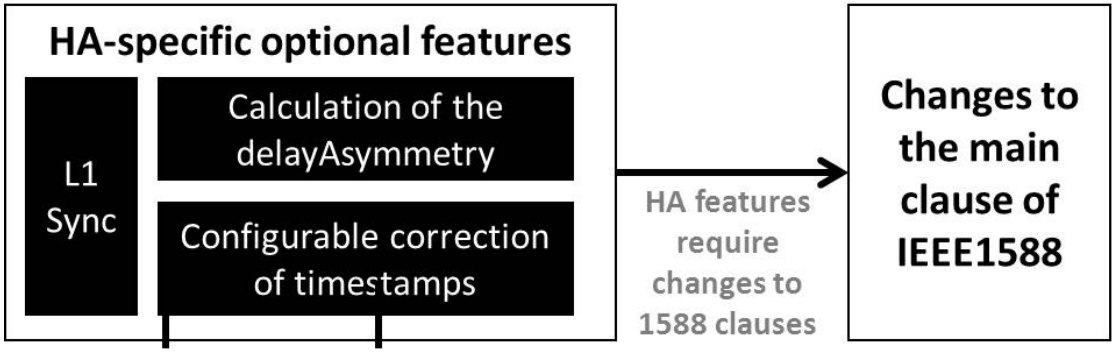

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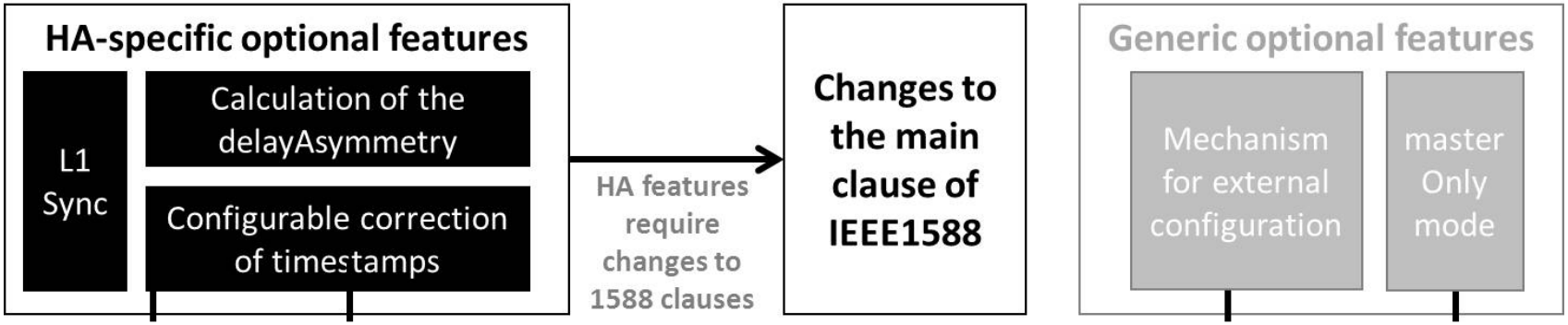

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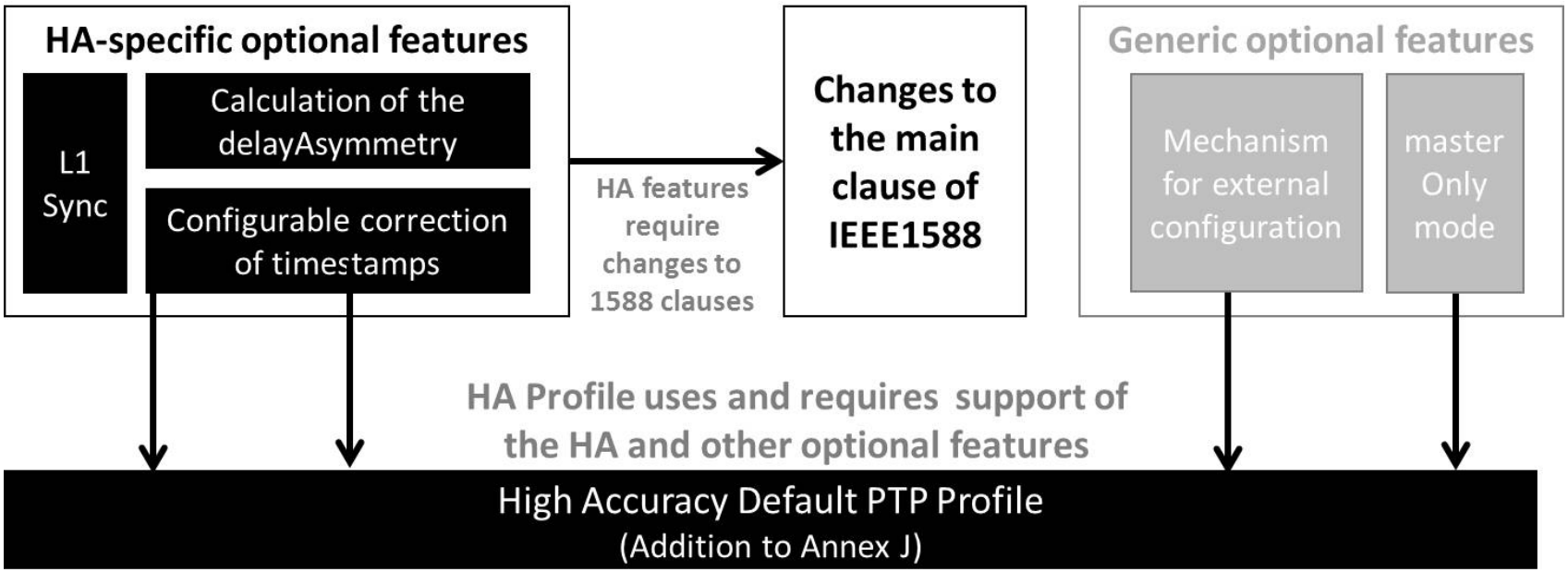

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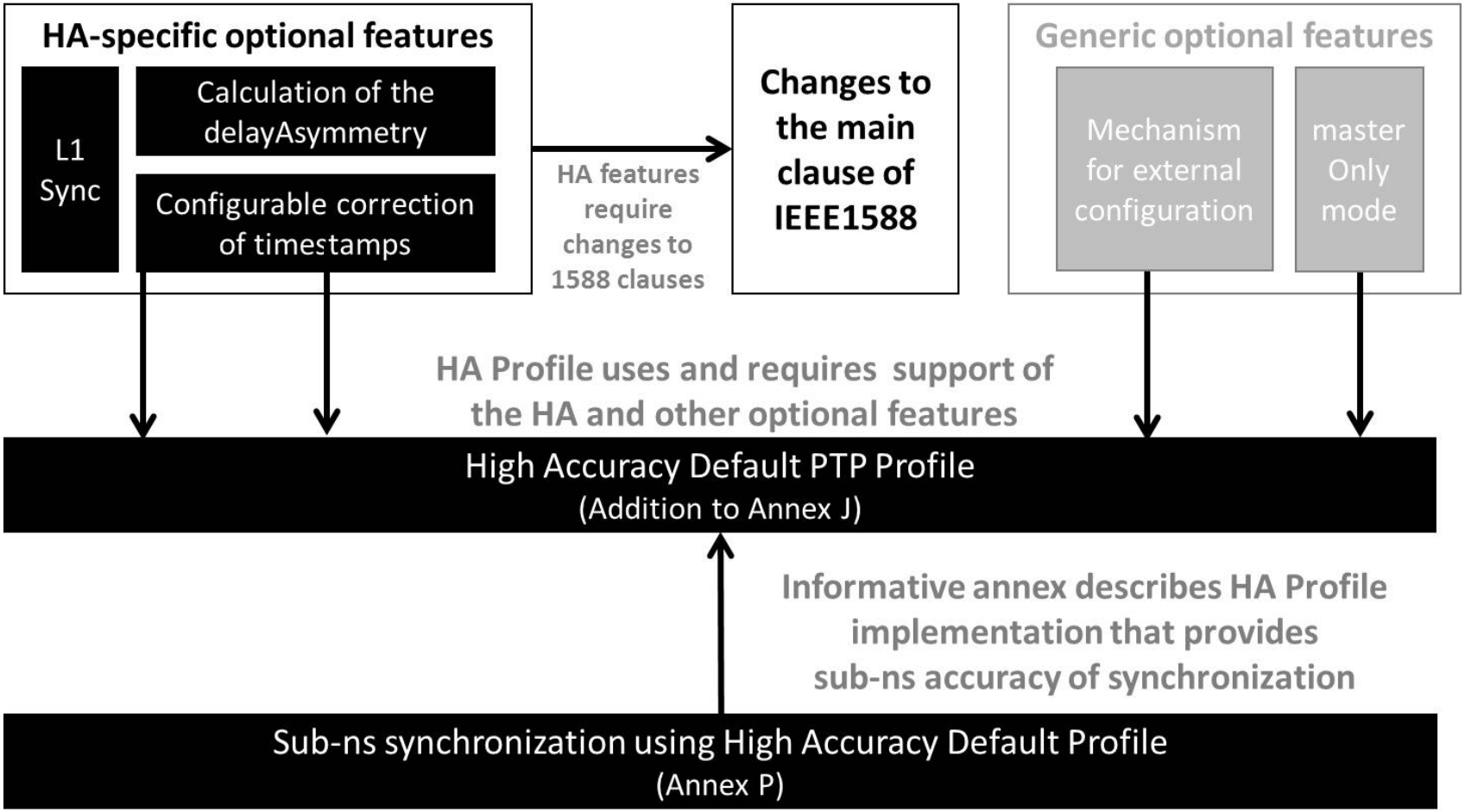

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Outline

Conclusions

- A standard-based, open and commercially available

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- Keeps getting better

Thank you

Thank you !

`www.cern.ch/white-rabbit`