White Rabbit: accurate time and frequency transfer over Ethernet networks

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

Management and monitoring of time and frequency technologies

21 June 2022

Outline

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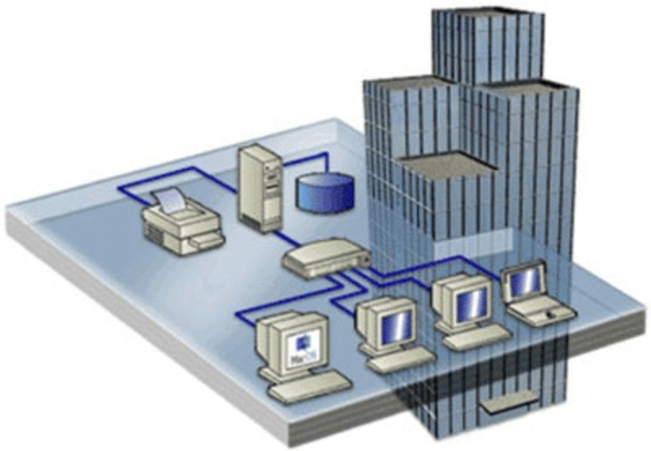

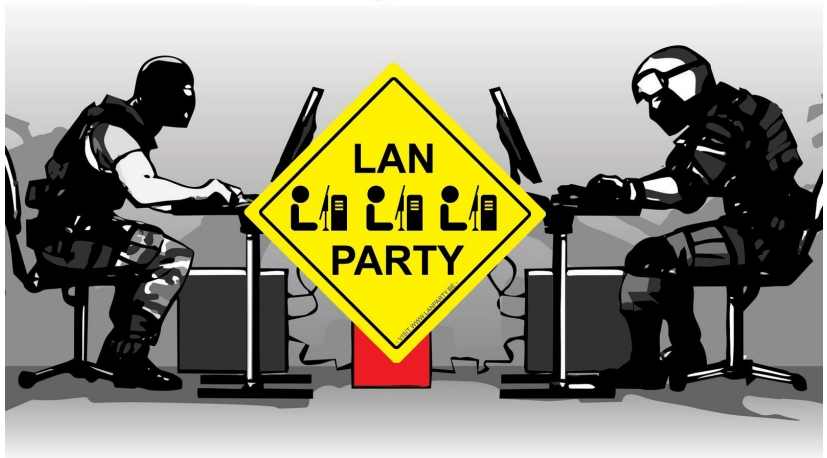

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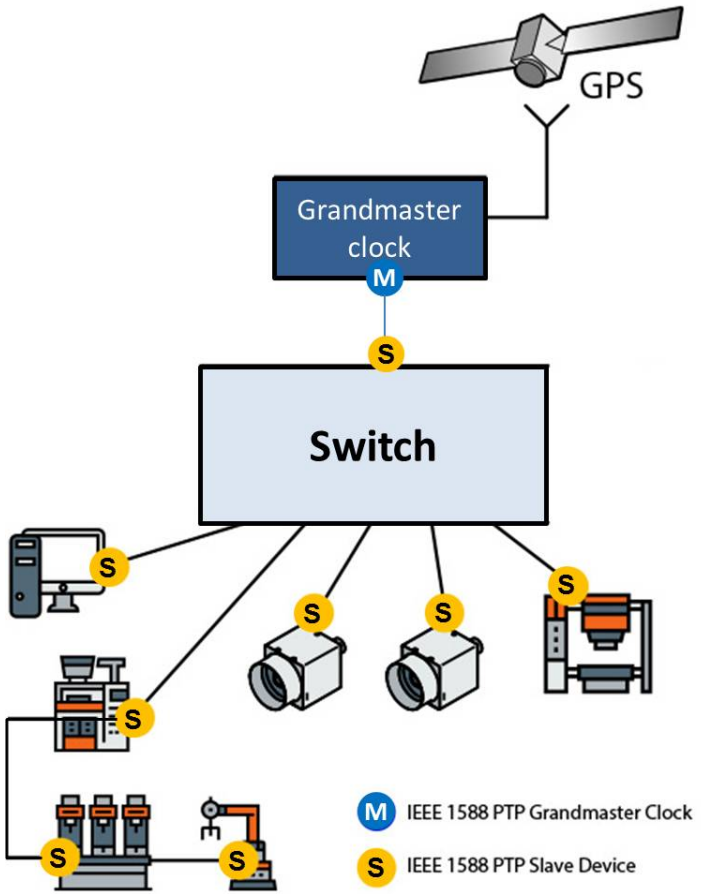

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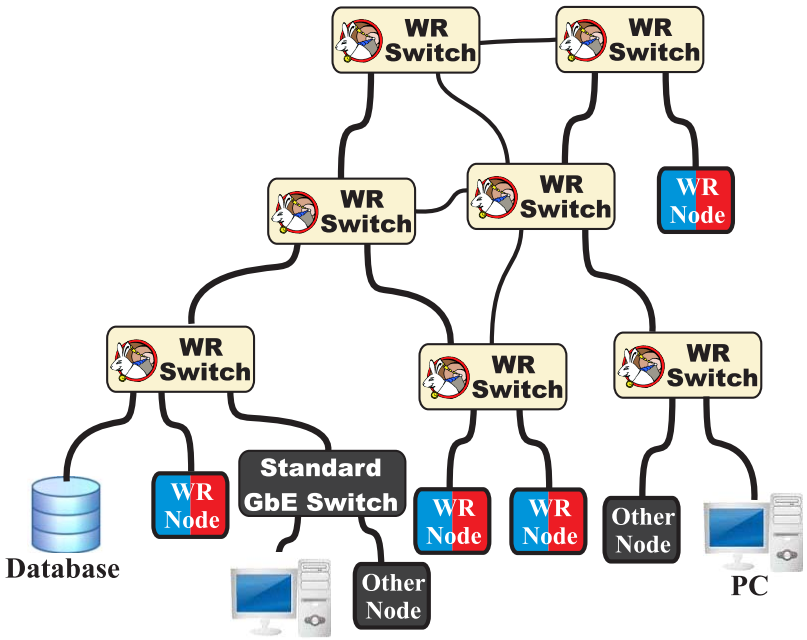

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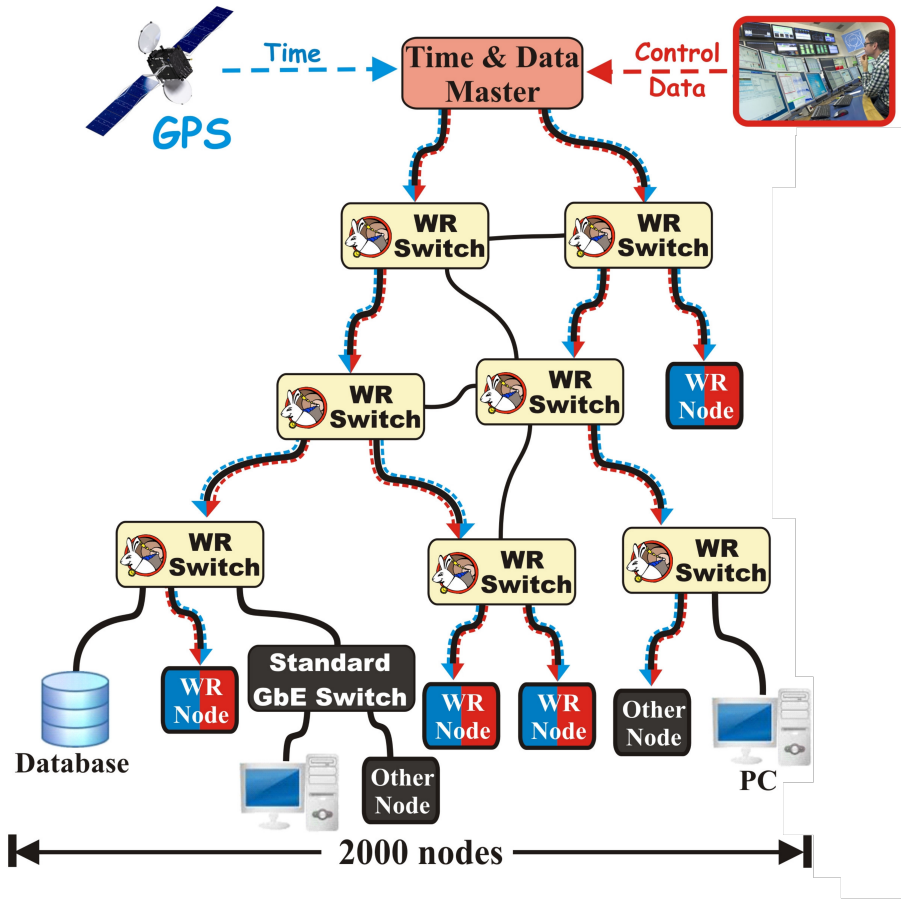

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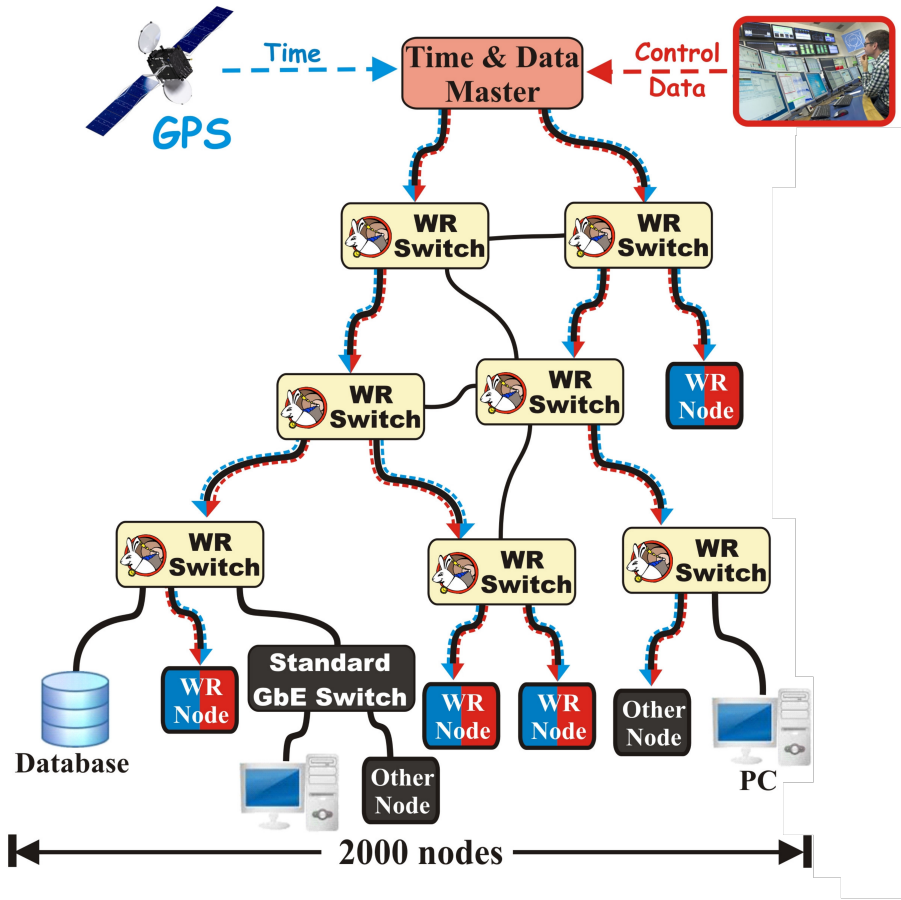

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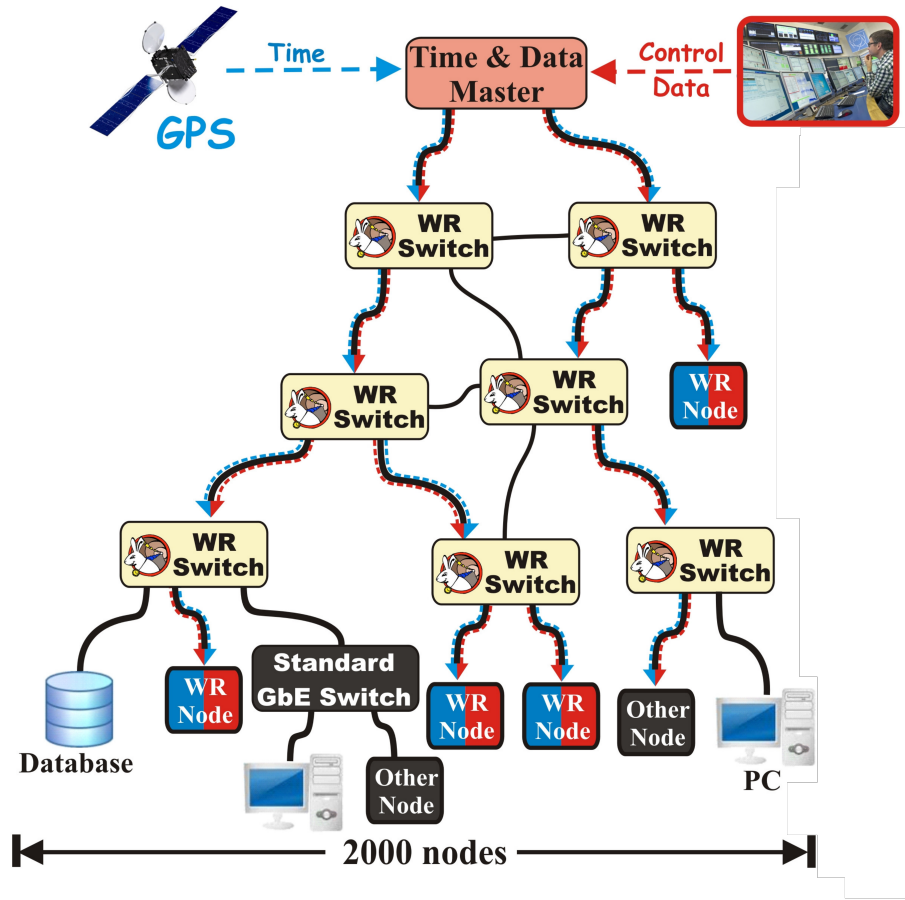

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Many users worldwide, including metrology labs...

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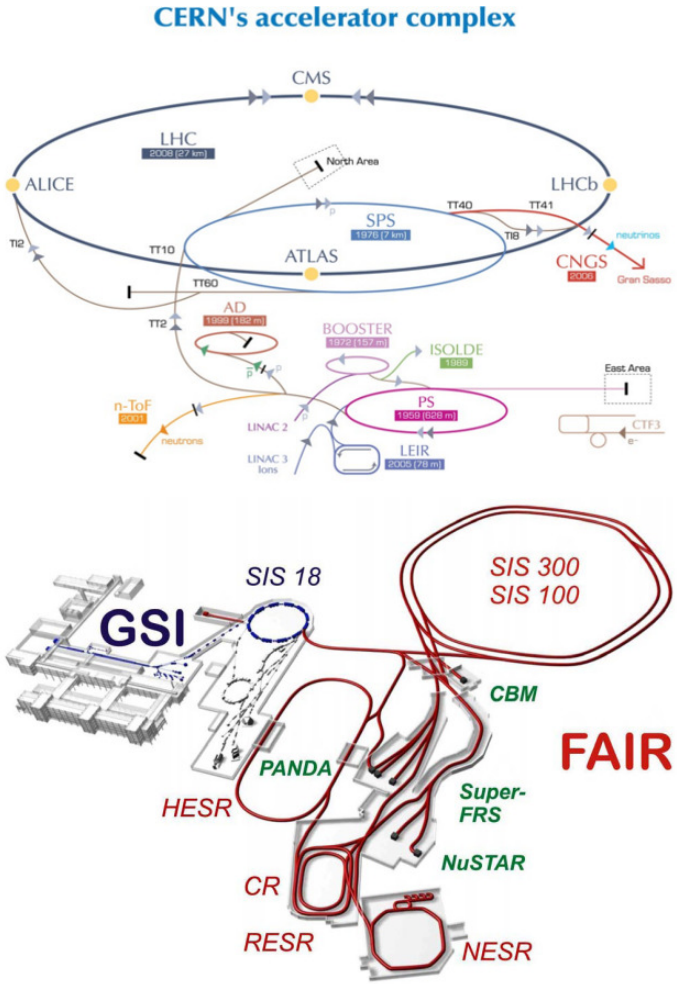

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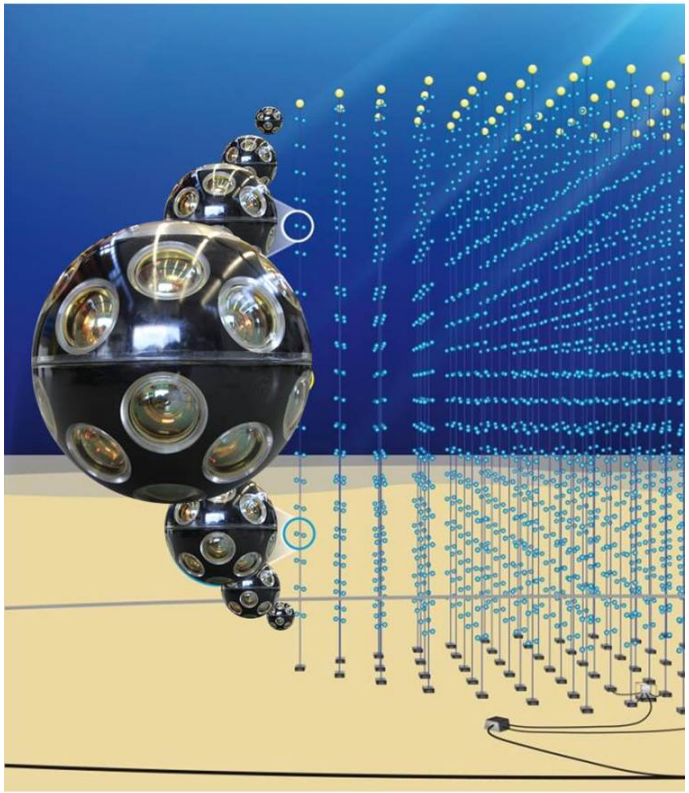

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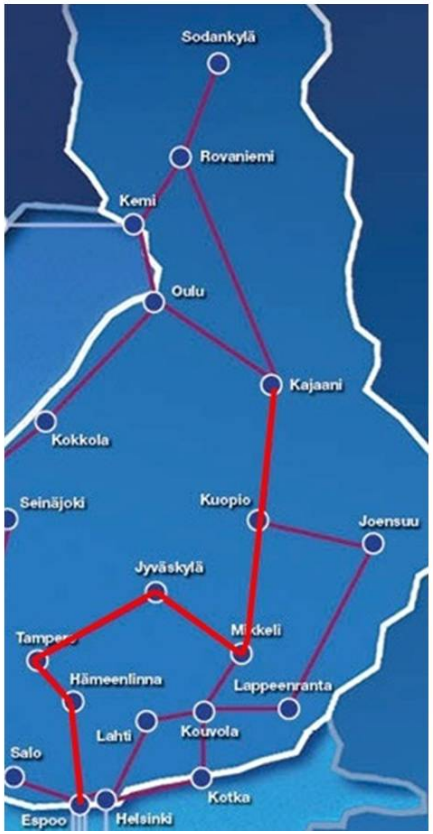
MIKES

The longest WR link of 950 km



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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

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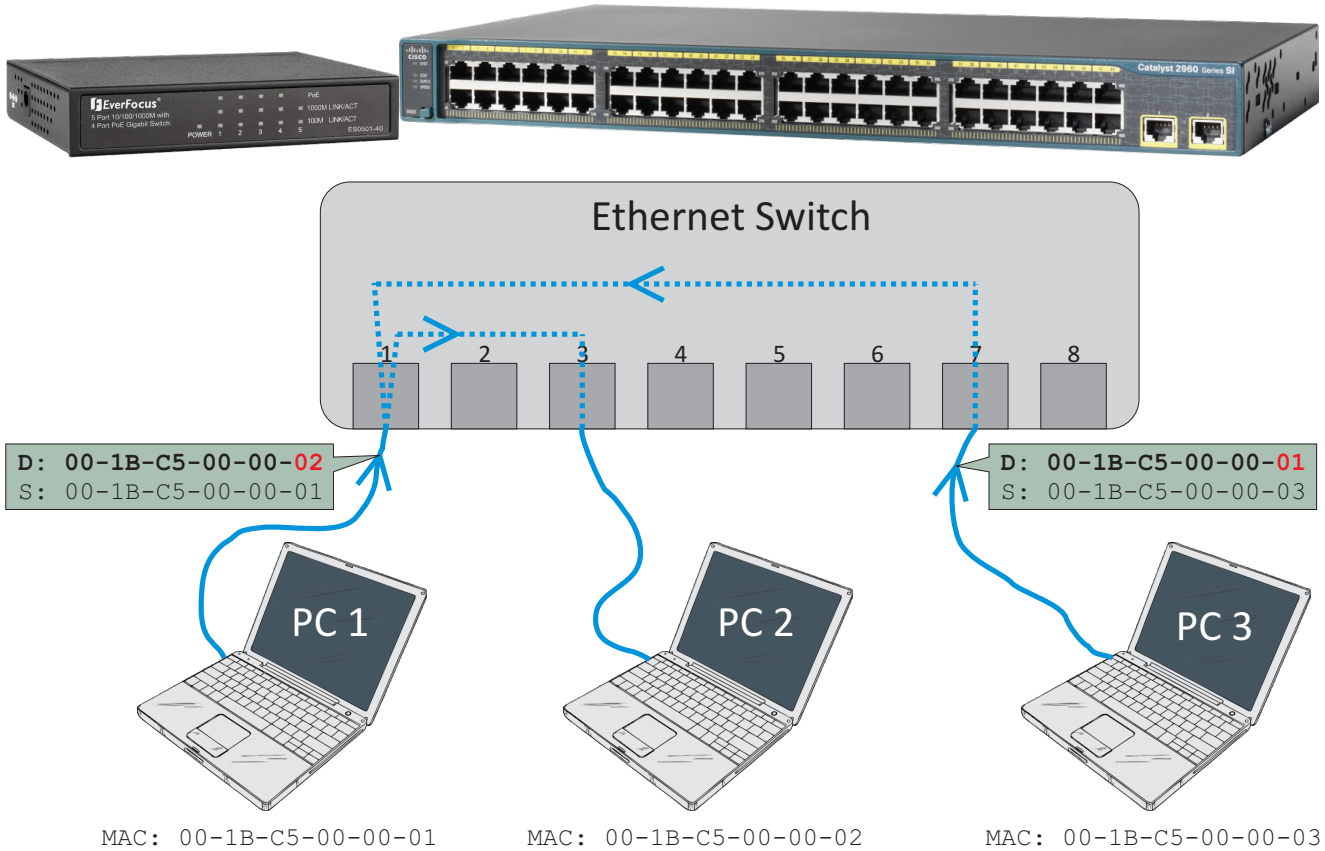
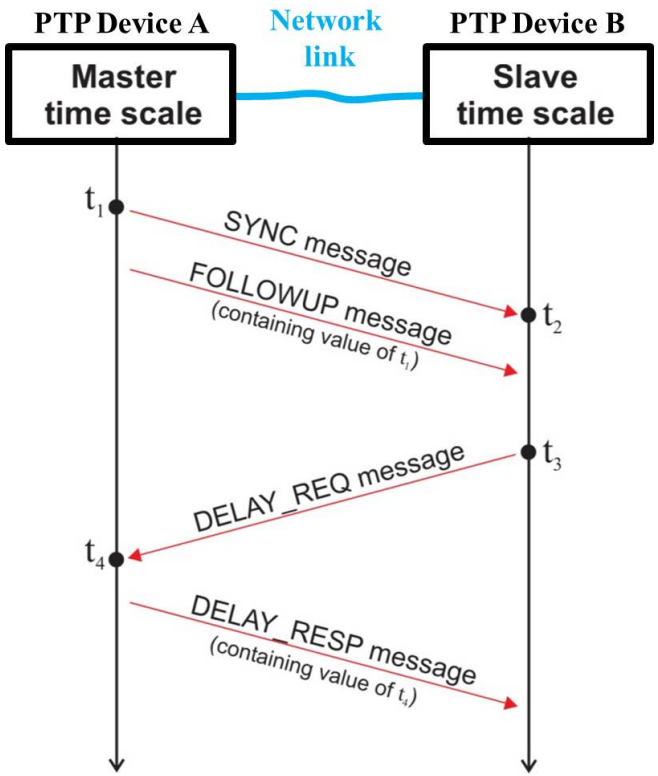
Enhanced with

- Layer 1 syntonisation
- Digital Dual Mixer Time Difference (DDMTD)
- Link delay model

Gigabit Ethernet Local Area Network over fibre



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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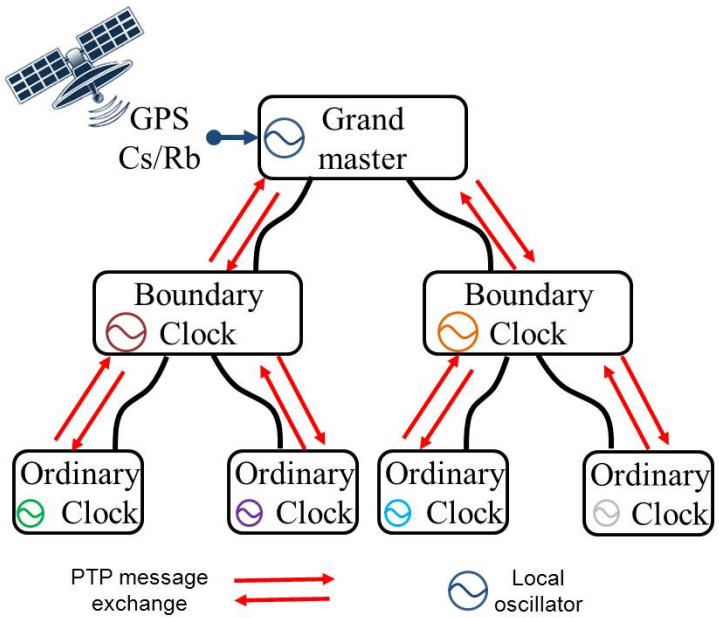

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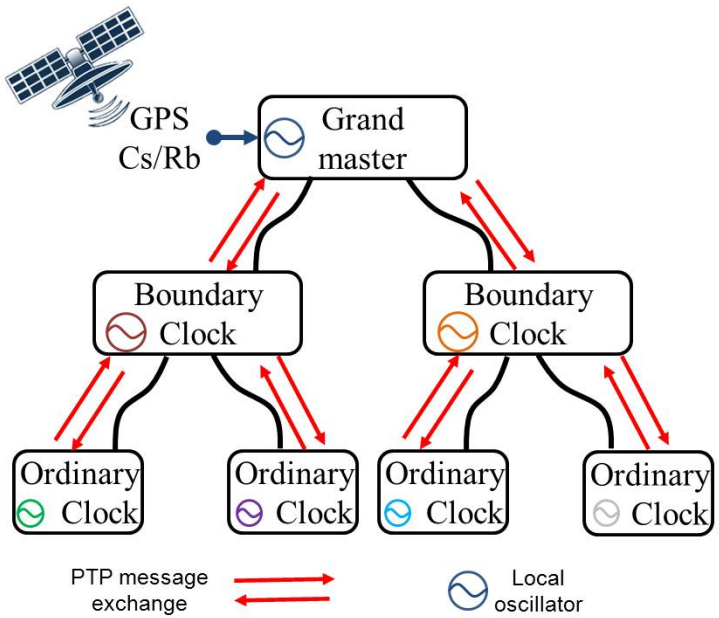

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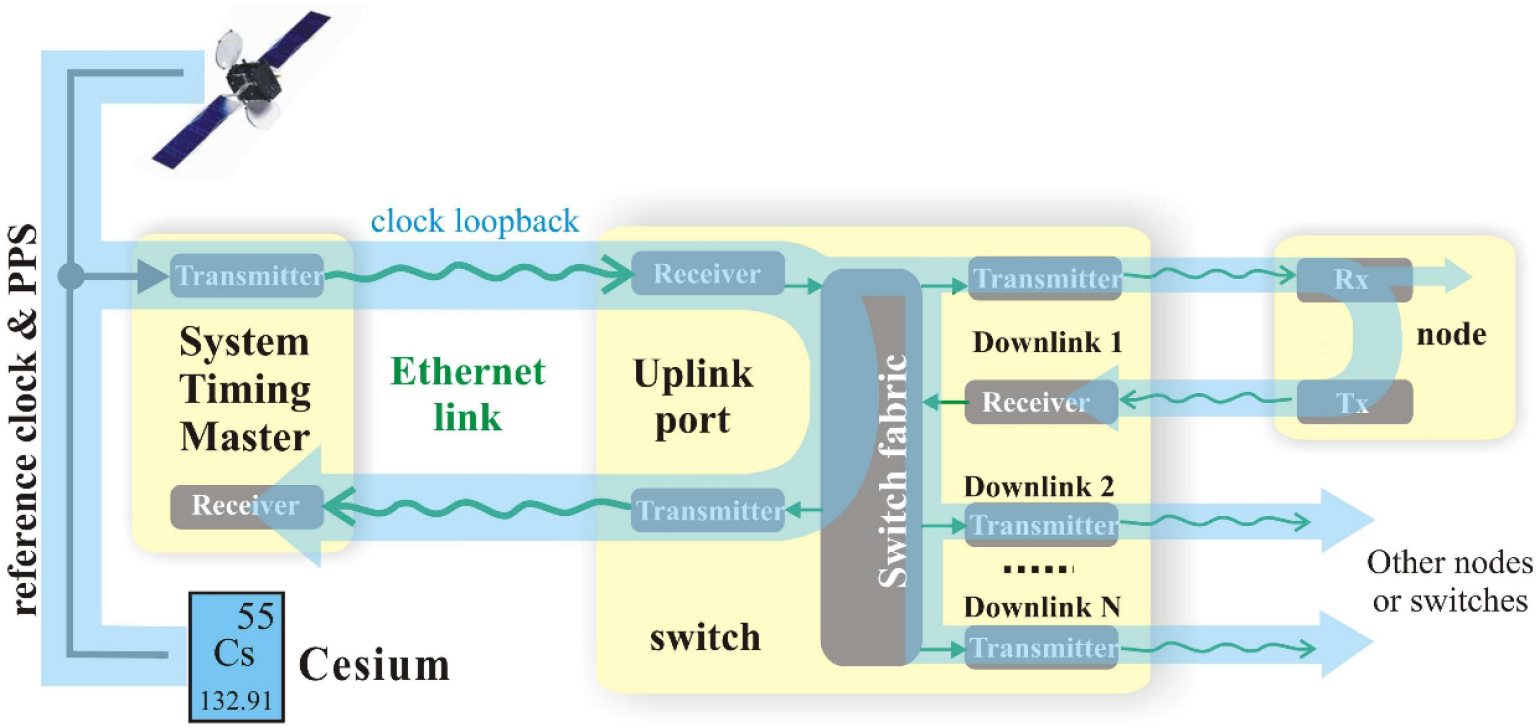
- Hierarchical network
- Shortcomings:
  - devices have free-running oscillators
  - frequency drift compensation vs. message exchange traffic
  - assumes symmetry of medium
  - timestamps resolution

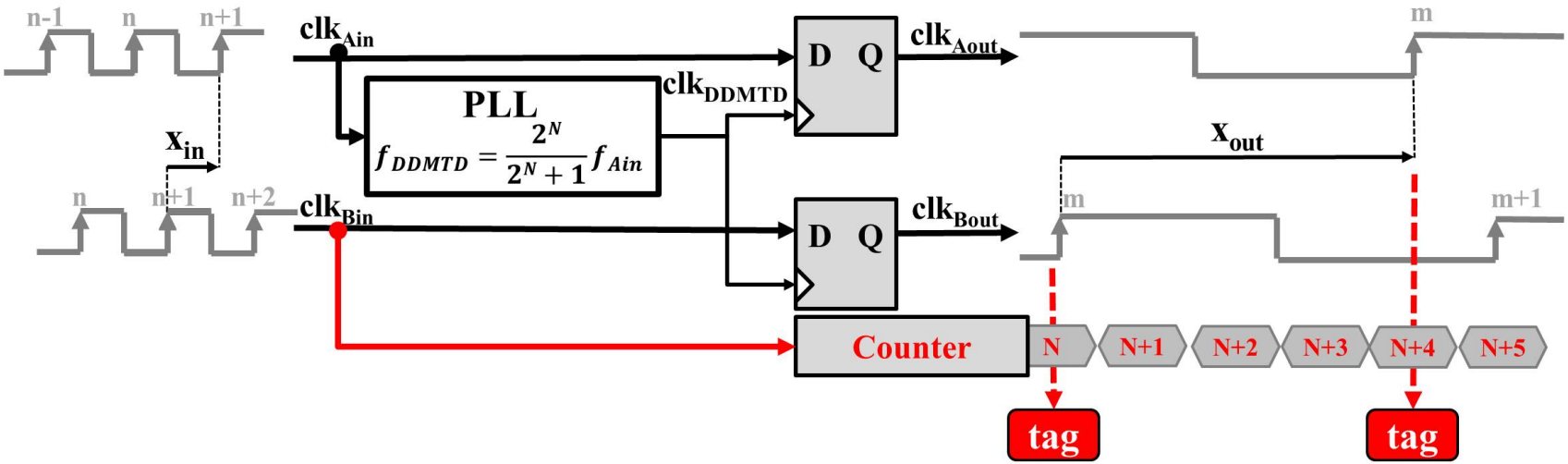
Layer 1 Syntonisation

- 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



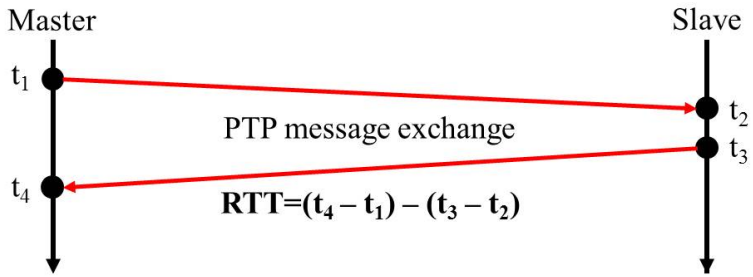
Digital Dual Mixer Time Difference (DDMTD)

- Precise phase measurements in FPGA
- WR parameters:
  - clk_{in} = 62.5 MHz
  - clk_{DDMTD} = 62.496185 MHz (N=14)
  - clk_{out} = 3.814 kHz
- Theoretical resolution of 0.977 ps



Link delay model

- Correction of RTT for asymmetries



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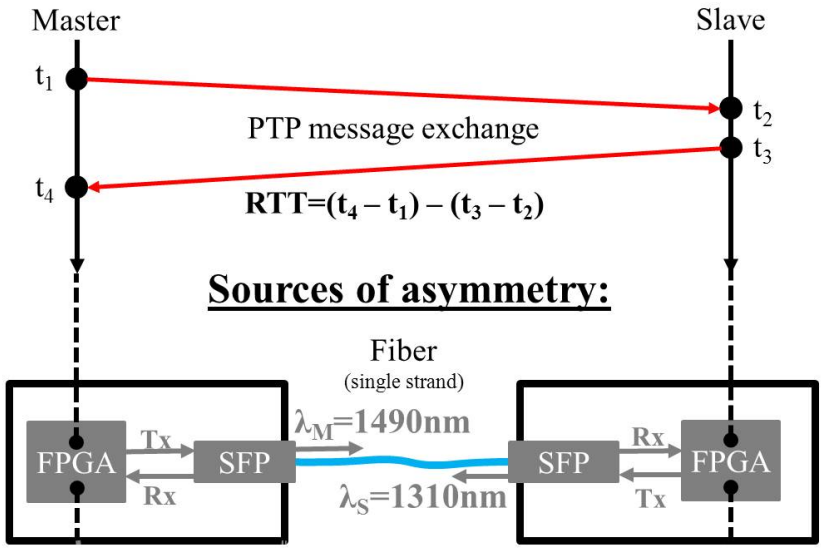

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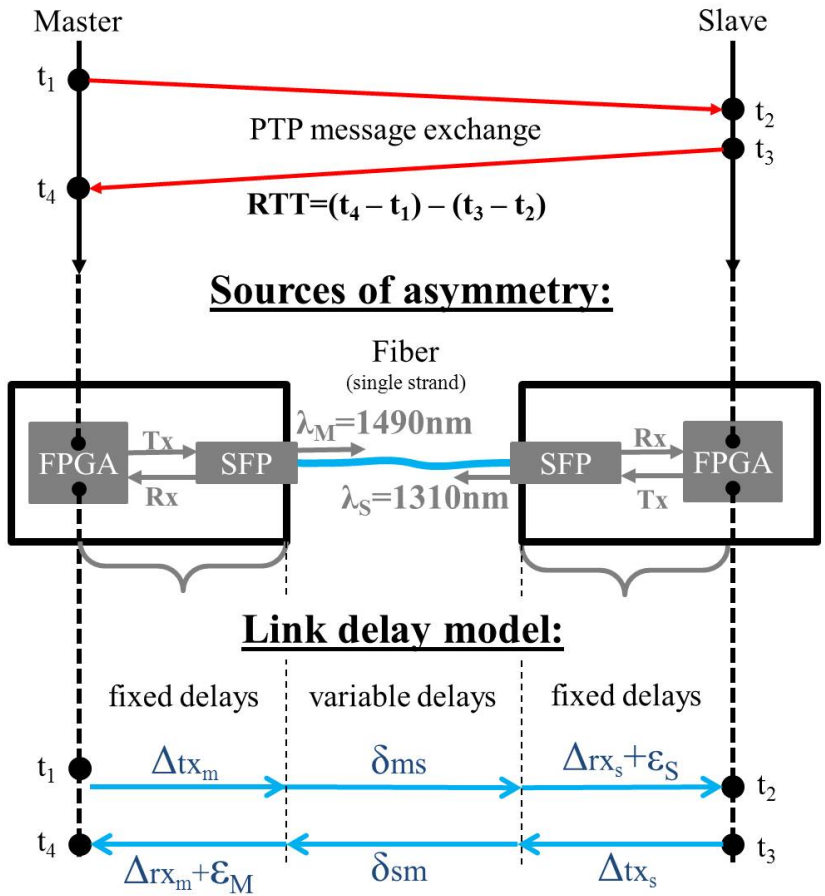
  - Calibration procedure to find fixed delays and α



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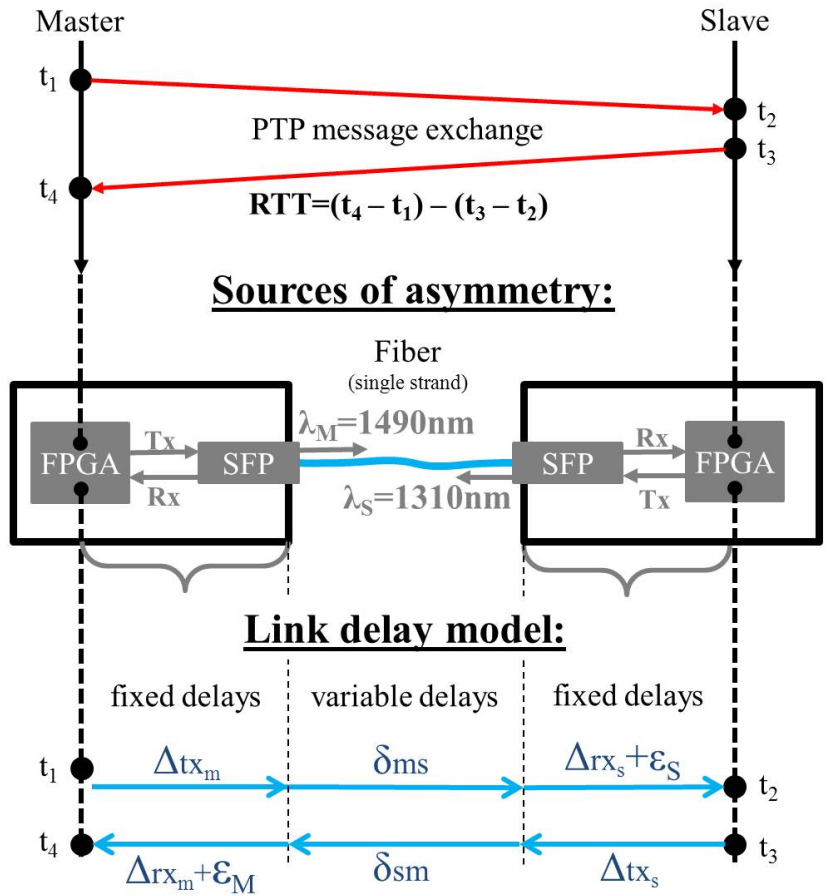
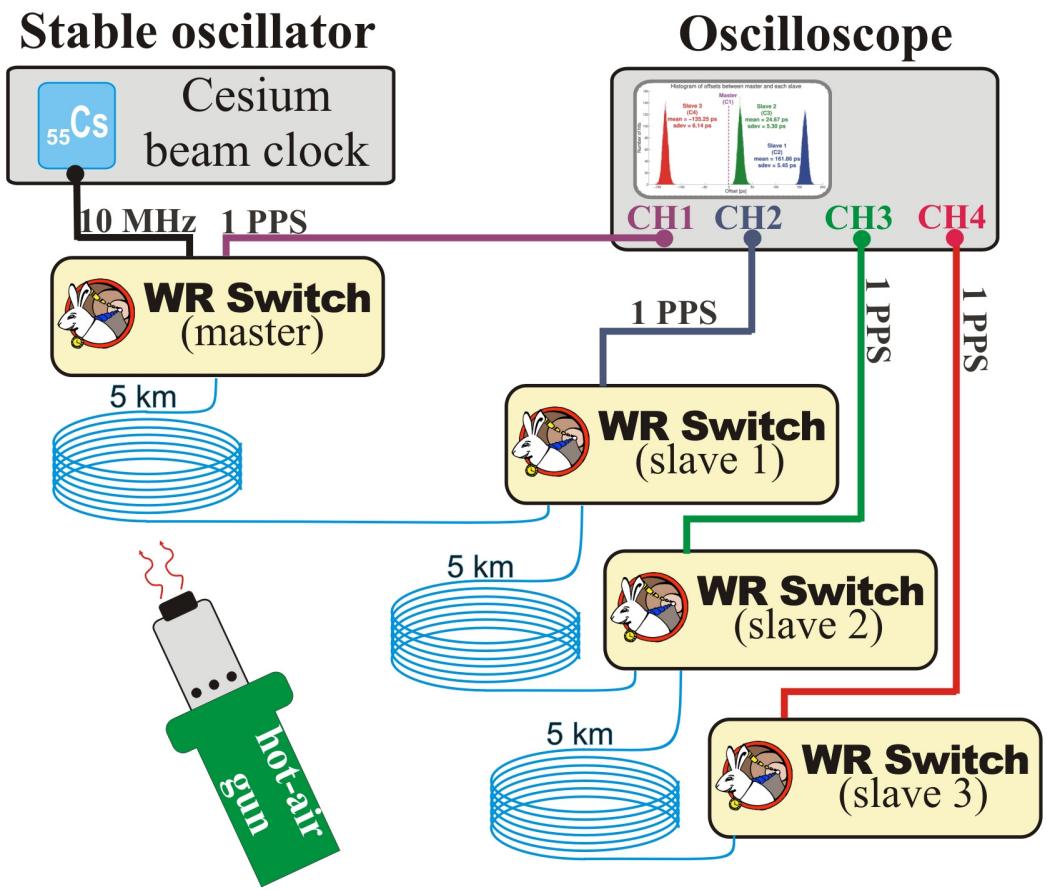
  - Calibration procedure to find fixed delays and α
- Accurate offset from master (OFM):

$$\delta_{ms} = \frac{1+\alpha}{2+\alpha}\left(RTT - \sum \Delta - \sum \epsilon\right)$$

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



Out-of-the-box performance



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

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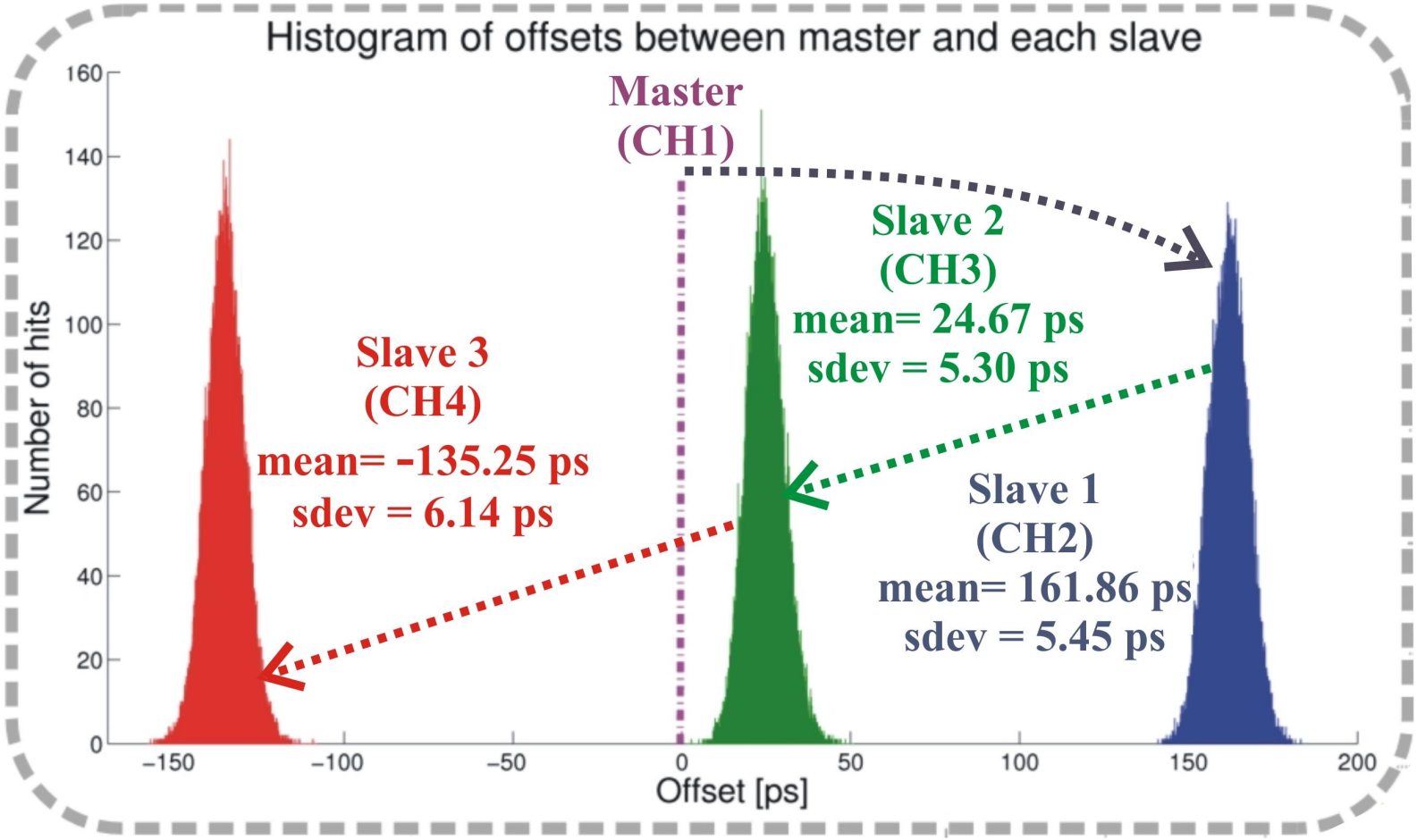

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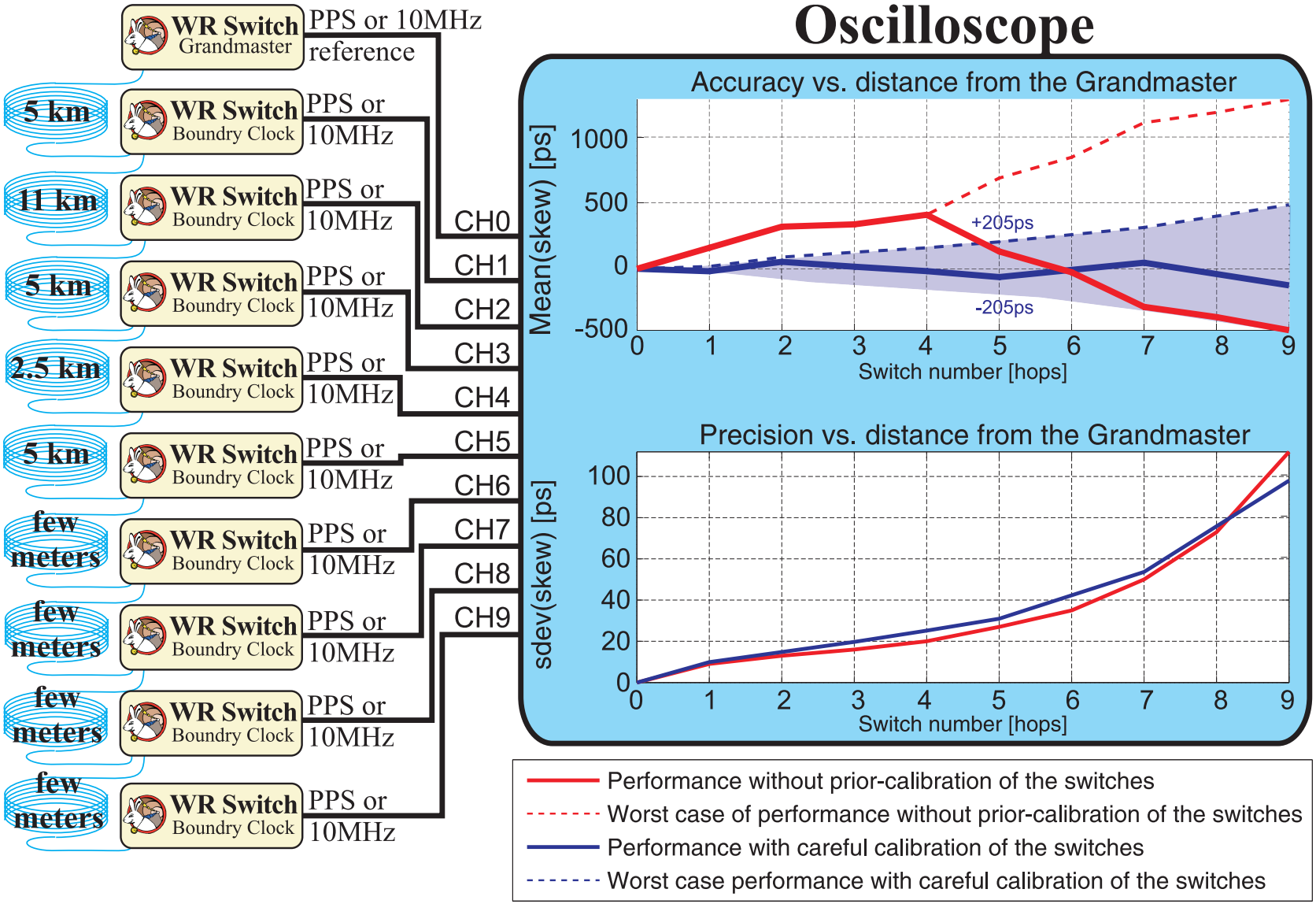
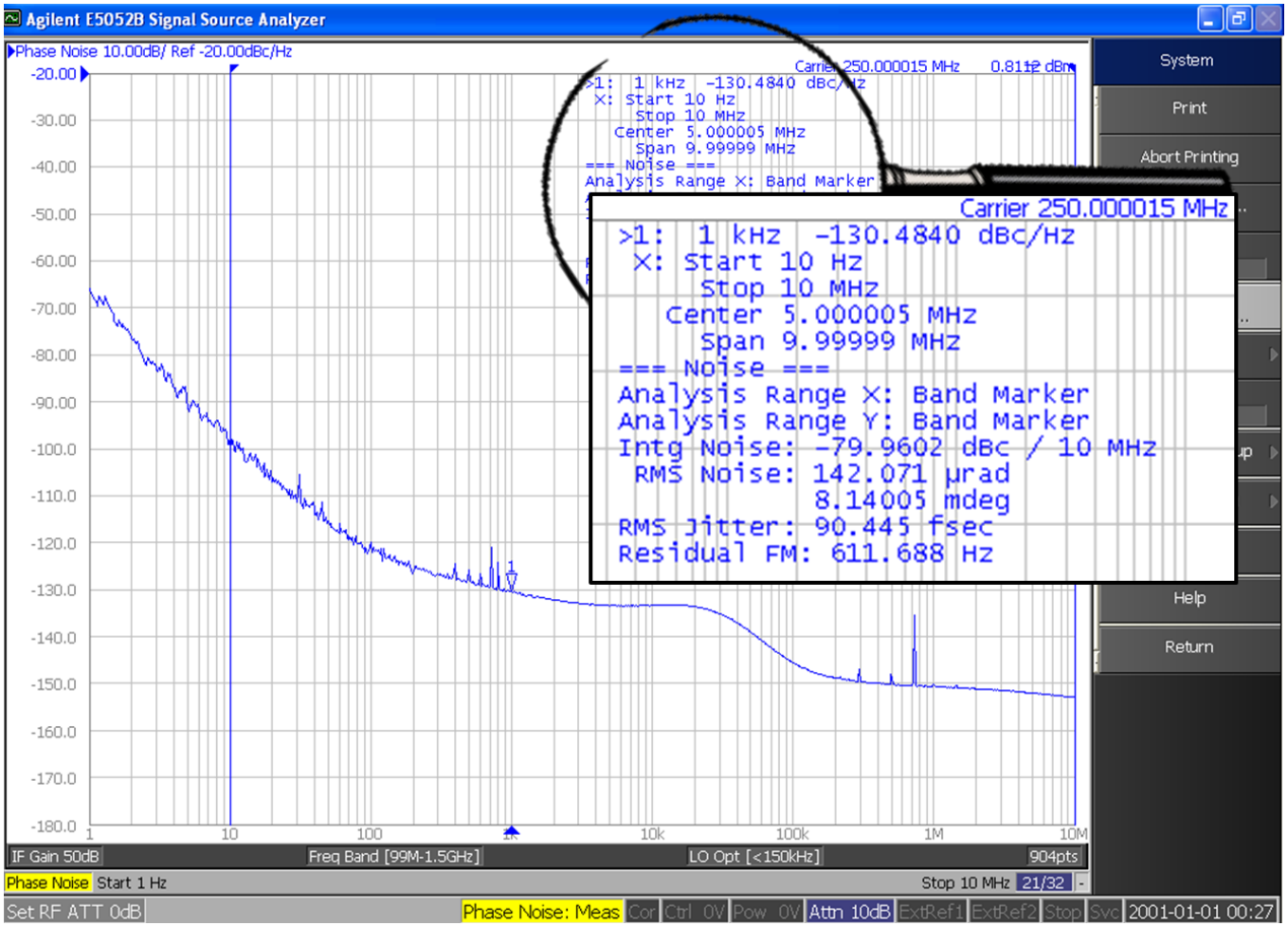


State of the art performance



- **Accuracy:** $<$**10 ps**
- **Jitter:** $<$**100 fs** RMS 10 Hz–10 MHz

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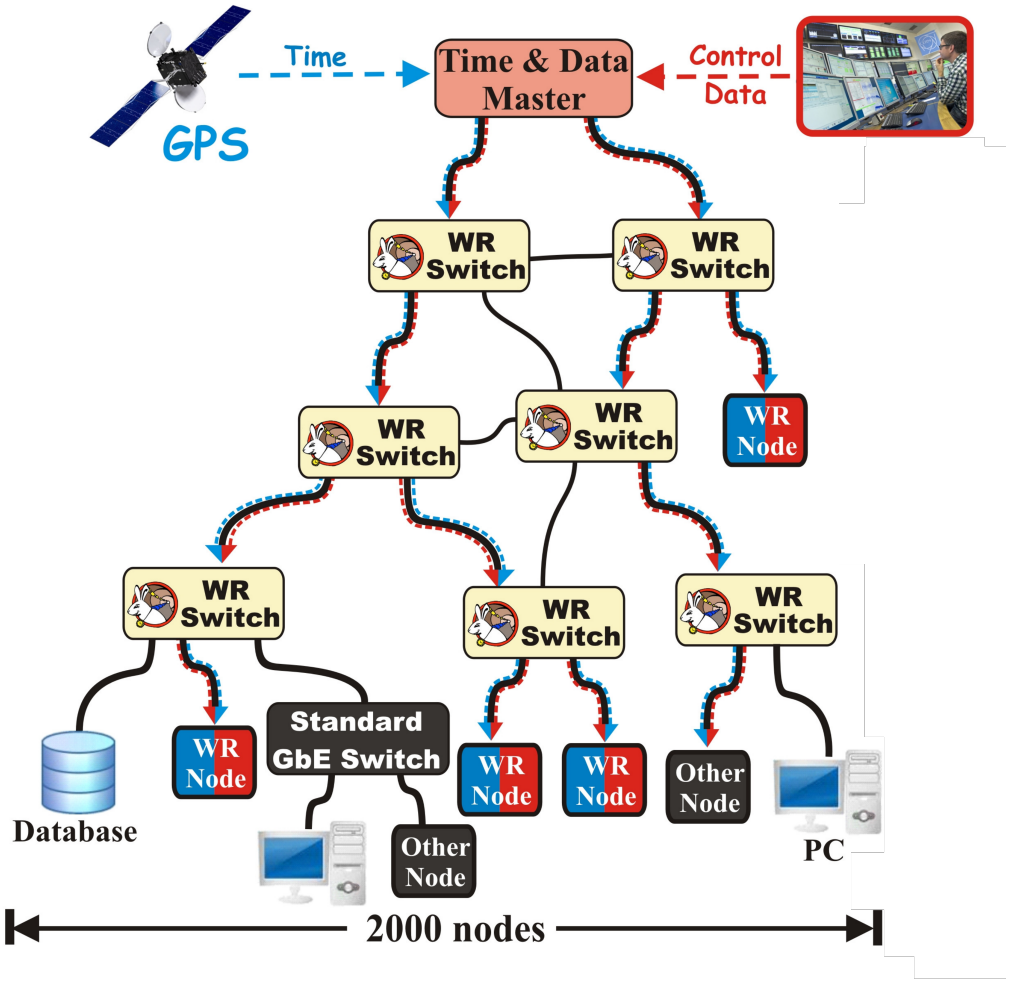
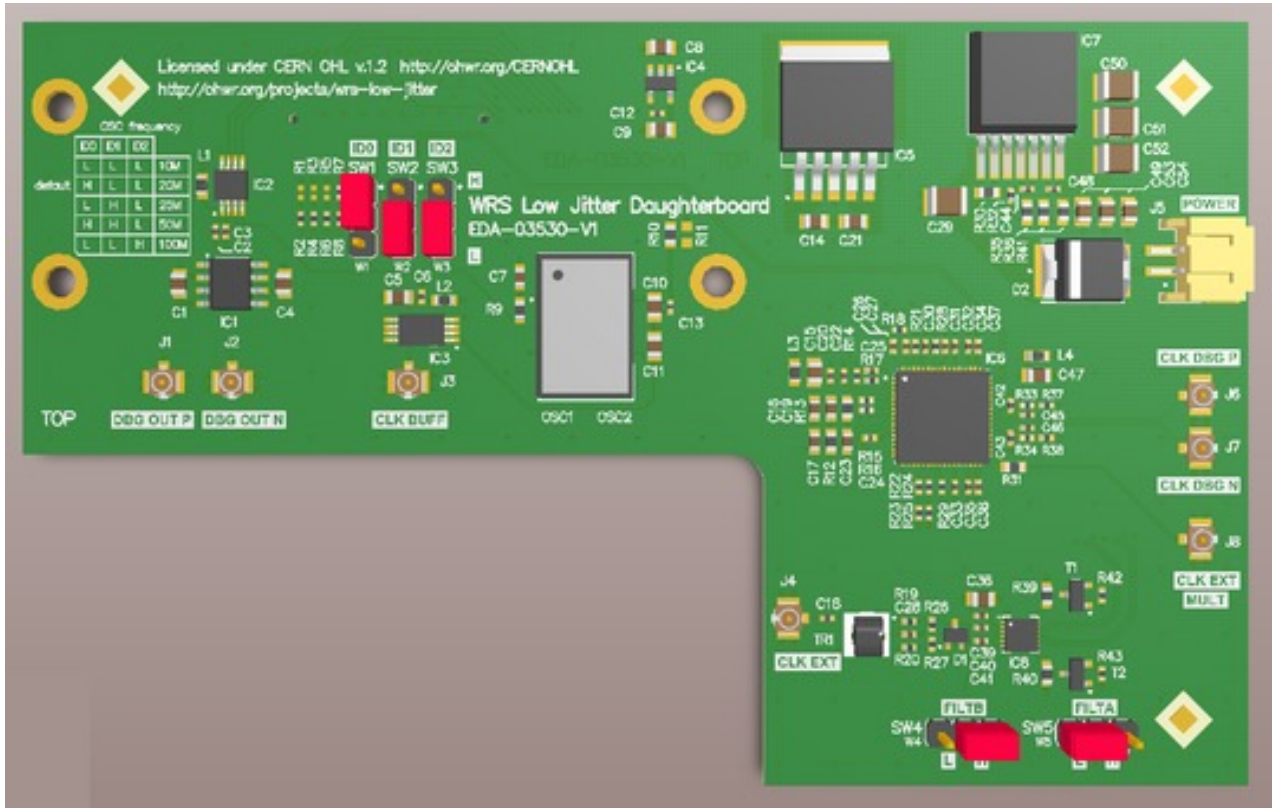
Typical WR network



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 fibre
- Fully open-source, commercially available from 4 companies

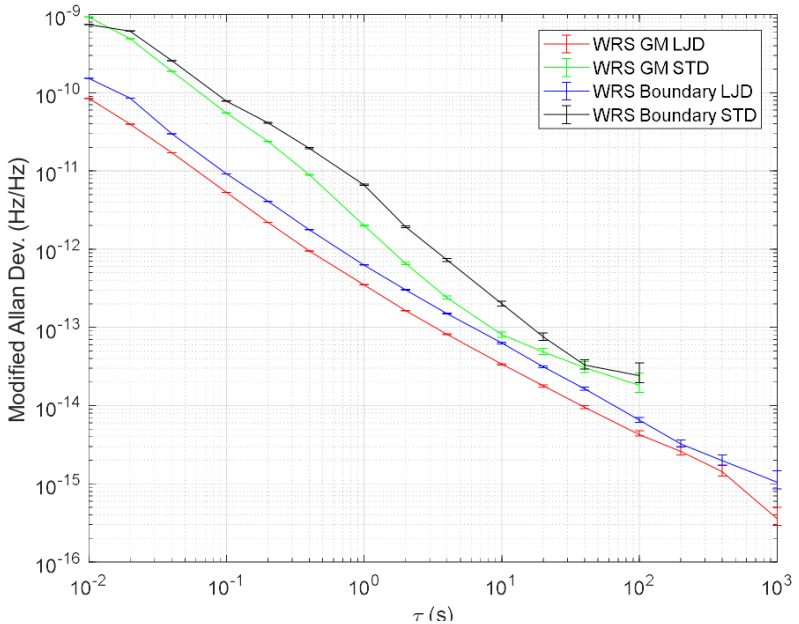
Low-jitter variant of v3 switch



Uses external PLL and better VCTCXO in a daughter card or directly integrated in the main switch PCB to improve short and long-term stability.

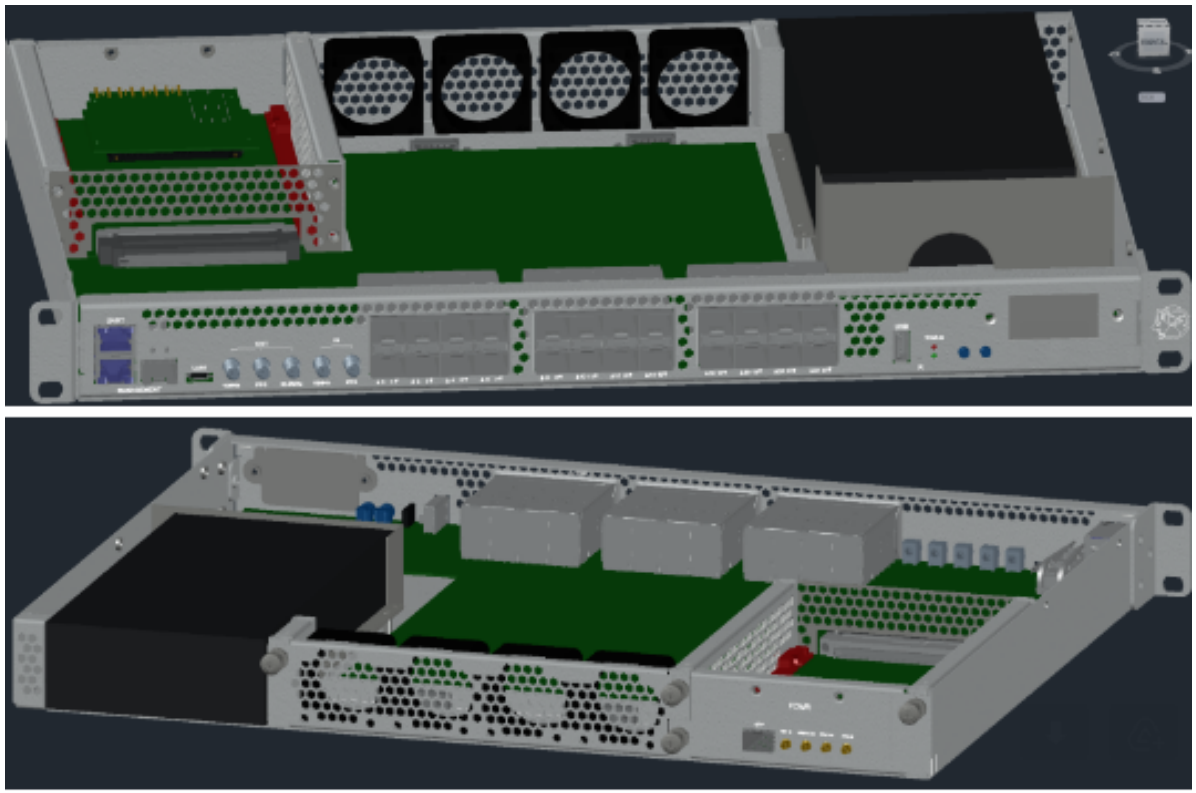
Switch types and their performance

WR Switch type	Ports 1-12 (LPDC ports)		Ports 13-18	
	Accuracy	Precision	Accuracy	Precision
“Standard”	<10 ps	<10 ps	<100 ps	<10 ps
“Low-jitter”	<10 ps	<1 ps	<100 ps	<1 ps



Measurement device: Microsemi/Microchip 3120A Phase Noise Test Probe

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

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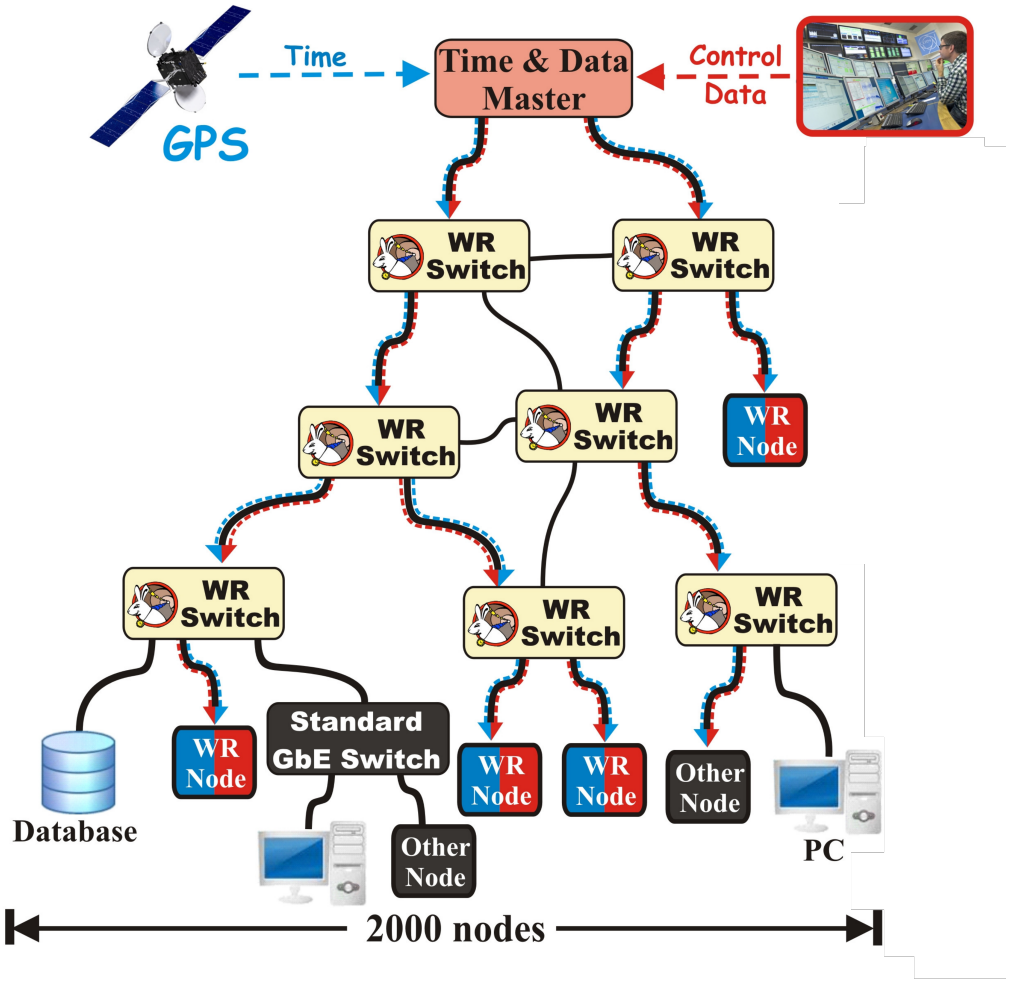
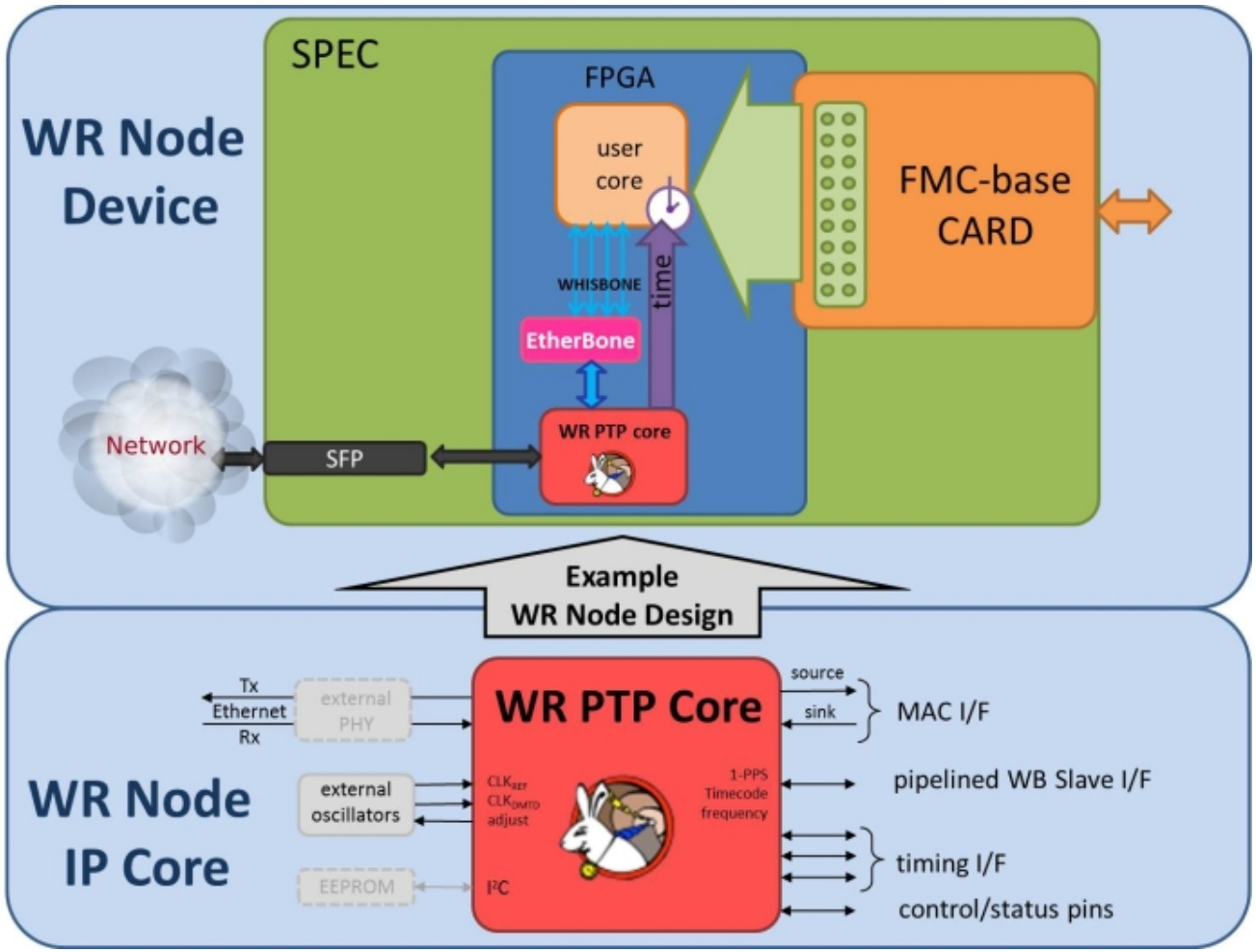
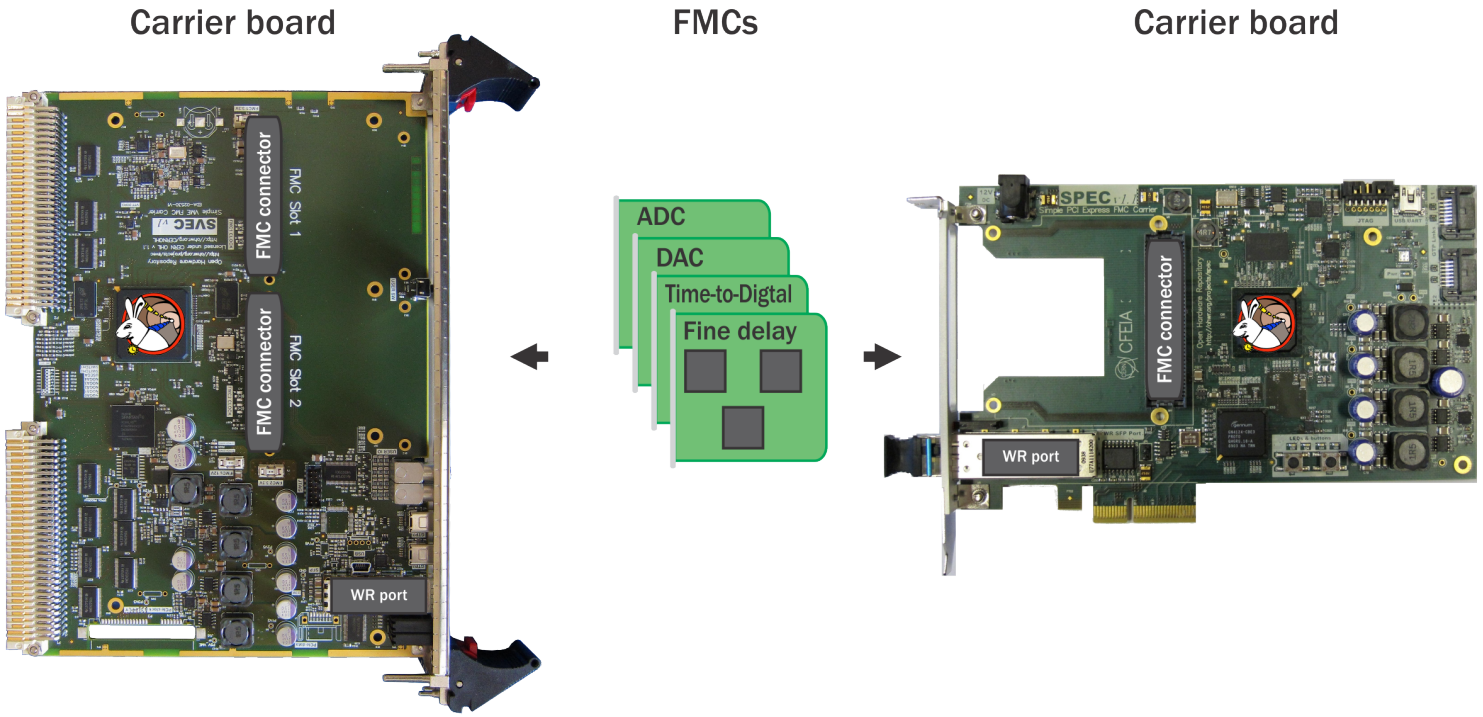


WR Node: WR PTP Core



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, ...)

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

WR Switch

Seven Sol, Spain
Creotech, Poland

OPNT, Netherlands
SyncTechnology, China

Simple VME FMC carrier (SVEC)
Janz Tec AG, Germany

Simple PCIe FMC carrier (SPEC)
Creotech, Poland
INCAA, Netherlands
Seven Solutions, Spain
ISD S.A., Greece

Compact Universal Timing Endpoint (Cute-WR-DP)
SyncTech, China

Digitizers
Struck, Germany
SP Devices, Sweden

GPS Disciplined Oscillator
Seven Solutions, Spain

ZEN TP-32 BNC
Seven Solutions, Spain

PXI module
Sundance, UK

Companies selling White Rabbit and their products:

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

NOTE: Not all WR equipment is open source

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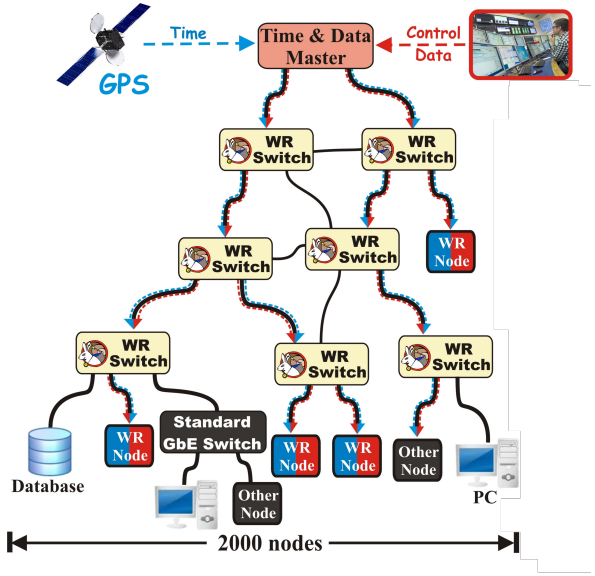
WR Calibration - why

- Ensures sub-ns accuracy between
  - The PPS output of the WR Grandmaster, and
  - The PPS outputs of the WR Devices connected (directly/indirectly) to the WR Grandmaster



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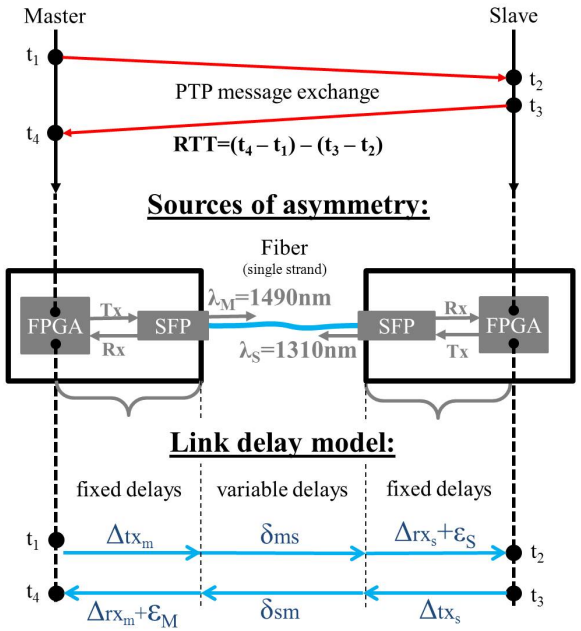

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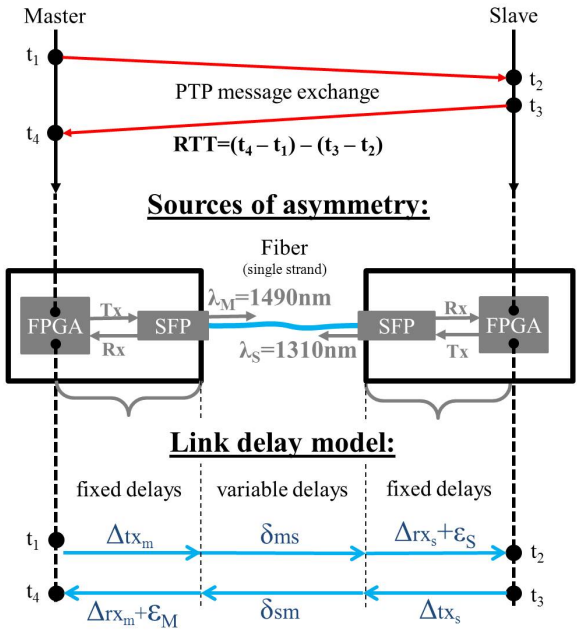
  - Each fiber type deployed



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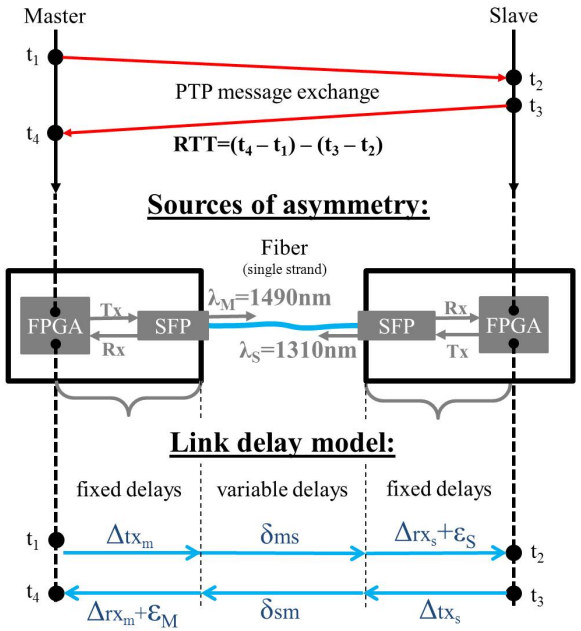

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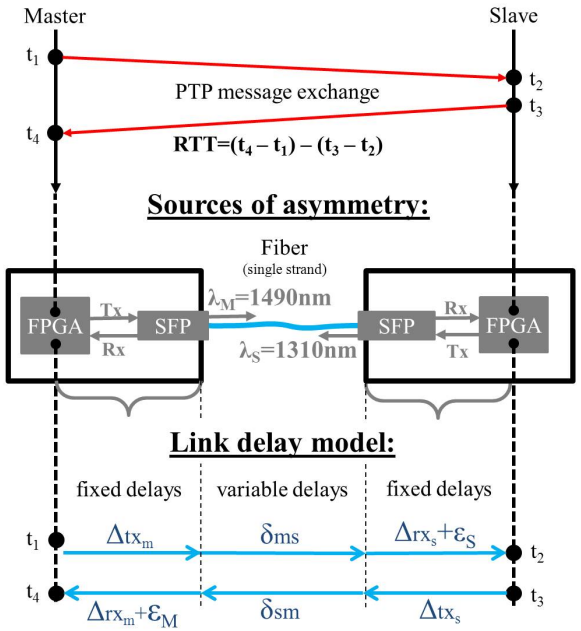
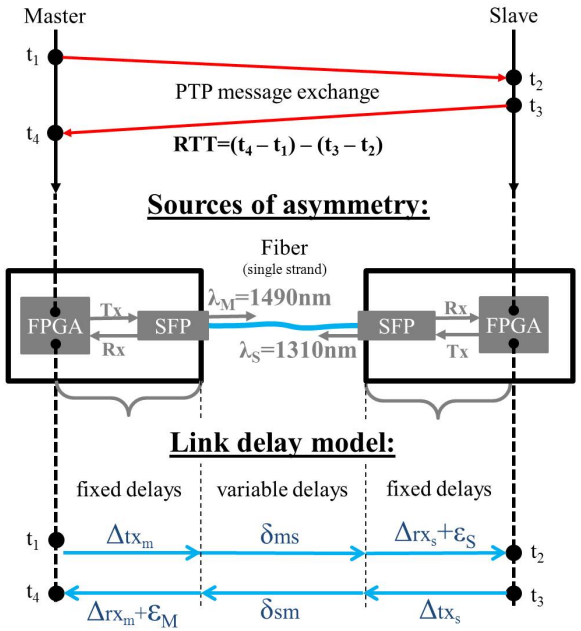


WR Calibration - why

- Ensures sub-ns accuracy between
  - The PPS output of the WR Grandmaster, and
  - The PPS outputs of the WR Devices connected (directly/indirectly) to the WR Grandmaster
- Determines the value of
  - Ingress/Egress latency (fixed delays)
  - Relative delay coefficient for fiber type used (α)
- Must be performed for
  - Each WR device type, its port, SFP type, release

    Note: can be performed for each device/SFP instance to increase accuracy
  - Each fiber type deployed
- Described in WR Calibration procedure v1.1
- Calibration values provided for
  - WR Switch releases
  - WR Node releases (reference designs)
- Useful
  - Which SFP and fibre type to use for WR
  - Calibration



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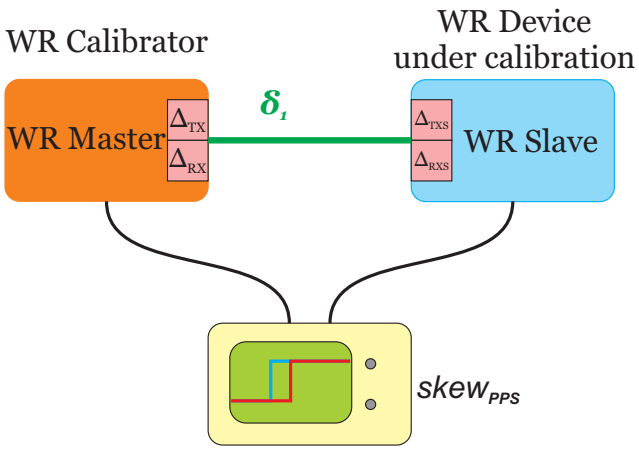

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- In-lab procedure, requires
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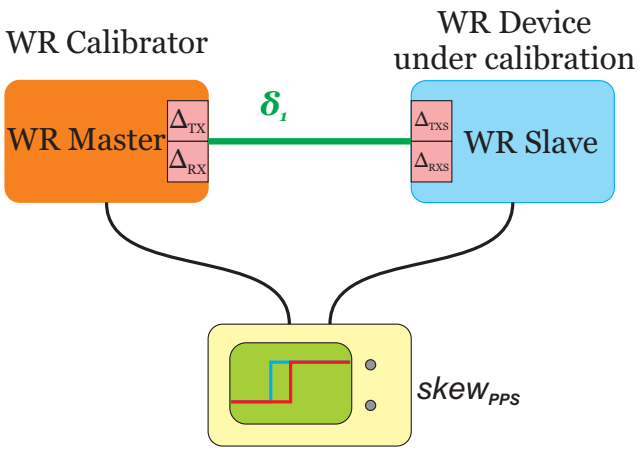

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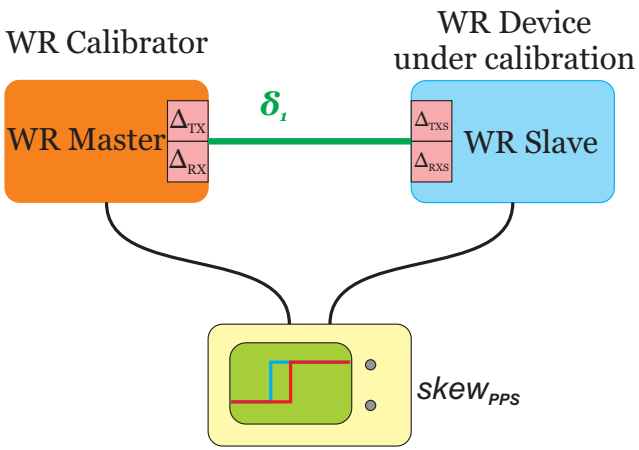

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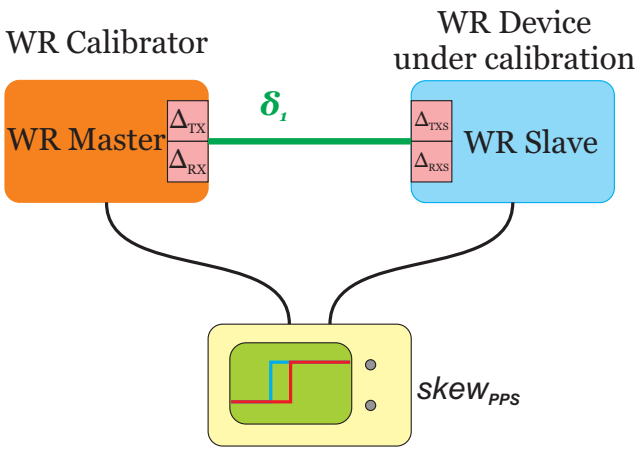

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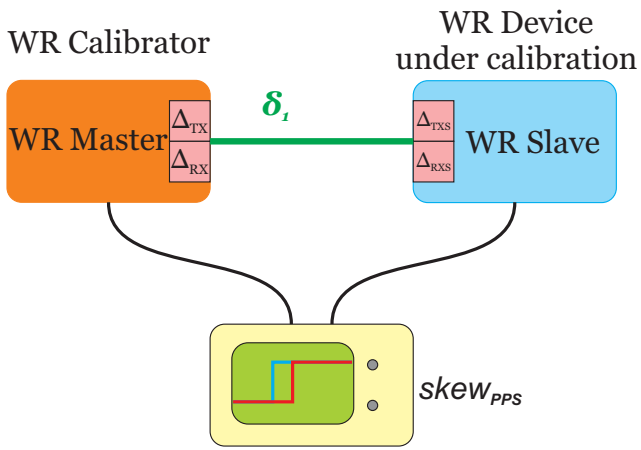
- In-situ calibration of relative delay coefficient
  - Experimental: Insitu determination of alpha
  - Active standardization: 1588f project



Outline

Management of WR networks

- White Rabbit is an extension of Ethernet

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- White Rabbit is an extension of Ethernet
- It implements standard protocols and tools (*):
  - Simple Network Management Protocol (SNMP)
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- **WR Switch configuration:**
  - Recommended for large networks: download dot-config (*) file from server

```
#
# Automatically generated file; DO NOT EDIT.
# White Rabbit Switch  configuration
#
CONFIG_DOTCONF_FW_VERSION="6.0.1"
CONFIG_DOTCONF_HW_VERSION="3.4"
CONFIG_DOTCONF_INFO="gen_time=2022-05-06+14:14:45;gen_user=mlipinsk;md5sum=7eaaebed213b48a9c813b96170c5bfbc;"
# CONFIG_DOTCONF_SOURCE_LOCAL is not set
# CONFIG_DOTCONF_SOURCE_REMOTE is not set
CONFIG_DOTCONF_SOURCE_FORCE_DHCP=y
# CONFIG_DOTCONF_SOURCE_TRY_DHCP is not set
# CONFIG_LEAPSEC_SOURCE_LOCAL is not set
# CONFIG_LEAPSEC_SOURCE_REMOTE_FORCE is not set
CONFIG_LEAPSEC_SOURCE_REMOTE_TRY=y
CONFIG_LEAPSEC_URL="tftp://BOOTSERVER/white_rabbit/leap-seconds.list"
CONFIG_BR2_CONFIGFILE="wrs_release_br2_config"
CONFIG_PPSI=y

#
# Local Network Configuration
#
CONFIG_ETH0_DHCP=y
# CONFIG_ETH0_DHCP_ONCE is not set
# CONFIG_ETH0_STATIC is not set
CONFIG_HOSTNAME_DHCP=y
# CONFIG_HOSTNAME_STATIC is not set

#
# Authorization and authentication
#
# CONFIG_ROOT_ACCESS_DISABLE is not set
CONFIG_LDAP_ENABLE=y
CONFIG_LDAP_SERVER="ldap://xldap.cern.ch"
CONFIG_LDAP_SEARCH_BASE="dc=cern,dc=ch"
# CONFIG_LDAP_FILTER_NONE is not set
# CONFIG_LDAP_FILTER_EGROUP is not set
CONFIG_LDAP_FILTER_CUSTOM=y
CONFIG_LDAP_FILTER_CUSTOM_STR="(memberOf=CN=white-rabbit-switch-root,OU=e-groups,OU=Workgroups,DC=cern,DC=ch)"
# CONFIG_AUTH_LDAP is not set
CONFIG_AUTH_KRB5=y
CONFIG_AUTH_KRB5_SERVER="CERN.CH"

#
# Root Password
#
CONFIG_ROOT_PWD_IS_ENCRYPTED=y
CONFIG_ROOT_PWD_CYPHER="$1$YSMM6Ch4$qlAct1hjJNtYuw3CZzY0M1"
CONFIG_NTP_SERVER="ip-time-1.cern.ch"
CONFIG_DNS_SERVER=""
CONFIG_DNS_DOMAIN=""
CONFIG_LOCAL_SYSLOG_FILE="/tmp/syslog"
CONFIG_REMOTE_SYSLOG_SERVER="cs-ccr-testbed4"
CONFIG_REMOTE_SYSLOG_UDP=y
CONFIG_WRS_LOG_HAL="daemon.info"
CONFIG_WRS_LOG_LEVEL_HAL="6"
CONFIG_WRS_LOG_RTU="daemon.info"
CONFIG_WRS_LOG_LEVEL_RTU="6"
CONFIG_WRS_LOG_PTP="daemon.info"
CONFIG_WRS_LOG_LEVEL_PTP=""
CONFIG_WRS_LOG_SNMPD="5wd"
CONFIG_WRS_LOG_MONIT="syslog"
- dot-config 1/5066 0%
```

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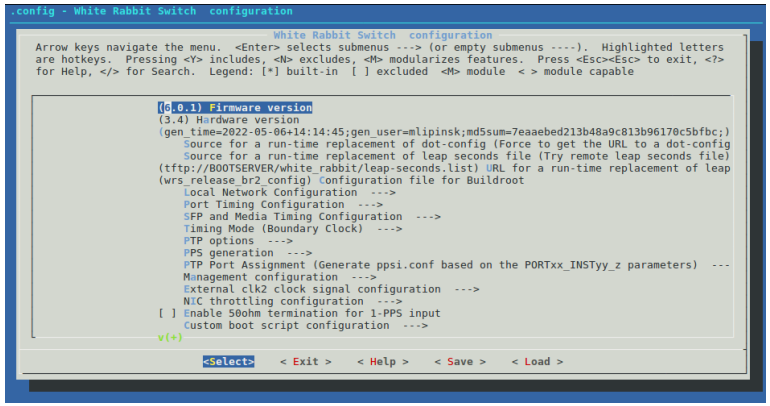

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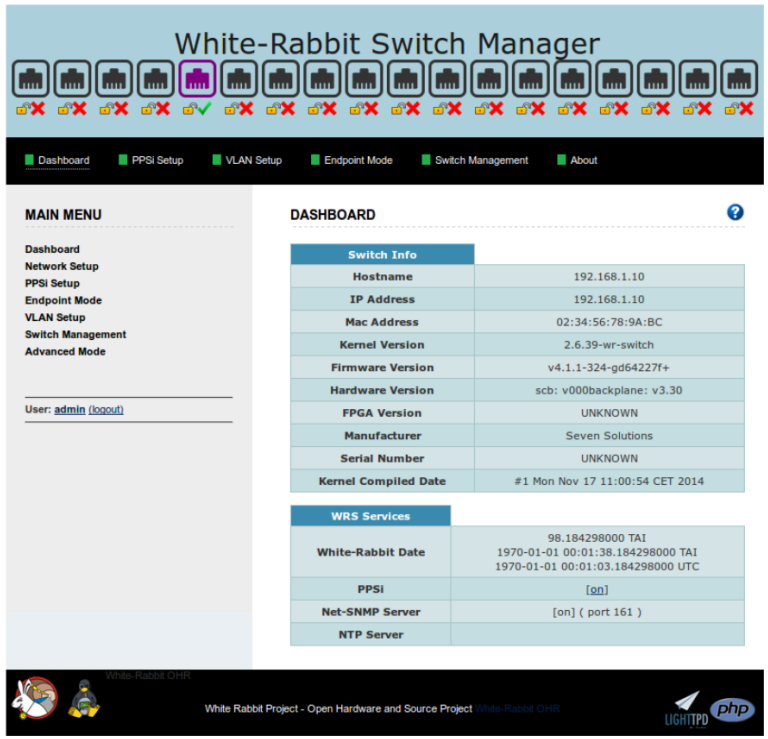

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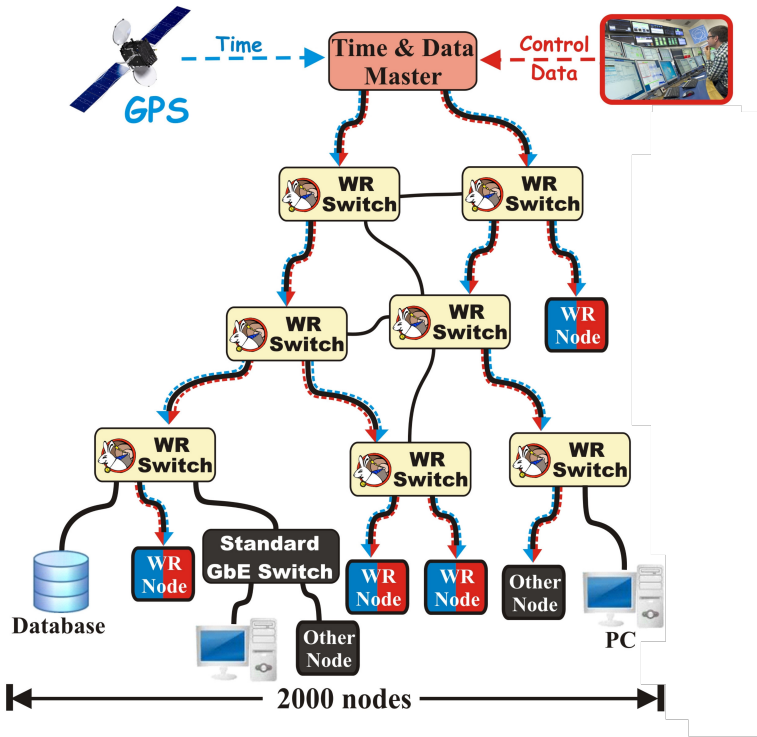
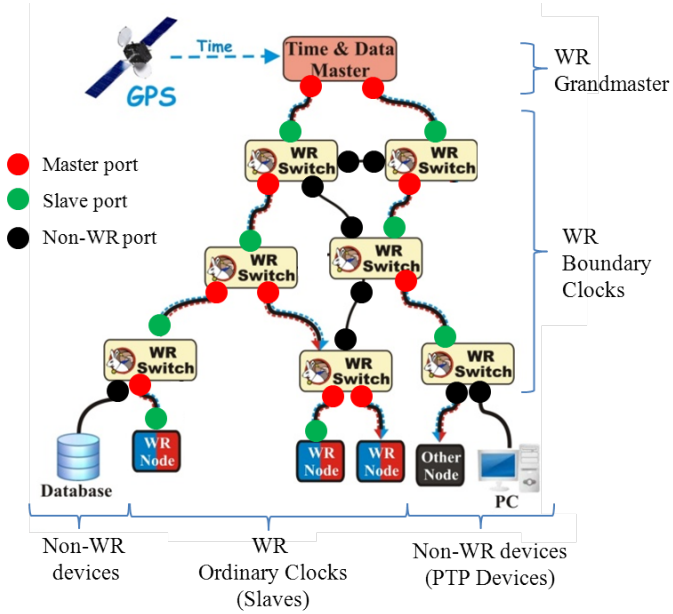
WR network configuration

- Device:
  - Management port IP
  - Enable/configure services (SNMP, Syslog, LLDP...)
- Data plane:
  - Virtual LANs (VLANs)
  - Forwarding options
  - No support for advanced protocols: (R)STP, (M)SRP
- Time plane:
  - PTP-generic
  - WR-specific



Generic time plane configuration

- Device role:
  - Grandmaster - 1 PPS & 10 MHz inputs required
    Useful: Note on using WR Switch in Grandmaster mode
  - Free-running GM - 1 PPS & 10 MHz NOT required
  - **Boundary Clock** - one of the ports is Slave



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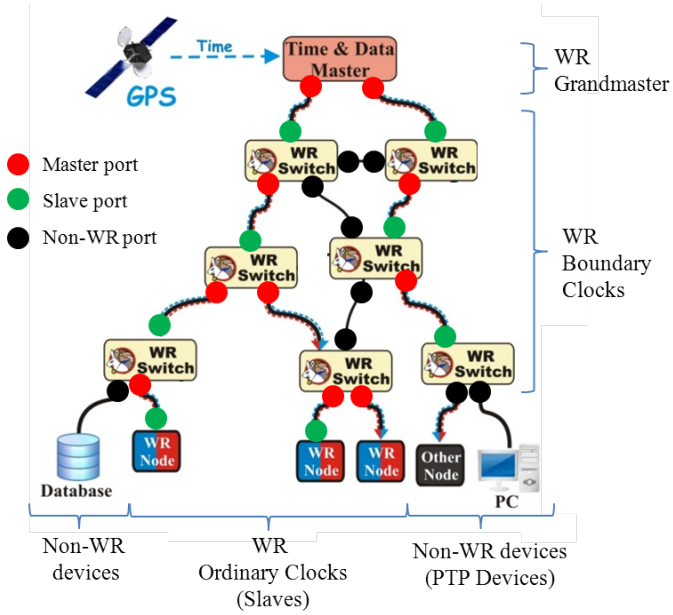

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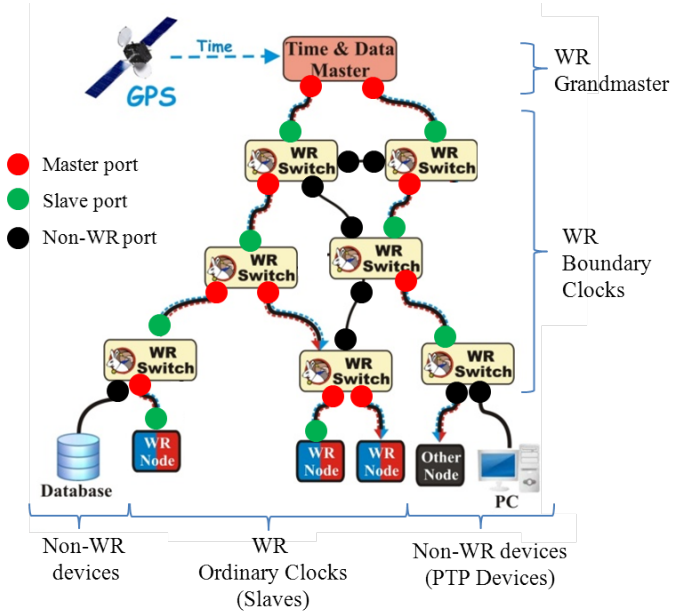

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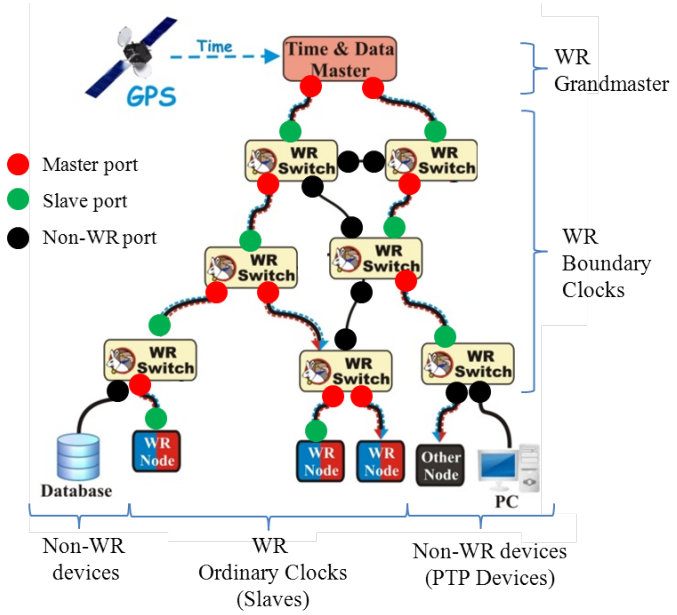
- Mapping and VLANs:
  - **IEEE802.3** - VLAN support
  - UDP/IP - no VLAN support, need IP on wriX
    Useful: Synchronizing WR master and a non-WR node using PTP



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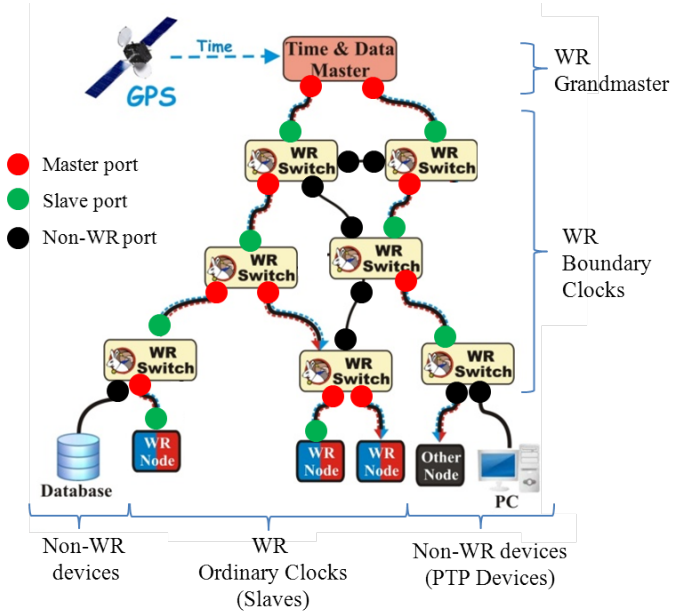
- Profile:
  - **WR** - compatible with Default PTP Profile
  - Default PTP - ”standard” PTP
  - none



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- Ingress/Egress latency (Fixed delays)
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  - Automatically chosen from database based on SFP type
  - Values available for typically used SFPs (1000BASE-BX10, single strand & mode, 1490/1310mm)
  - WR Switch
    - Calibrated out-of-the box for typical SFPs
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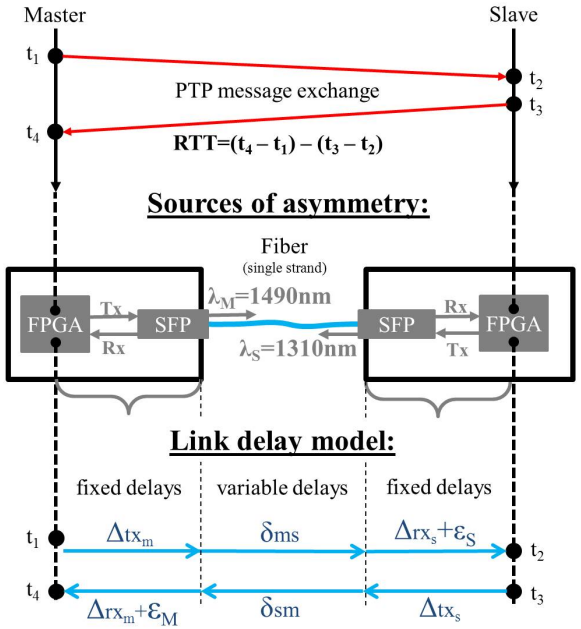
    - SFP database needs to be configured via *shell* or *snmp*



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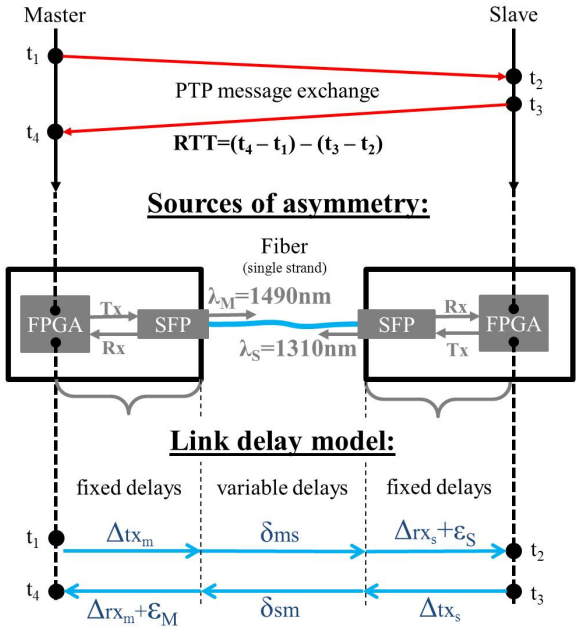

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  - WR Switch - database in *dot-config* file
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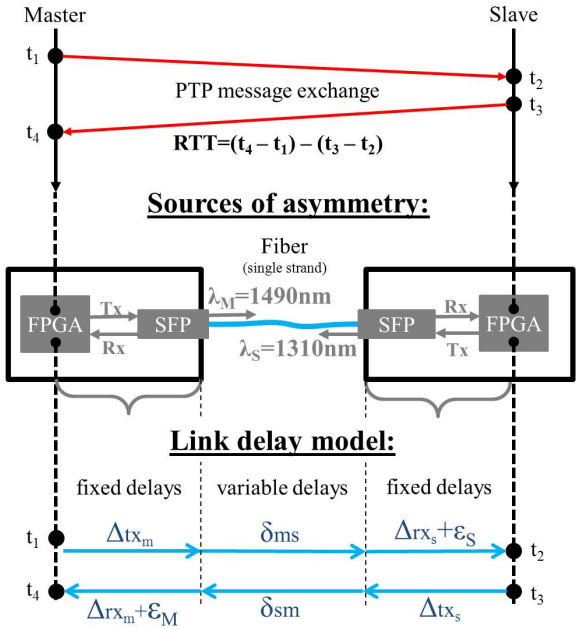
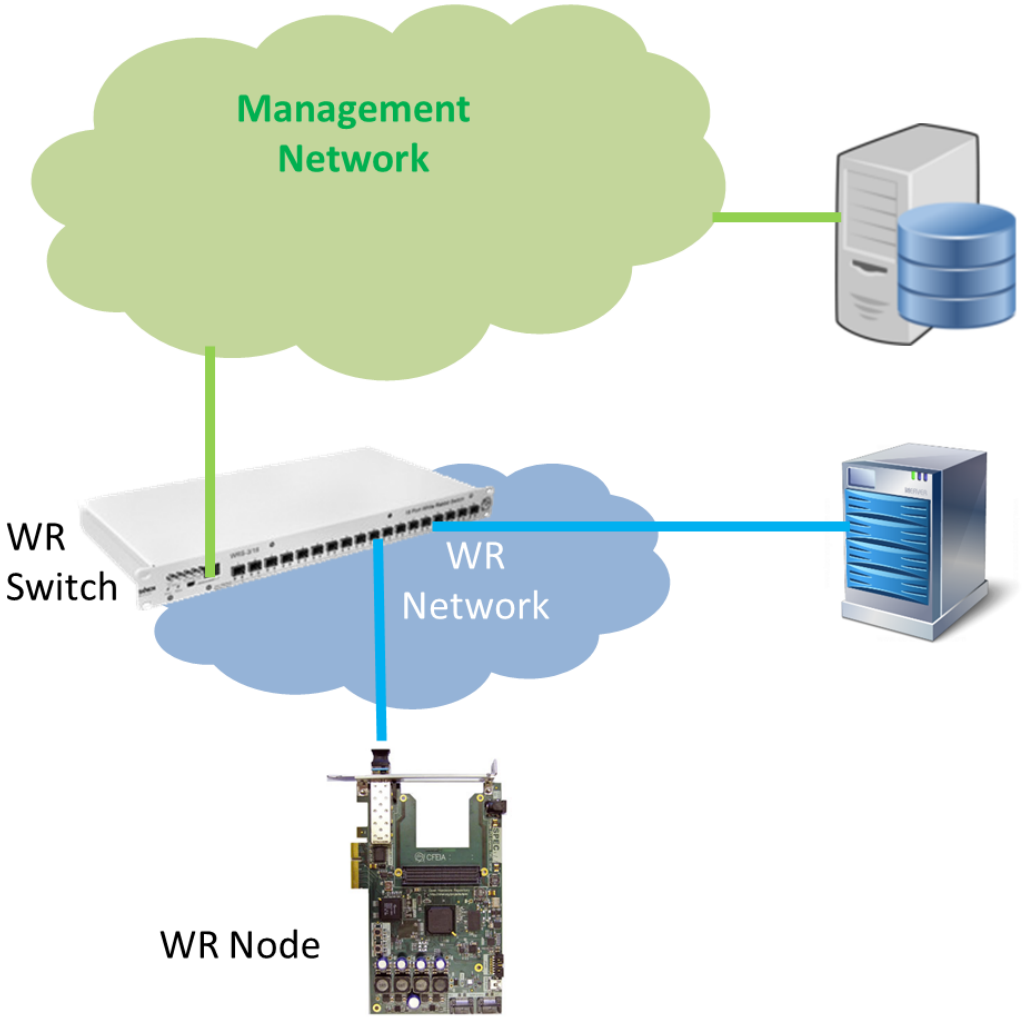
- Values for more SFPs and fiber types can be determined using WR calibration and added easily to configuration

Useful: Which SFP and fibre type to use for WR



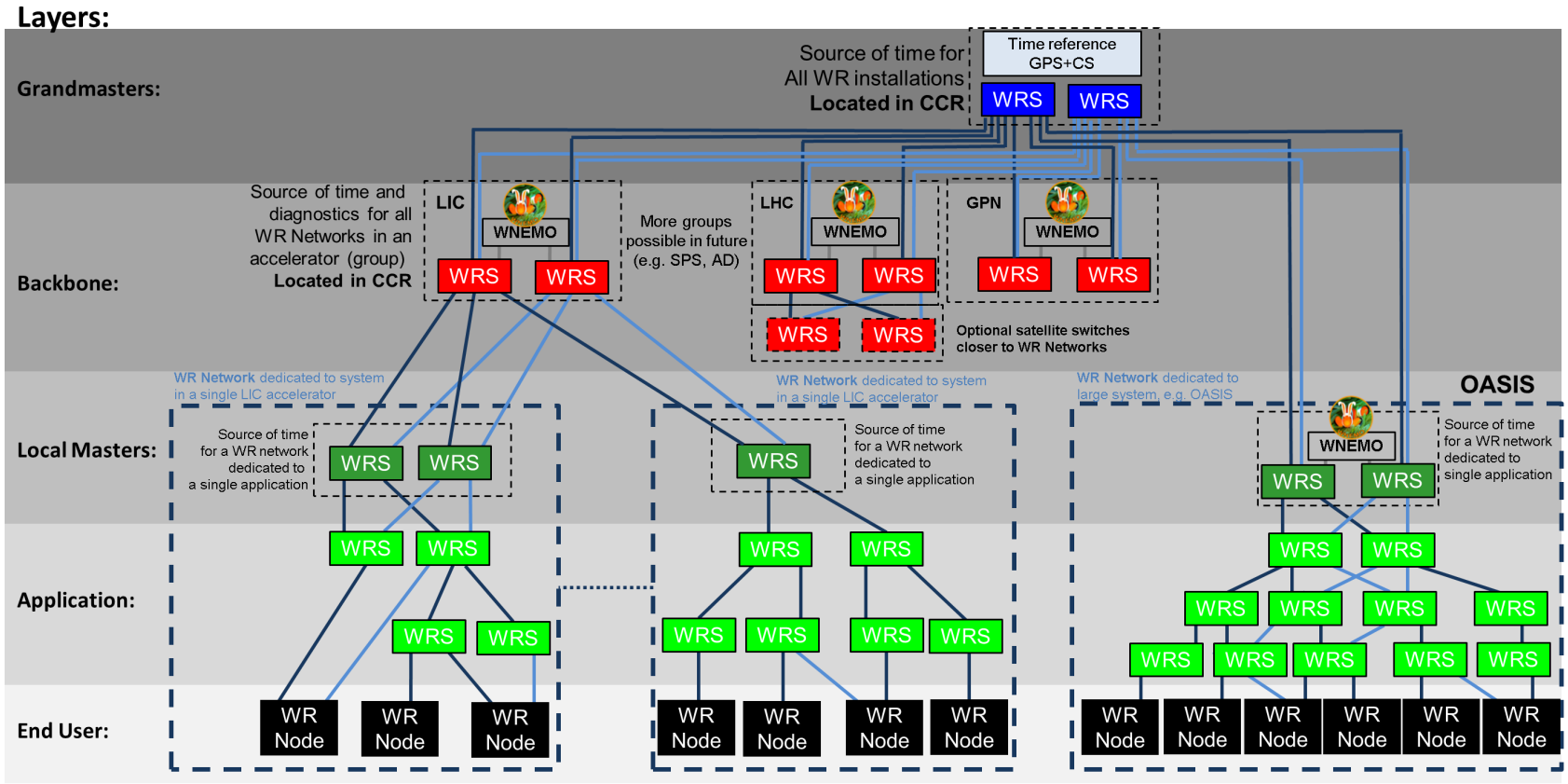
WR Network vs. Management Network



(*)

Explained in subsequent presnetation

Architecture WR network at CERN



WRS WRS WRS — WR Switch

Active fiber Ethernet link

Backup fiber Ethernet link

Copper Ethernet link

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

Thanks!

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

Backup slides

Backup slides

Outline

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)

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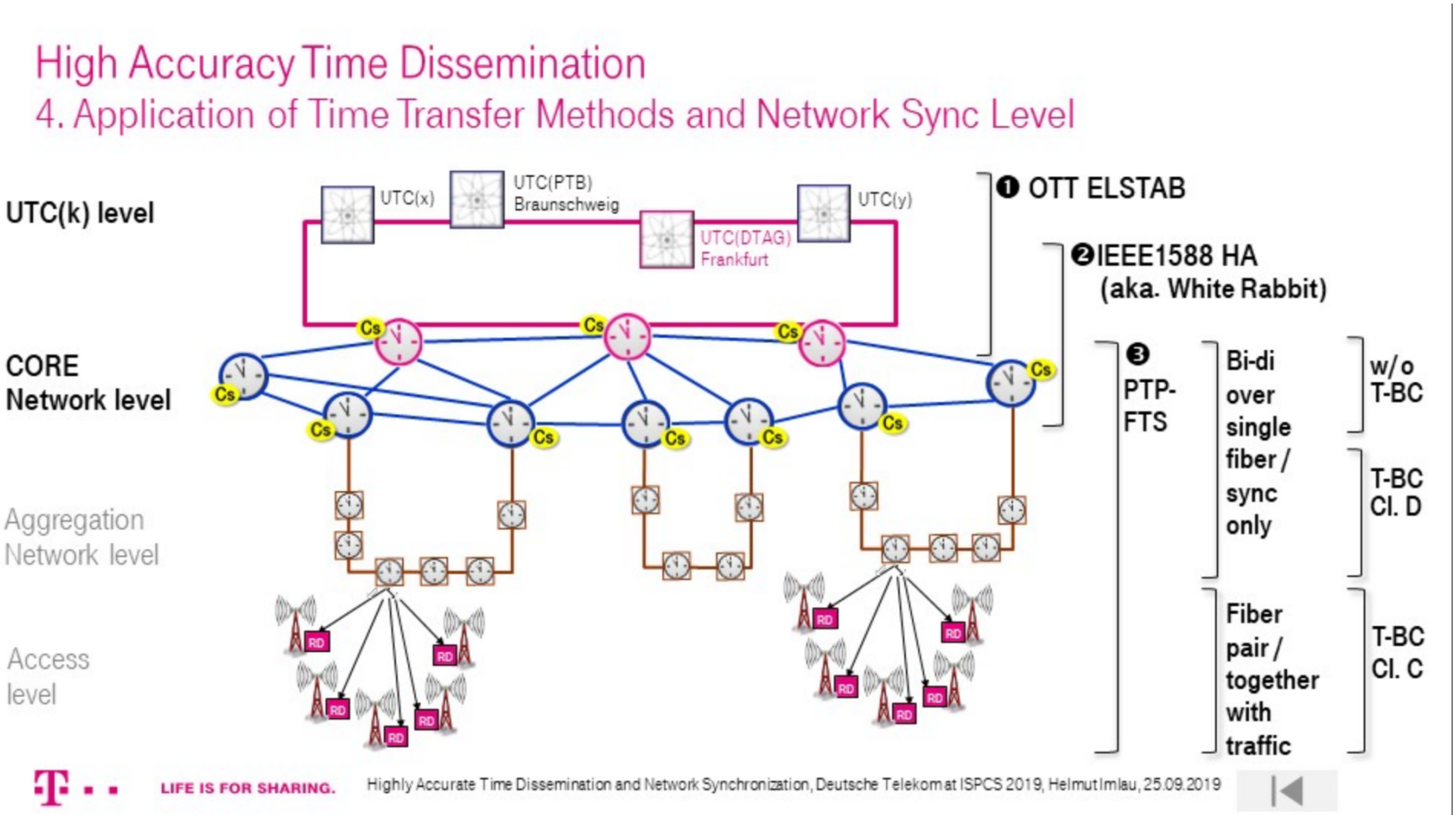
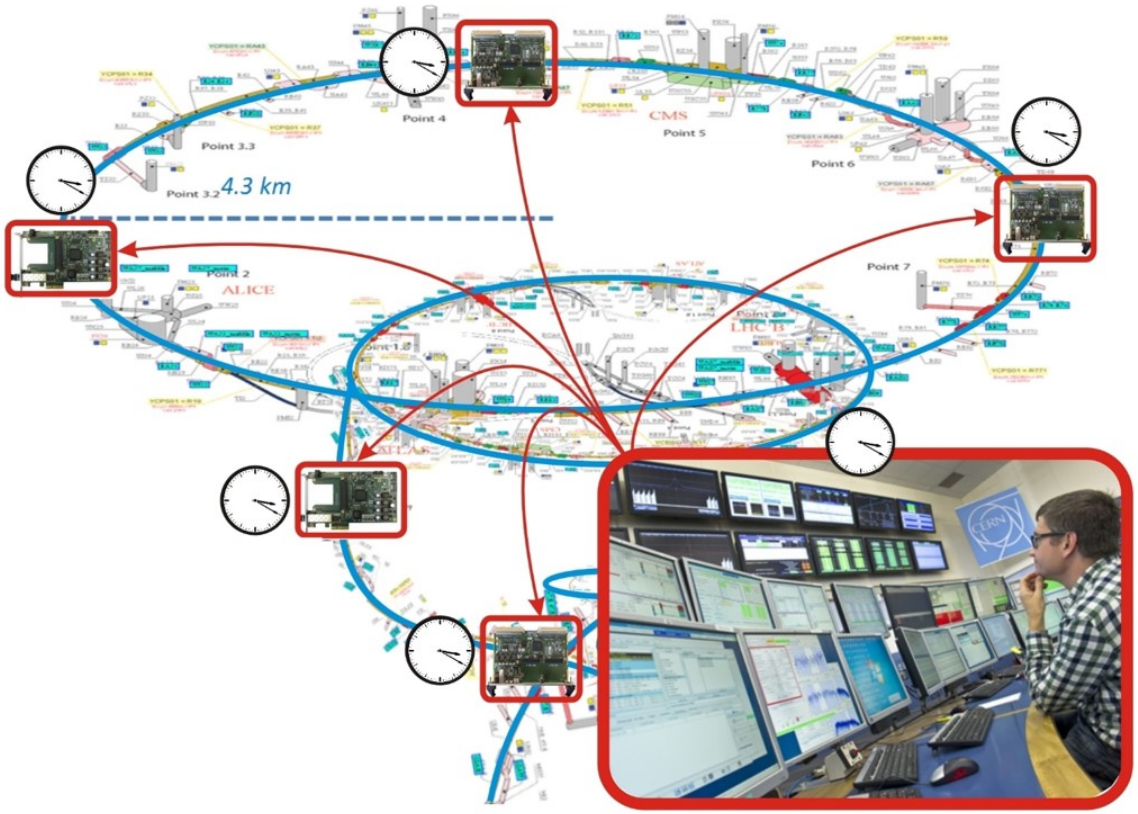


ISPCS keynote *Highly Accurate Time Dissemination & Network Synchronisation*, Helmut Imlau, Deutsche Telekom

Time-based control



Time-based control

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

Control Message (CM)

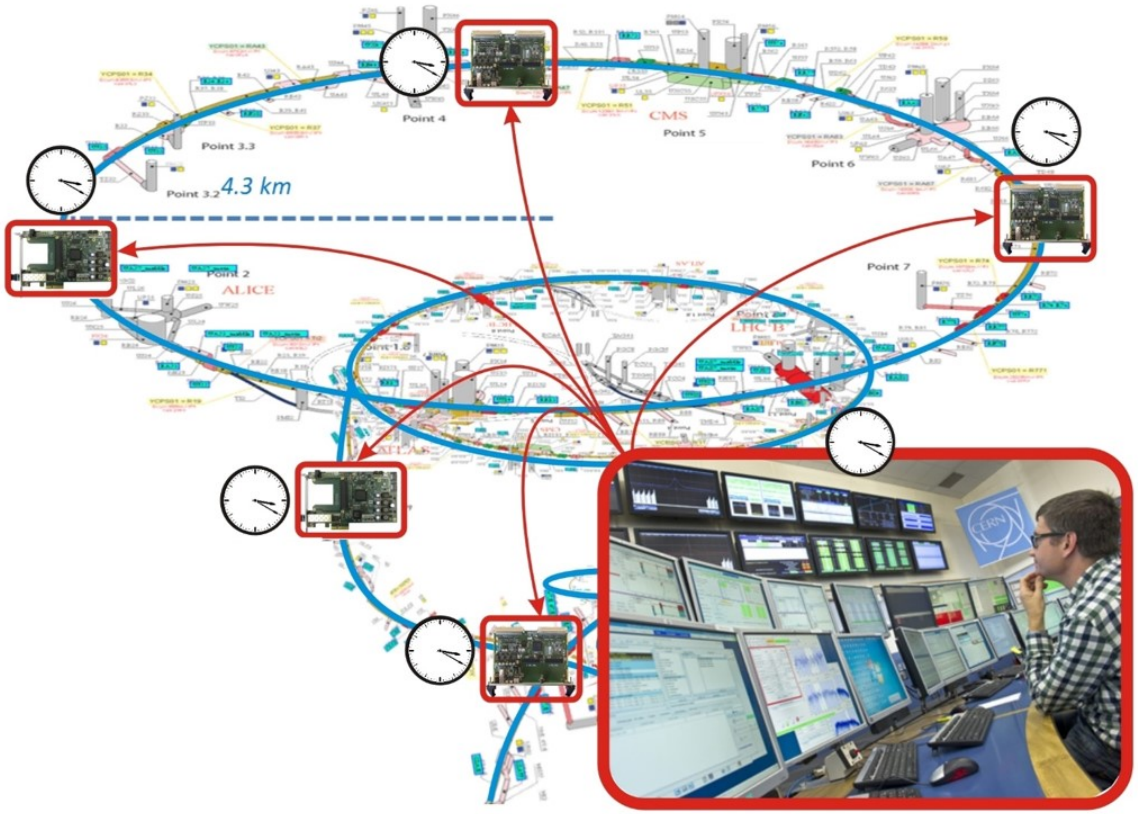
Data Master (Controller)

Magnet SPS

actuator

Magnet in PS

sensor



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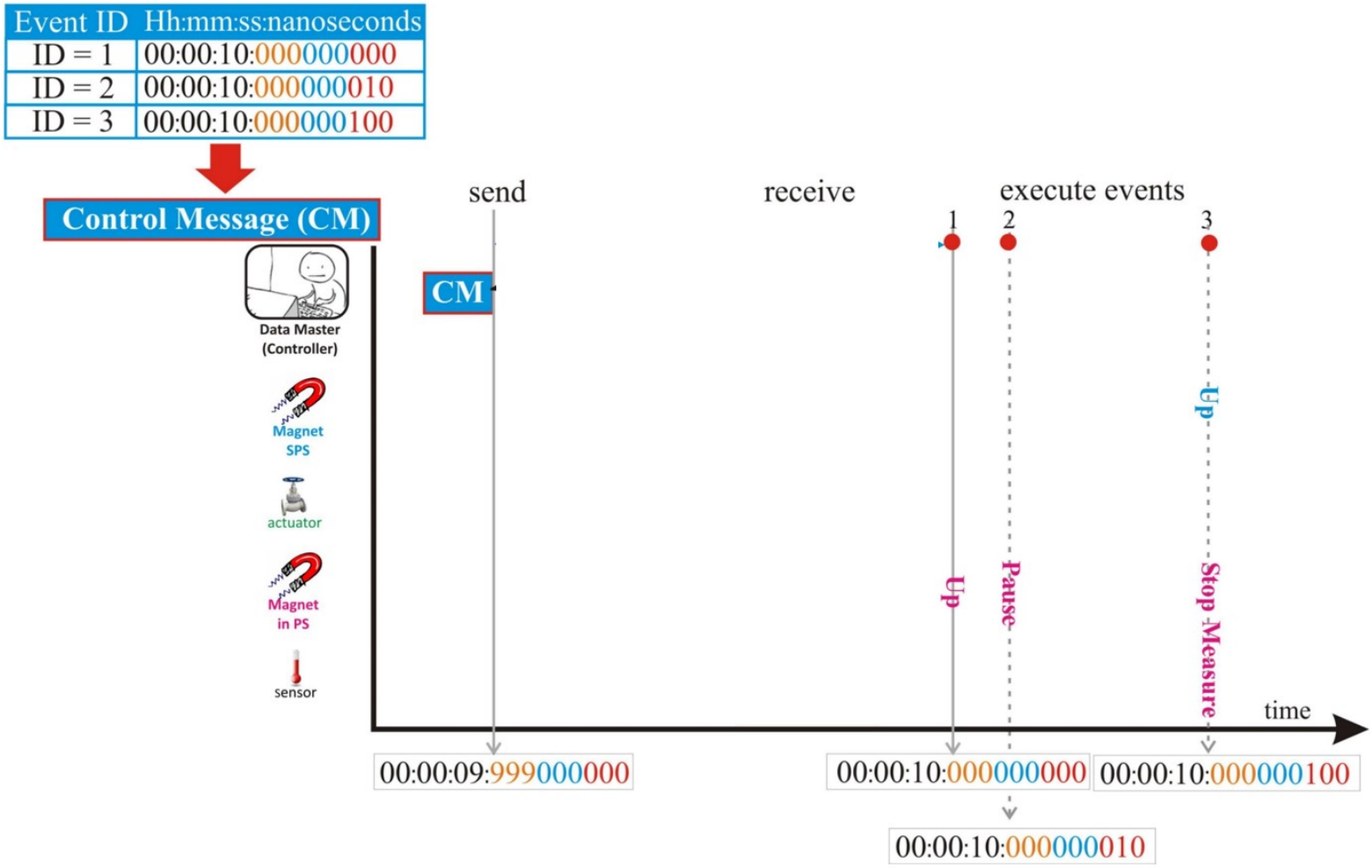

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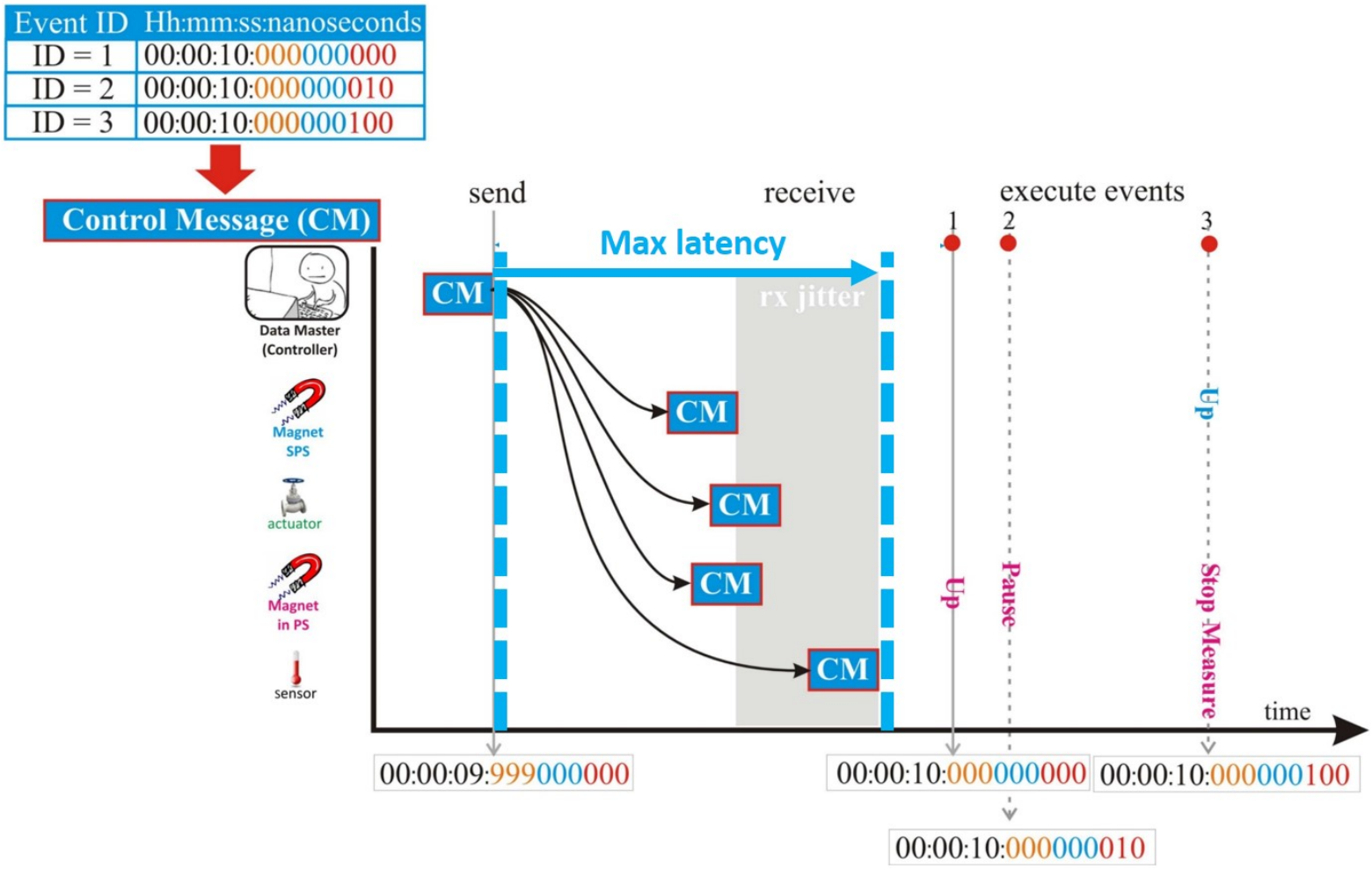
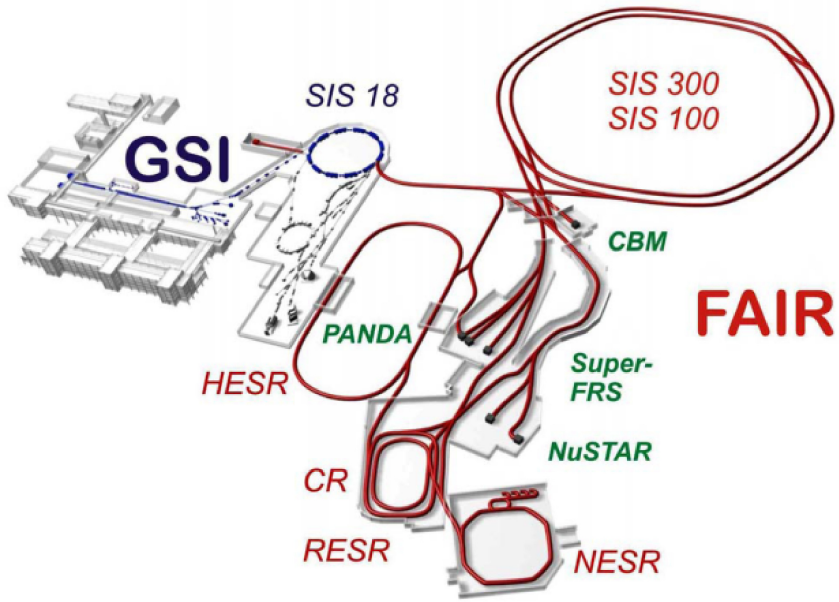


Time-based control - example application

- GSI Helmholtz Centre for Heavy Ion Research in Germany



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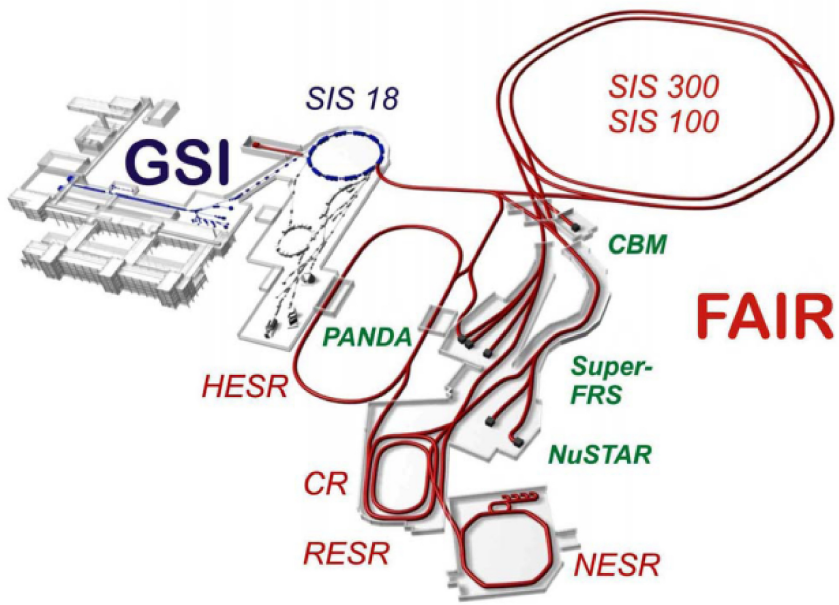
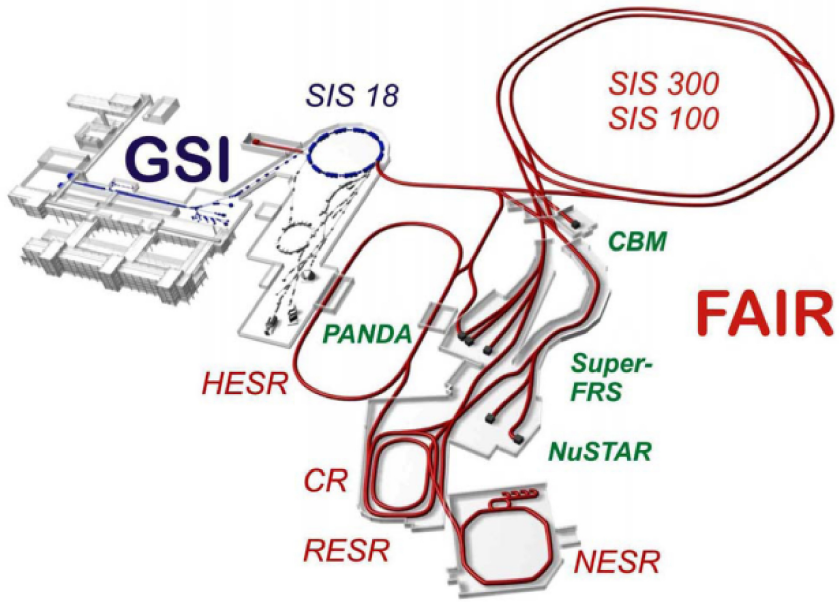


Time-based control - example application

- 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
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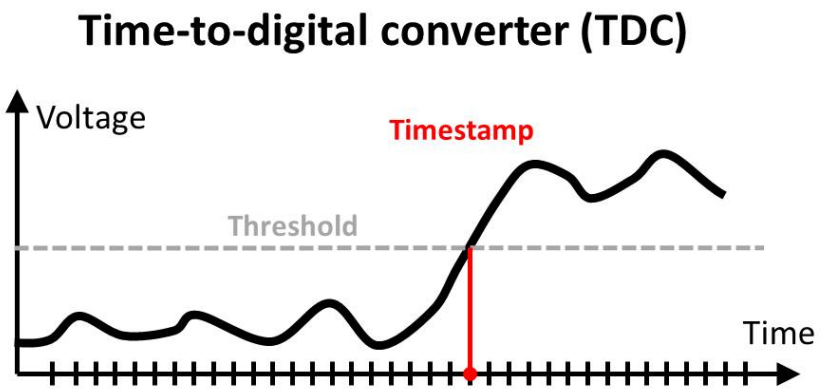
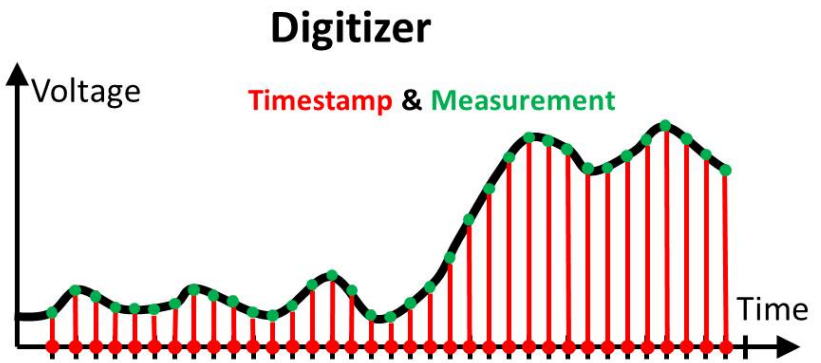
  - a sample (measured value)





Precise timestamping

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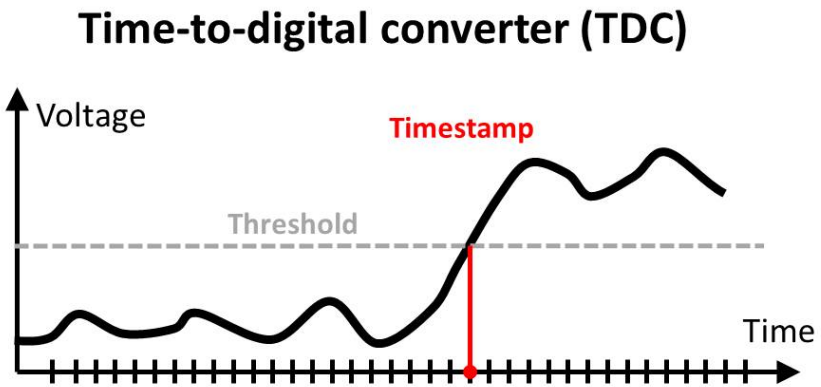
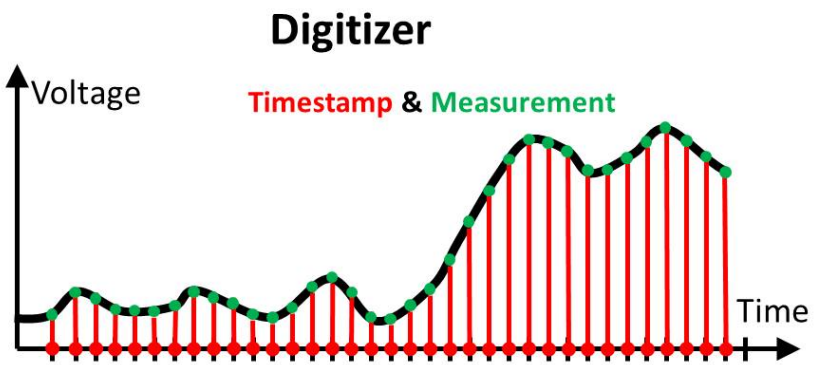
- The most widely used WR application





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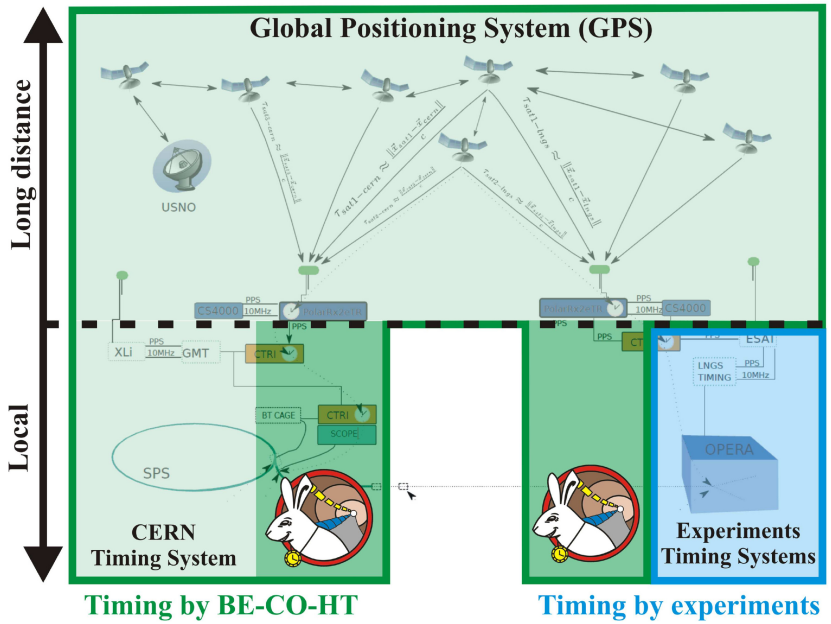
- The most widely used WR application
  - Time-of-flight measurement
    - Speed of neutrinos - CNGS



Precise timestamping

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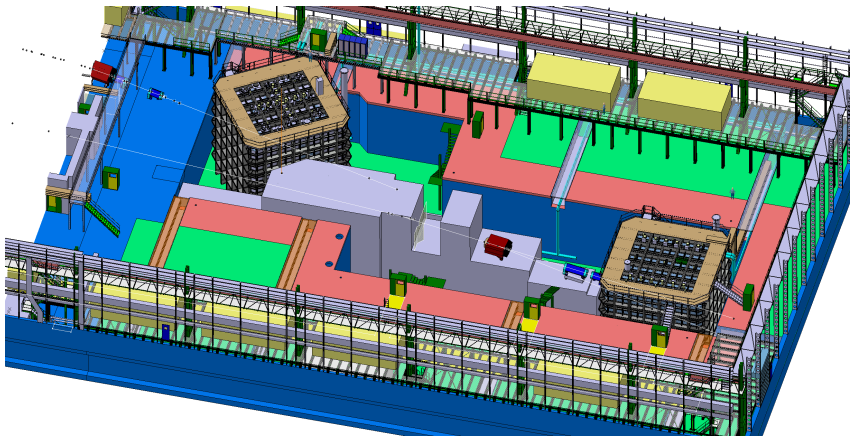

Precise timestamping

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Precise timestamping

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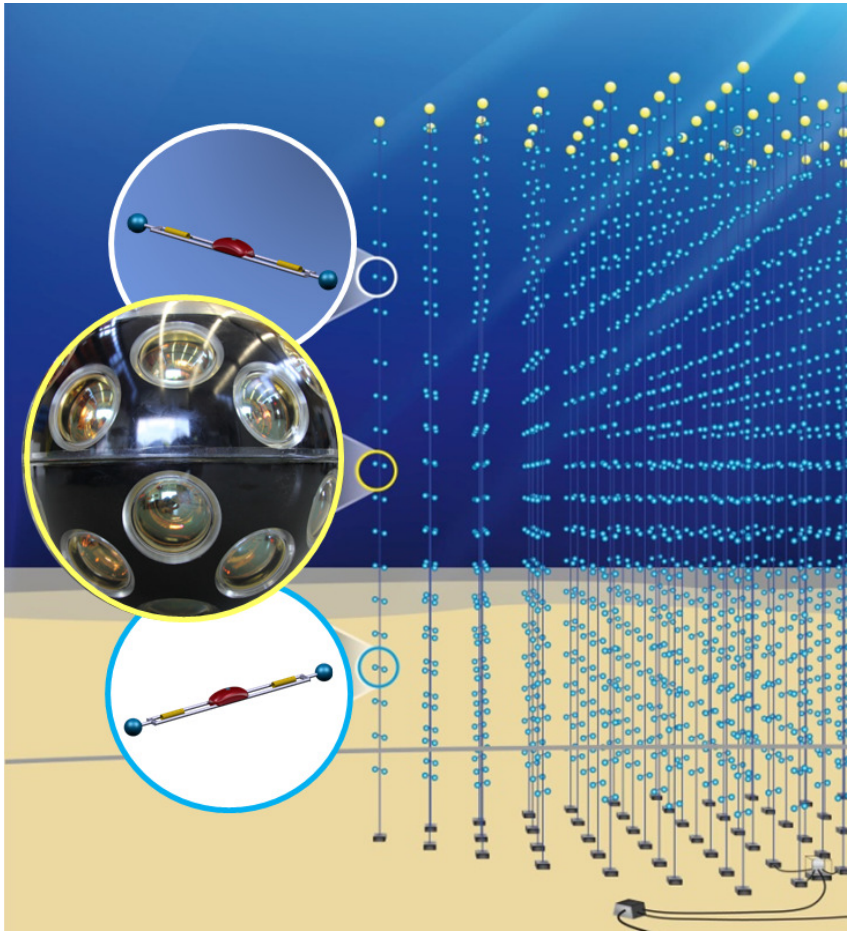

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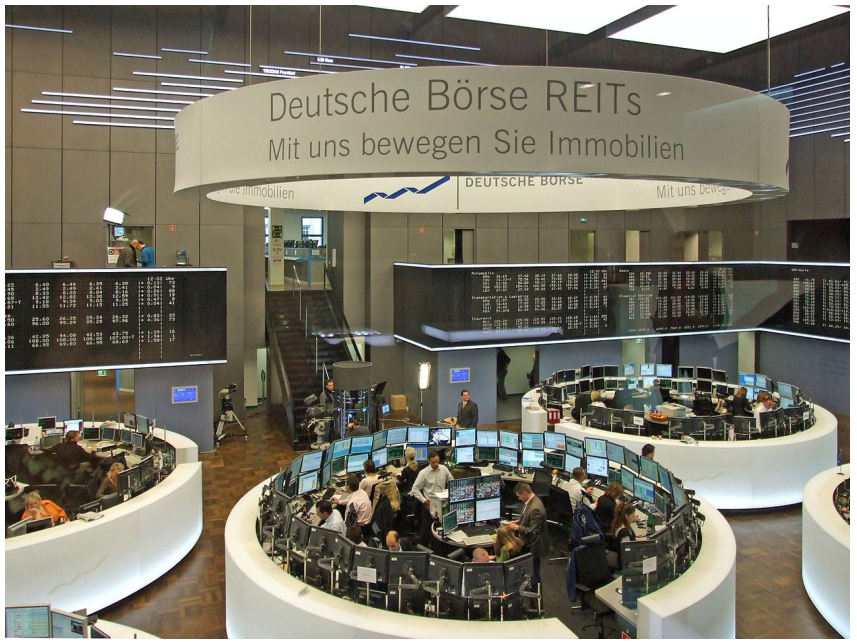
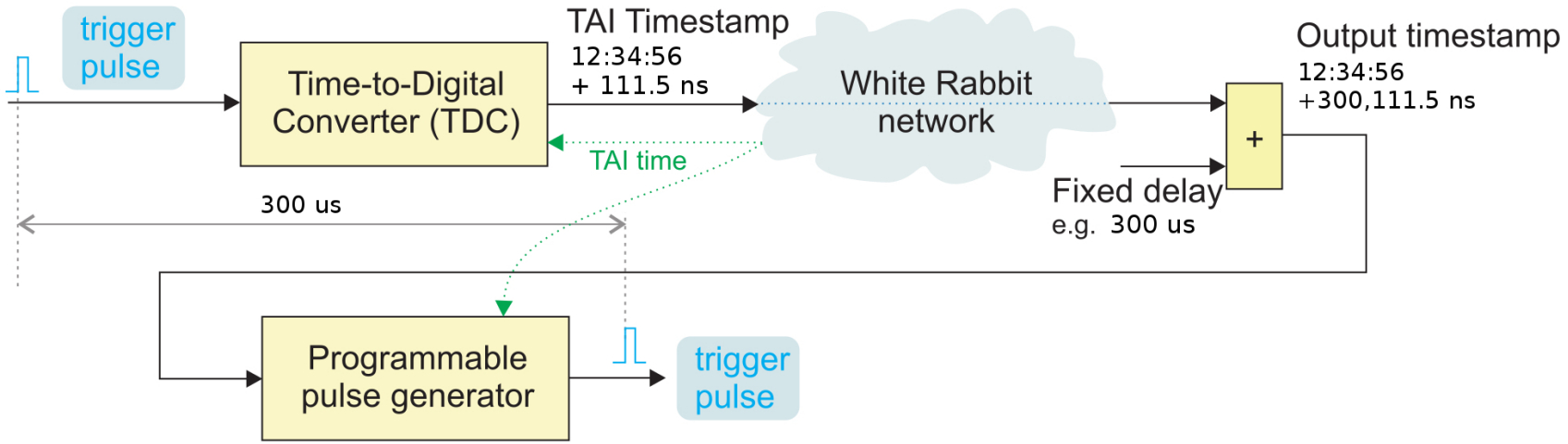
  - High Frequency Trade monitoring
    - German Stock Exchange

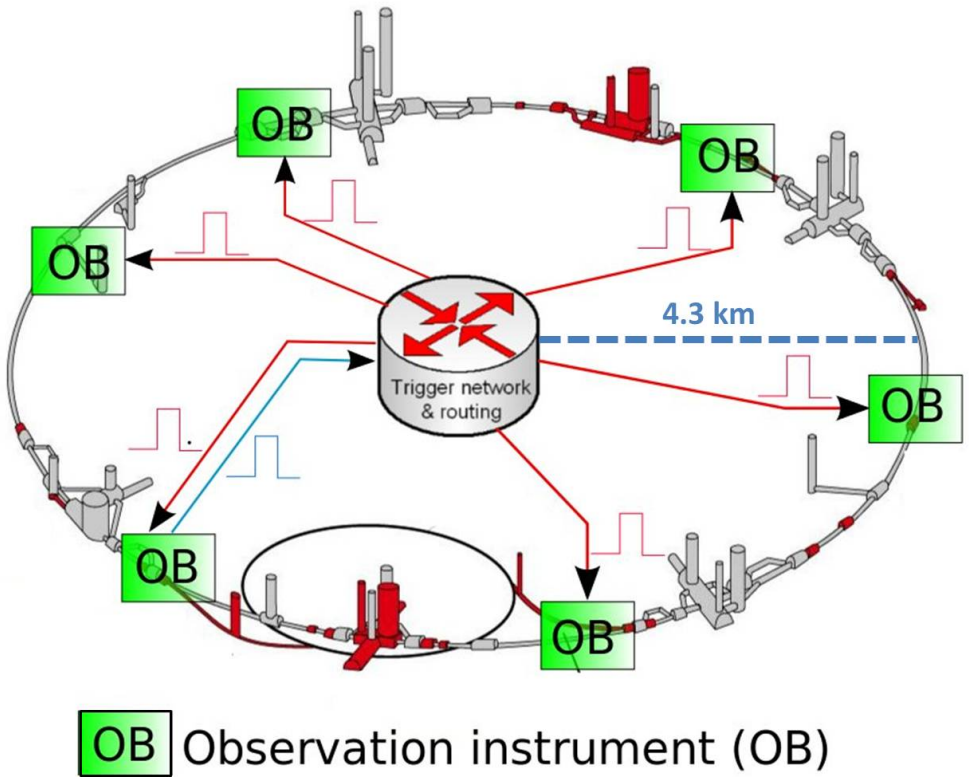


Trigger distribution



Trigger distribution - example applications

LHC trigger distribution to measure beam instabilities - since 2016



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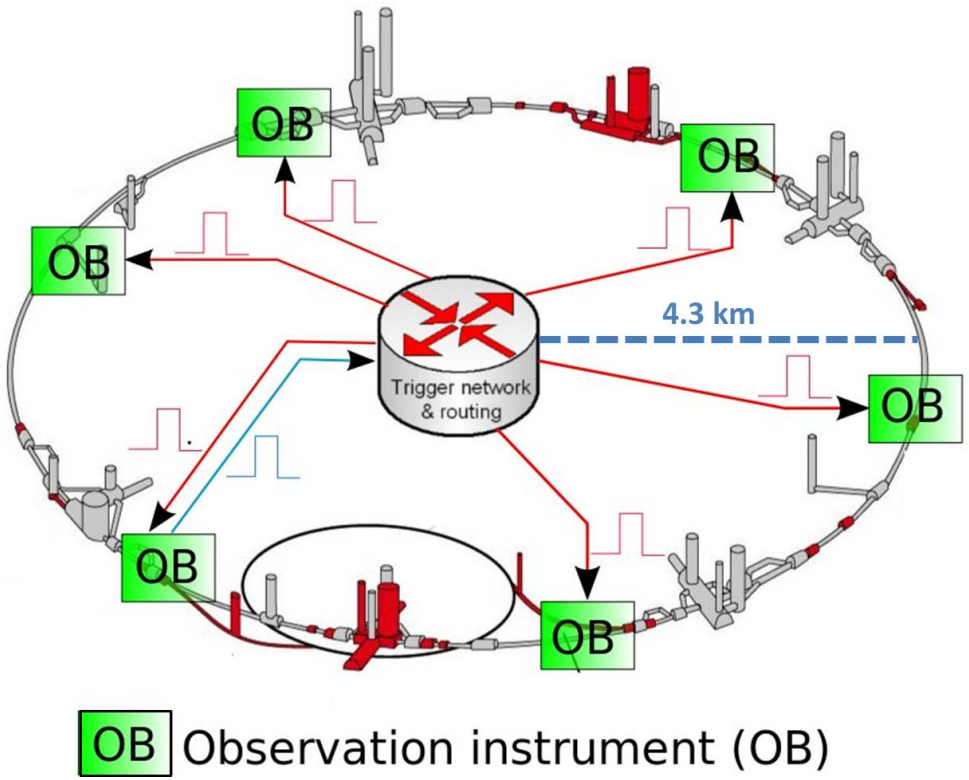
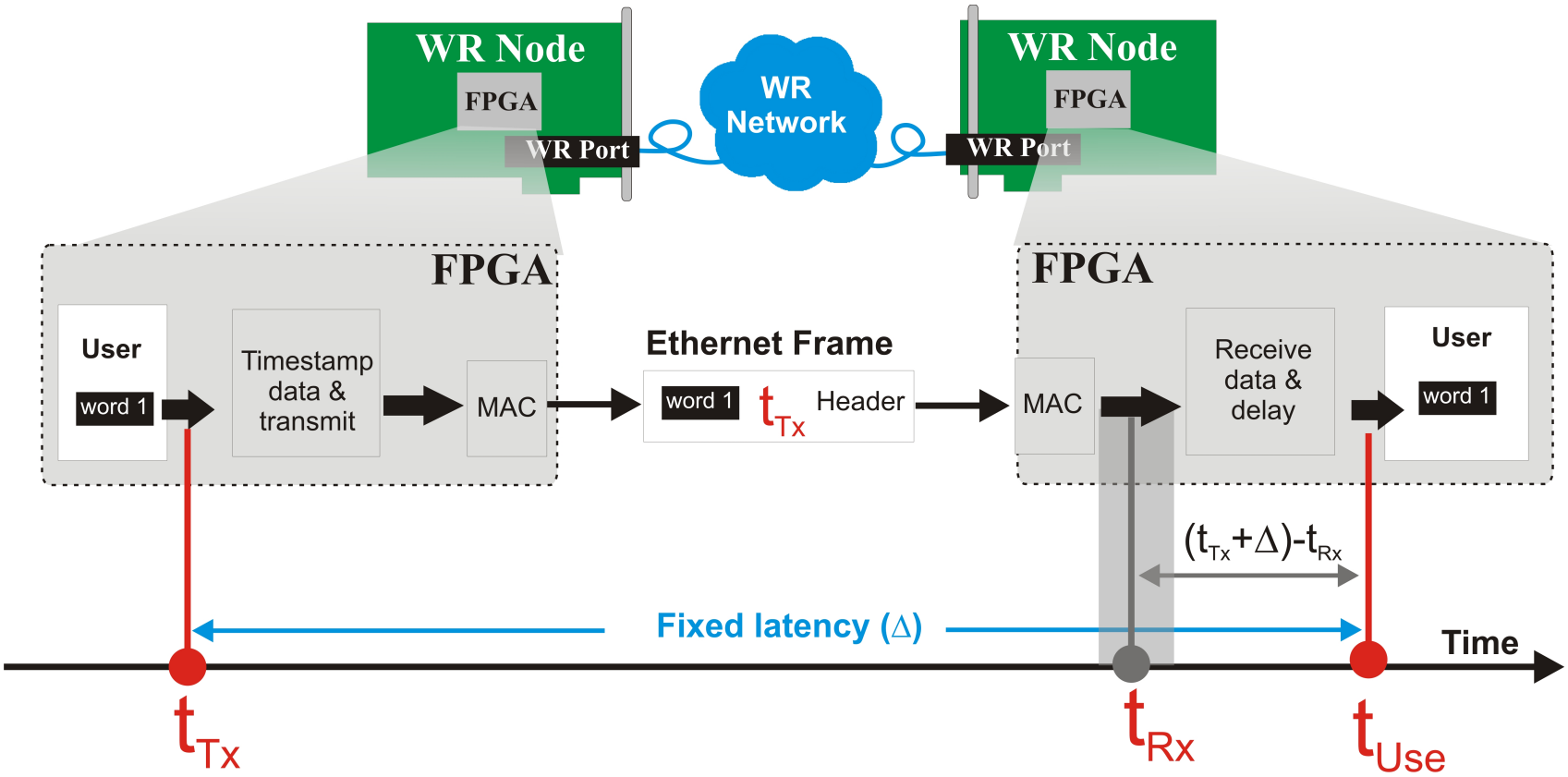


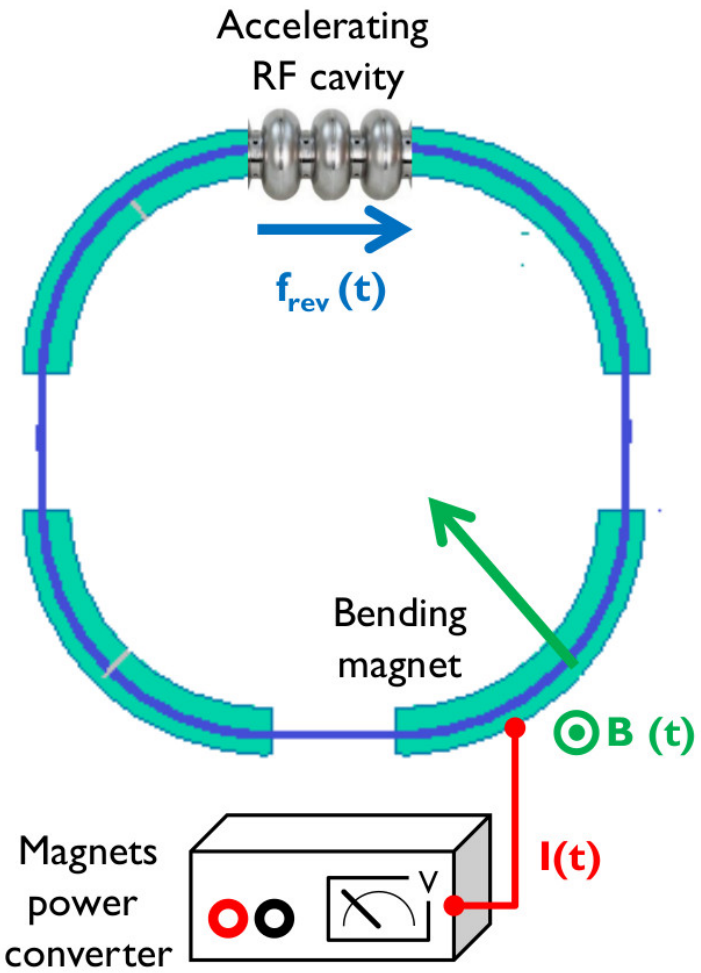
WRTD - White Rabbit Trigger Distribution- to be used for CERN's Open Analog Signals Information System (OASIS)

Fixed-latency data transfer

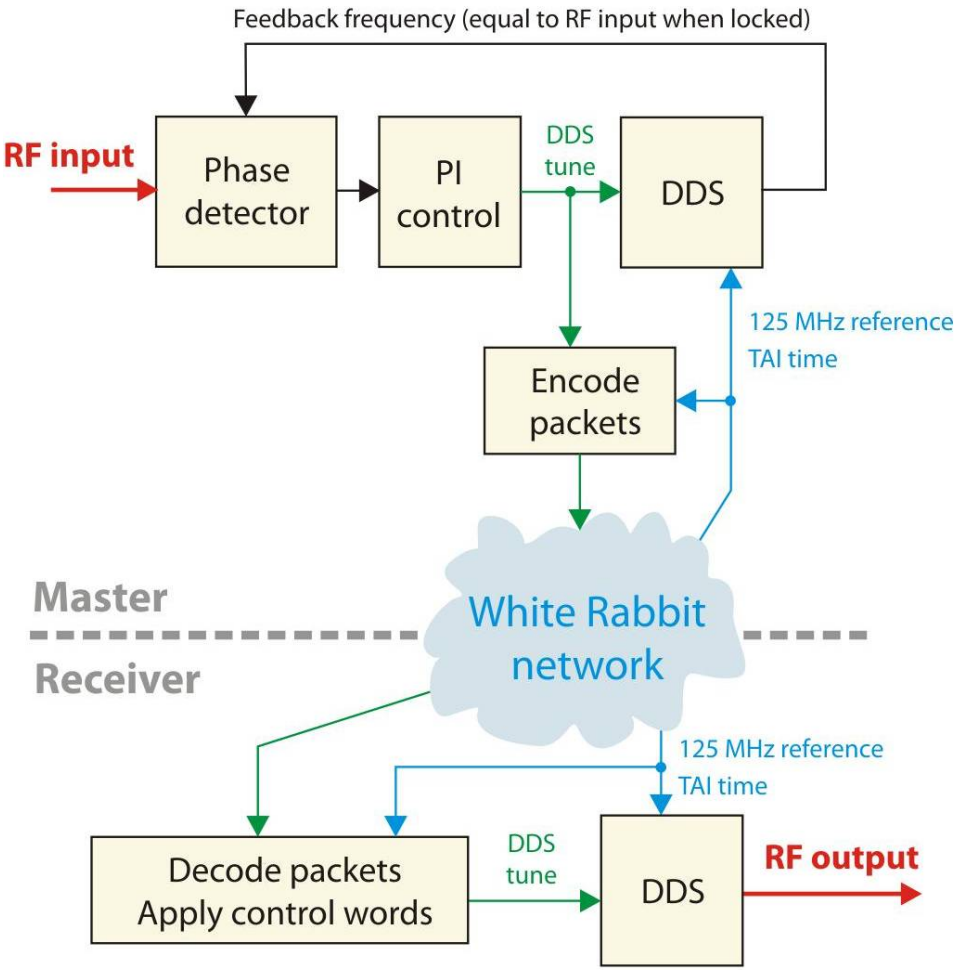


Fixed-latency data transfer- example application

Distribution of magnetic field in CERN accelerators



Radio-frequency transfer



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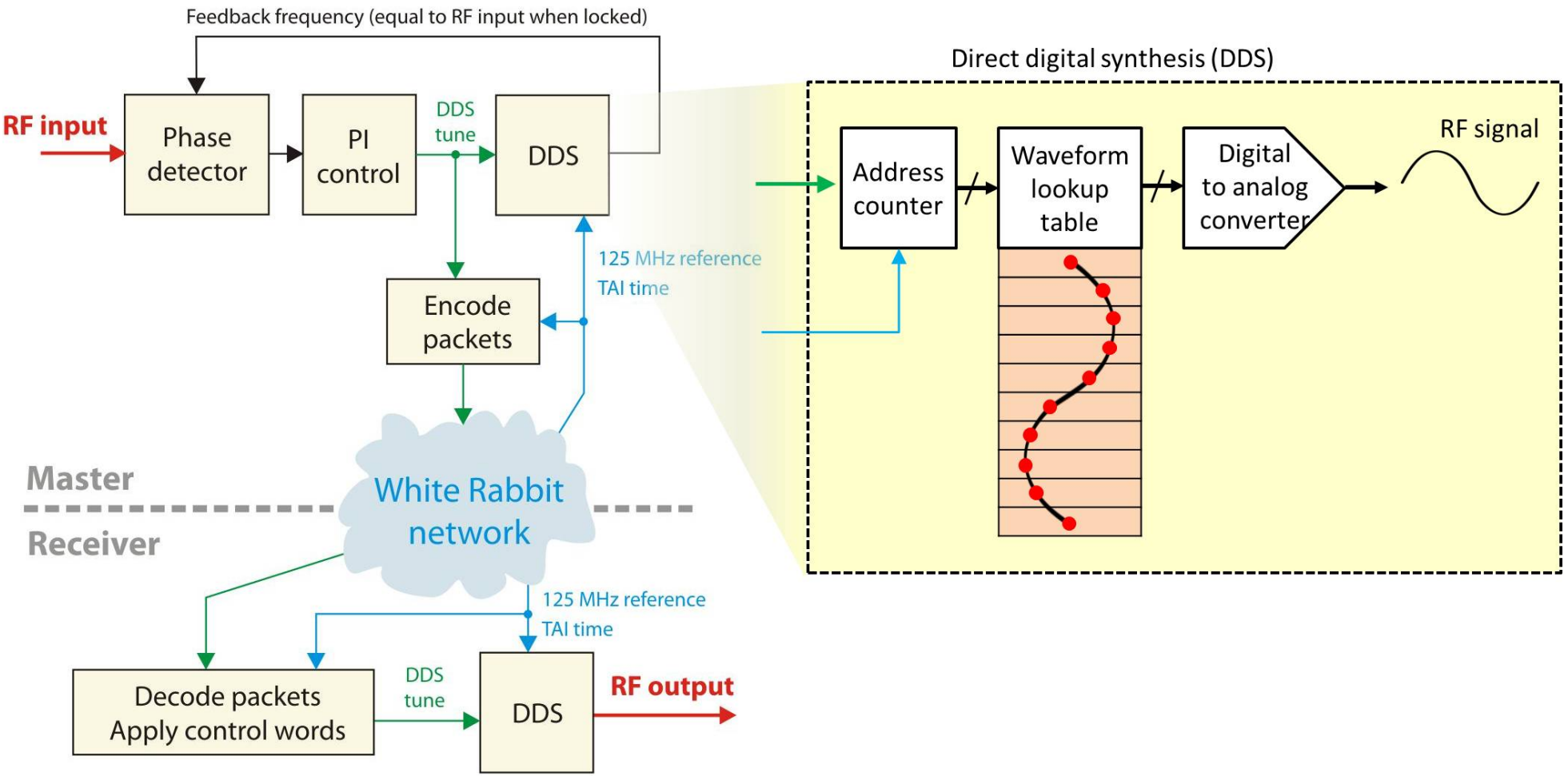

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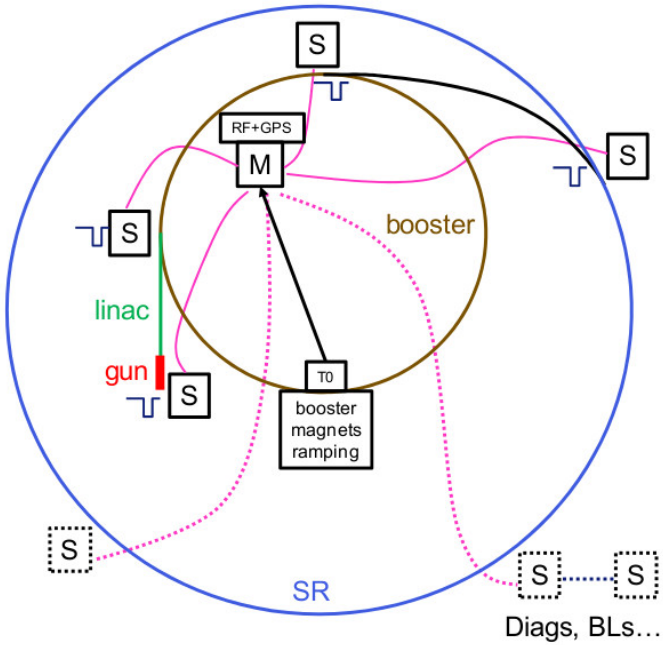

- RF over WR at European Synchrotron Radiation Facility (ESRF)
  - A prototype tested in operation: $<$10 ps jitter
- RF over WR at CERN
  - A prototype: $<$100 fs jitter and $<$10 ps reproducibility over reboots

Outline

WR standardisation in IEEE 1588 (1)

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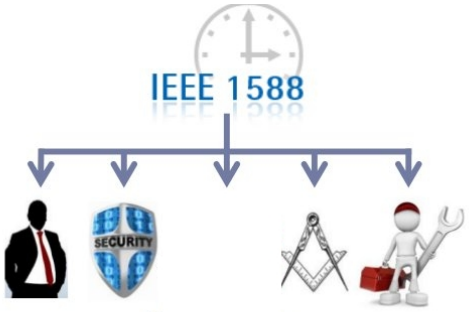

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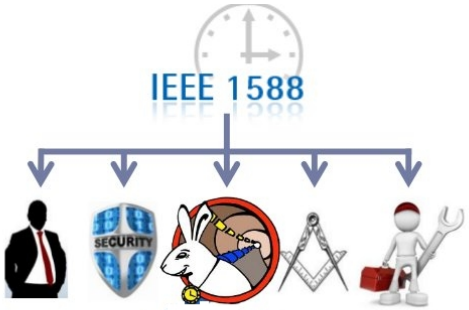
  - Experts from industry and academia
  - Division of WR into self-contained parts
  - Definition of Optional Features and PTP Profile that allow WR-like implementation and WR performance



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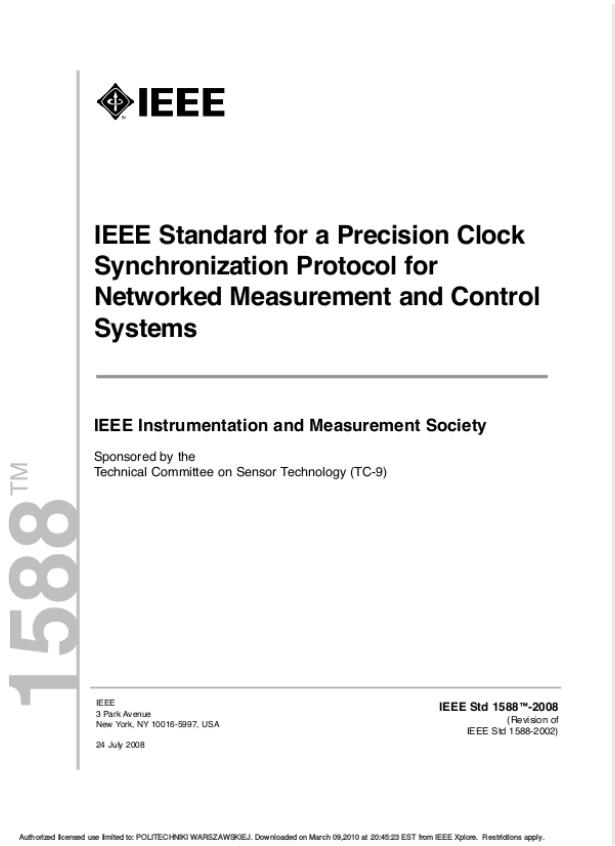
- Revised IEEE 1588 approved on 7 Nov 2019

WR standardisation in IEEE 1588 (2)



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™

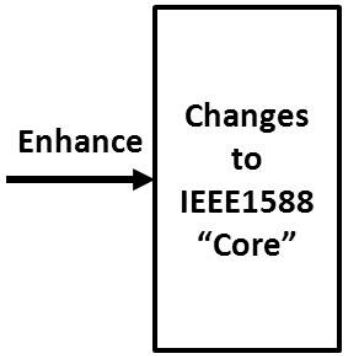
IEEE
3 Park Avenue
New York, NY 10016-5997, USA

24 July 2008

IEEE Std 1588™-2008
(Revision of
IEEE Std 1588-2002)

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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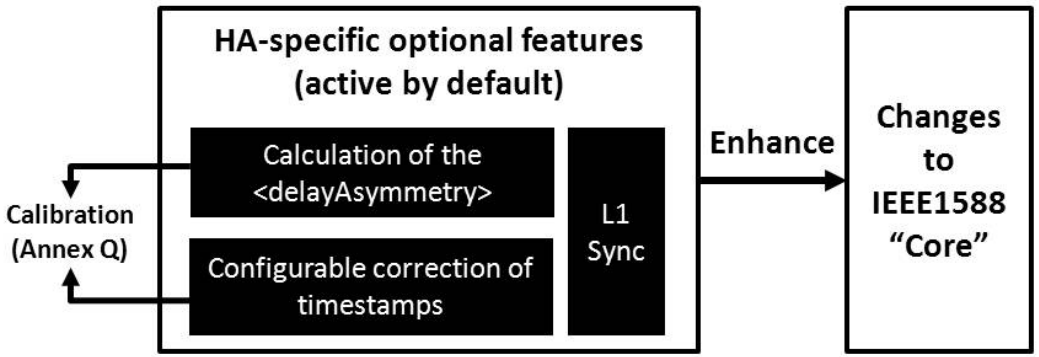

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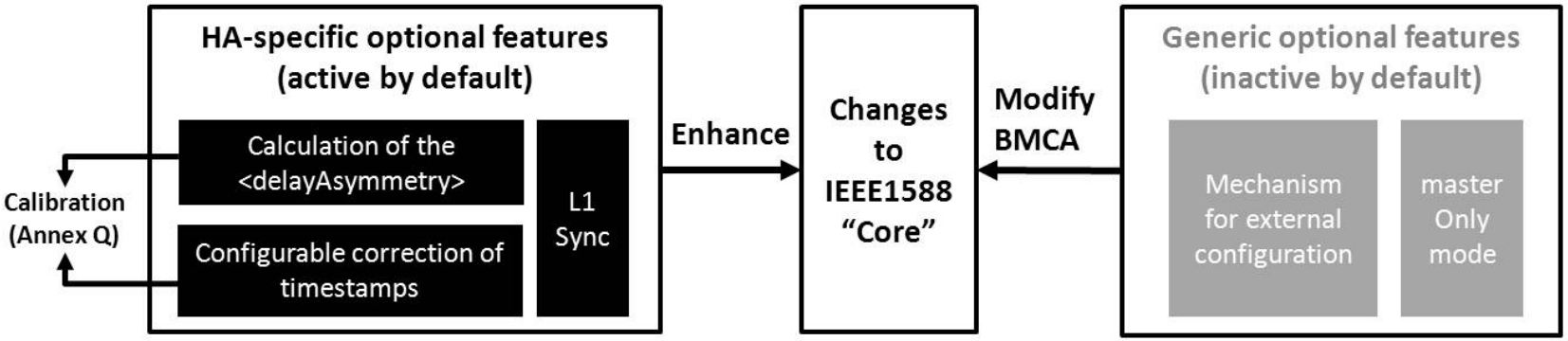

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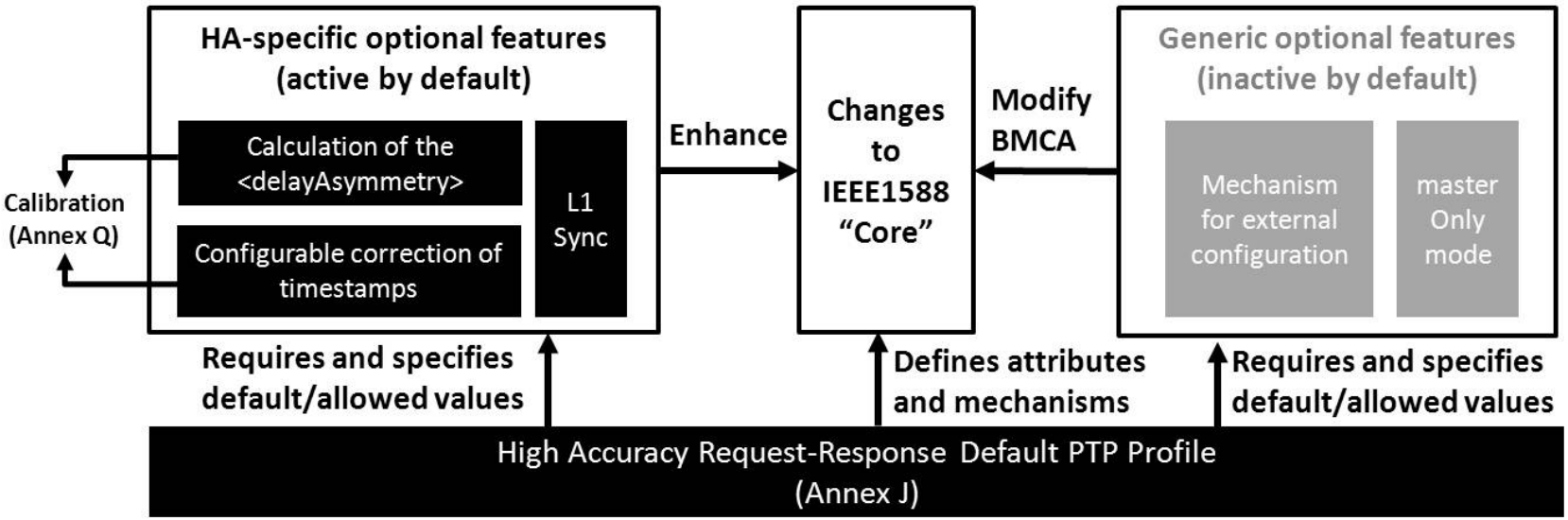

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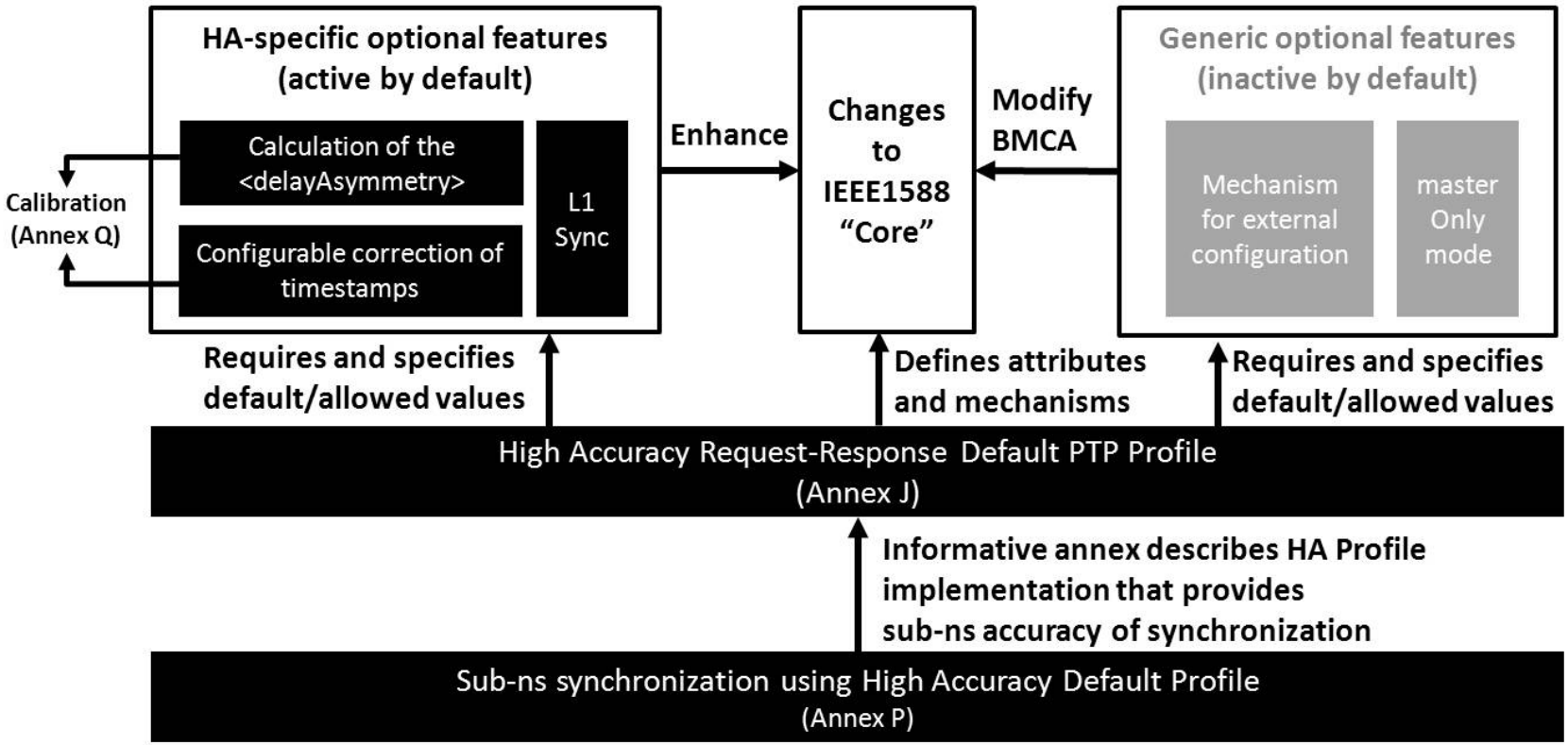

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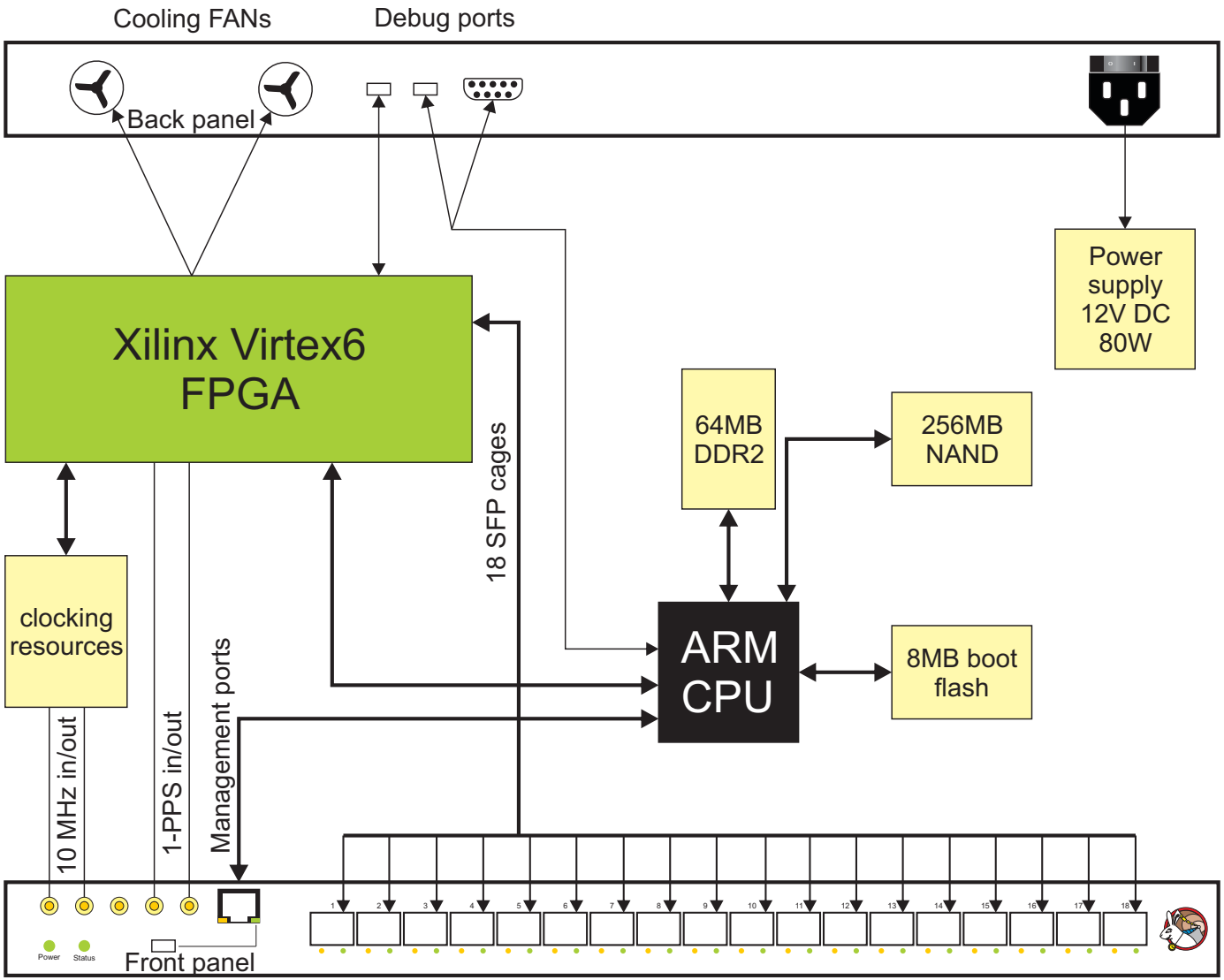
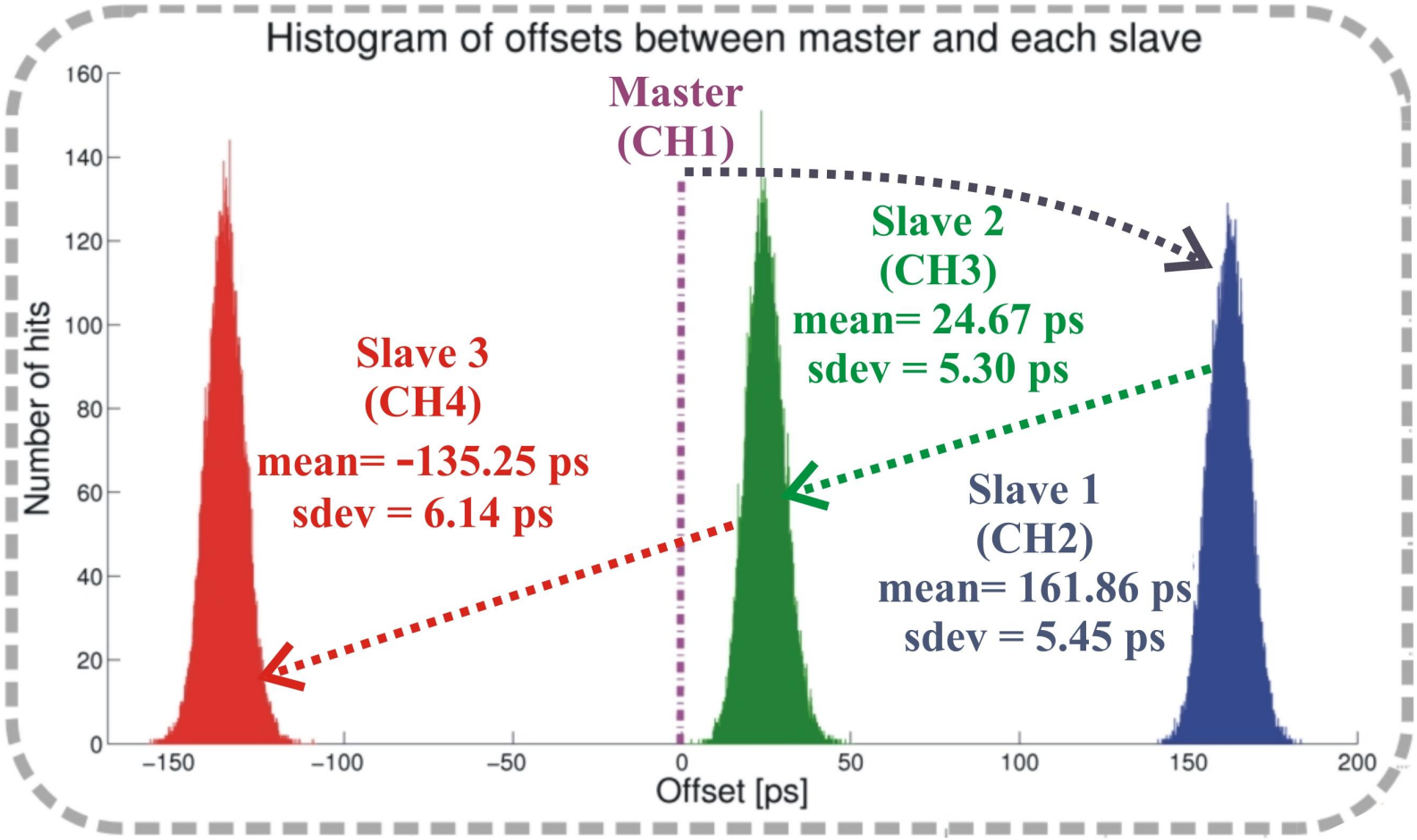
Outline

Simplified block diagram of the WR Switch hardware



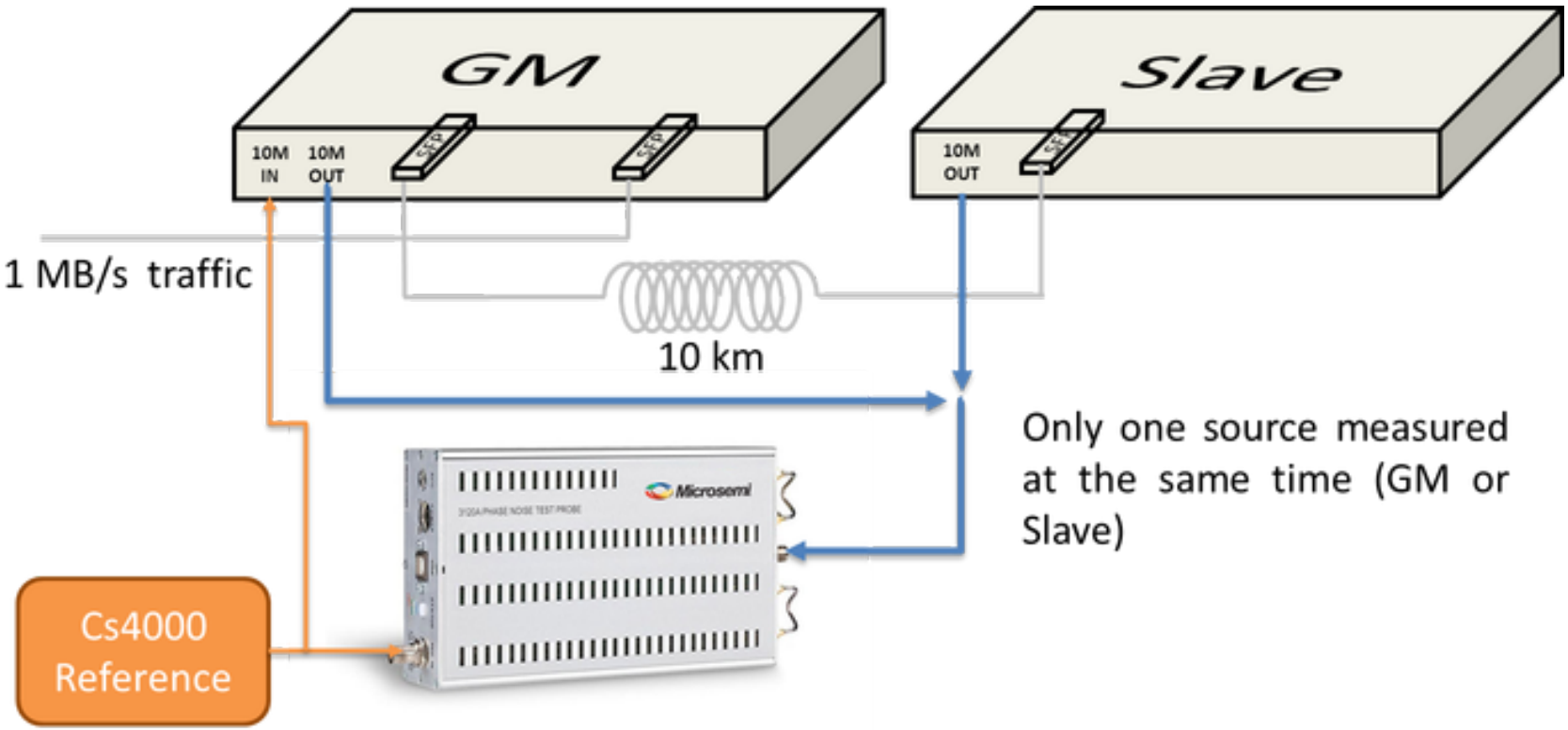
Outline

Time transfer: out-of-the-box



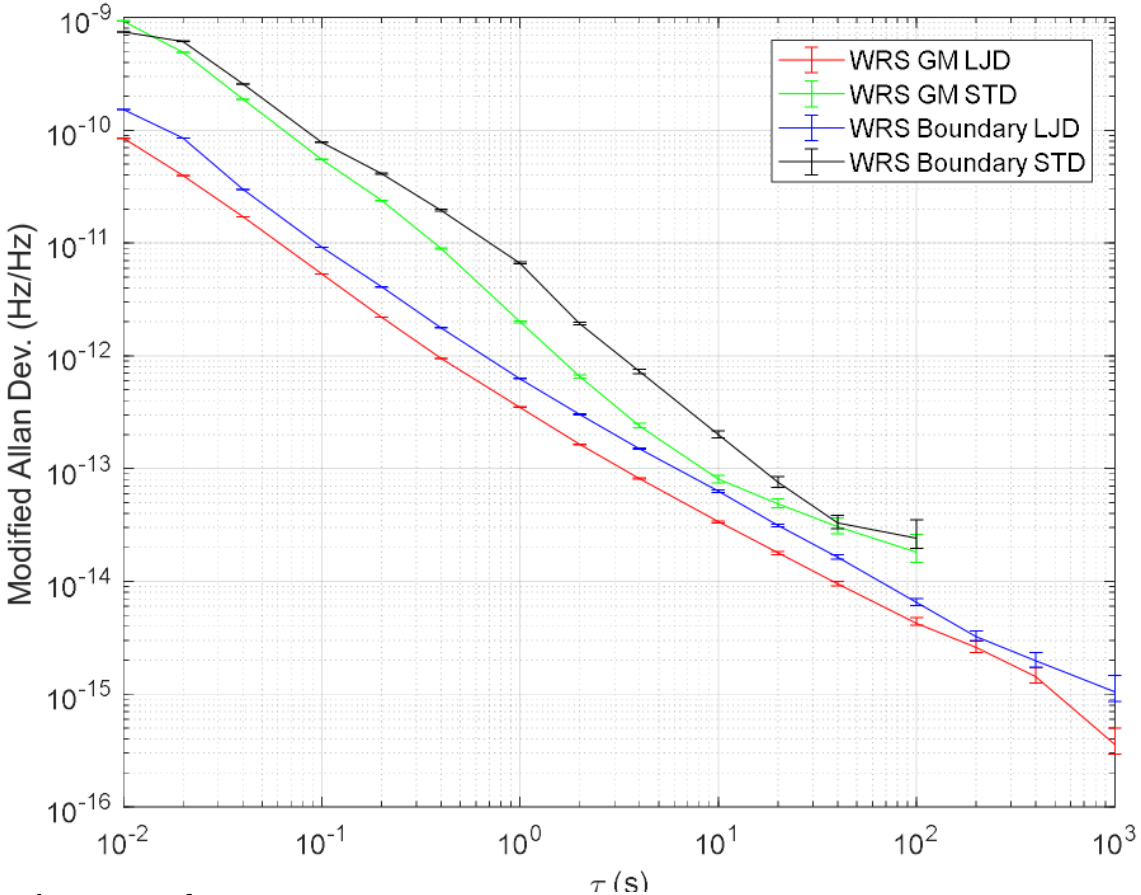
Reported in 2011

Frequency transfer: out-of-the-box and improved



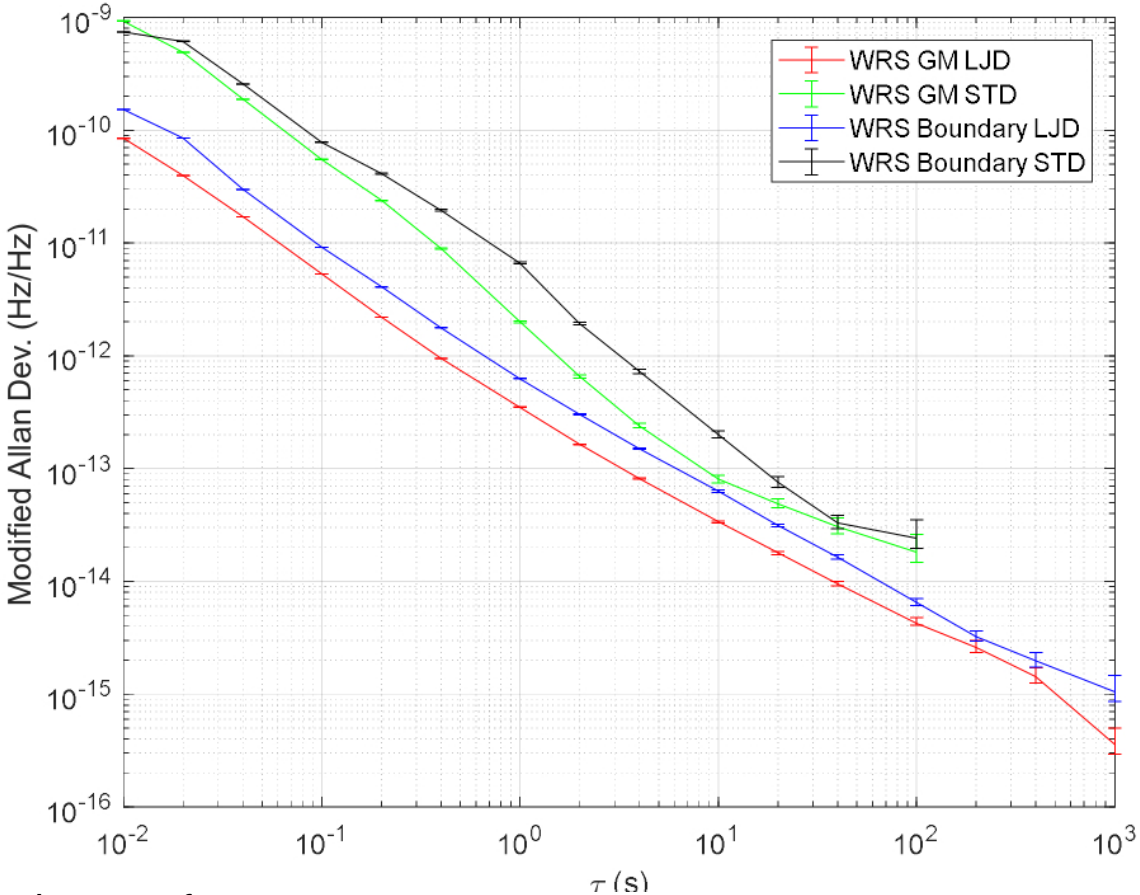
Measurement device: Microsemi/Microchip 3120A Phase Noise Test Probe

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** τ=1 s ENBW 50 Hz
  - **GM-in to Slave-out**: jitter of **11 ps** RMS 1 Hz–100 kHz and MDEV of **4E-12** τ=1 s ENBW 50 Hz

Frequency transfer: out-of-the-box and improved



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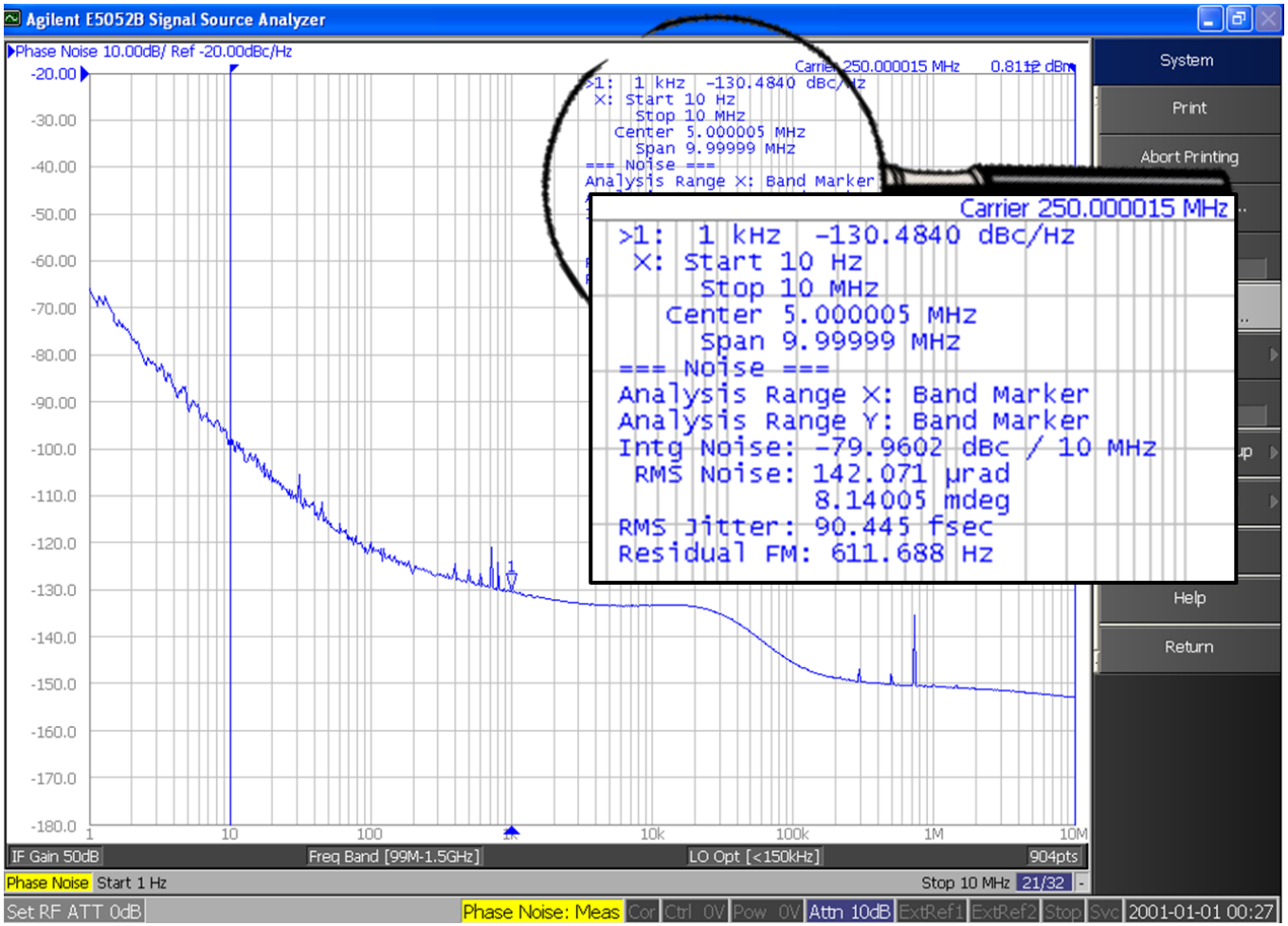
- WR Switches improved with Low Jitter Daughterboard (LJD):
  - **GM-in to GM-out**: jitter of **1 ps** RMS 1 Hz–100 kHz and MDEV of $<$**5E-13** τ=1 s ENBW 50 Hz
  - **GM-in to Slave-out**: jitter of $<$**2 ps** RMS 1 Hz–100 kHz and MDEV of $<$**7E-13** τ=1 s ENBW 50 Hz

WR time & frequency tranfser: state of the art

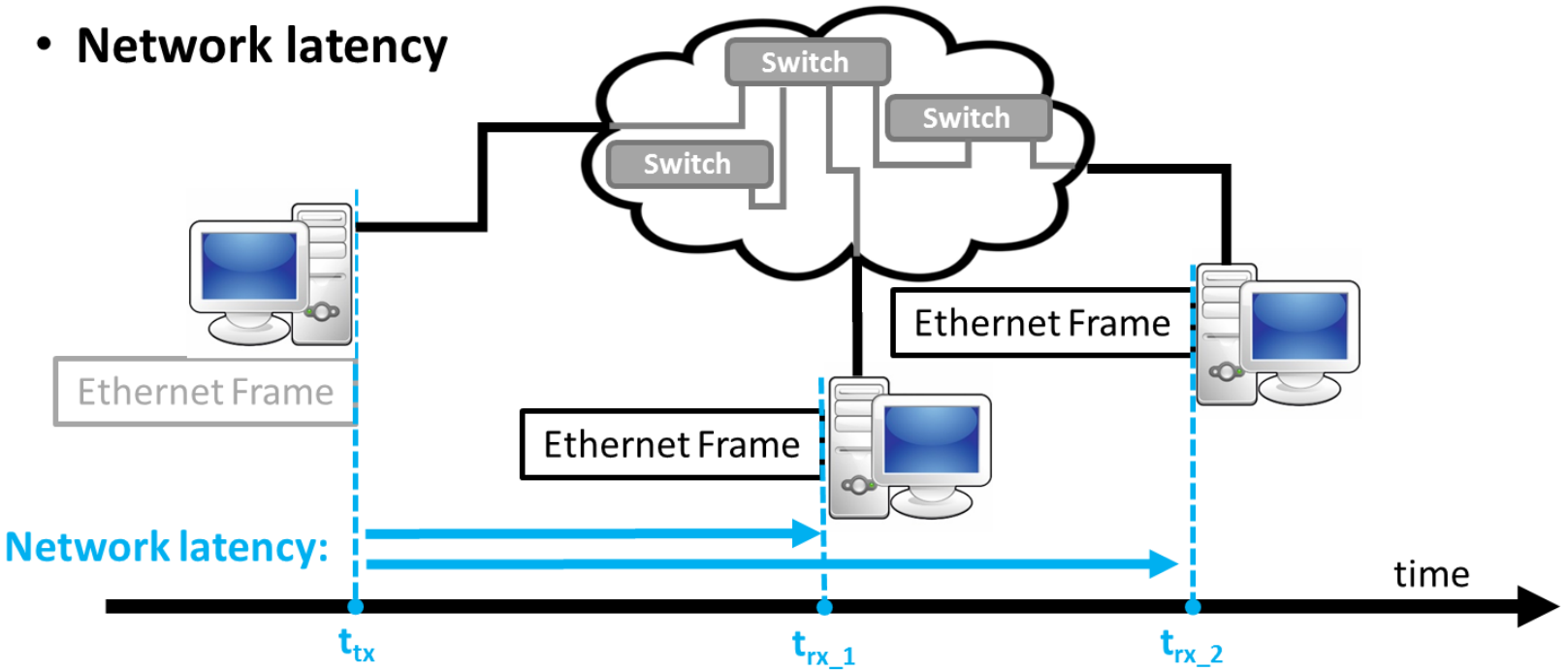


- **GM-out to end-node-out**: accuracy of $<$**10 ps**
- **GM-out to end-node-out**: jitter of $<$**100 fs** RMS 10 Hz–10 MHz

Outline

Determinism and Network Latency

- **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**

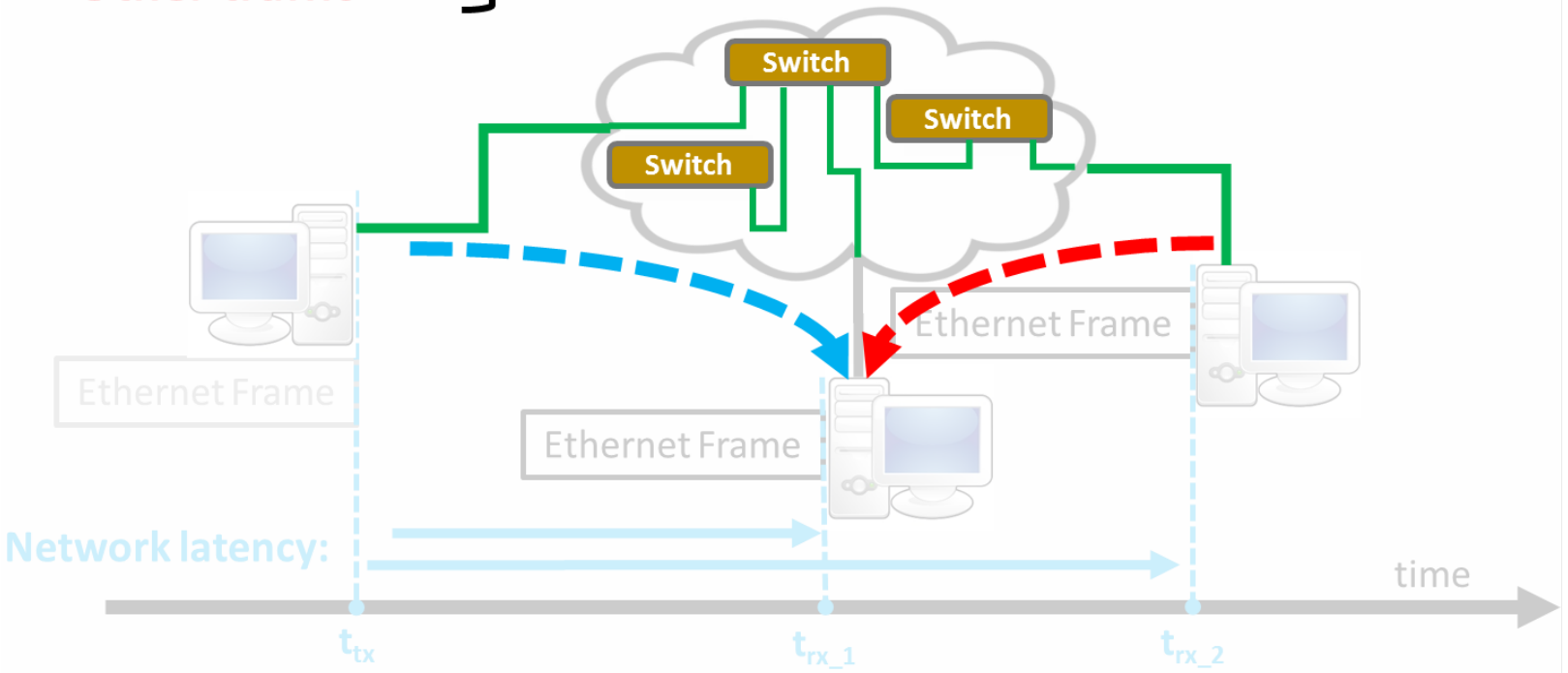


Deterministic network is a network in which we can calculate the maximum latency

Network Latency Contributors

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

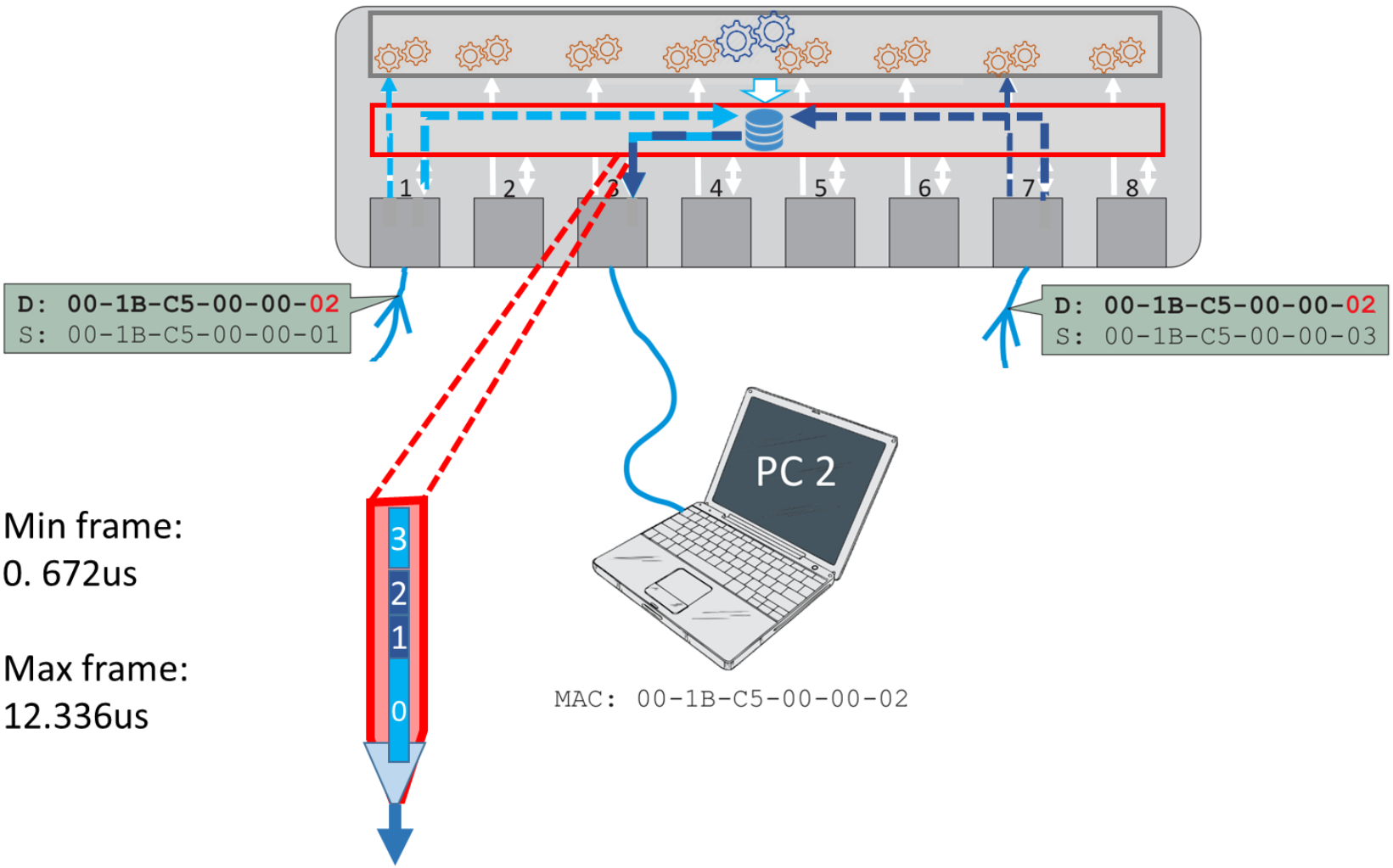
We can do something about this



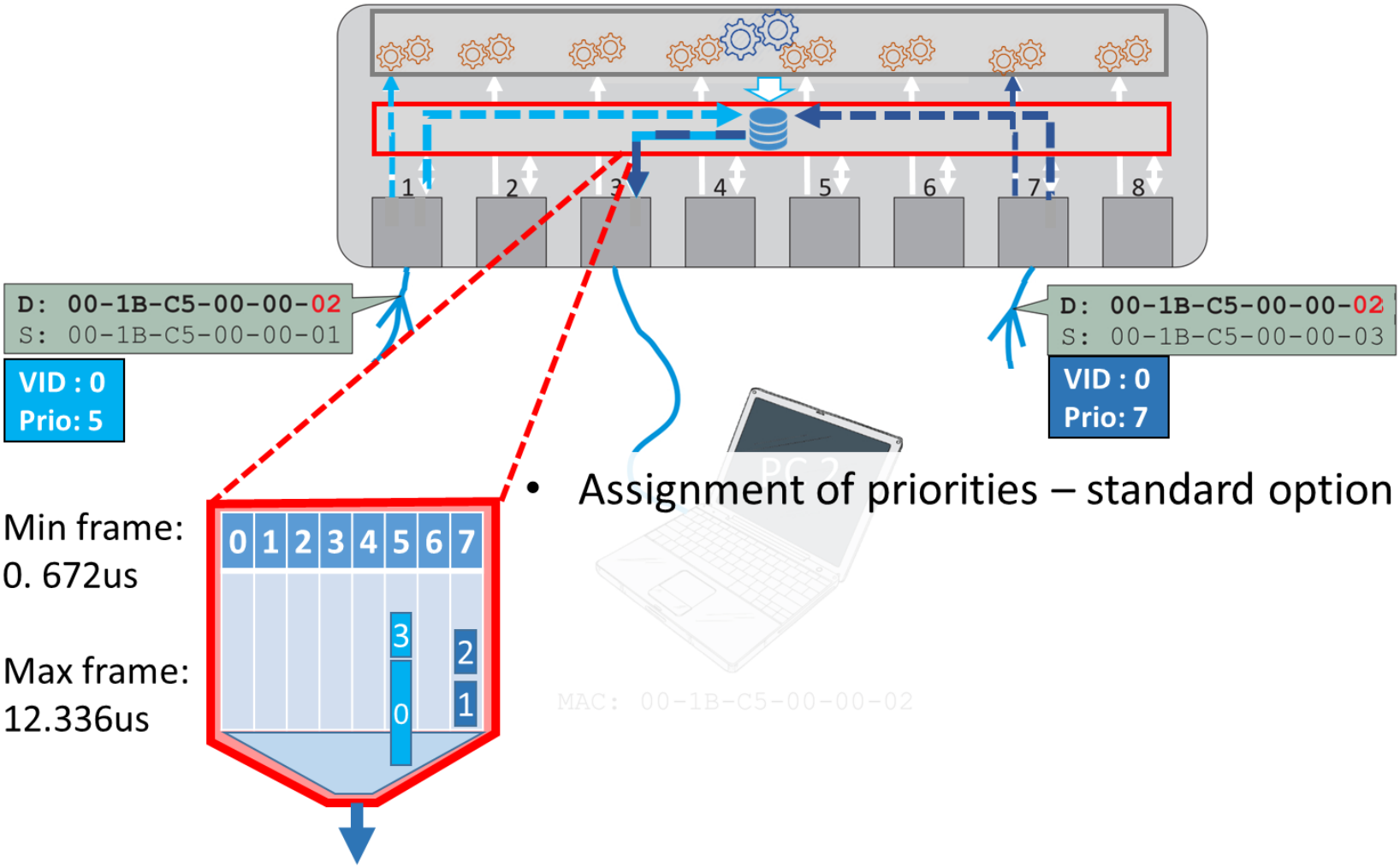
Determinism in WR

- ”White Box” design of WR switch - allows thorough analysis
- Backward-compatible extension of the IEEE 802.1Q std

Priorities

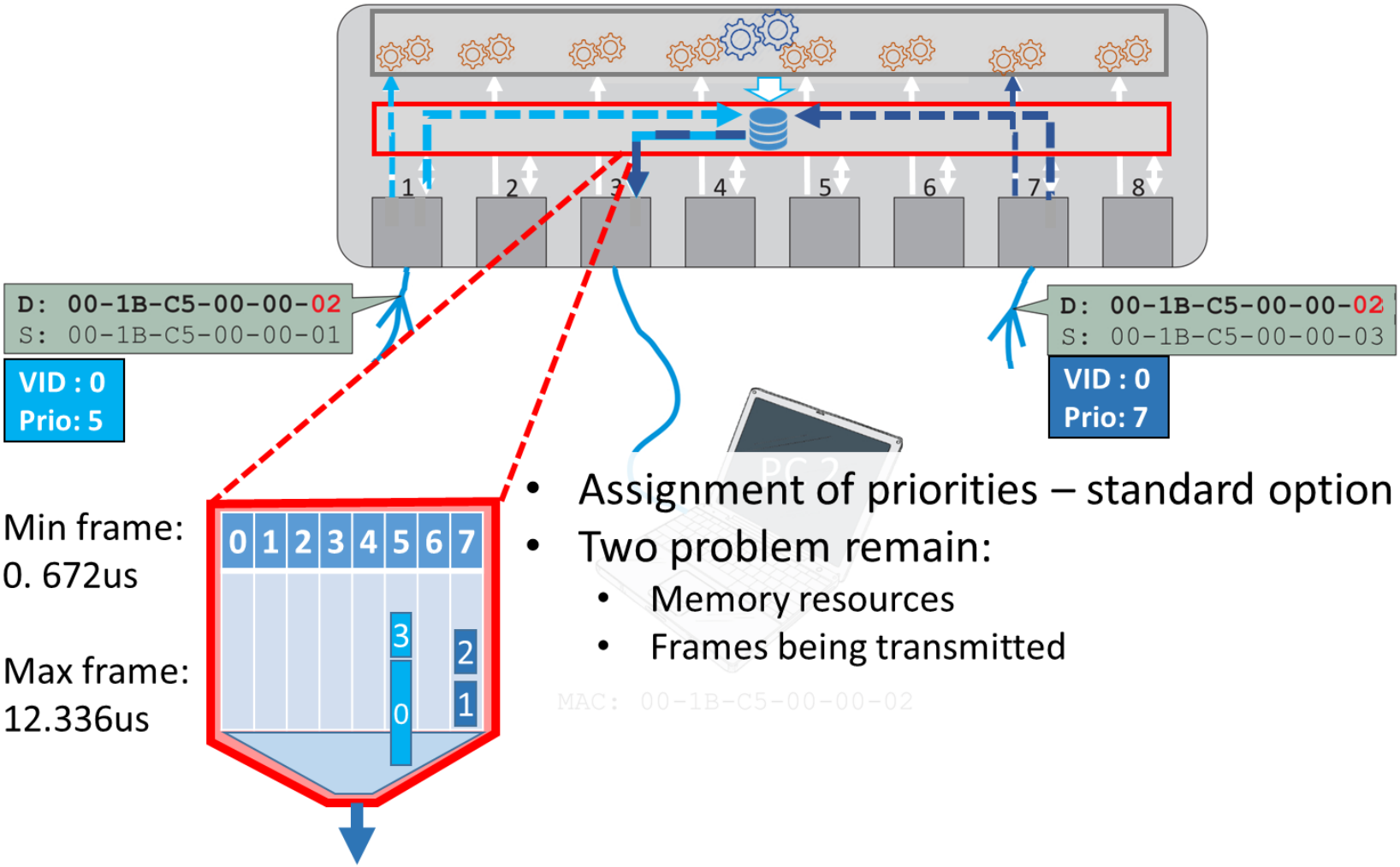

1
2
3
4
5
6
7
8
D: 00-1B-C5-00-00-02
S: 00-1B-C5-00-00-01
D: 00-1B-C5-00-00-02
S: 00-1B-C5-00-00-03
PC 2
MAC: 00-1B-C5-00-00-02
3
2
1
0
Min frame:
0. 672us
Max frame:
12.336us

Priorities

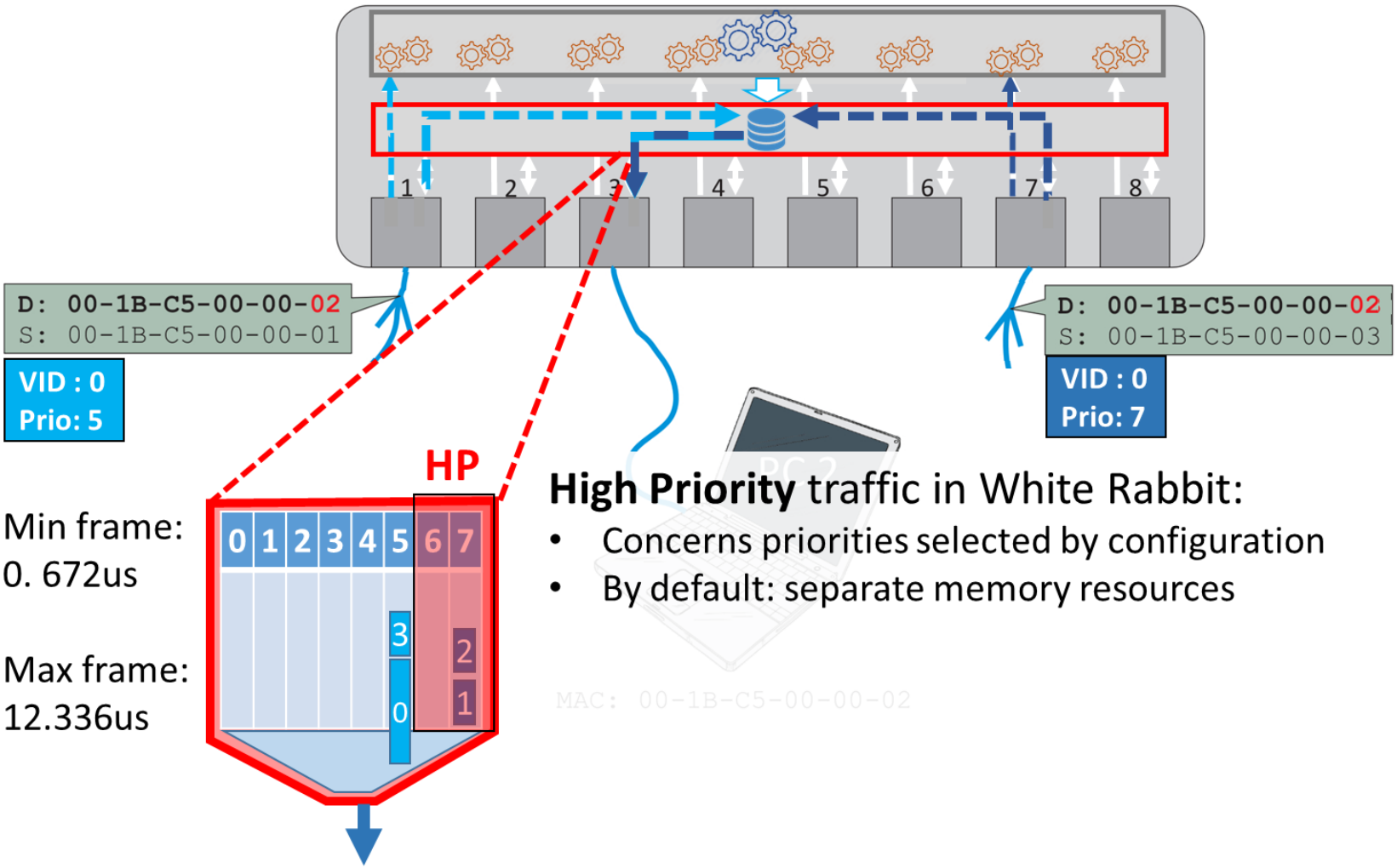


- Assignment of priorities – standard option

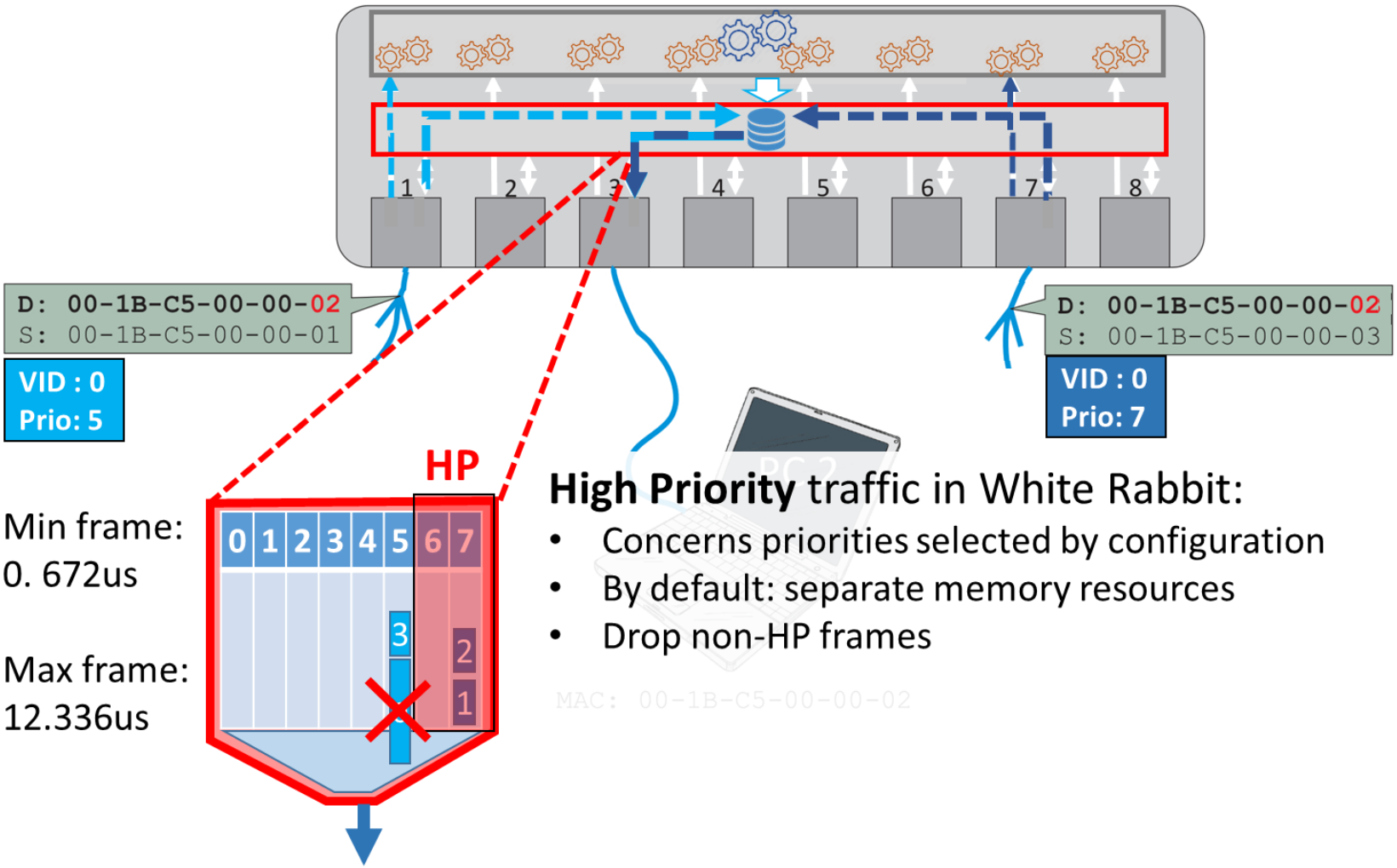
Priorities


1
2
3
4
5
6
7
8
D: 00-1B-C5-00-00-02
S: 00-1B-C5-00-00-01
VID : 0
Prio: 5
D: 00-1B-C5-00-00-02
S: 00-1B-C5-00-00-03
VID : 0
Prio: 7
Min frame:
0. 672us
Max frame:
12.336us
0 1 2 3 4 5 6 7
3
2
0
1
• Assignment of priorities – standard option
• Two problem remain:
• Memory resources
• Frames being transmitted

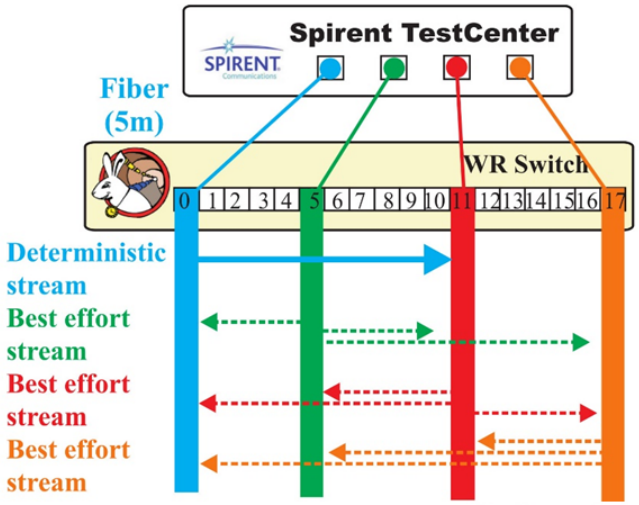
High Priority



High Priority



WR Switch Latency



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