A White Rabbit Synchronized PMU

Reza Razzaghi, Asja Derviškadić and Mario Paolone

Swiss Federal Institute of Technology Lausanne (EPFL)
Distributed Electrical Systems Laboratory (DESL)

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Outline

- Motivations
- Time synchronization for PMUs
- The White Rabbit time synchronization protocol
- The White Rabbit for PMU applications
- PMU calibration
- Performance Assessment
- Conclusions

Time synchronization techniques for PMUs

Introduction

The Global Positioning System (GPS) ➔ most common

- Accuracy 100 ns
- One dedicated GPS antenna installed for each PMU

Open issues:

- **Accuracy** ➔ Power distribution systems
- **Accessibility** ➔ Substations access to the sky
- **Security** ➔ Easy manipulation of GPS signals

The Network Time Protocol (NTP)

- Accuracy 1 ms
- Non deterministic

The Precision Time Protocol (PTP) – IEEE 1588

- Accuracy 1 μs (implementation-dependent)
- Non deterministic

The White Rabbit Protocol

Introduction

Ultra-precise timing system for CERN's accelerators, based on:

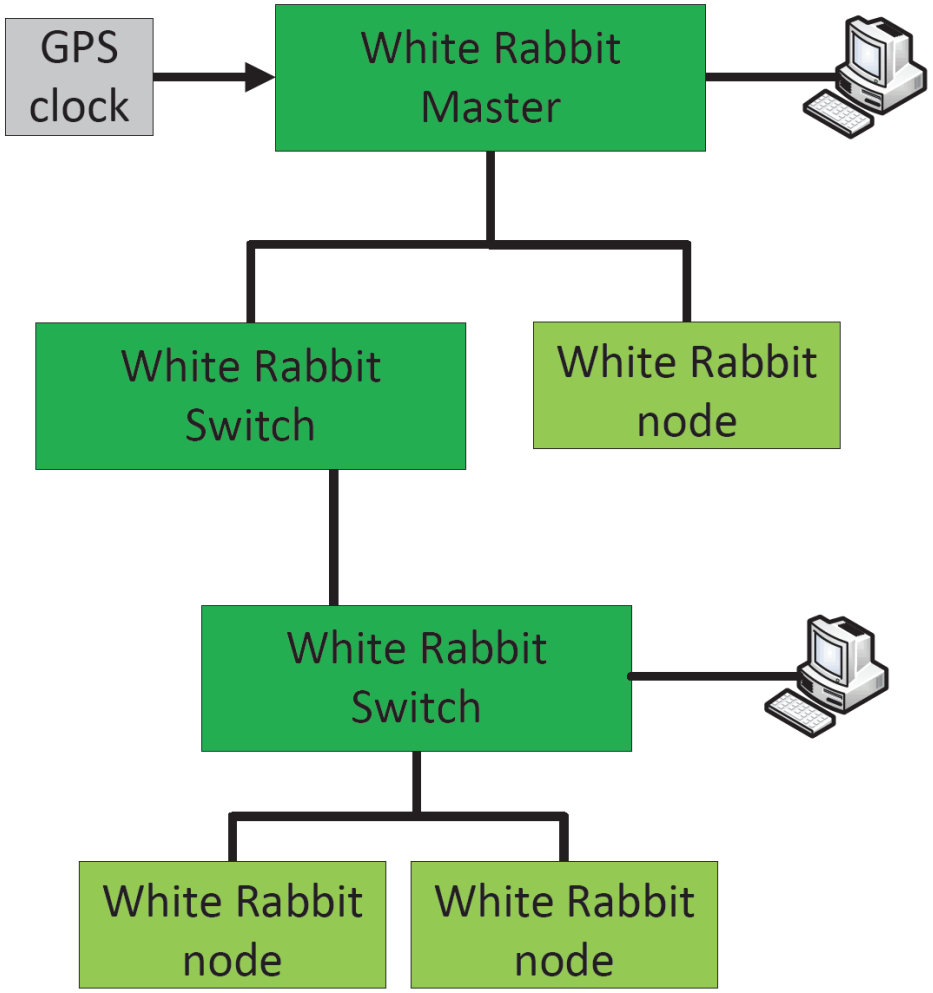
- Ethernet (IEEE 802.3)
- **PTPv2** (IEEE 1588)
- Synchronous Ethernet (**SyncE**) ➔ Hardware synchronization
- **Precise phase measurement**

Deployable on already existing Ethernet-based networks

Ethernet-based	Accurate	Deterministic
1000 nodes	**Accuracy 1 ns**	Upper-bound low latency
10 km		
Gbit/s data rate	Precision 10 ps	High reliability

The White Rabbit Protocol

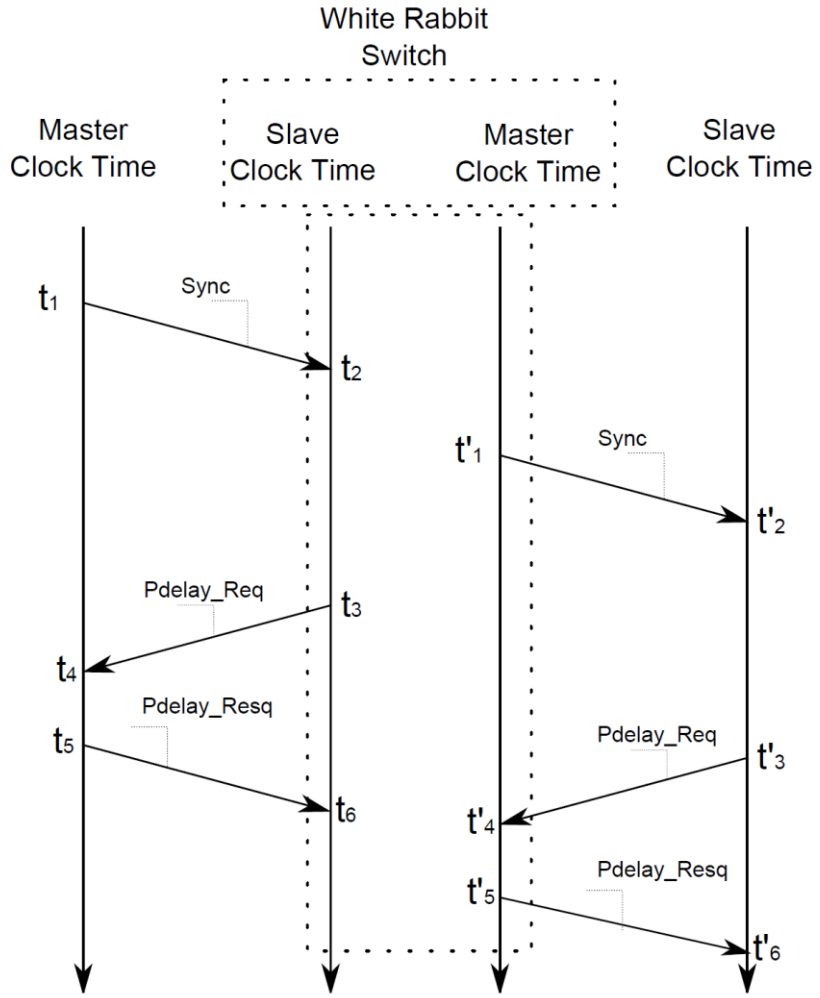
The White Rabbit Network (WRN) architecture



The White Rabbit principles of operation

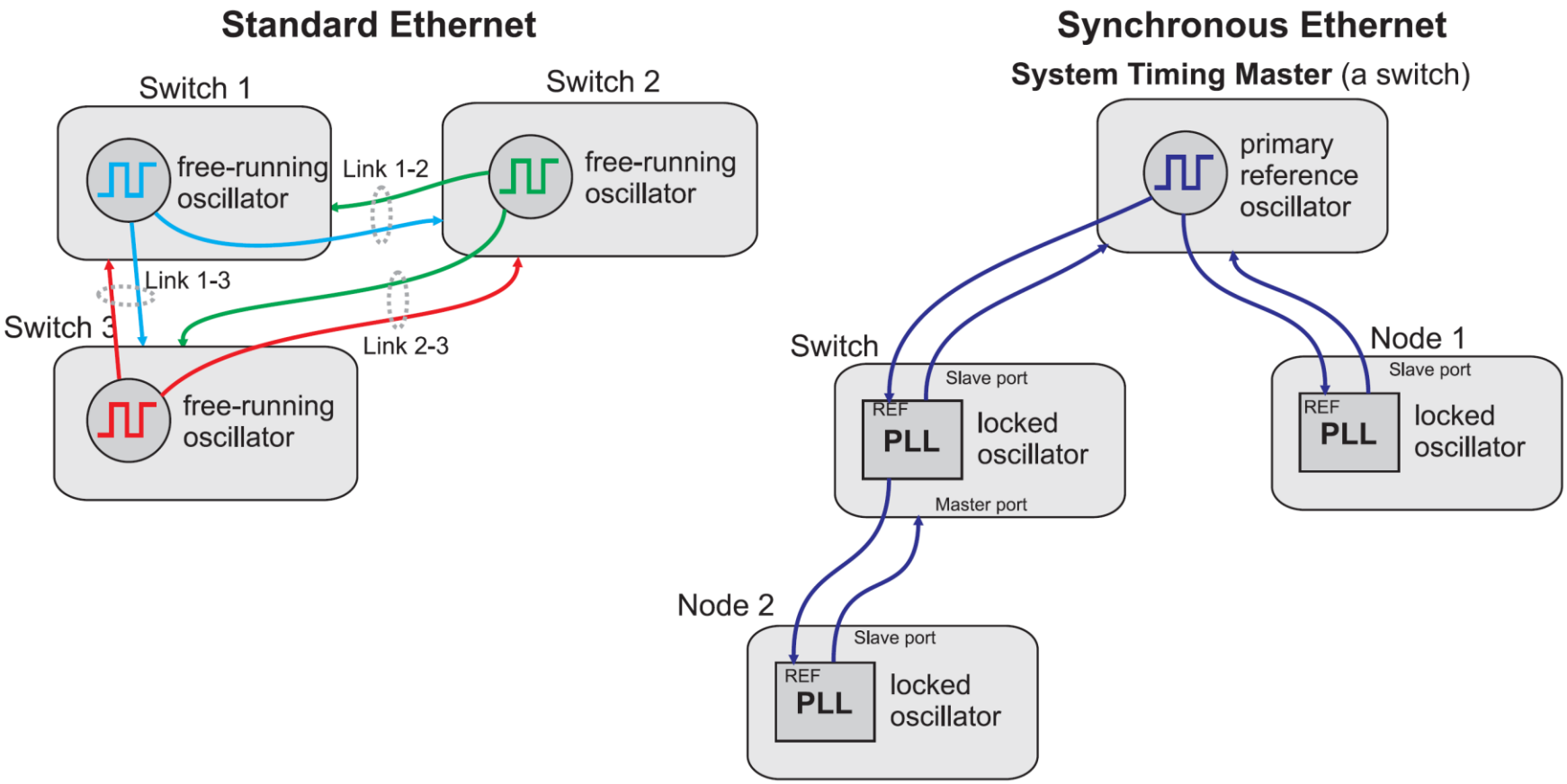
PTPv2

$$\Delta t = \frac{(t_4 - t_1) - (t_3 - t_2)}{2}$$



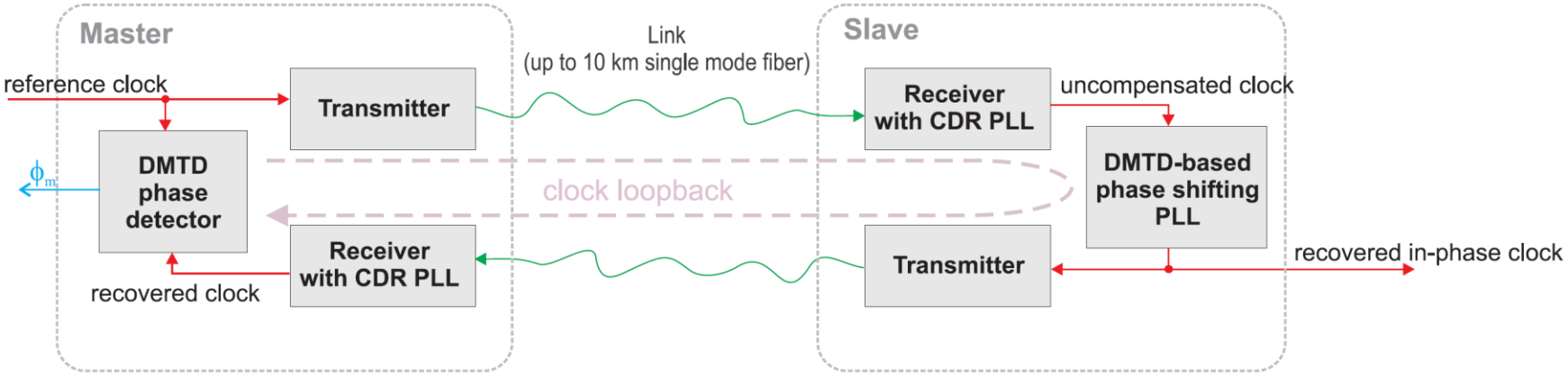
The White Rabbit principles of operation

SyncE



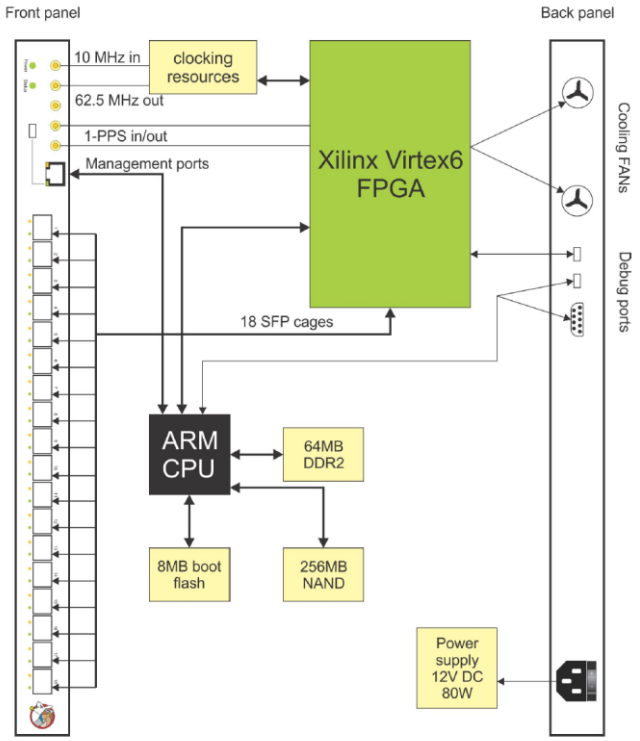
The White Rabbit principles of operation

Precise Phase Measurement



The White Rabbit Switch

Principles of operation

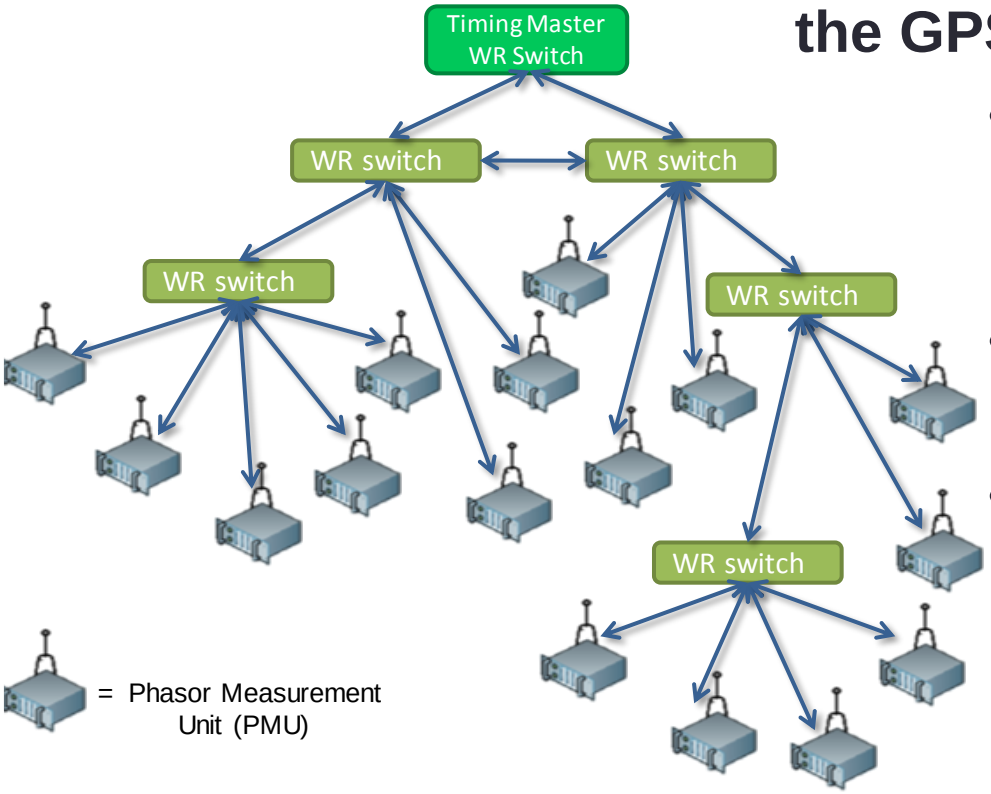


Seven Solutions S.L. http://sevensols.com/

The White Rabbit Protocol

Applicability to Power Systems and PMUs

Potential use of **legacy Ethernet-based infrastructure** of any power grid.



Alternative/complementary for the GPS in case:

- The **sky is not accessible** (e.g., urban areas),
- The **telecommunication infrastructure** is available
- The length between two PMUs are less than **10km** (subtransmission or power distribution networks).

The proposed White Rabbit Synchronized PMU

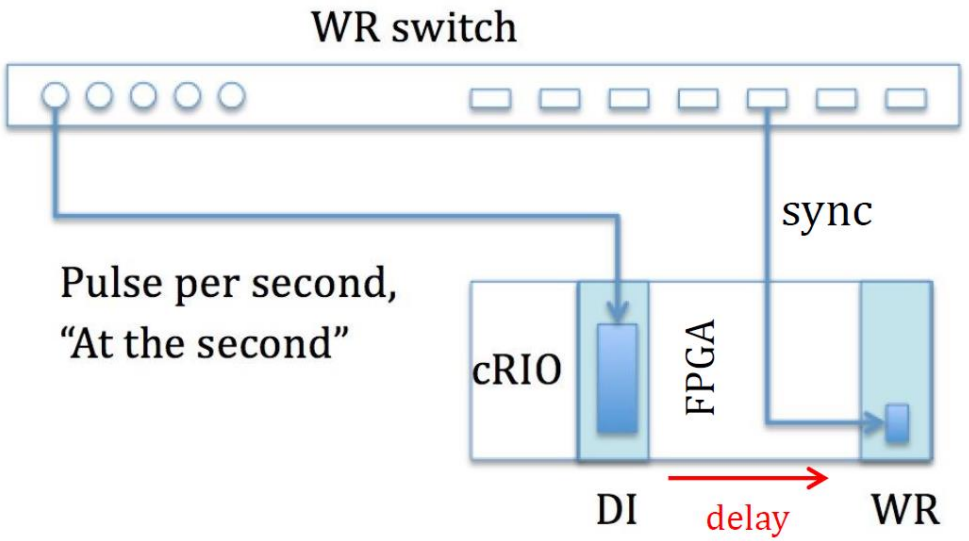
Based on the National Instruments cRIO platform

- FPGA-based PMU ➔ National Instruments cRIO platform
- Synchrophasor Estimation ➔ Enhanced Interpolated-DFT
- **With GPS time synchronization ➔ NI 9467 GPS module ➔** TVE ~ 0.0X %
- **WR cRIO module** integration into the PMU prototype

http://www.ohwr.org/projects/crio-wr/wiki

The White Rabbit cRIO

Acquisition of the reference time



Algorithm 1: Retrieving T_{WR}

```
While True
        Go to normal operation
        Start
        While T_trig
                Wait for node start (Trigger)
        end
        Read the time→ T_WR
        Idle
        End
end
```

WR-cRIO hardware limitations

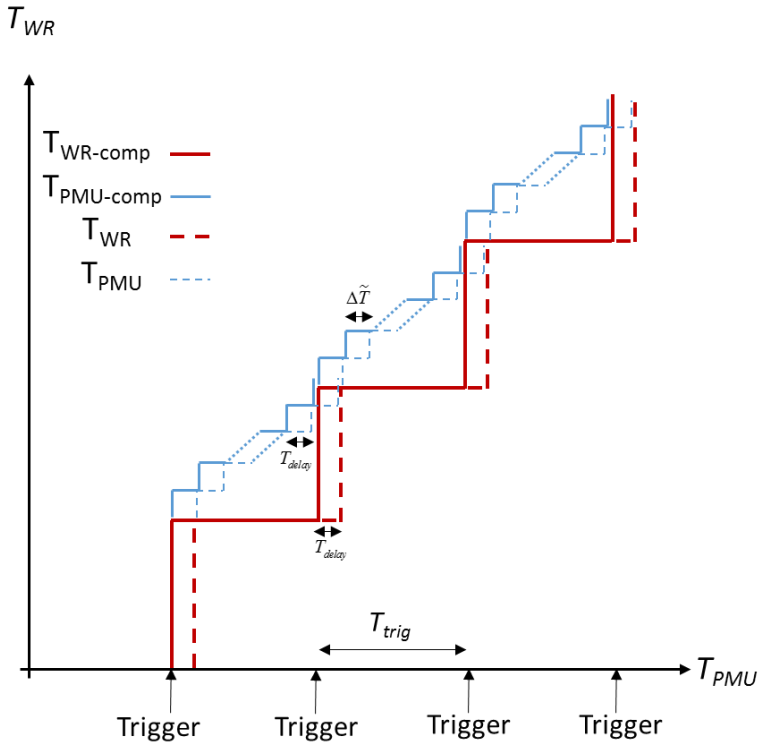
- FPGA WR time **polling finite resolution ~ 10 µs**
- FPGA WR time **reading deterministic delay ~ 300 ticks ➔ 1.2 µs**

The White Rabbit cRIO

Internal free-running clock

How to overcome the WR cRIO hardware limitations

- Time polling finite resolution ➔ **Free-running clock ➔ but** $\Delta\tilde{T} = 25$ ns (FPGA clock) >> 1 ns
- Deterministic delay time reading ➔ **Delay compensation**

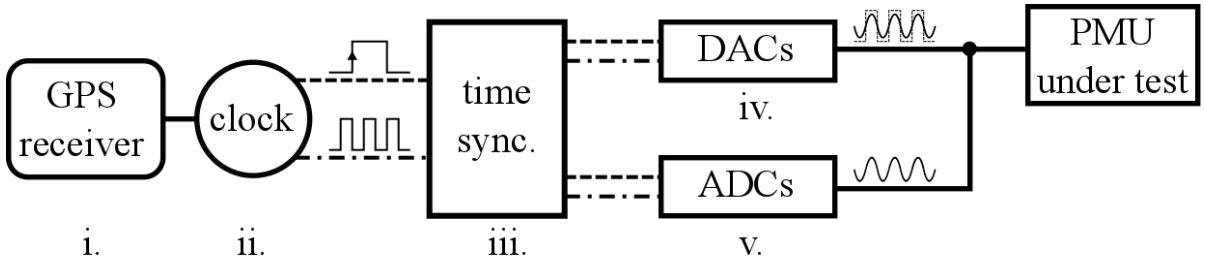


Algorithm 2: Internal free-running clock

```
1:  if      T_WR(n) ≠ T_WR(n-1)
2:      T_PMU(n) = T_WR(n)
3:  else
4:      T_PMU(n) = T_PMU(n) + ΔT
5:  end
```

The adopted PMU calibrator

The hardware and software architecture



trigger (PPS)
timebase (10 MHz)
synchronized waveform
re-acquired waveform

i. **GPS-receiver** ➔ absolute time reference (*Meinberg GPS169PCI*)

ii. **Atomic clock** ➔ short-time accuracy (*Stanford Research Systems FS725 rubidium atomic clock*)

iii. **Time synchronisation board** (*NI PXI 1042Q chassis + NI PXI-8110 controller + NI PXI-6682 timing and synchronization module*)

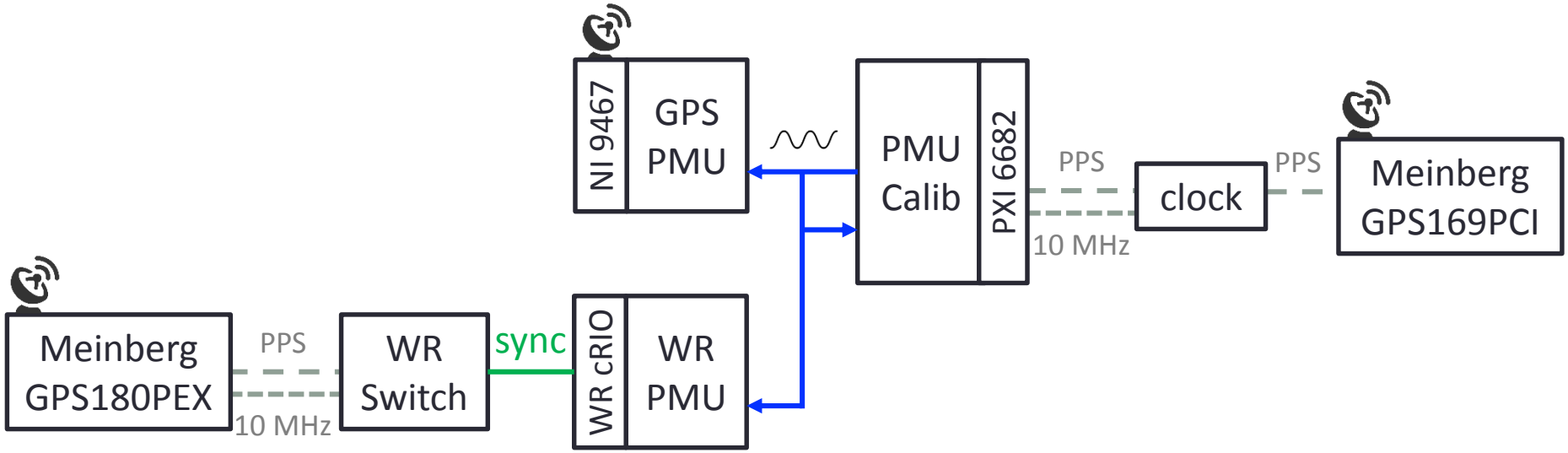
iv. **DACs** ➔ generate V/I reference (*NI PXI-6289 DAQ)*

v. **ADCs** ➔ re-acquire the V/I reference (*NI PXI-6289 DAQ)*

Performance Assessment

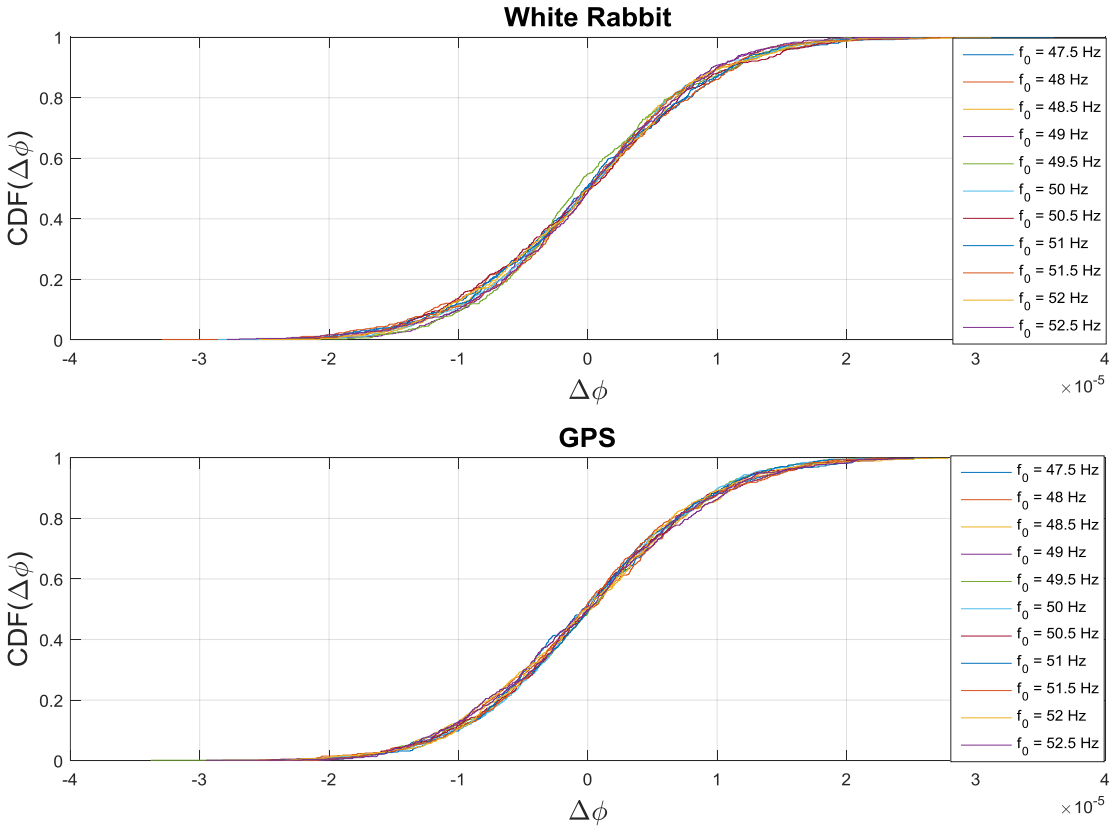
The setup

- **GPS PMU** and **WR PMU** simultaneously coupled with the calibrator
- PMUs based on the **same hardware** and **same synchrophasor estimation** algorithm ➔ the only difference is the adopted time synchronization technique
- The calibrator and the White Rabbit Switch do not share the same master clock



Performance Assessment

Characterization of the absolute and relative phase error



f0 [Hz]	WR PMU	GPS PMU
	Std. [µrad]	Std.[µrad]
47.5	8.97	8.54
48	9.10	8.60
48.5	8.13	8.67
49	7.83	8.62
49.5	7.81	8.17
50	8.16	7.94
50.5	8.87	8.29
51	8.52	8.00
51.5	8.11	8.21
52	8.47	8.29
52.5	8.13	8.48

Error	WR PMU	GPS PMU
Mean [µrad]	9.96	11.65
Std. [µrad]	7.99	8.74

Conclusions

- Use of the White Rabbit time synchronization protocol for PMU applications
- Integration of the WR in a PMU prototype
- Performance assessment by means of a PMU calibrator ➔ similar performance of WR PMU and GPS PMU ➔ **Finite resolution of the FPGA polling of WR time**
- Alternative for specific applications where the GPS signal is not available

A White Rabbit Synchronized PMU

Reza Razzaghi, Asja Derviškadić and Mario Paolone

Swiss Federal Institute of Technology Lausanne (EPFL)
Distributed Electrical Systems Laboratory (DESL)

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

References

- J. Serrano, P. Alvarez, M. Cattin, E. G. Cota, P. M. J. H. Lewis, T. Włostowski, and E. Al., “The White Rabbit Project,” in ICALEPCS TUC004, 2009.
- Serrano, Javier, et al. "The white rabbit project ,” Proceedings of IBIC2013, Oxford, UK, 2013.
- Moreira, Pedro, et al. "White rabbit: Sub-nanosecond timing distribution over ethernet." Precision Clock Synchronization for Measurement, Control and Communication, 2009. ISPCS 2009. International Symposium on. IEEE, 2009.
- M. Lipinski, T. Wlostowski, J. Serrano, and P. Alvarez, “White rabbit: a PTP application for robust sub-nanosecond synchronization,” in 2011 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control and Communication, 2011, pp. 25–30.
- Brückner, M., and R. Wischnewski. "A White Rabbit setup for sub-nsec synchronization, timestamping and time calibration in large scale astroparticle physics experiments." Proceedings of the 33rd ICRC, Rio de Janeiro, paper 1146 (2013).
- Seven Solutions: http://sevensols.com/
- http://www.ohwr.org/projects/white-rabbit/wiki/synchronization
- D. Colangelo, L. Zanni, M. Pignati, P. Romano, M. Paolone, J.-P. Braun, and L.-G. Bernier, “Architecture and characterization of a calibrator for PMUs operating in power distribution systems,” in 2015 IEEE Eindhoven PowerTech, 2015, pp. 1–6.
- G. Frigo, D. Colangelo, M. Pignati, M. Paolone, and C. Narduzzi, “Definition and assessment of reference values for PMU calibration in static and transient conditions,” in AMPS, 2016 IEEE Aachen, 2016.
- P. Romano and M. Paolone, “Enhanced Interpolated-DFT for Synchrophasor Estimation in FPGAs: Theory, Implementation, and Validation of a PMU Prototype,” IEEE Trans. Instrum. Meas., vol. 63, no. 12, pp. 2824–2836, Dec. 2014.