Time synchronisation needs in Phasor Measurement Units for the real-time monitoring of power grids

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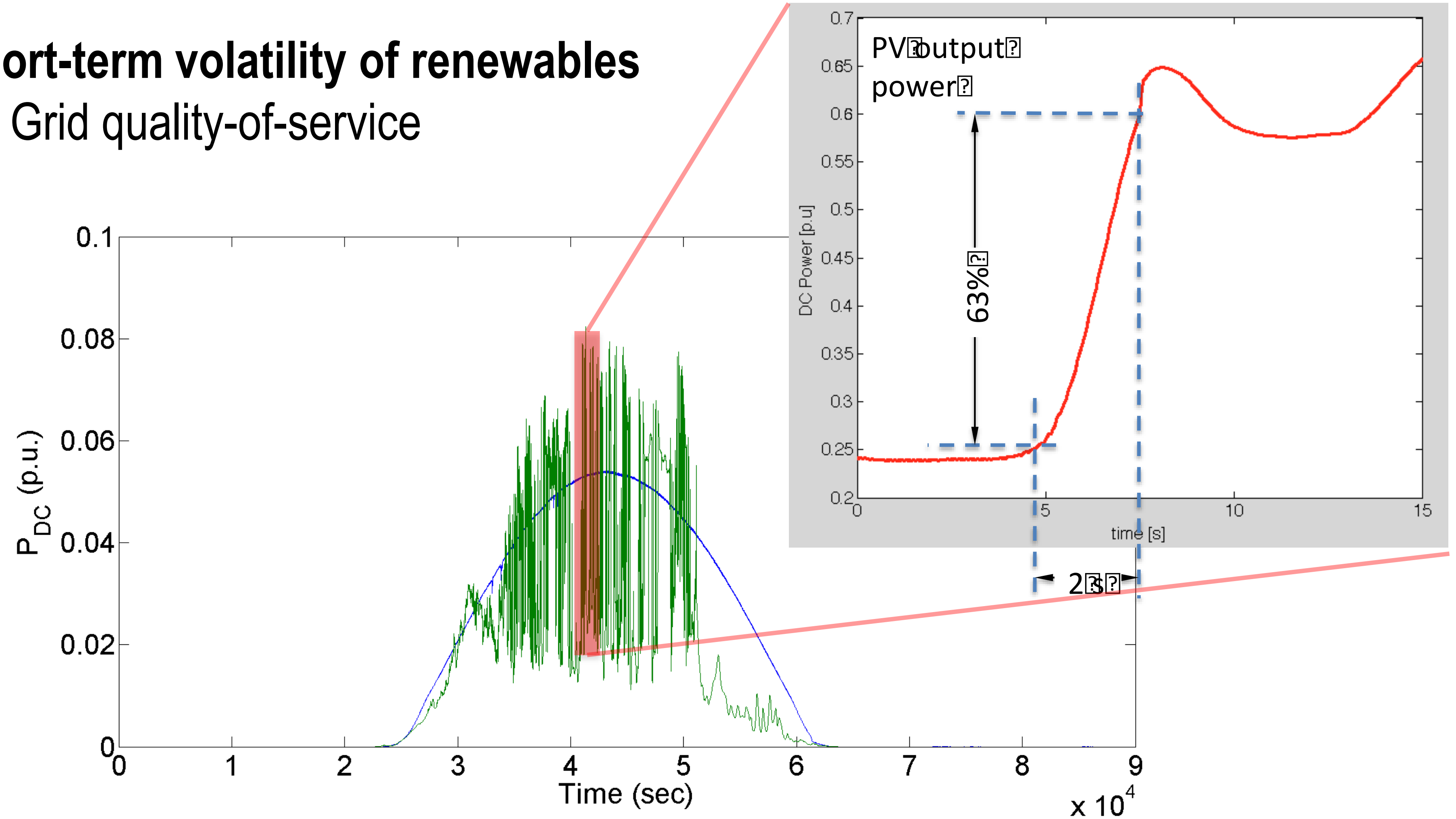
Active Distribution Network Needs

Data coming from the EPFL-DESL.

Drivers

Short-term volatility of renewables

→ Grid quality-of-service



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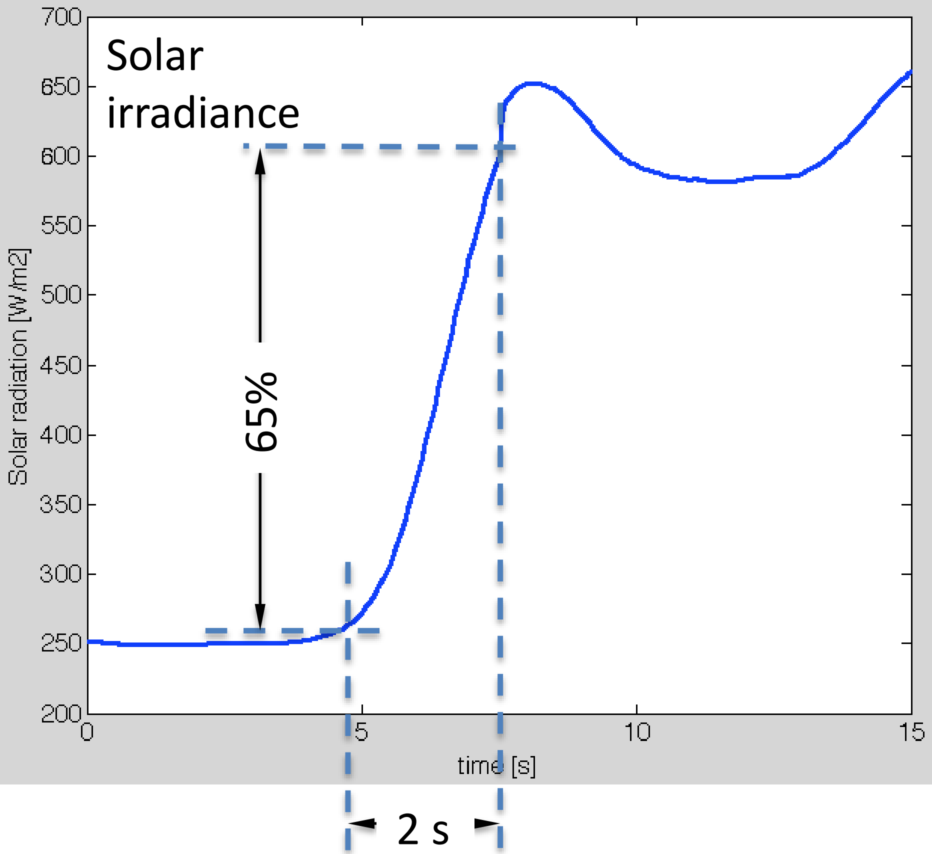
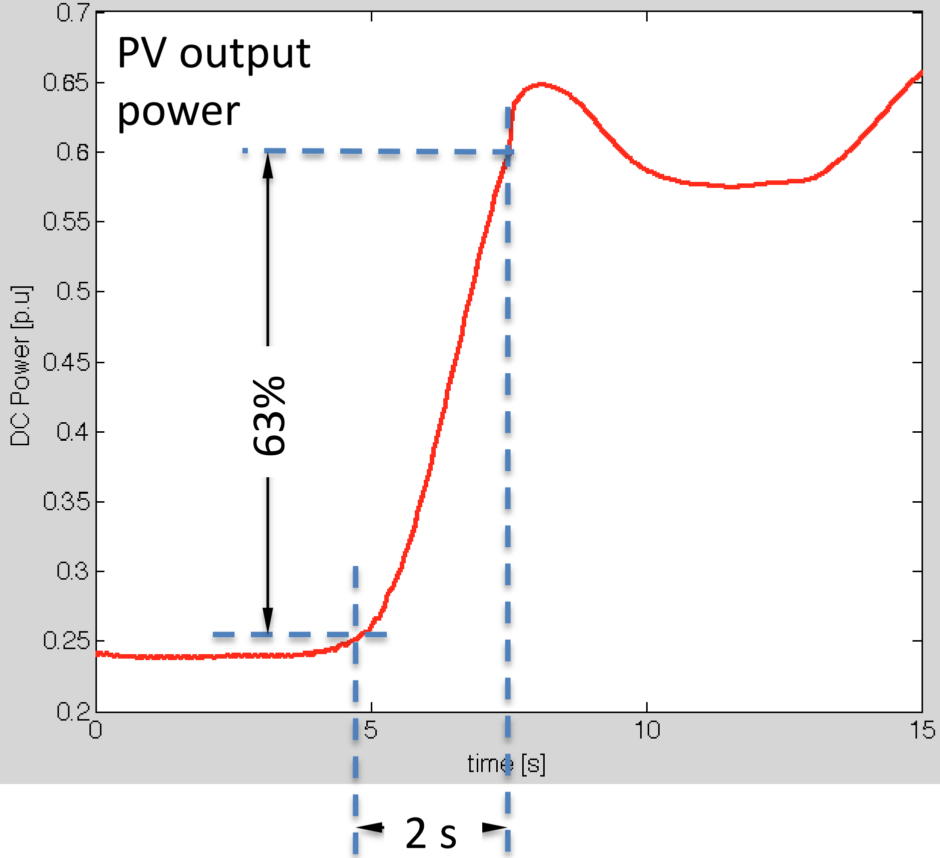
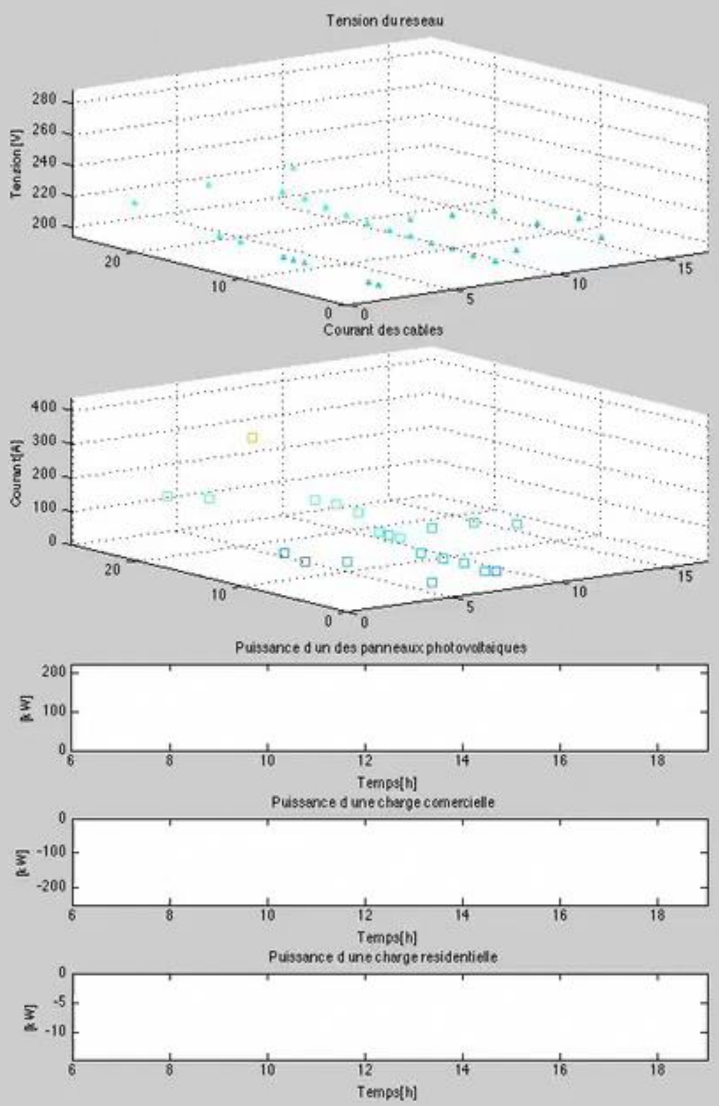
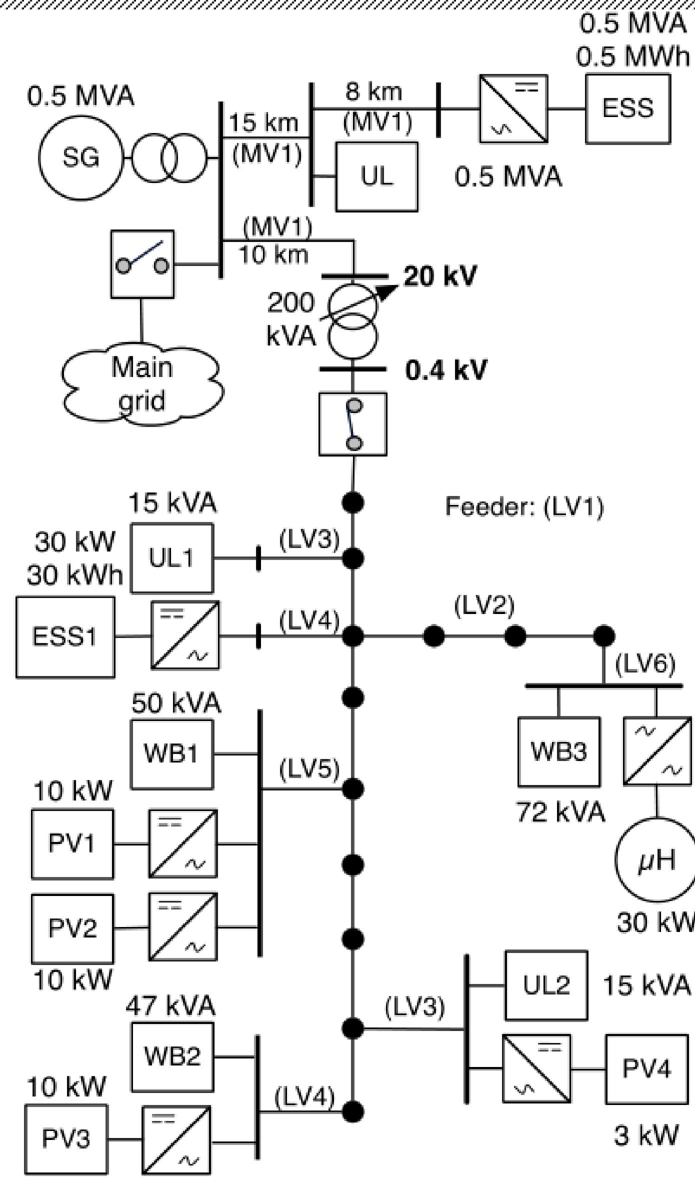




Active Distribution Network Needs



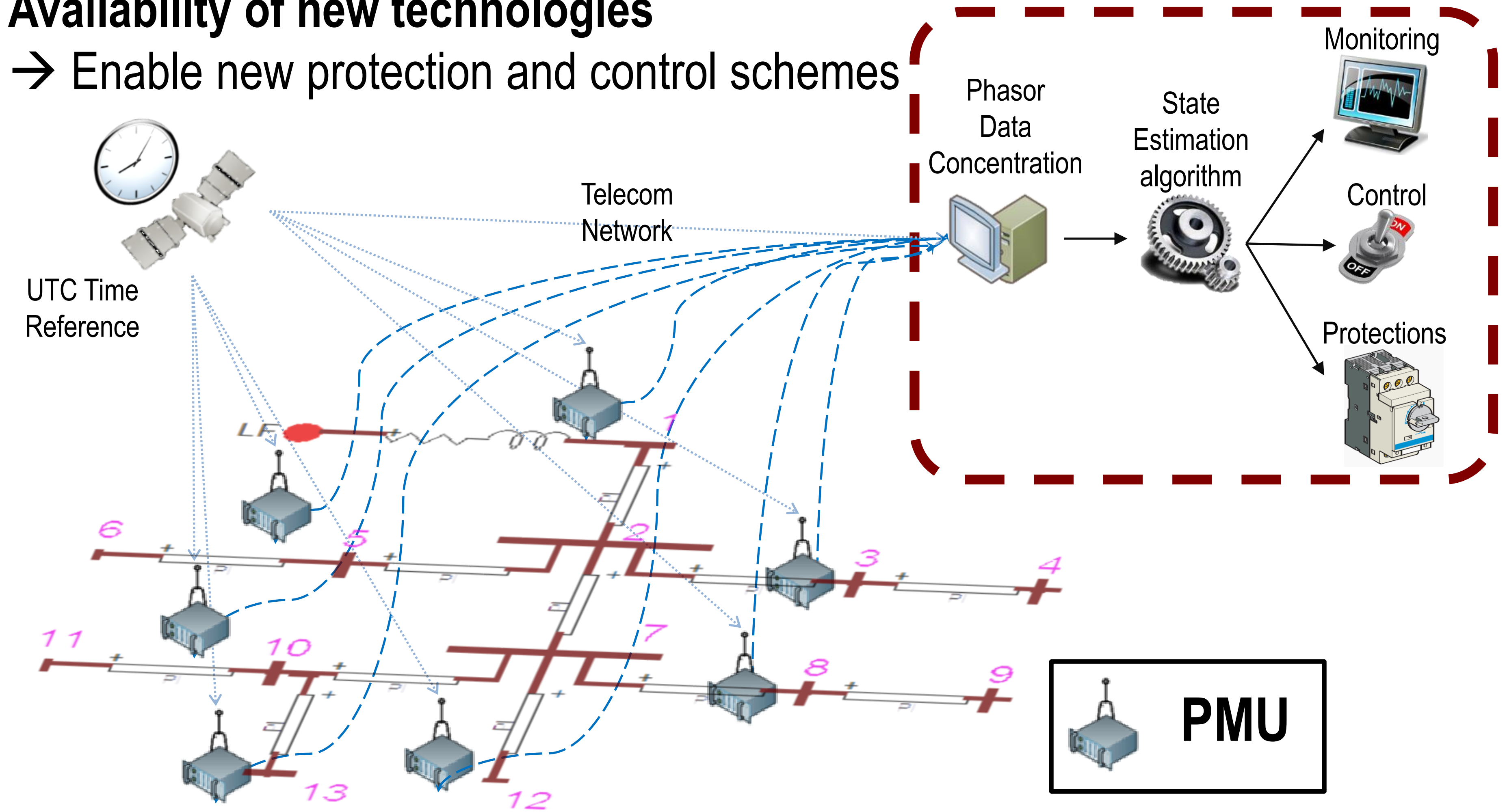


Active Distribution Network Needs

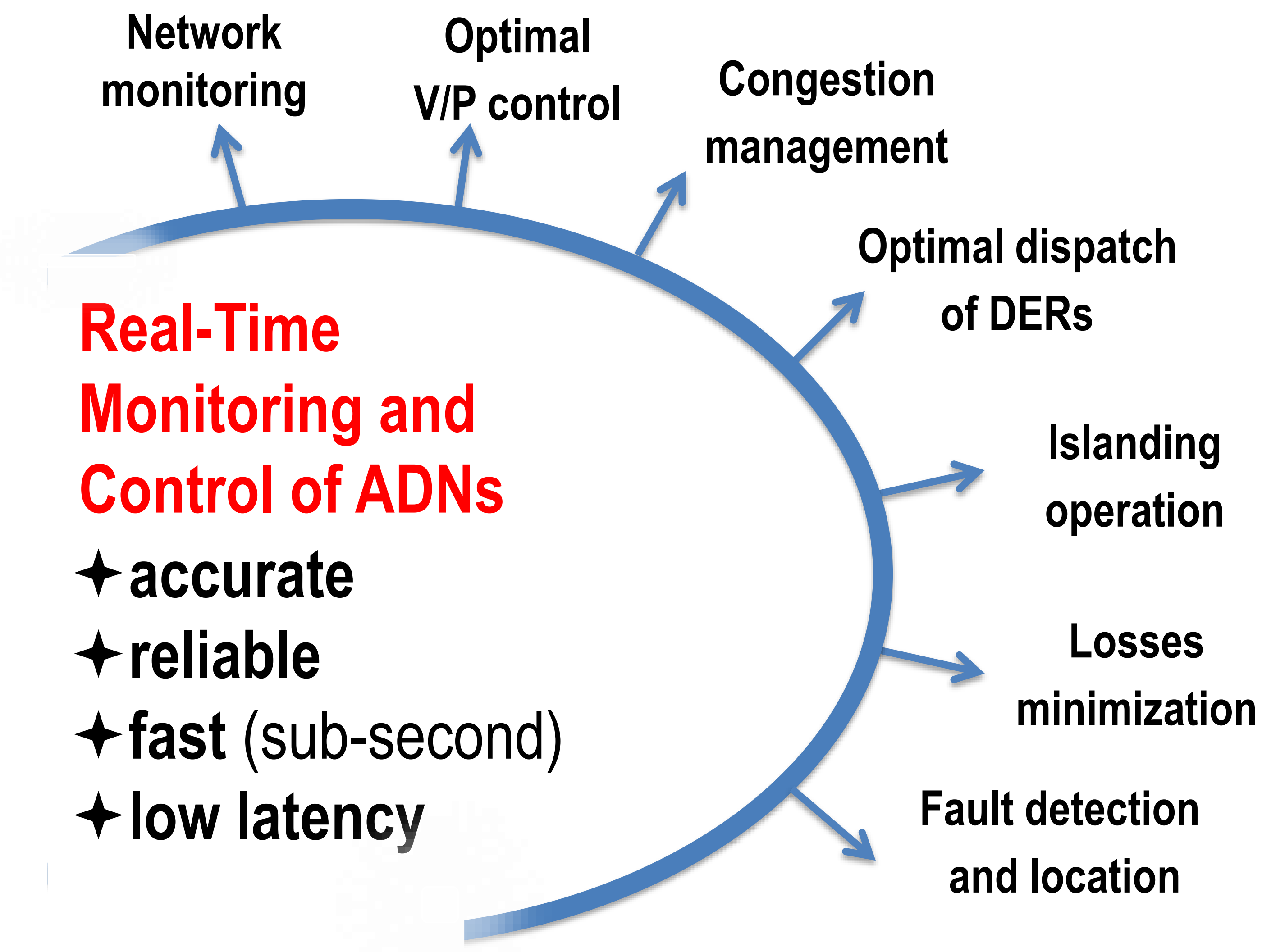
Drivers

Availability of new technologies

→ Enable new protection and control schemes



Active Distribution Network Needs



Real-Time State Estimation via PMUs

Definition 1/2

To fix the ideas, in what follows with the term

Real-Time State Estimation – RTSE

we make reference to the process of **estimating the network state** (i.e., **phase-to-ground node voltages**) with an **extremely high refreshing rate** (typically of **several tens of frames per second**) enabled by the use of **synchrophasor measurements**.

Definition 2/2

Phasor Measurement Unit

(IEEE Std.C37.118-2011)

“A device that produces **synchronized measurements of phasor** (i.e. its **amplitude** and **phase**), **frequency**, **ROCOF** (**Rate of Change Of Frequency**) from voltage and/or current signals based on a **common time source** that typically is the one provided by the **Global Positioning System UTC-GPS**.”

PMU accuracy requirements (IEEE Std C47.118.2011)

Preliminary remarks

1. IEEE Std C37.118.1-2011/2014a: developed for transmission networks PMUs and defines the metrics for the PMU accuracy assessment and their limits.

2. PMUs are evolving towards DSs → accuracy levels beyond IEEE Std C37.118.1-2011/2014a

PMU accuracy requirements (IEEE Std C47.118.2011)

Reporting rates:

System frequency	50 Hz			60 Hz					
Reporting rates (F_s—frames per second)	10	25	50	10	12	15	20	30	60

Performance classes:

- P-class: faster response time but less accurate
- M-class: slower response time but greater precision

Measurement accuracies:

Frequency measurement Error: $$FE = \left| f_{true} - f_{measured} \right|$$

ROCOF measurement Error: $$RFE = \left| \left(df/dt\right)_{true} - \left(df/dt\right)_{measured} \right|$$

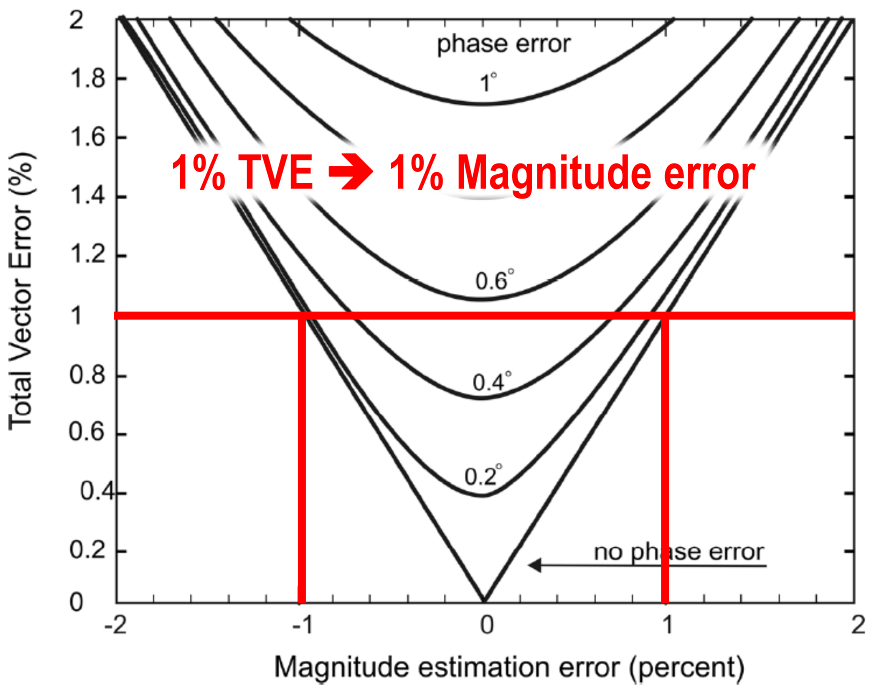
Total Vector Error $$\text{TVE}(n) = \sqrt{\frac{\left(\hat{X}_r(n) - X_r(n)\right)^2 + \left(\hat{X}_i(n) - X_i(n)\right)^2}{\left(X_r(n)\right)^2 + \left(X_i(n)\right)^2}}$$

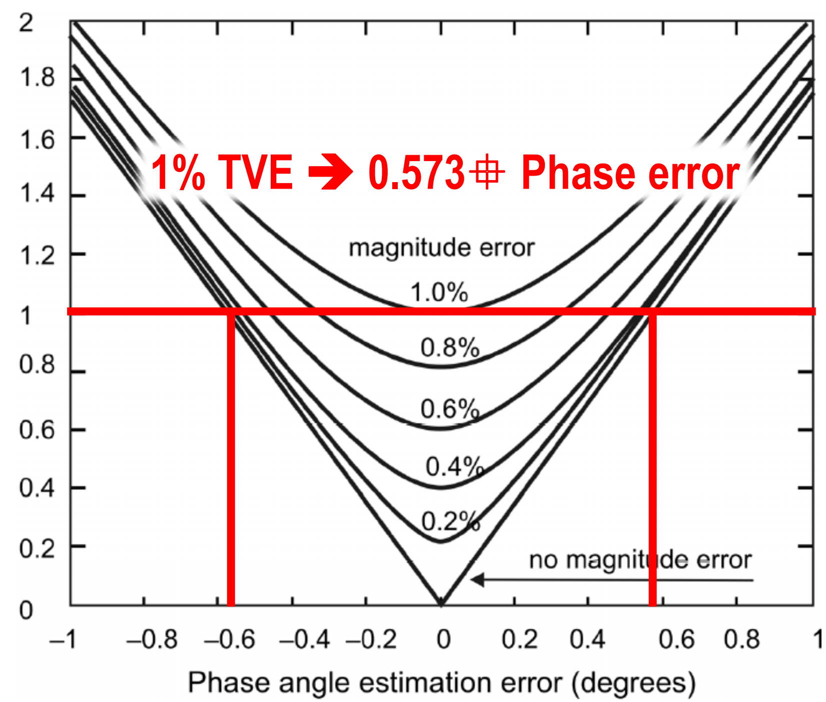
Advanced DNs monitoring via PMUs

IEEE Std. C37.118-2011

TVE limits

$$\mathrm{TVE}(n) = \sqrt{\frac{\left(\hat{X}_r(n) - X_r(n)\right)^2 + \left(\hat{X}_i(n) - X_i(n)\right)^2}{\left(X_r(n)\right)^2 + \left(X_i(n)\right)^2}}$$

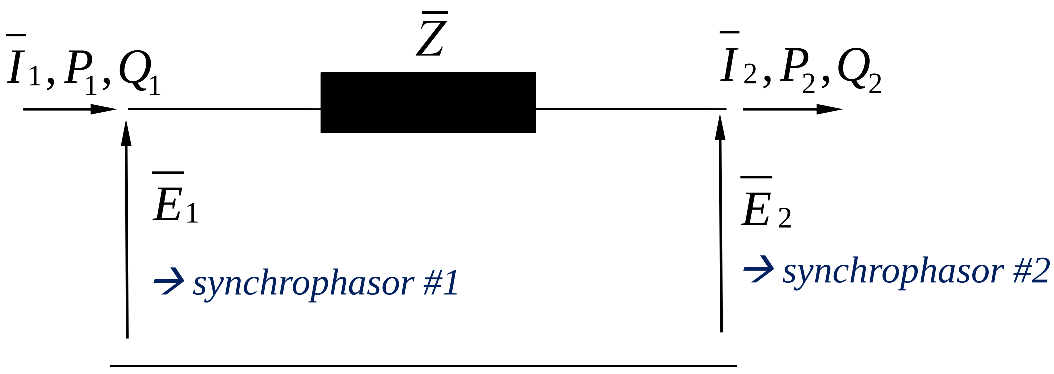




Is a 1% TVE-compliant PMU sufficiently accurate to allow its use in Active Distribution Networks (ADNs)?

Advanced DNs monitoring via PMUs

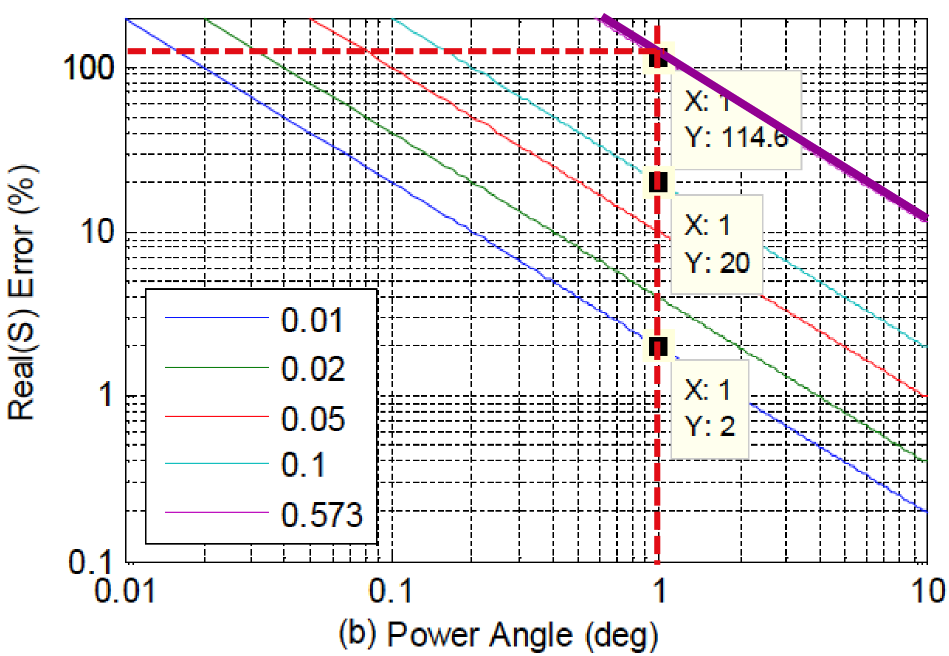
IEEE Std. C37.118-2011 vs. ADNs requirements

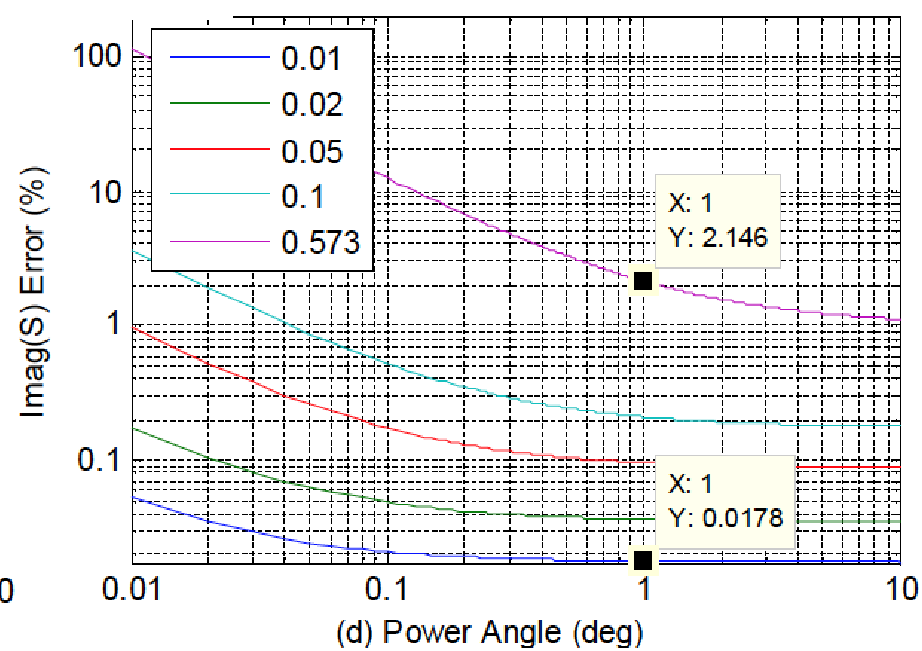


$$\Delta \bar{S}_{12}\Big|_{\Delta\vartheta} = \frac{1 - e^{j(\delta + 2\Delta\vartheta)}}{1 - e^{j\delta}} - 1$$

δ = angle difference between phasors

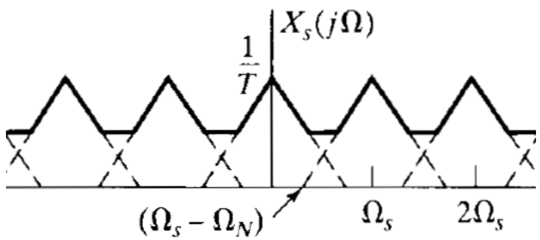
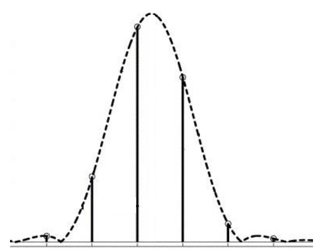
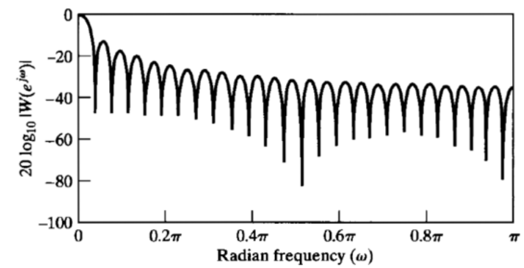
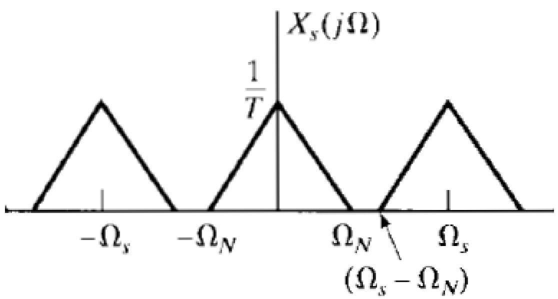
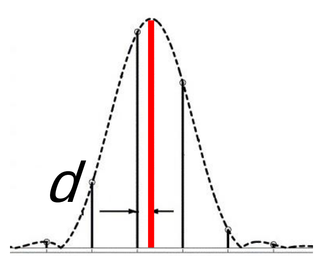
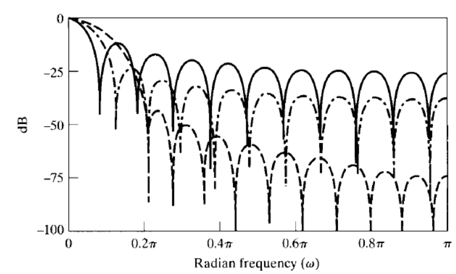
$\Delta\vartheta$ = estimated phase error





The EPFL PMU – Algorithm

Synchrophasor estimation by means of IpDFT

DFT-based algorithms error sources		
Aliasing	**Spectral leakage**	
	Short-term	Long-term
		
IpDFT correction approaches		
Fs > $2f_{max}$ (Nyquist)	DFT bins interpolation	Specific windowing functions
		

The EPFL PMU – Algorithm

IpDFT main limitations and proposed solutions

LATENCY

The measurement reporting latencies are typically proportional to the [illegible] window length (N).

↓

The algorith[illegible] can only be improved [illegible] reducing the window length [illegible]ating the PMU accuracy levels

MSDFT

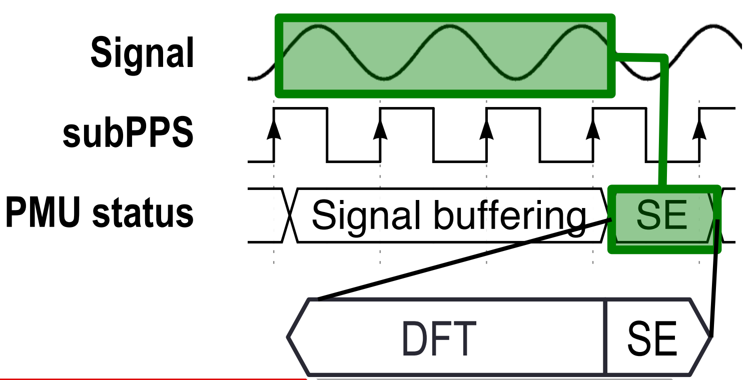
SPECTRAL INTERFERENCE

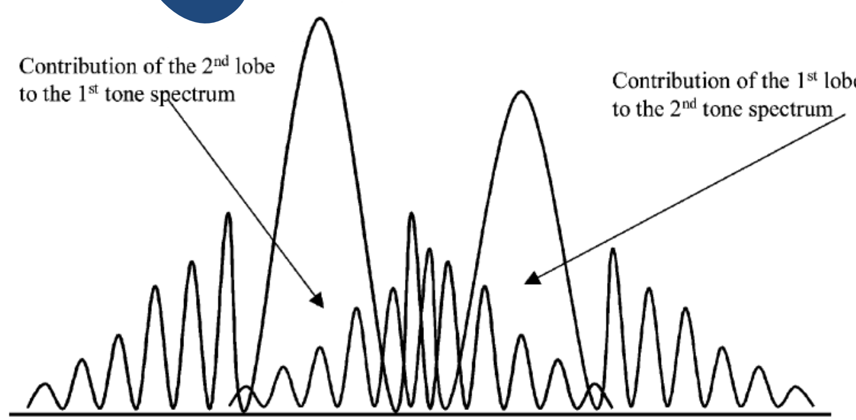
Due to the long-term leakage [illegible]ffects, the neighboring tones might in[illegible] with the main one.

↓

The bins [illegible] [illegible]erform the DFT interpolati[illegible] [illegible]rupted by the tails produce[illegible] [illegible]er tones composing the signal [illegible]m.

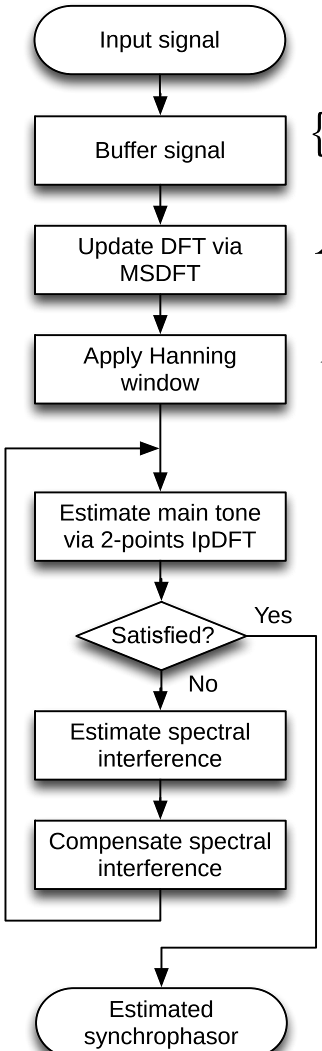
e-IpDFT





The EPFL PMU – Algorithm

e-IpMSDFT process



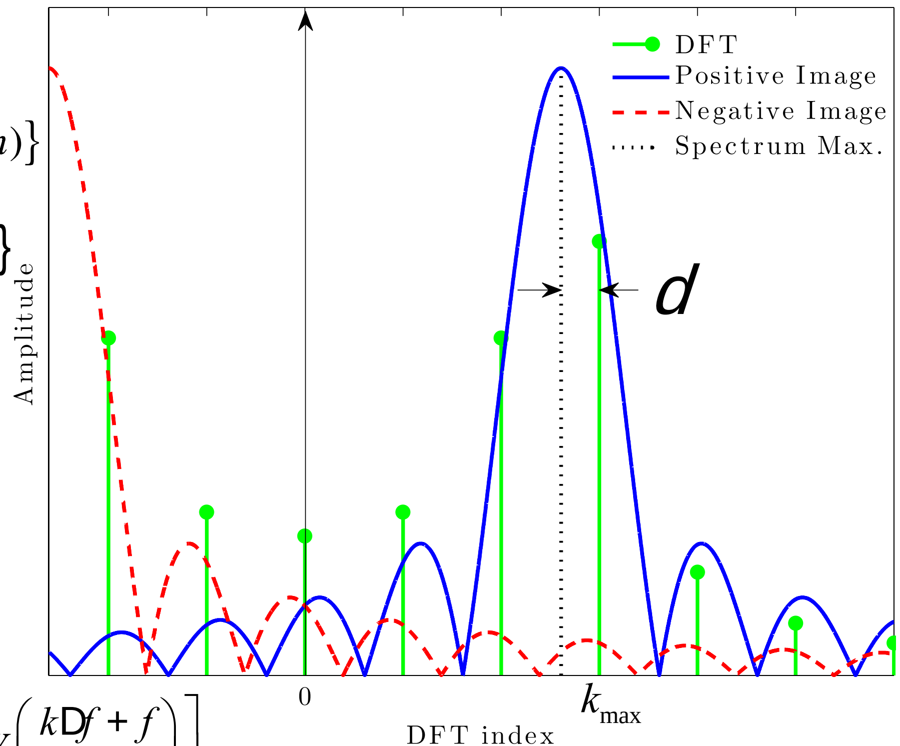
$$x(n)$$

$$\{x(n-M+1), x(n-M+1), \cdots, x(n)\}$$

$$X_k(n),\ k \in k_{\max} + \{-2, -1, 0, +1, +2\}$$

$$X_k(n) = -0.25 \cdot X_{k-1}(n) + 0.5 \cdot X_k(n) - 0.25 \cdot X_{k+1}(n)$$

$$d = \frac{2 \cdot S(k+e) - S(k)}{S(k+e) + S(k)}$$



$$X_k \approx \frac{1}{B}\left[V \cdot W\left(\frac{k\Delta f - f}{\Delta f}\right) + V^* \cdot W\left(\frac{k\Delta f + f}{\Delta f}\right)\right]$$

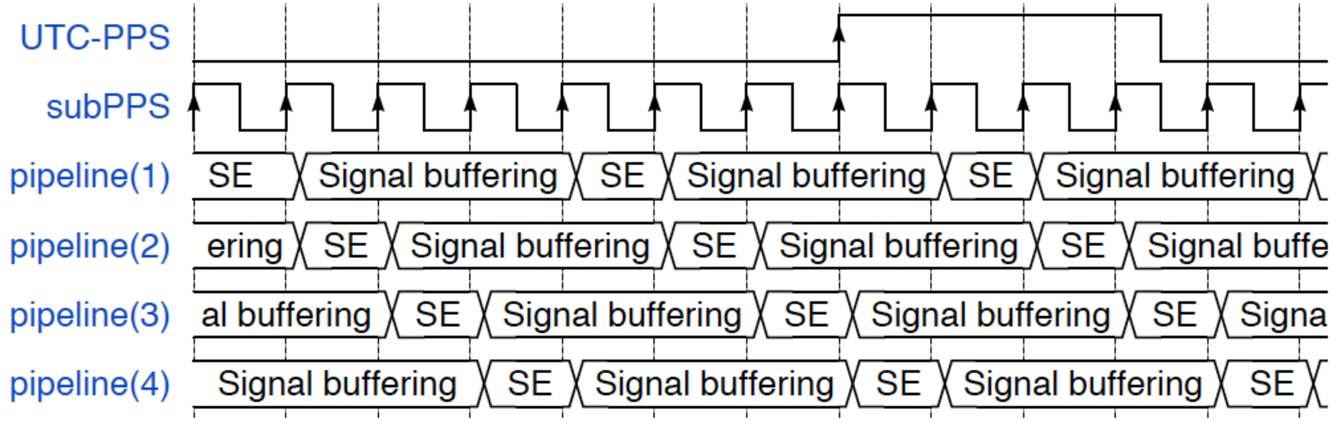
Positive Image — Negative Image

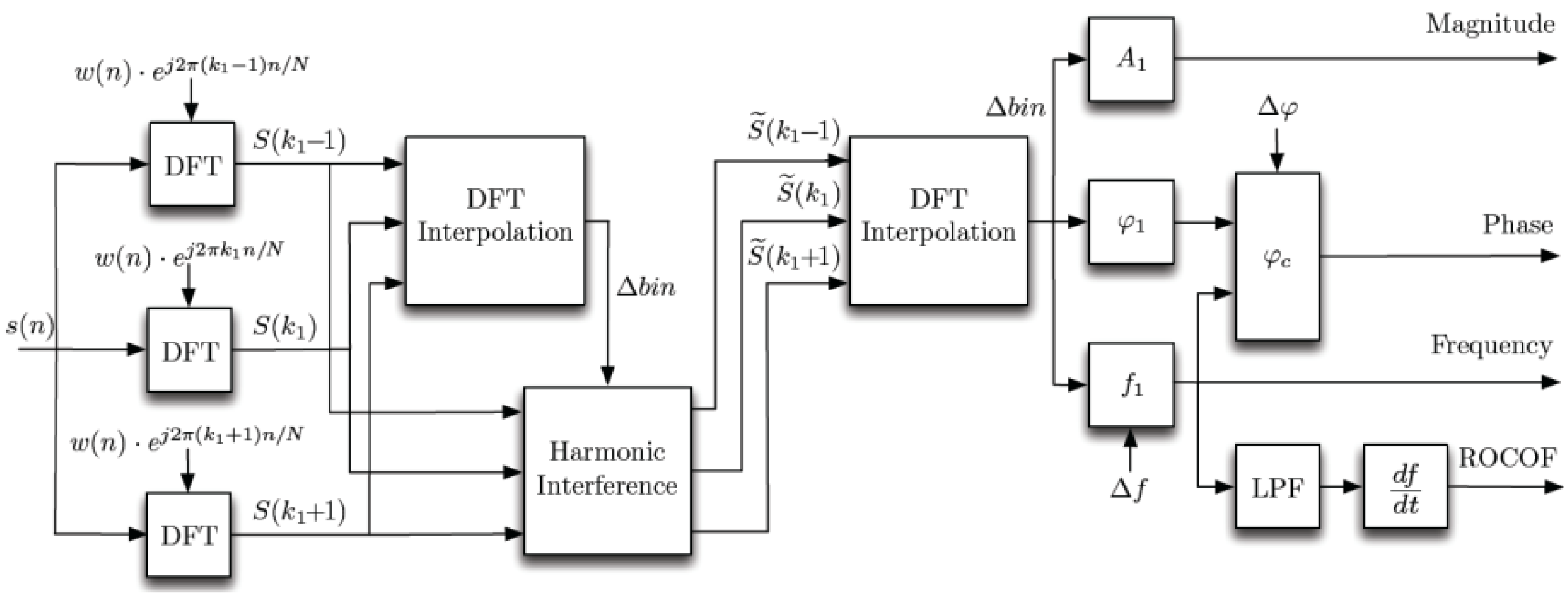
$$\tilde{X}_{k_{\max}} = X_{k_{\max}} - \frac{1}{B} V^* \cdot W\left(2 \cdot k_{\max} + \delta\right)$$

Negative Image

The EPFL PMU – FPGA implementation

FPGA-optimized software implementation



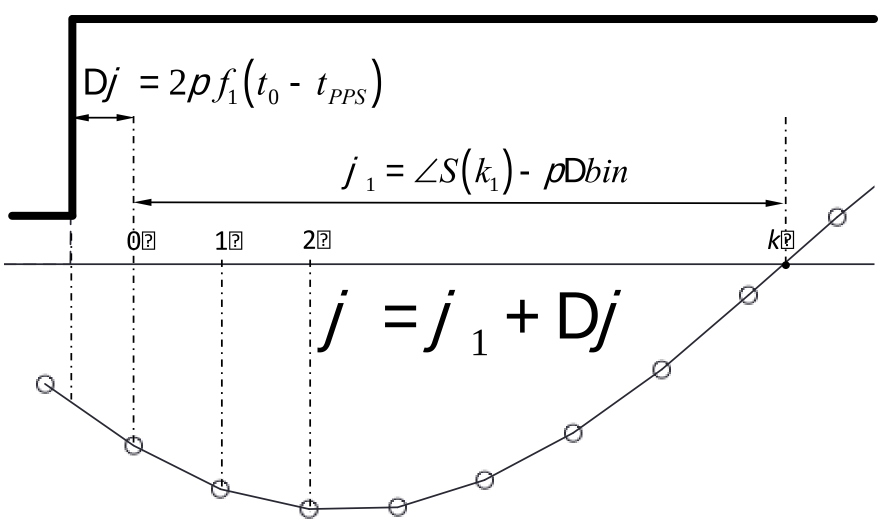


The EPFL PMU – FPGA implementation

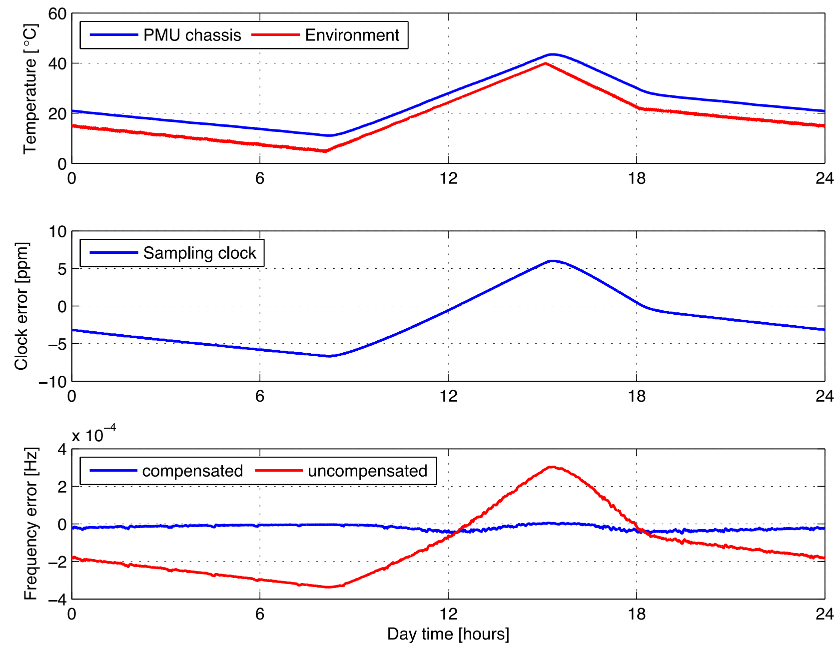
Free-running clock compensation

If a free running clock is adopted for the sampling of the analog waveforms, countermeasures must be taken to face the unavoidable timing issues that this choice generates. Based on the fact that PMUs are inherently equipped with accurate timing units like GPS, the drifts/delays introduced by a free running clock can be easily compensated.

Phase offset compensation

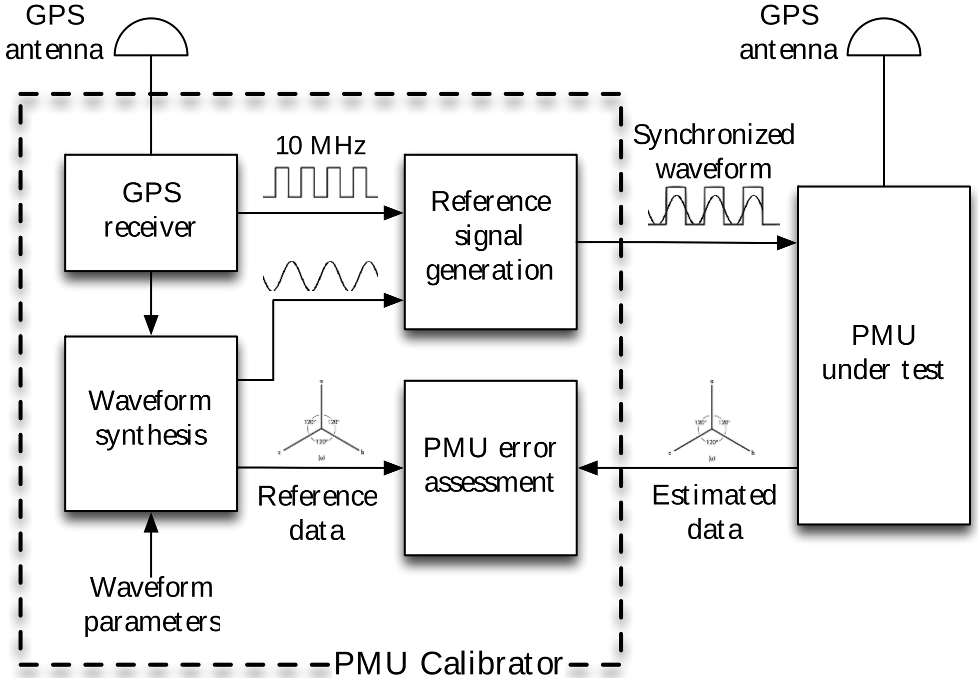


Clock's drift compensation



The EPFL PMU – Metrological performances

PMU realised at the EPFL and its calibration

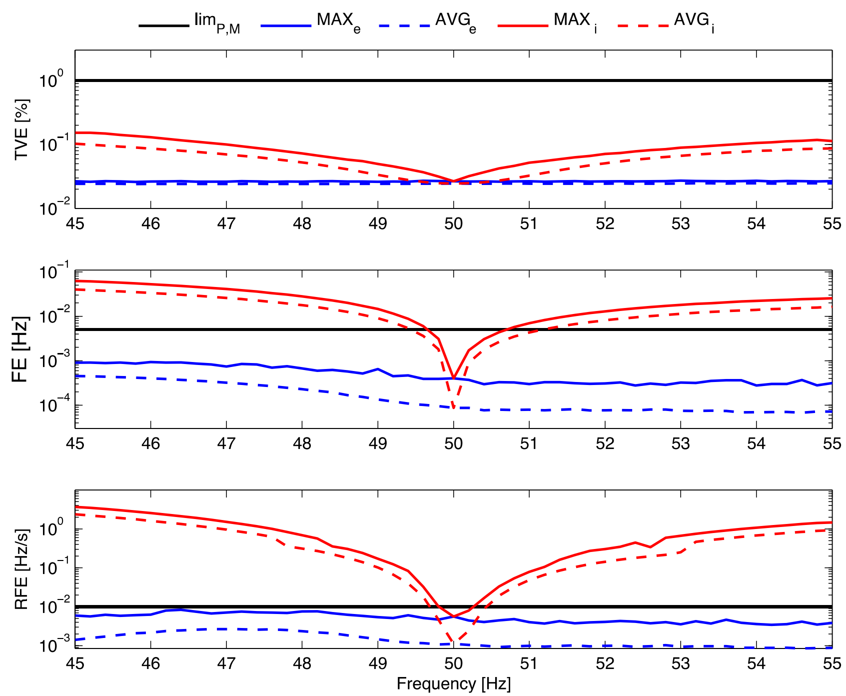


Component	Functionality	Accuracy
Controller	Reference waveform synthesis and PMU error assessment	-
GPS receiver	Synchronization of the signal generation clock to the GPS time reference	± 40 ns, <8 ns std
DAC	Generation (18-bit, 500 kS/s) of a low voltage (± 10 V) reference waveform	1540 µV (max error)

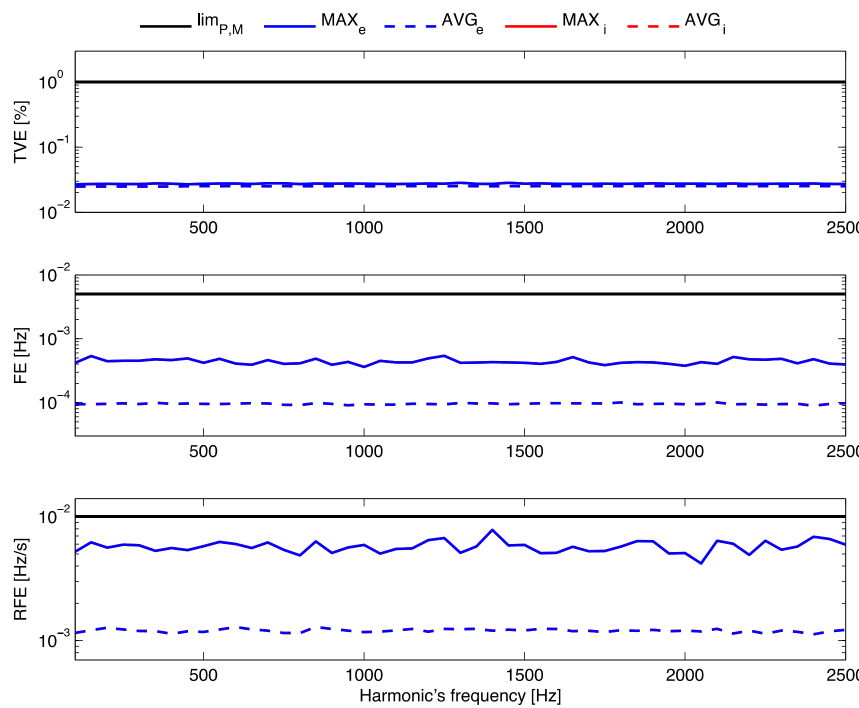
The EPFL PMU – Metrological performances

Compliance to IEEE Std. C37.118-2011 – Static tests

SINGLE TONE SIGNALS



MULTI TONE SIGNALS



Comments:

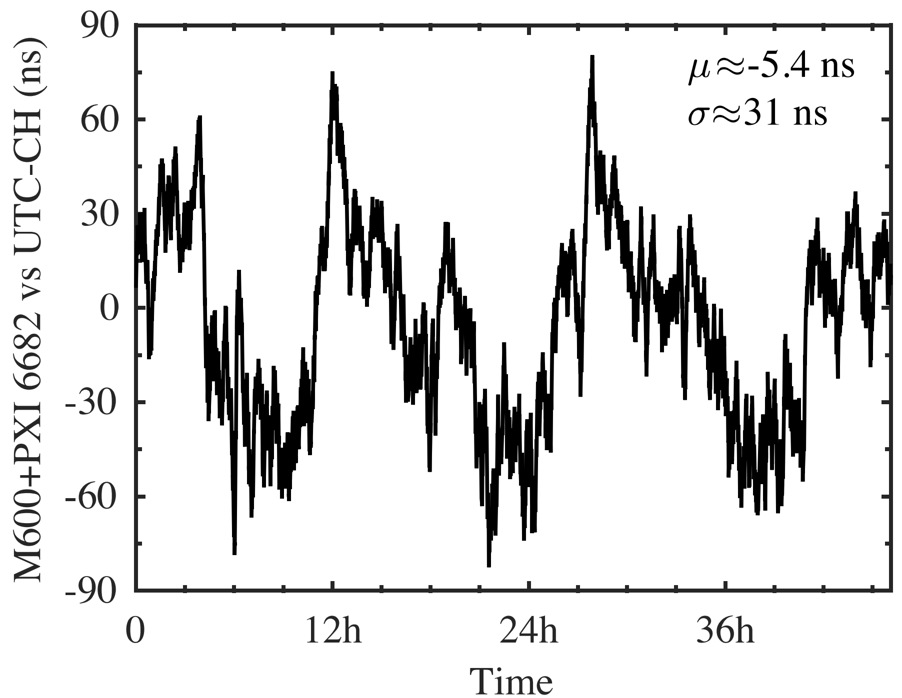
- TVE_{max} = 0.027 % – TVE_{avg} = 0.024 % **(1.5 µrad)**
- FE_{max}= $4 \cdot 10^{-4}$ – FE_{avg}= $9 \cdot 10^{-5}$
- RFE_{max}= $6 \cdot 10^{-3}$ – RFE_{avg} = $1 \cdot 10^{-3}$

Comments:

- Identical performances w.r.t. single tone signals
- Perfect harmonic rejection

The issue of the long-term time stability (> 24 h)

- PMU under test and Calibrator referenced to UTC via GPS-PPS signal

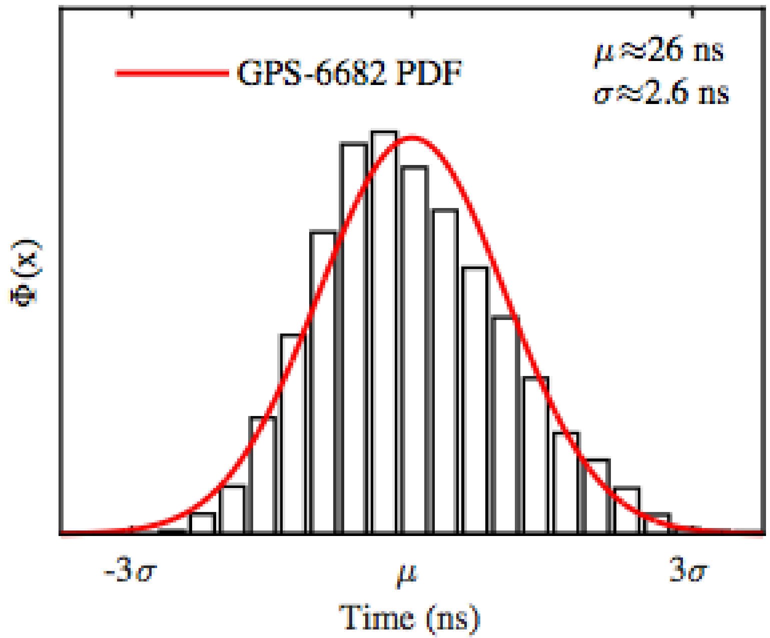


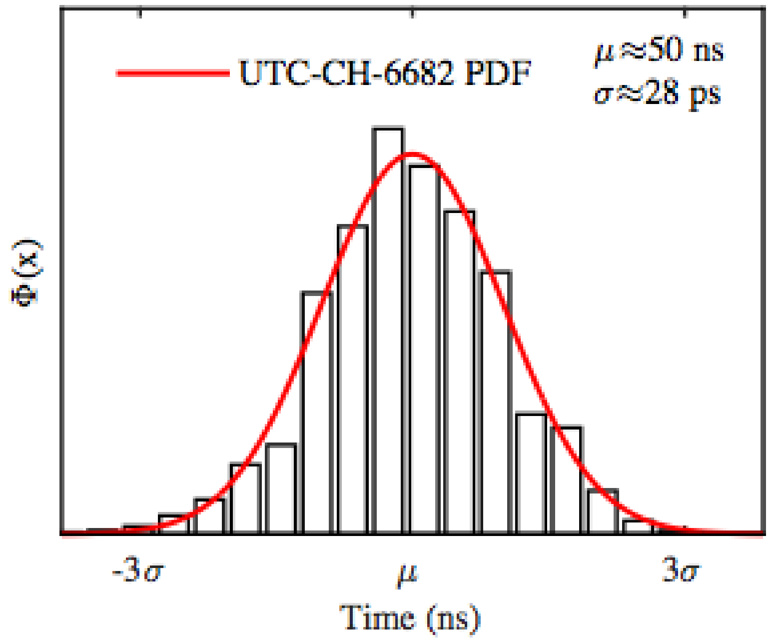
Δt_{TE} caused by two GPS-receivers ≈ 100 ns (30 µrad @ 50 Hz)

The importance of the master clock

Two configurations have been compared

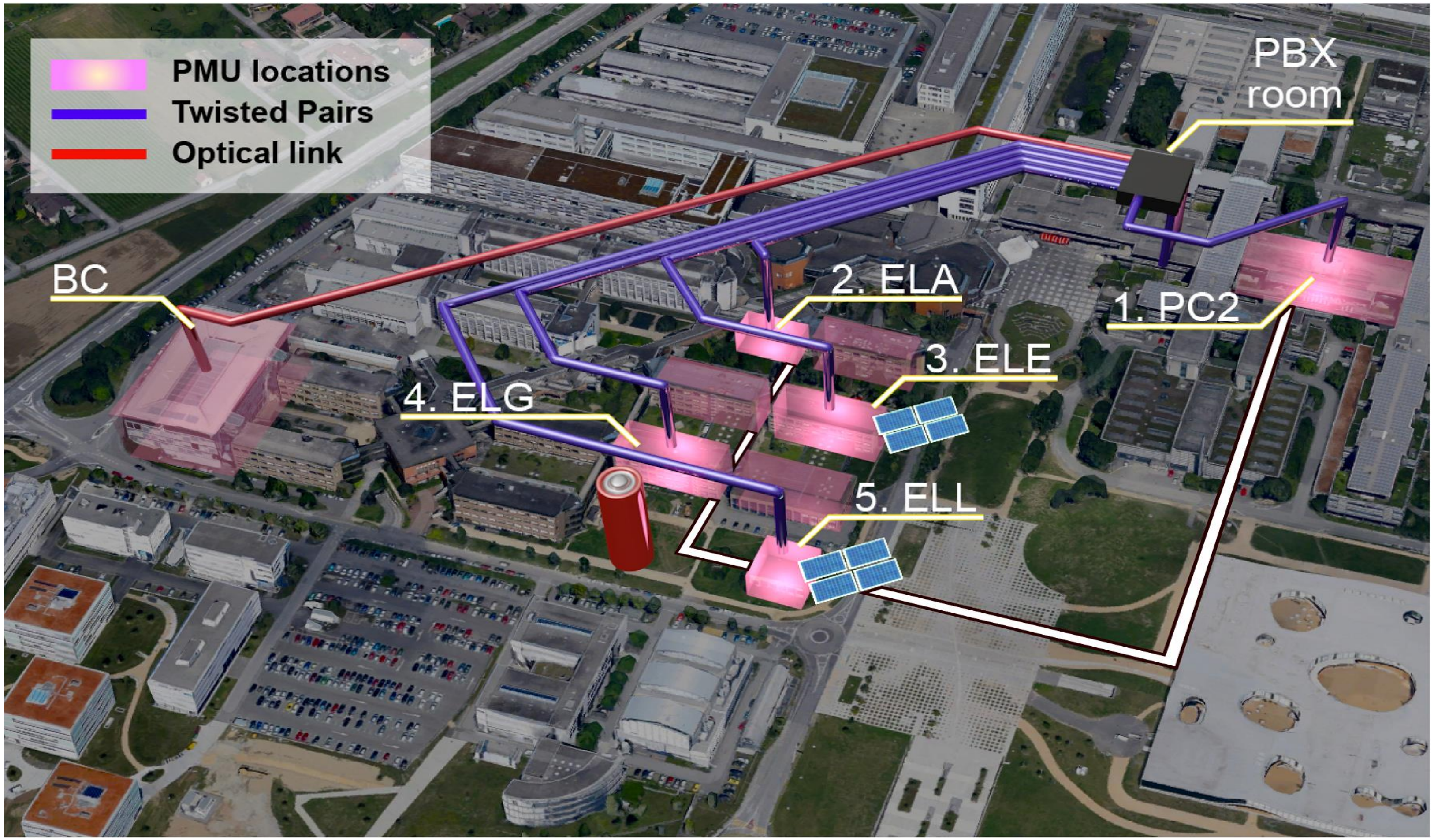
- PXI-6682 using a master clock disciplined by GPS
- PXI-6682 using a master clock disciplined by UTC-CH





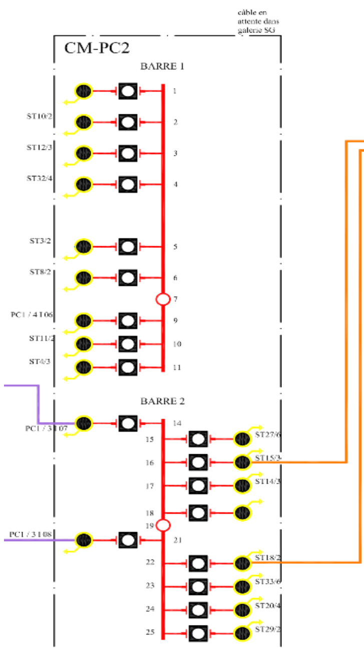
Real-Time State Estimation via PMUs

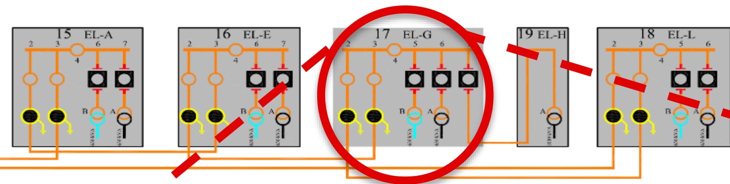
First achievement: PMU-based real-time state estimator of the EPFL MV grid



Real-Time State Estimation via PMUs

Phasor Measurement Units (class-P) specific for ADNs monitoring





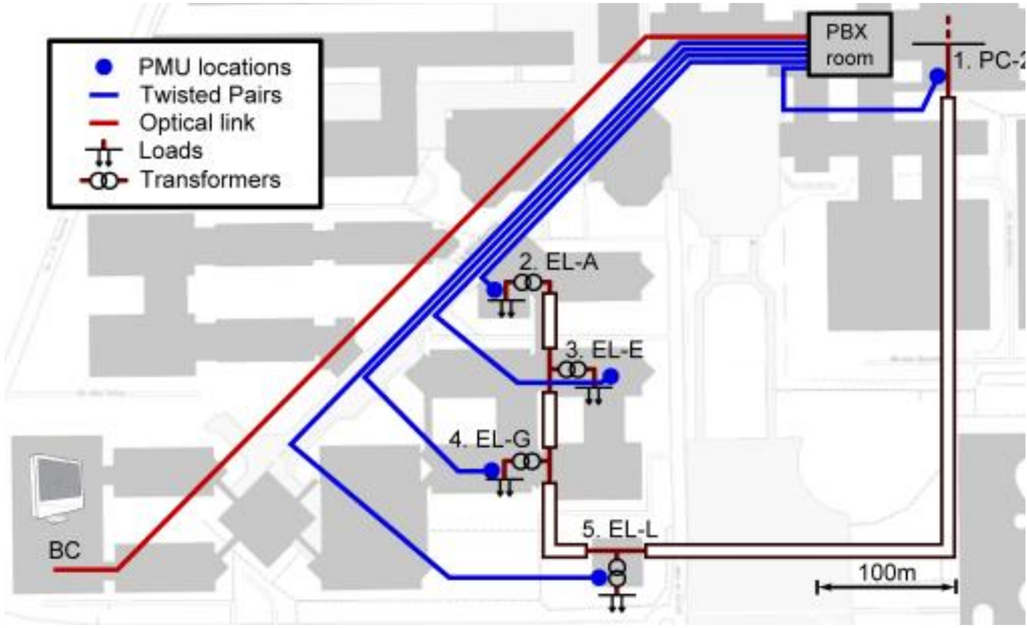
Voltage and current 0.1-class Sensors

Rack with UPS, router and PMU

Real-Time State Estimation via PMUs

Communication network

- SHDSL links (2 Mb/s) PMUs and telephone exchange room (PBX).
- DSLAM installed (PBX) to concentrate the traffic (star network)
- Optical link (100 Mb/s) between PBX and BC building.



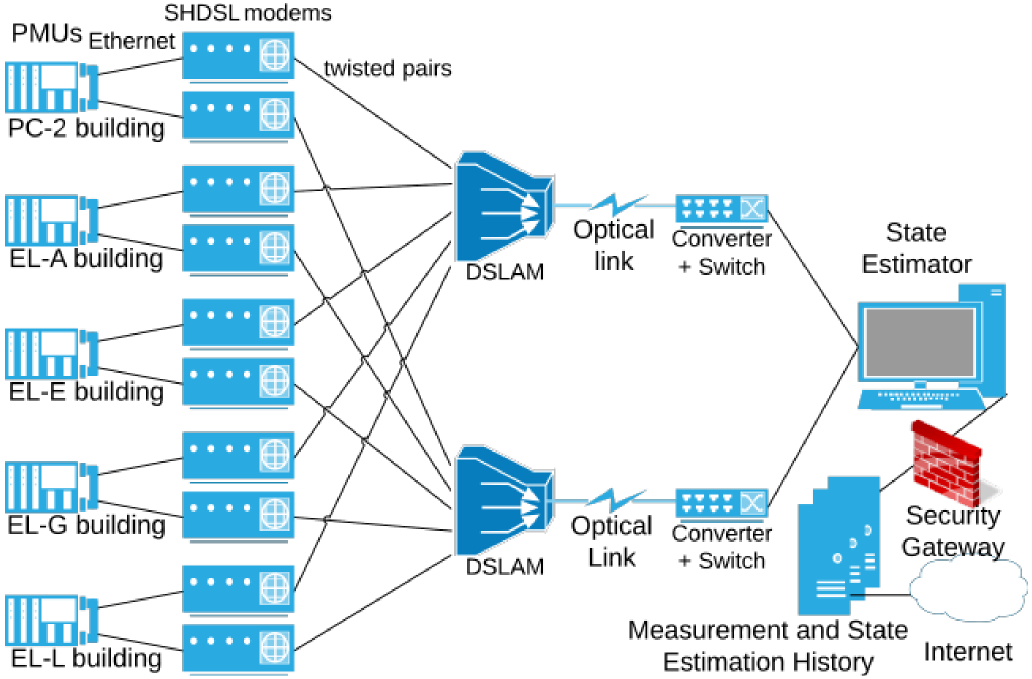
- The network is traffic engineered = > no traffic congestion.
- RTT in the order of 3-4 ms, no losses (e.g. one observed period of 10h).
- Communication network resilient to power outages. It is duplicated to protect against failure of any device. To this end we use IPRP.

Real-Time State Estimation via PMUs

Communication network

Redundancy protocol to ensure 0-ms switchover in case of any single network failure.

- Inspired by Parallel Redundancy Protocol (PRP) but designed to work with IP routed networks and multicast destination addresses.
- At the sender side every outgoing packet is duplicated and labeled with a sequence number.
- Two copies are transferred over two fail-independent IP networks.

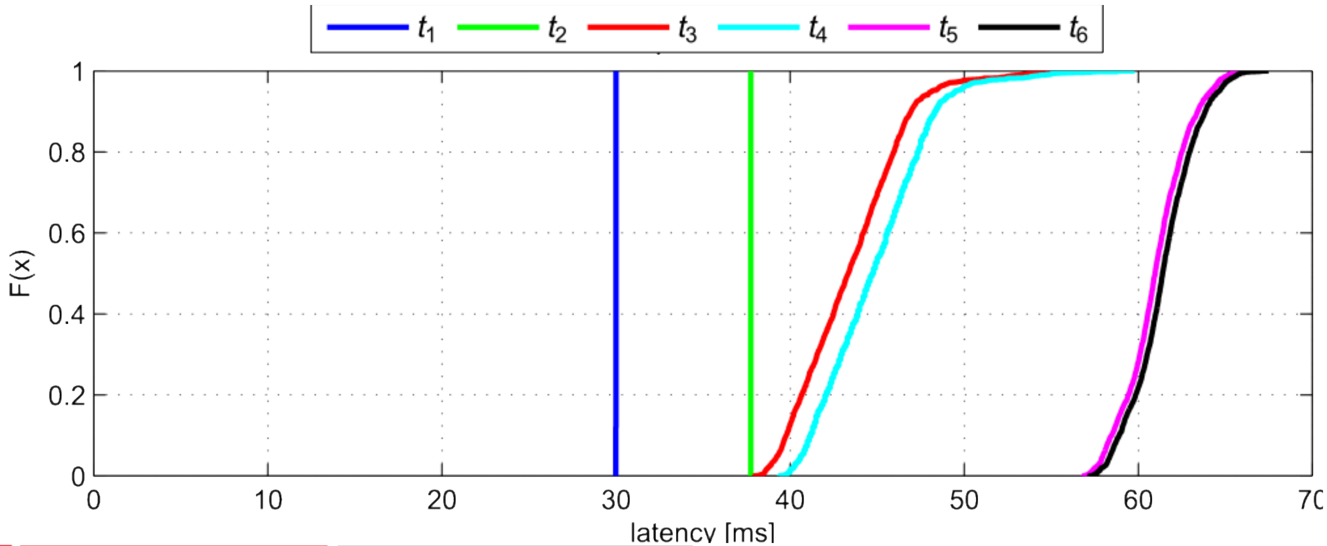


Real-Time State Estimation via PMUs

Total latency of the process

PMU		Telco	PDC+RTSE		
Signal acquisition	Synchrophasors estimation and data encapsulation	Telco network delay	Data frame time-alignment	Bad-data Detection	State Estimation
t1 (~30 ms)	**t2 (~10 ms)**	**t3 (~1-3 ms)**	**t4 (0-20 ms)**	**t5 (<1 ms)**	**t6 (<1 ms)**

Time



Total latency:

- **61 ms (mean)**
- **1.8 ms (std)**

Conclusions

- Future monitoring systems of Active Distribution Networks are expected to make large use of **Phasor Measurement Units.**
- These devices require **synchrophasor phase estimation** characterized by accuracies in the order to **ppm of radians** and **response times** in the order of **few ms**. These requirements call for
  - high computational determinism to minimize jitter of the time latency;
  - **synchronization of distributed metering systems with jitters of few tens of ns → peculiarities of the PTPv3 enable a potential improve of PMU accuracy and, also, reliability.**
- **Dedicated hardware platforms are needed to achieve these requirements.**