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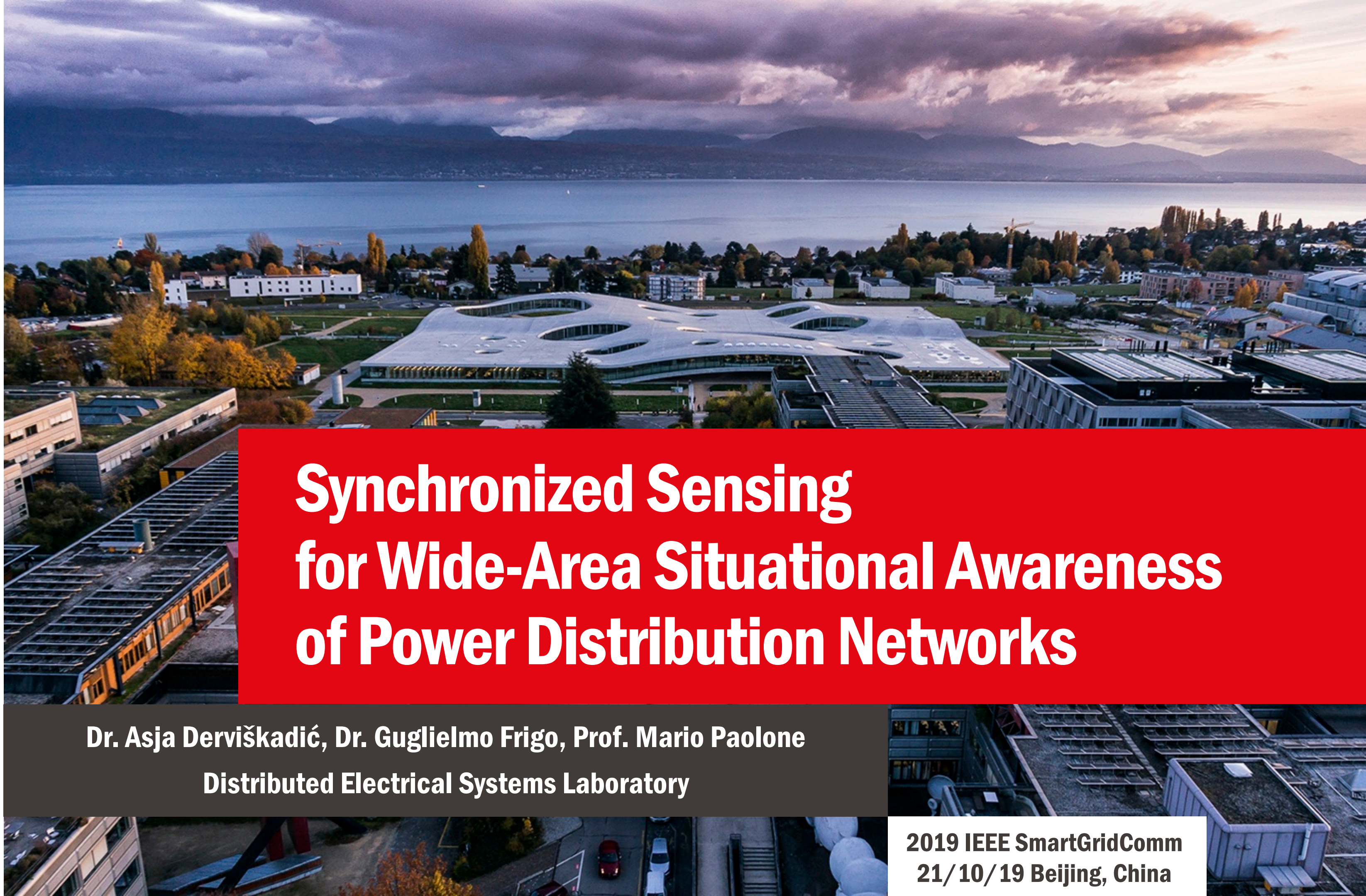

Synchronized Sensing for Wide-Area Situational Awareness of Power Distribution Networks

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École polytechnique fédérale de Lausanne

Outline

- Synchrophasor Networks and Phasor Measurement Units
- The Iterative-Interpolated Discrete Fourier Transform and its Application to Synchrophasor Estimation
- Advanced Calibrator for the Metrological Characterization of PMUs
- Time Dissemination Techniques for PMUs

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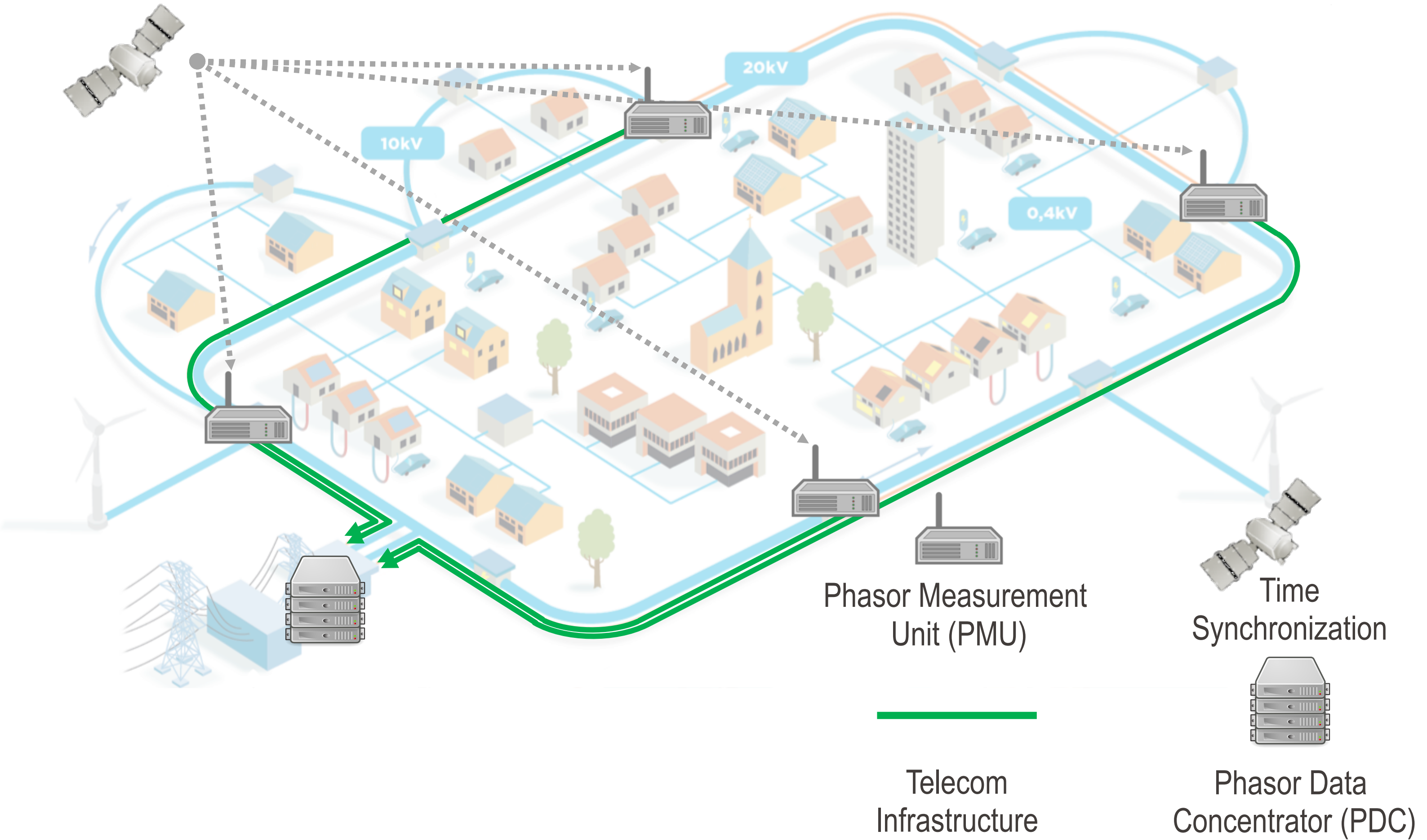
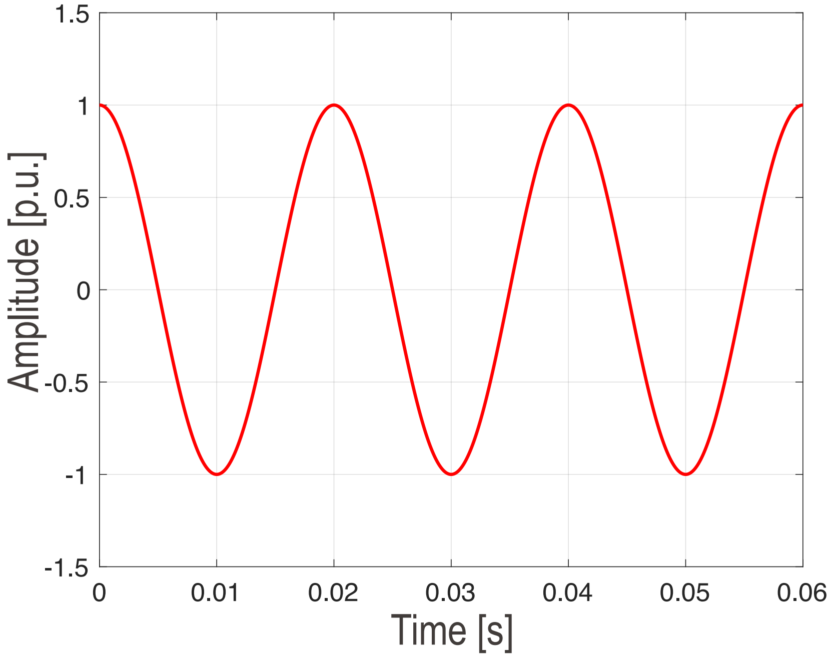
Situational Awareness in Power Grids via PMUs

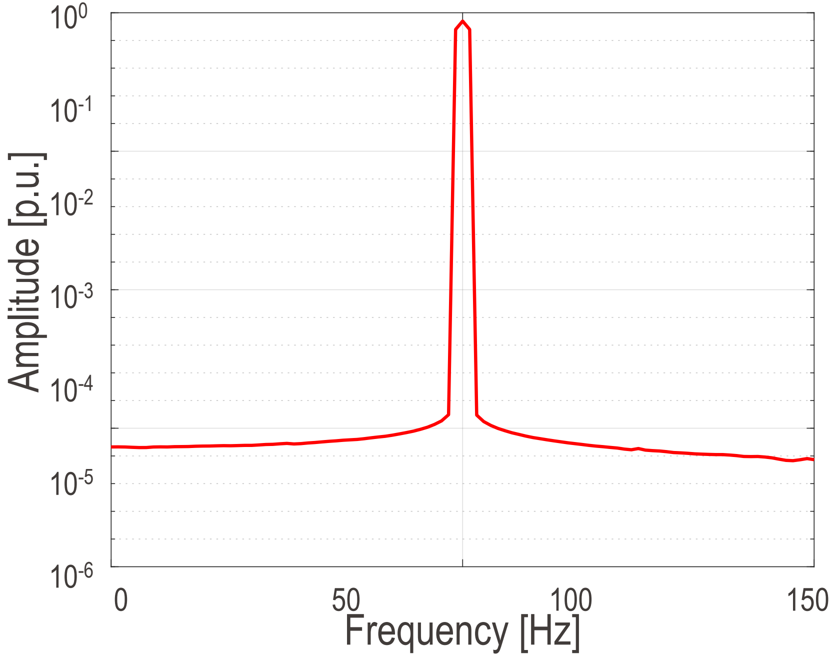


The Synchrophasor Model vs Power System Signals

Phasor ➔ Nominal operating conditions signal model

$$x(t) = A_0 \cdot \cos(2\,\pi\, f_0 t + \varphi_0) = A_0 \cdot \cos \Phi_0 \qquad \leftrightarrow \qquad X = A_0 \cdot e^{j\Phi_0}$$

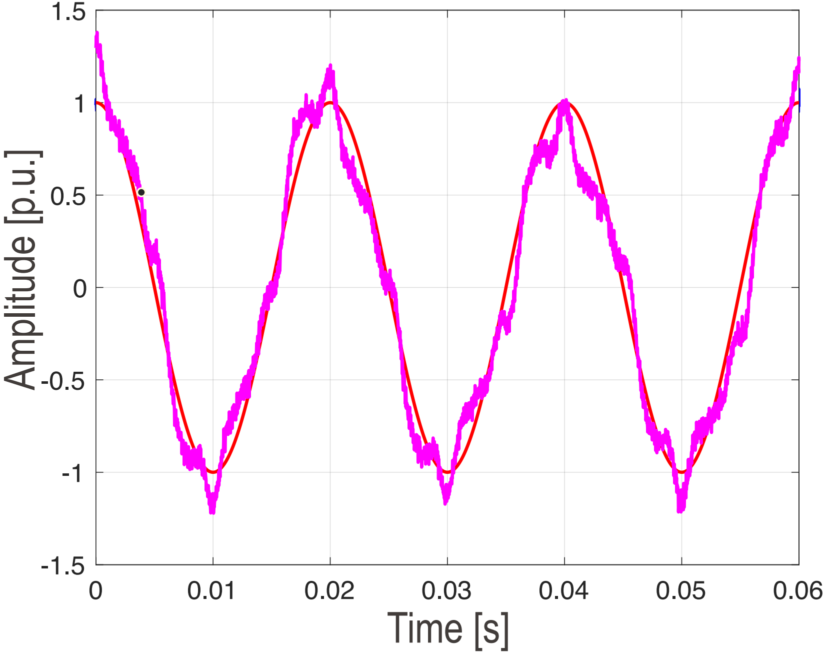


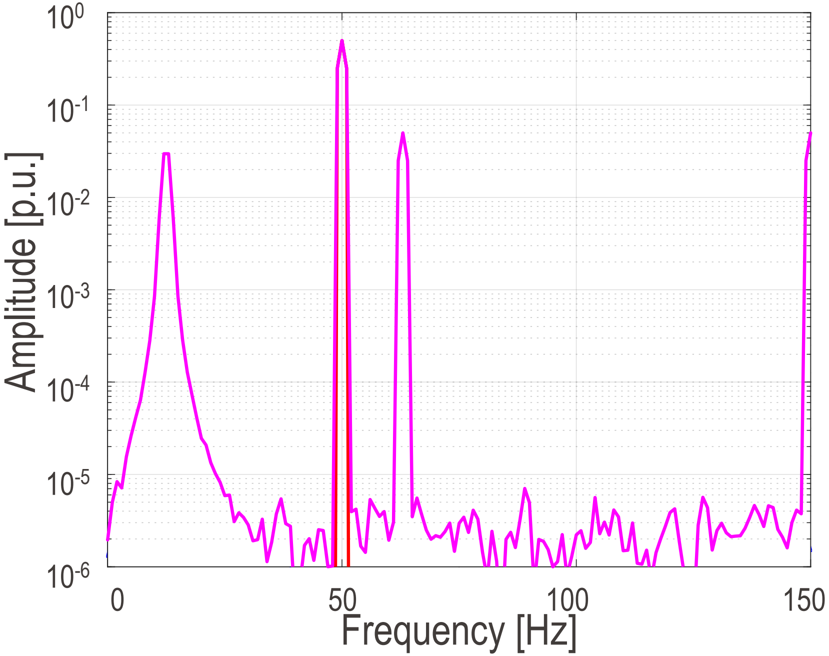


The Synchrophasor Model vs Power System Signals

Distorted operating conditions: static

$$x(t) = A_0 \cdot \cos(2\,\pi\,f_0\,t + \varphi_0) + \nu(t) + \eta(t)$$

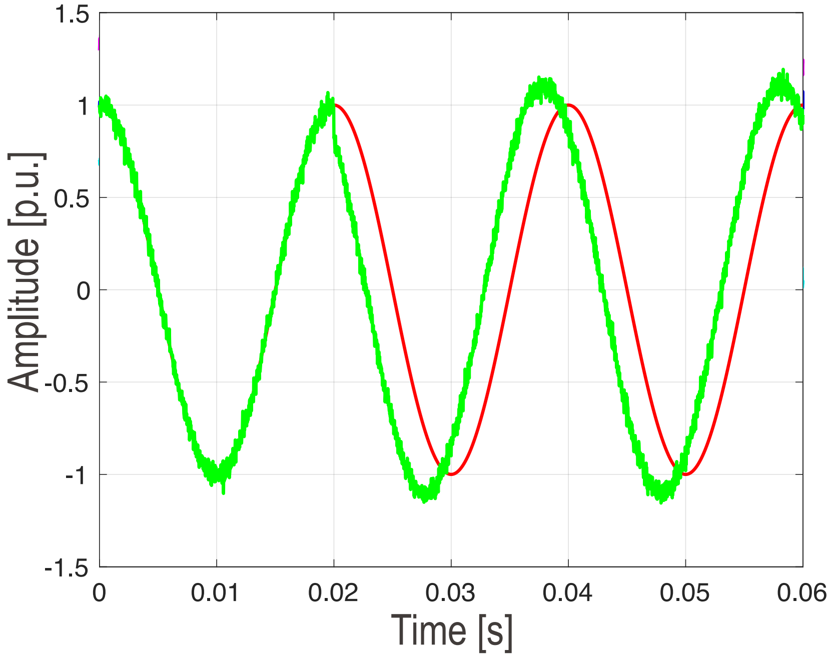


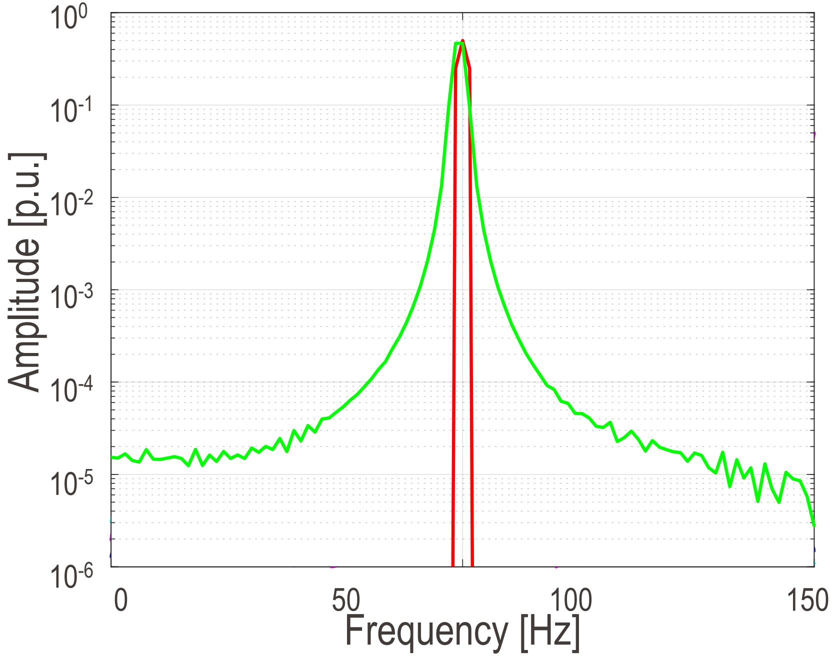


The Synchrophasor Model vs Power System Signals

Distorted operating conditions: dynamic

$$x(t) = A_0(t)\left(1 + \varepsilon_{A_0}(t)\right) \cdot \cos\left(2\pi f_0(t)t + \varphi_0 + \varepsilon_{\varphi_0}(t)\right) + \nu(t) + \eta(t) + \gamma(t)$$





The Synchrophasor Model vs Power System Signals

Dr. Asja Derviškadić

- Phasor

$$x(t) = A_0 \cdot \cos(2\,\pi\, f_0\, t + \varphi_0\,) = A_0 \cdot \cos(\Phi_0) \leftrightarrow A_0 \cdot e^{j\Phi_0}$$

- Realistic non-stationary power system signal model

$$x(t) = A_0(t)\,\left(1 + \varepsilon_{A_0}(t)\right) \cdot \cos\left(2\pi f_0(t)\,t + \varphi_0 + \varepsilon_{\varphi_0}(t)\right) + \eta(t) + \gamma(t) + \nu(t)$$

- Synchrophasor signal model [IEEE Std. C37.118 & IEEE/IEC 60255-118-1-2018]

$$x(t) = A_0(t) \cdot \cos(2\,\pi\, f_0(t)\, t + \varphi_0\,) \leftrightarrow A_0(t) \cdot e^{j\Phi_0(t)}$$

Outline

- Synchrophasor Networks and Phasor Measurement Units
- The Iterative-Interpolated Discrete Fourier Transform and its Application to Synchrophasor Estimation

  A. Derviškadić, P. Romano, M. Paolone, "*Iterative-interpolated DFT for synchrophasor estimation: A single algorithm for P- and M- class compliant PMUs,*" in IEEE Transactions on Instrumentation and Measurements, March 2018.
- Advanced Calibrator for the Metrological Characterization of PMUs
- Time Dissemination Techniques for PMUs

Motivation

i-IpDFT for Synchrophasor Estimation

- Grids characterized by high shares of harmonic and interharmonic components
- IEEE Std. C37.118 (IEEE/IEC 60255-118-1-2018)

↙	↘
P-class	M-class
Protection → Latency	**Measurement** → Accuracy

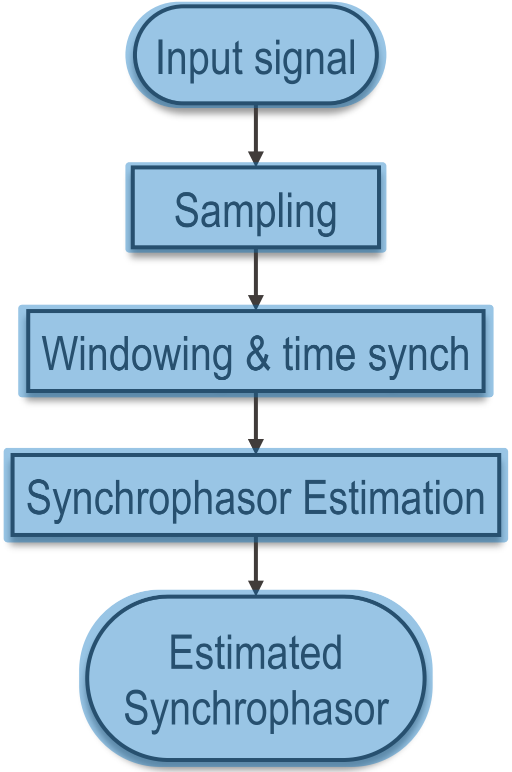
Single PMU satisfying both the P and M-class PMU requirements at the same time?

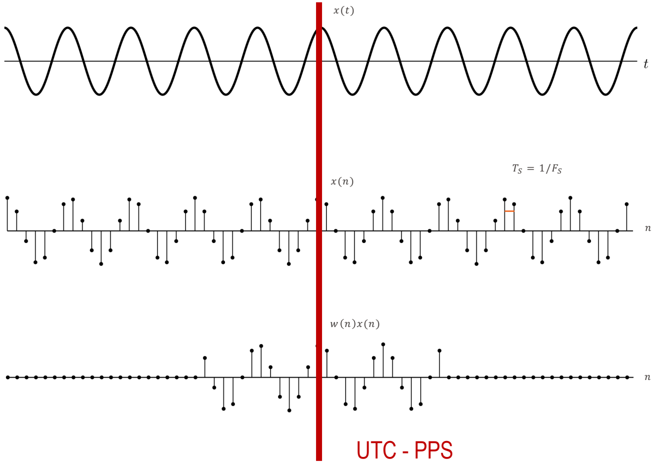
↓

- **Lower cost**: the same PMU simultaneously supplies monitoring and protection functionalities
- **Higher measurement reliability**: protection and control applications are not degraded by disturbances (interharmonics)

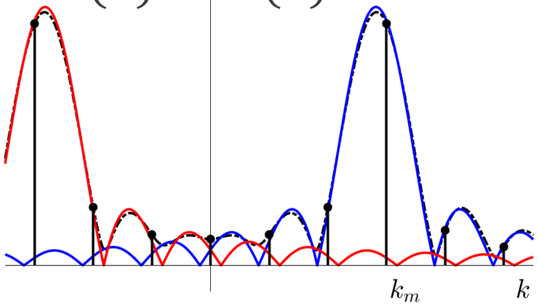
DFT-based Synchrophasor Estimation Algorithms

Dr. Asja Derviškadić





$x(n)$ ➔ $X(k)$ ➔ ?



Frequency f_0, Amplitude A_0, Phase φ_0

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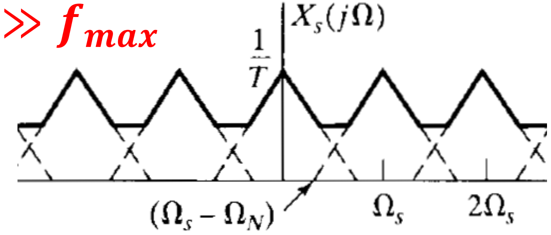
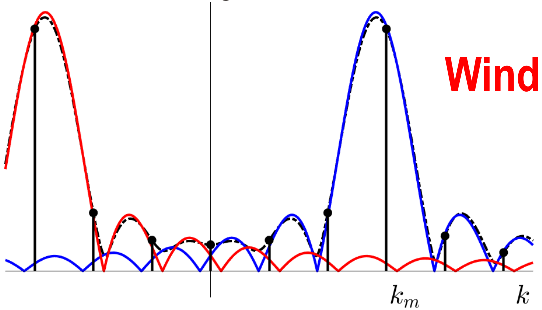
DFT-based Synchrophasor Estimation Algorithms

Aliasing

$F_s \gg f_{max}$

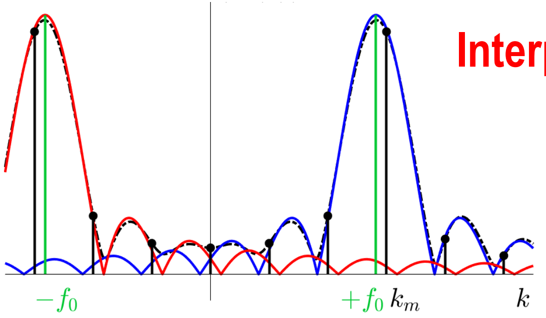


Incoherent Sampling ➔ **Spectral Leakage**



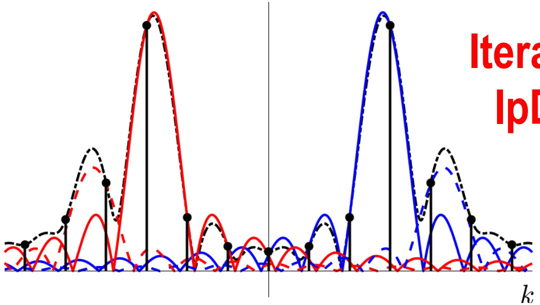
Windowing

Incoherent Sampling ➔ **Spectral Sampling**



Interpolation

Harmonic/Interharmonic **Interference**



Iterative IpDFT

Time-invariant parameters

Short window length

The Interpolated DFT (IpDFT)

Dr. Asja Derviškadić

The IpDFT is a technique to extract the parameters f_0, A_0 and φ_0 of a sinusoidal waveform by interpolating the highest DFT bins of the signal spectrum. It mitigates the effects of **incoherent sampling** ($f_0/\Delta f \notin \mathbb{N}$) by:

- Applying special windowing functions ➔ reduce **spectral leakage**
- Interpolating the highest DFT bins ➔ minimize **spectral sampling**

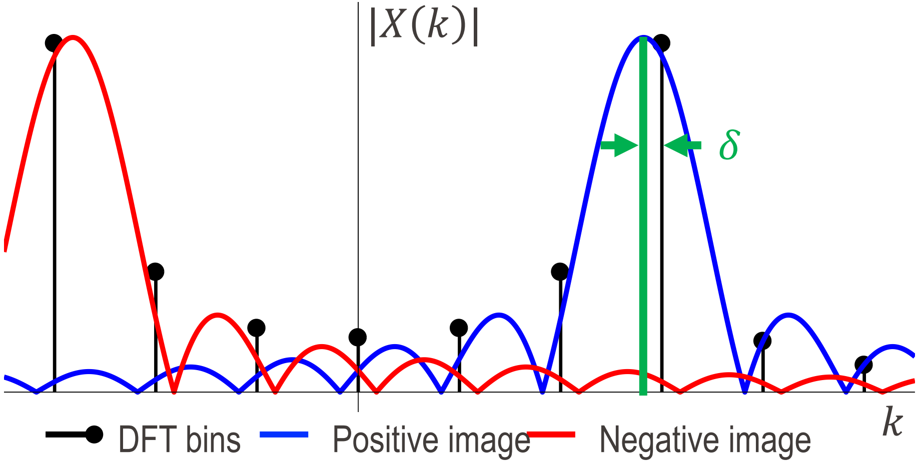
$$\delta = a \cdot \varepsilon \frac{|X(k_m+\varepsilon)| - |X(k_m-\varepsilon)|}{|X(k_m-\varepsilon)| + 2|X(k_m)| + |X(k_m+\varepsilon)|},$$ a = 1.5 cos, a = 2 hann

$$f_0 = (k_m + \delta)\Delta f$$

$$\varphi_0 = \angle X(k_m) - \pi\delta$$

$$A_{0C} = 4 \cdot |X(k_m)| \left| \frac{\delta^2 - 0.25}{\cos(\pi\delta)} \right|$$

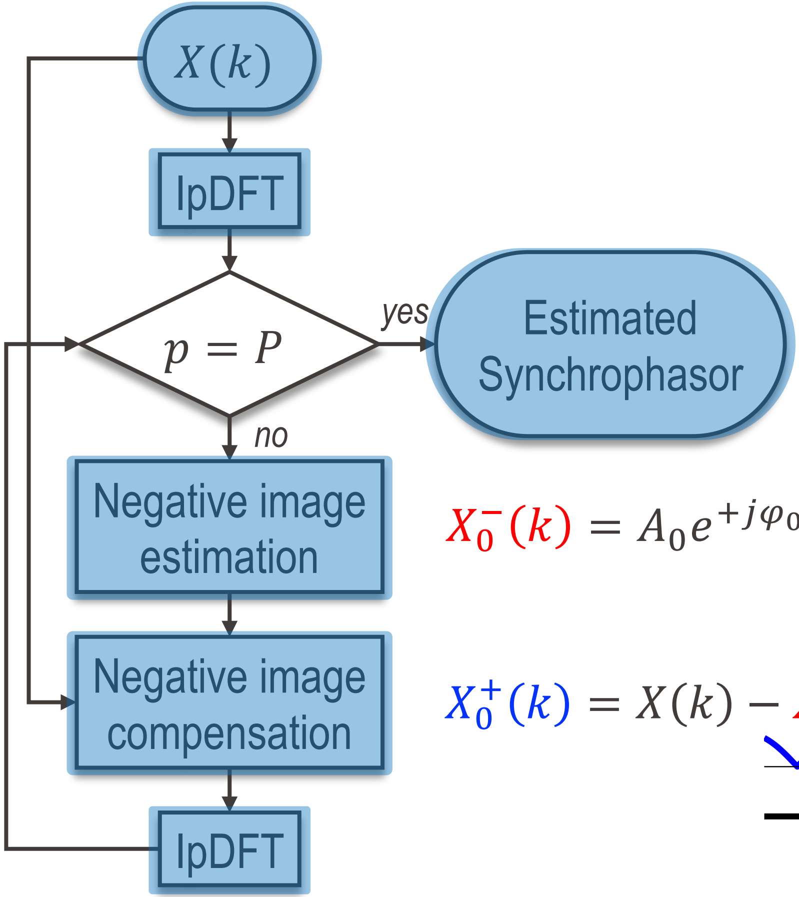
$$A_{0H} = |X(k_m)| \left| \frac{\pi\delta}{\sin(\pi\delta)} \right| |\delta^2 - 1|$$



The Interpolated DFT (IpDFT)

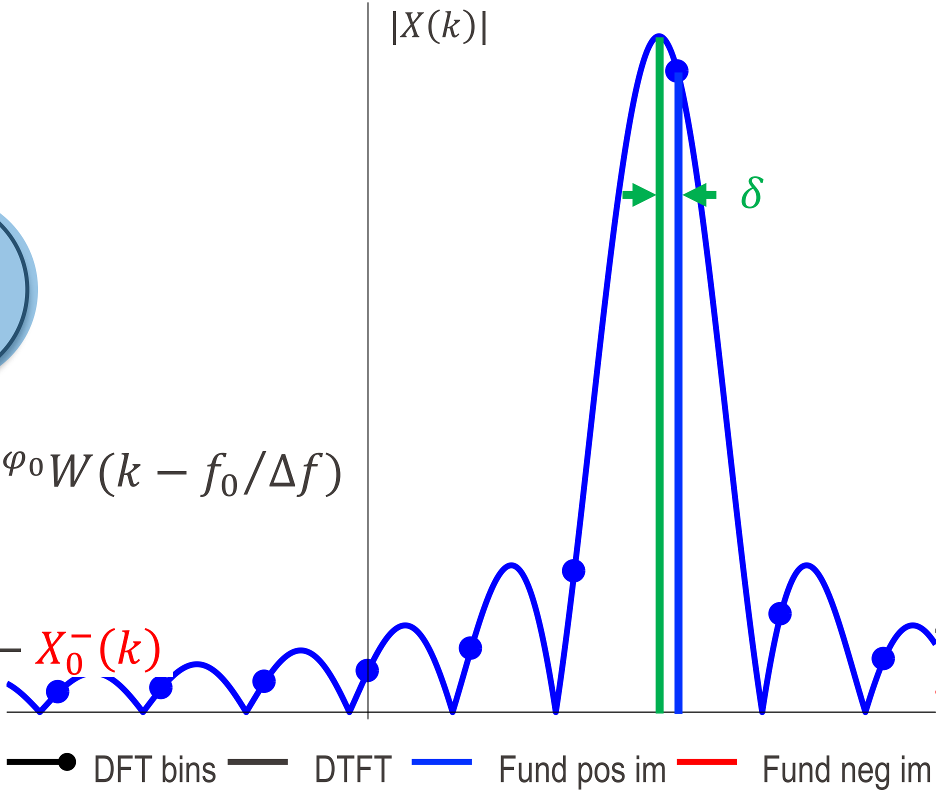
Assumptions behind the IpDFT	Possible solutions
The input signal is characterized by time-invariant parameters	Window lengths containing few cycles of a signal at the rated power system frequency
The sampling rate is higher than the highest signal's spectral component	Sampling rate F_S in the order of tens of kHz
The DFT bins used to perform the interpolation are only generated by the positive image of the tone under analysis	▪ **Enhanced IpDFT (e-IpDFT)** ➔ Iterative compensation of the spectral interference produced by the main tone negative image ▪ **Iterative IpDFT (i-IpDFT)** ➔ Iterative compensation of the spectral interference produced by the nearby tones

The enhanced Interpolated-DFT (e-IpDFT)

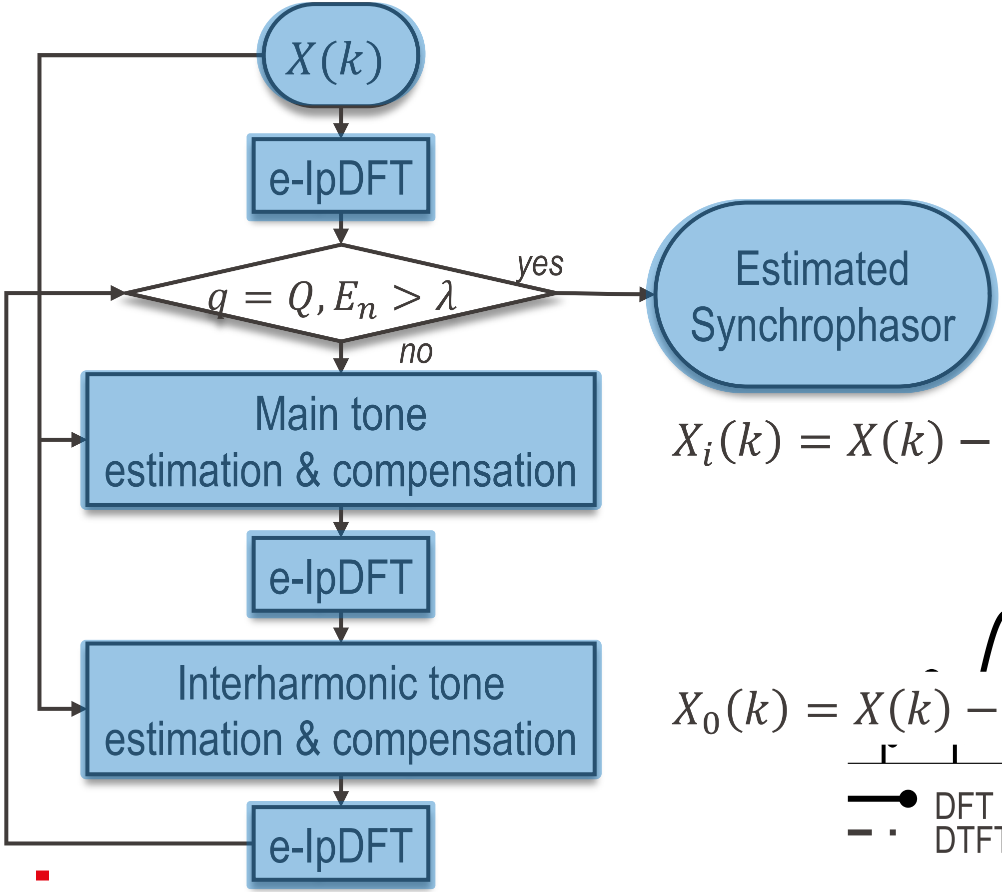


$$X_0^-(k) = A_0 e^{+j\varphi_0} W(k - f_0/\Delta f)$$

$$X_0^+(k) = X(k) - X_0^-(k)$$

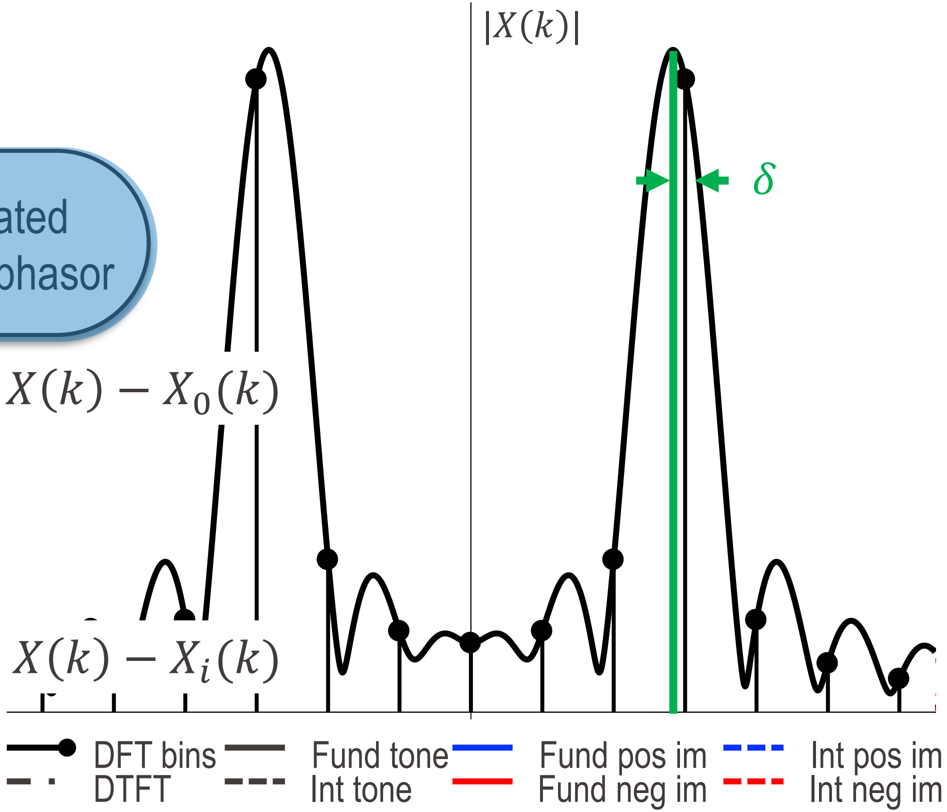


The iterative-IpDFT (i-IpDFT)



$$X_i(k) = X(k) - X_0(k)$$

$$X_0(k) = X(k) - X_i(k)$$



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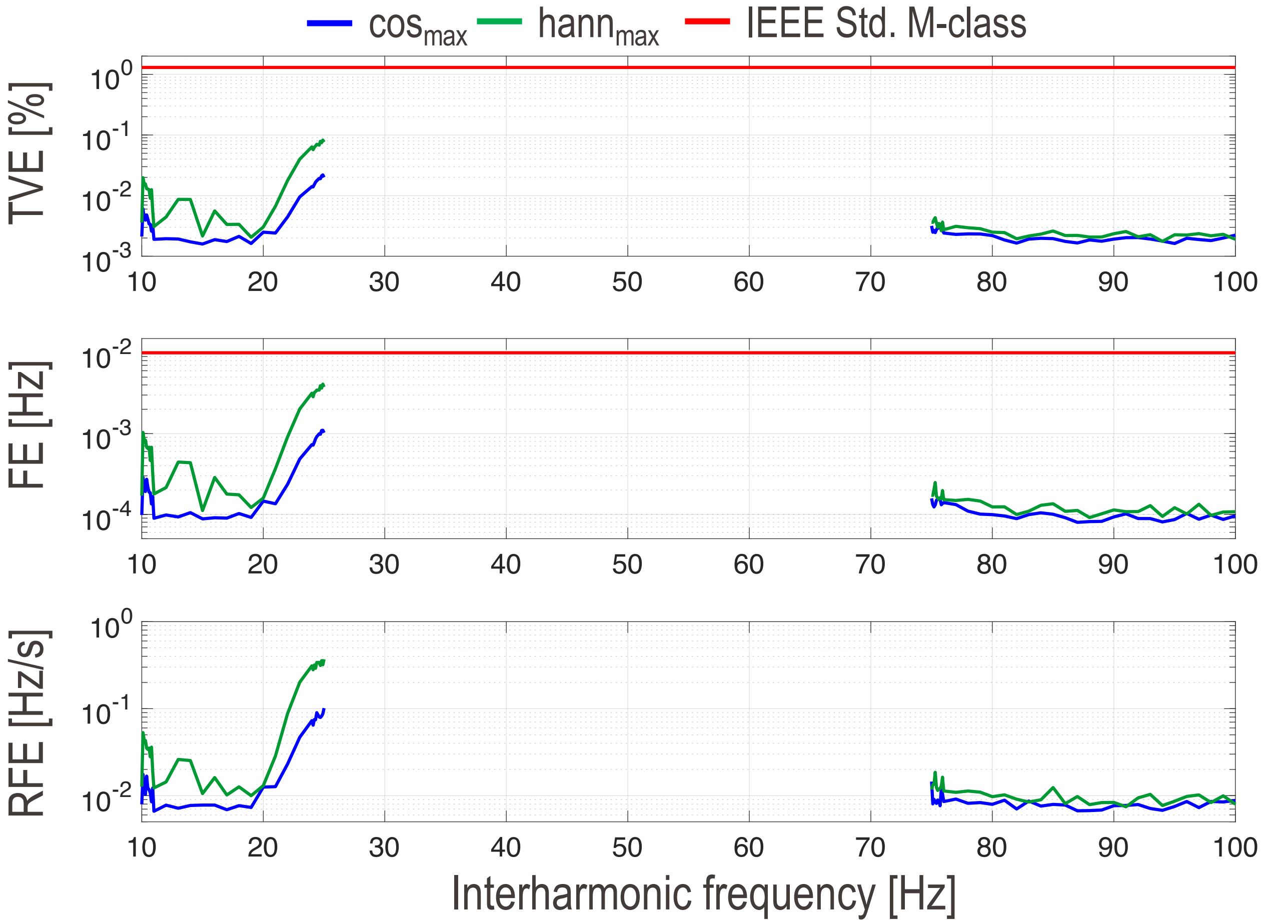
The iterative-IpDFT (i-IpDFT)

Parameters	Value
Nominal system frequency	50 Hz
Window length	**3-cycles (60 ms)**
Window profile	Cosine & Hanning
Sampling rate	50 kHz
PMU reporting rate	50 fps
# DFT bins	11 (cos) & 8 (Hann)
IpDFT interpolation points	3-points
# iterations P	2
# iterations Q	16 (cos) & 28 (Hann)
Noise	80 dB

Performance Assessment – OOBI



Max Errors:

TVE

M = 1.3%

cos = 0.02%

hann = 0.08%

FE

M = 10 mHz

cos = 1.1 mHz

hann = 4.1 mHz

RFE

cos = 0.1 Hz/s

hann = 0.4 Hz/s

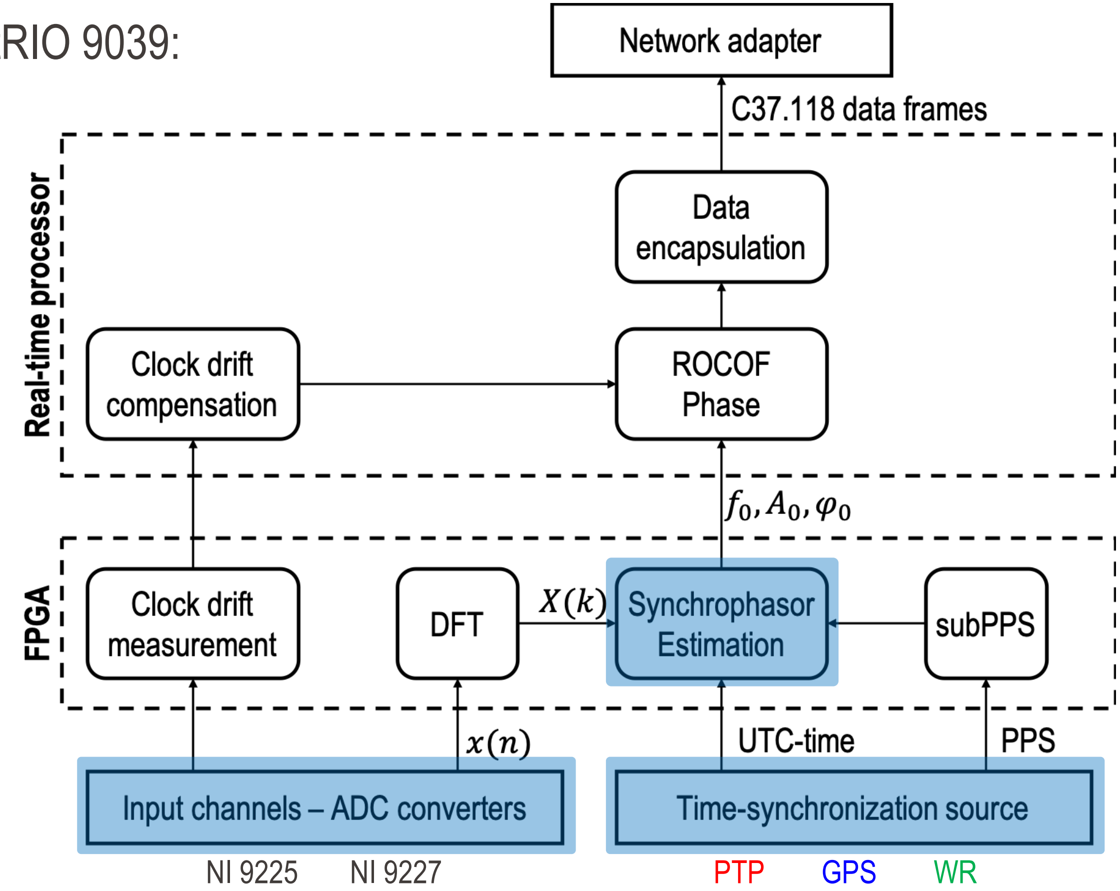
Embedded Hardware Implementation

National Instruments compactRIO 9039:
- Xilinx Kintex-7 325T FPGA
- 6 channels (3V, 3I)

FPGA Allocation: 54 %

Latency [ms]:

	1 ch	6 ch
Q = 0	0.34	2.04
Q = 28	1.20	**7.20**



Conclusion

i-IpDFT for Synchrophasor Estimation

- We discussed the limits of IpDFT when estimating parameters of a signal corrupted by interharmonic
- We formulated a technique resilient against spectral leakage generated by any interfering tone
- We conducted a sensitivity analysis to tune the algorithm parameters
- IpDFT-based SE algorithm for P and M-class compliant PMUs
- **First IpDFT-based synchrophasor estimation technique resilient to OOBI**
- During OOBI test the maximum **TVE is 0,08%** (being 1,3% the maximum allowed limit) and the maximum **FE is 4 mHz** (being 10 mHz the maximum allowed limit)
- We implemented the i-IpDFT into an embedded device

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- The Iterative-Interpolated Discrete Fourier Transform and its Application to Synchrophasor Estimation
- Advanced Calibrator for the Metrological Characterization of PMUs

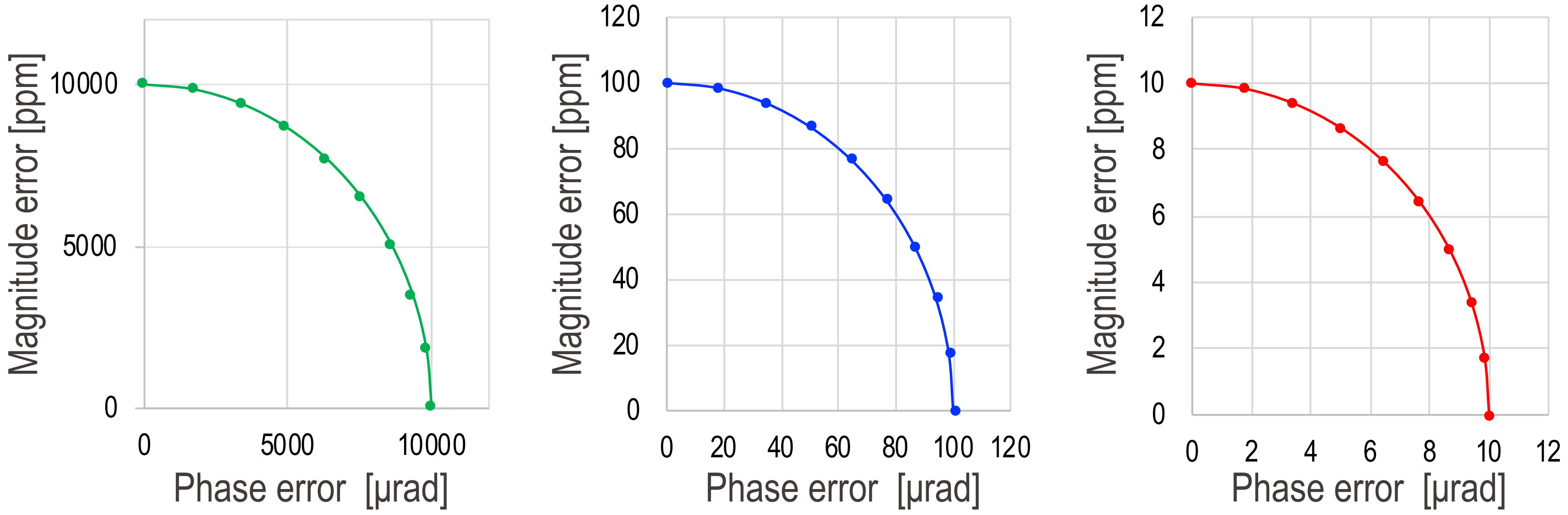
  G. Frigo, A. Derviškadić, D. Colangelo, J.-P. Braun, M. Paolone, *“Characterization of uncertainty contributions in a high-accuracy PMU validation system,”* in Measurement, vol. 146, pp. 72–86, Nov. 2019.
- Time Dissemination Techniques for PMUs

Motivation

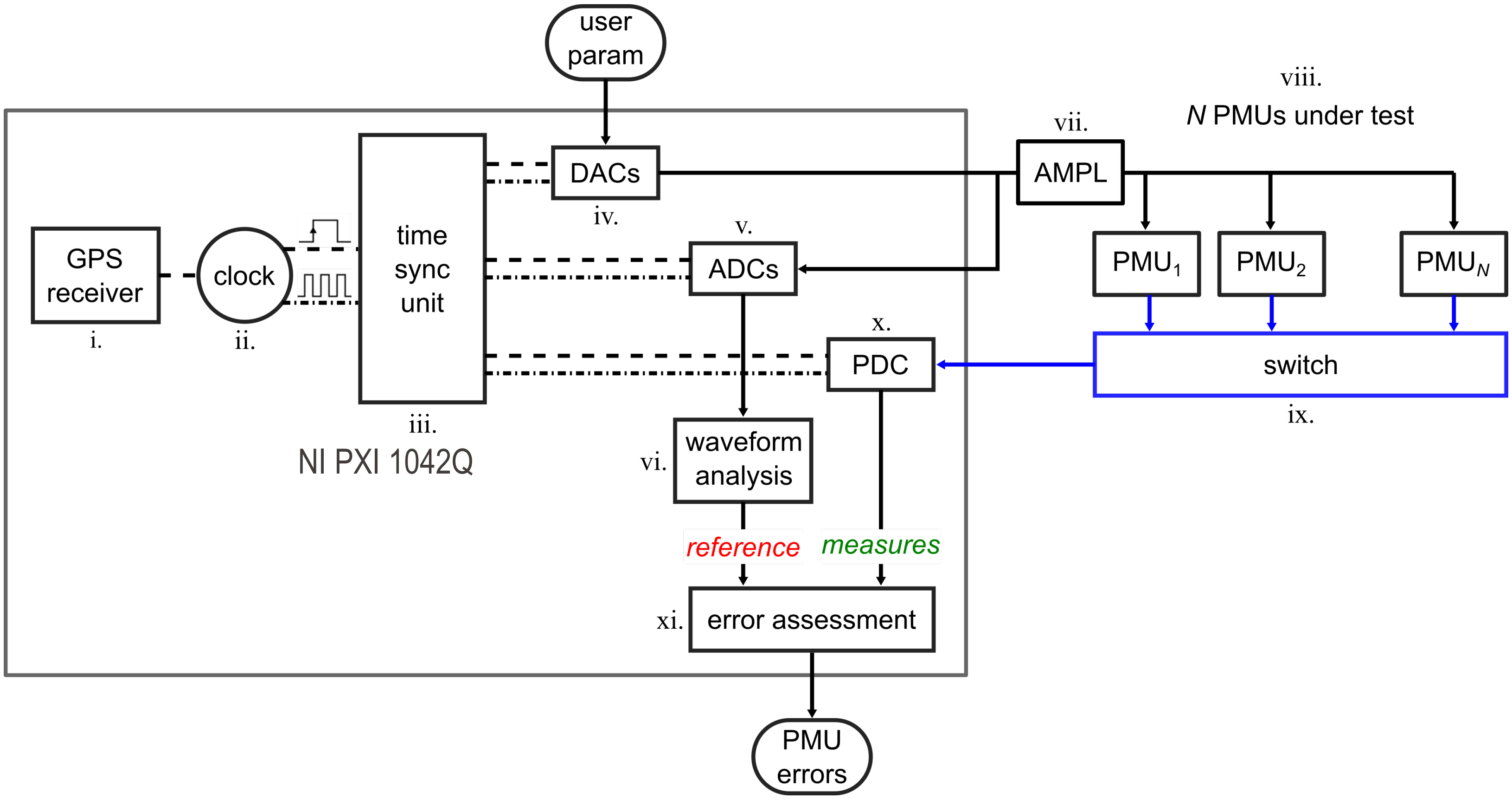
Advanced Calibrator for the Metrological Characterization of PMUs

IEEE Std. C37.118 → State-of-the-art PMUs → PMU calibrator

TVE ≤ 1 % → TVE ≤ 0.0x % → TVE ≤ 0.00x %



The proposed PMU calibrator



Reference values estimation

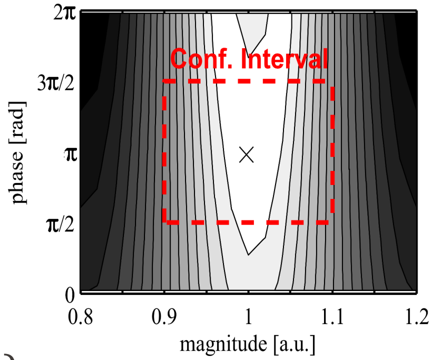
Signal model ➔ Generic time-variant noise-less power signal affected by disturbances:

$$x(t) = A\big(1 + \varepsilon_A(t)\big) \cdot cos\left(2\pi f t + \varphi_0 + \varepsilon_\varphi(t)\right) + \eta(t)$$

Working HP ➔ $\varepsilon_A(t), \varepsilon_\varphi(t)$ and $\eta(t)$ known a priori

Reference values ➔ estimation via non-linear least-squares (NL-LSQ) fit:

$$\{\hat{A}, \hat{f}, \hat{\phi}_0\} = \text{argmin}_{\hat{\mathcal{P}}} \|x[n] - \hat{x}[n]\|_2$$



$x(t)$ → NL-LSQ → $\hat{\mathcal{P}} = \{\hat{A}, \hat{f}, \hat{\phi}_0\}$

$x[n]$ → NL-LSQ → $\hat{s} = \hat{A} \cdot \exp\left(1j\ 2\pi\hat{f}\ nT_s + \hat{\phi}_0\right)$

$\mathcal{P}^* = \{A^*, f^*, \varphi_0^*\}$ → NL-LSQ → $\hat{x}[n] = \hat{A} \cdot \cos\left(2\pi\hat{f} nT_s + \hat{\phi}_0\right)$

Metrological Characterization

Uncertainty Sources

- DAC & ADC accuracy → affects magnitude, frequency and phase uncertainty
- Time-base stability → affects frequency and phase uncertainty
- Synchronization → affects phase uncertainty

True value → High-accuracy instrumentation (steady-state only)

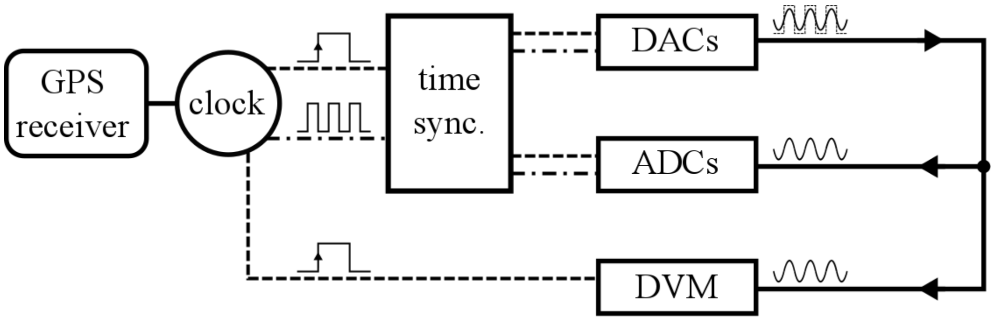
- Amplitude → HP3458A digital voltmeter (DVM) - resolution 1 μV
- Frequency → SR620 universal time counter (DFM) - resolution 10 nHz
- Initial Phase → 5s waveform processed with IpDFT - resolution of 10 nrad

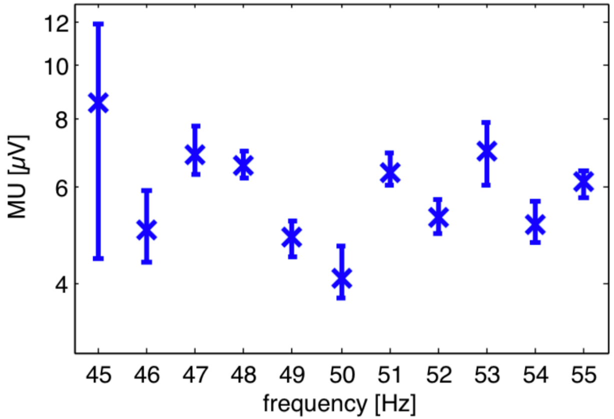
- Deviation between reference (*NL-LSQ estimates*) and true (*instrument measures*) values:
  - mean value μ → fixed → can be compensated
  - standard deviation σ → random → represents the actual uncertainty (HP: Gaussian)
- **Test waveforms:** 5 s, NL-LSQ observation interval 60 ms, reporting rate 50 fps

Metrological Characterization

Synchrophasor Magnitude Uncertainty (MU)

- NL-LSQ estimates vs DVM measurements (res. ±1 μV)
- DVM and DAC / ADC triggered by the same clock ➔ guaranteed synchronization
- Signal frequency [45, 55 Hz] ➔ Worst-case MU < 12 μV (1 ppm @ full input range)

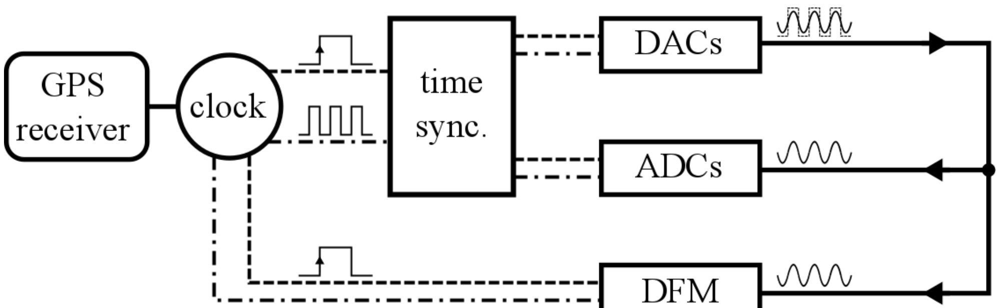


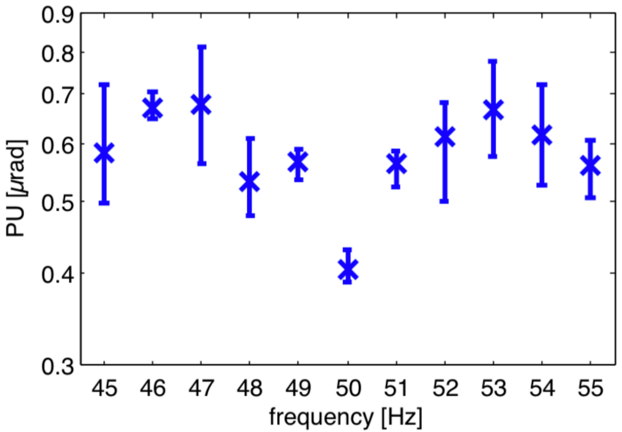


Metrological Characterization

Synchrophasor Phase Uncertainty (PU)

- NL-LSQ estimates vs:
  - DFM measurements (res. $\pm$10 nHz) : contribution to PU due to frequency
  - IpDFT estimates (res. $\pm$10 nrad): contribution to PU due to initial phase
- DFM and DAC / ADC triggered by the same clock ➔ guaranteed synchronization
- Signal frequency [45, 55 Hz] ➔ Worst-case PU < 0.8 μrad

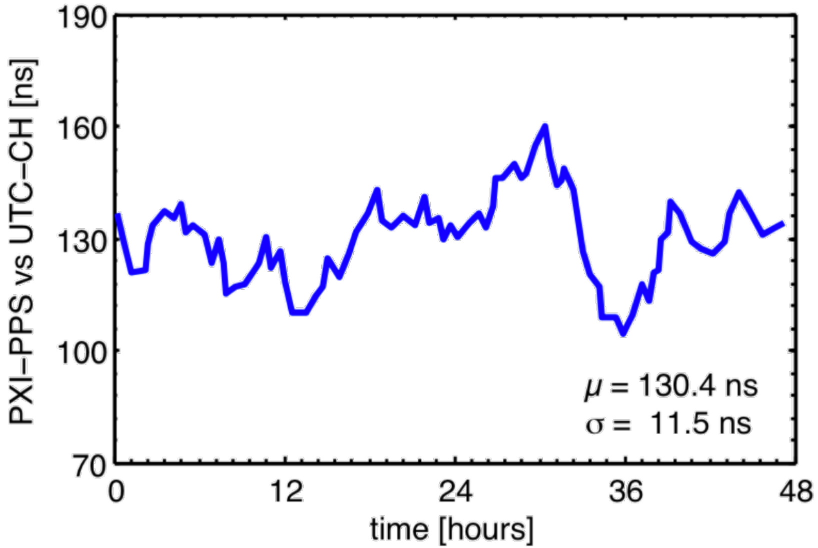


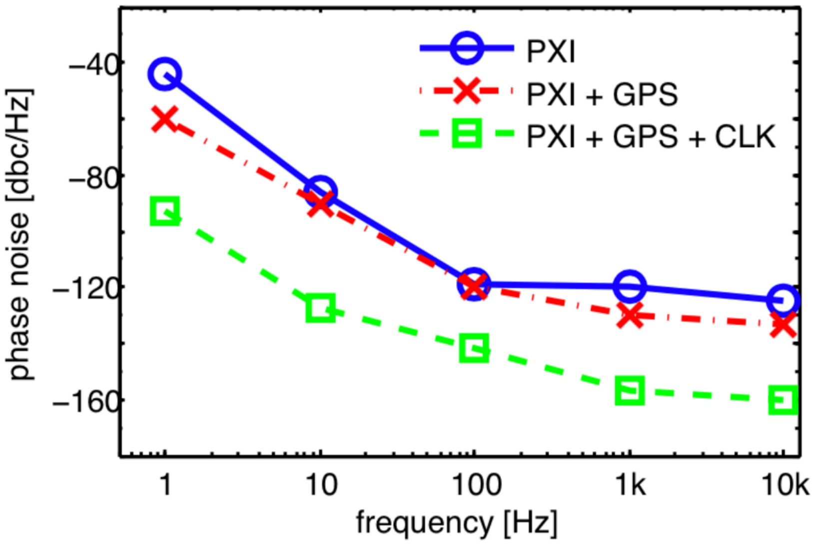


Metrological Characterization

Time Reference Uncertainty (TU) (Stability)

- PPS of PMU calibrator (PXI-PPS) vs UTC-CH (UTC-CH) @ METAS
- Over two days
- Worst-case TU $\sigma < 11.5$ ns ➔ PU < 4 μrad @ 50 Hz





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Metrological Characterization

Dr. Asja Derviškadić

IEEE Std C37.118

- Based on MU, PU, SU, TU ➔ equivalent TVE
- True Value: Steady state single-tone ➔ High-accuracy instruments
  Dynamic Tests ➔ User Parameters

	Test	TVE [%]	FE [Hz]
Static TVE < 0.00x %	Nominal	$2.03 \cdot 10^{-4}$	$2.29 \cdot 10^{-6}$
	Signal Amplitude	$1.84 \cdot 10^{-3}$	$2.02 \cdot 10^{-5}$
	Signal Frequency	$3.56 \cdot 10^{-4}$	$4.31 \cdot 10^{-6}$
	Harmonic Distortion	$1.74 \cdot 10^{-4}$	$4.19 \cdot 10^{-6}$
	OOBI	$4.02 \cdot 10^{-4}$	$1.50 \cdot 10^{-6}$
Dynamic TVE < 0.0x %	Amplitude Modulation	$2.53 \cdot 10^{-5}$	$6.40 \cdot 10^{-2}$
	Phase Modulation	$2.52 \cdot 10^{-2}$	$1.34 \cdot 10^{-3}$
	Frequency Ramp	$9.17 \cdot 10^{-2}$	$4.86 \cdot 10^{-3}$
	Step	$4.24 \cdot 10^{-4}$	$7.19 \cdot 10^{-6}$

Conclusion

Advanced Calibrator for the Metrological Characterization of PMUs

- We have developed and characterized a highly accurate calibration system for PMUs in distribution networks, that is able to reproduce all the test conditions defined by the IEEE Std. C37.118.1.

- We described the hardware and the software of the proposed PMU calibrator

- The developed PMU calibrator is characterized by a **TVE ≈ 0.00x %** in static conditions and **TVE ≈ 0.0x %** in dynamic conditions.

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- Time Dissemination Techniques for PMUs

  A. Derviškadić, R. Razzaghi, Q. Walger, M. Paolone, *"The White Rabbit Time Synchronization Protocol for Synchrophasor Networks,"* in IEEE Transactions on Smart Grid, 2019. *(Special Section on Theory and Application of PMUs in Power Distribution Systems)*

Motivation

Time Dissemination Techniques for PMUs

IEEE Std. C37.118

- Accurate: 1 μs
- Reliable: 24/7
- Available: urban area
- Secure: timing attacks

Common practice

GPS ±100 ns uncertainty

🡻

31 μrad @ 50 Hz

State-of-the-art PMUs

Phase uncertainty

🡻

5 μrad

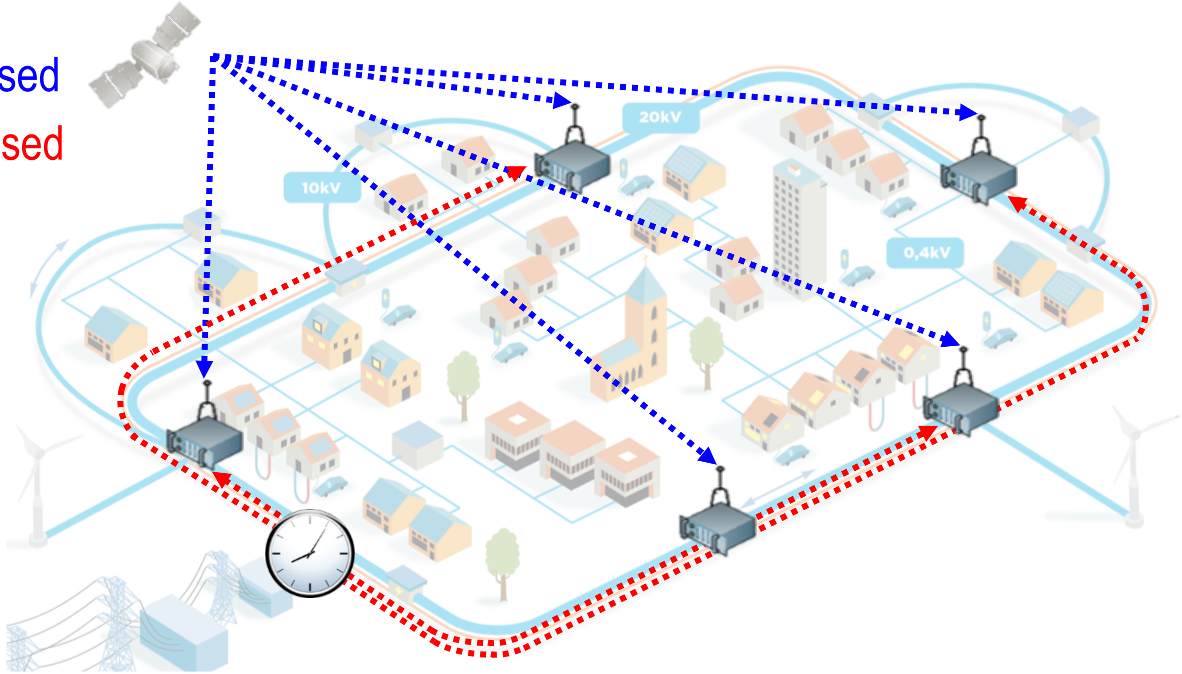
Transmission grids → TVE 1% → 1 μs [IEEE Std]

Distribution grids → TVE 0.01% → 10 ns [NASPI]

Time Dissemination Techniques for PMUs

Satellite-based

Network-based



Synchrophasor phase error source:

$$\Delta\varphi = 2\pi f \Delta t + \varepsilon_{alg} + \varepsilon_{acq}$$

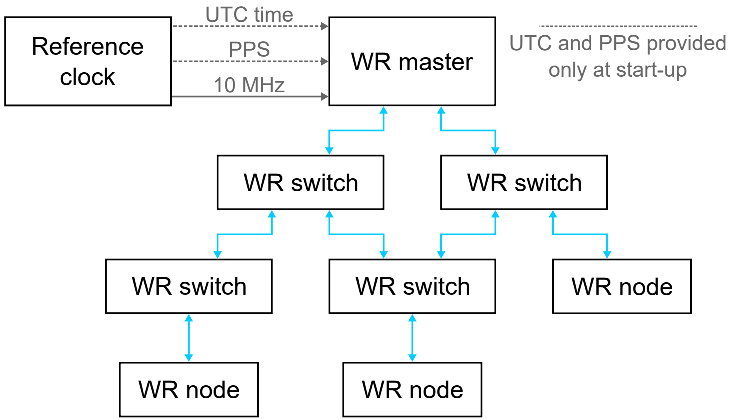
Time synch   Synchrophasor estimation   Acquisition process

Time Dissemination Techniques for PMUs

	Satellite-based	Network-based	
	Global Position System (GPS)	Precision Time Protocol (PTP)	White Rabbit (WR)
Uncertainty	**100 ns**	**1 μs**	**1 ns**
Features	▪ Low installation cost ▪ Widely used	▪ Time dissemination relies on the same Ethernet physical layer as PMU data transfer ▪ Standard profile for power systems	▪ Reliability ▪ Determinism
Limitations	▪ Accessibility ▪ Security	▪ Accuracy ▪ Non-determinism	▪ Fiber physical layer

The White Rabbit Protocol

- Ultra-precise timing for CERN's accelerators



- Based on:
  - **PTPv2** [IEEE 1588]
  - Ethernet [IEEE 802.3]
  - Synchronous Ethernet [SyncE]
  - Precise phase measurement

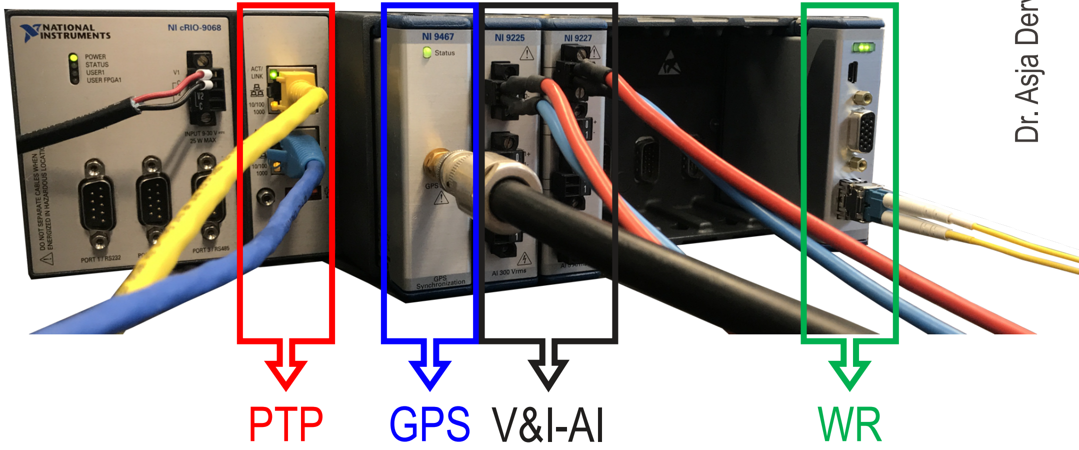
- Deployable on already existing fiber-based networks

The Developed PMU – Hardware Platform

National Instruments compactRIO

FPGA level:

- Time synchronization
- Signal acquisition
- Synchrophasor estimation

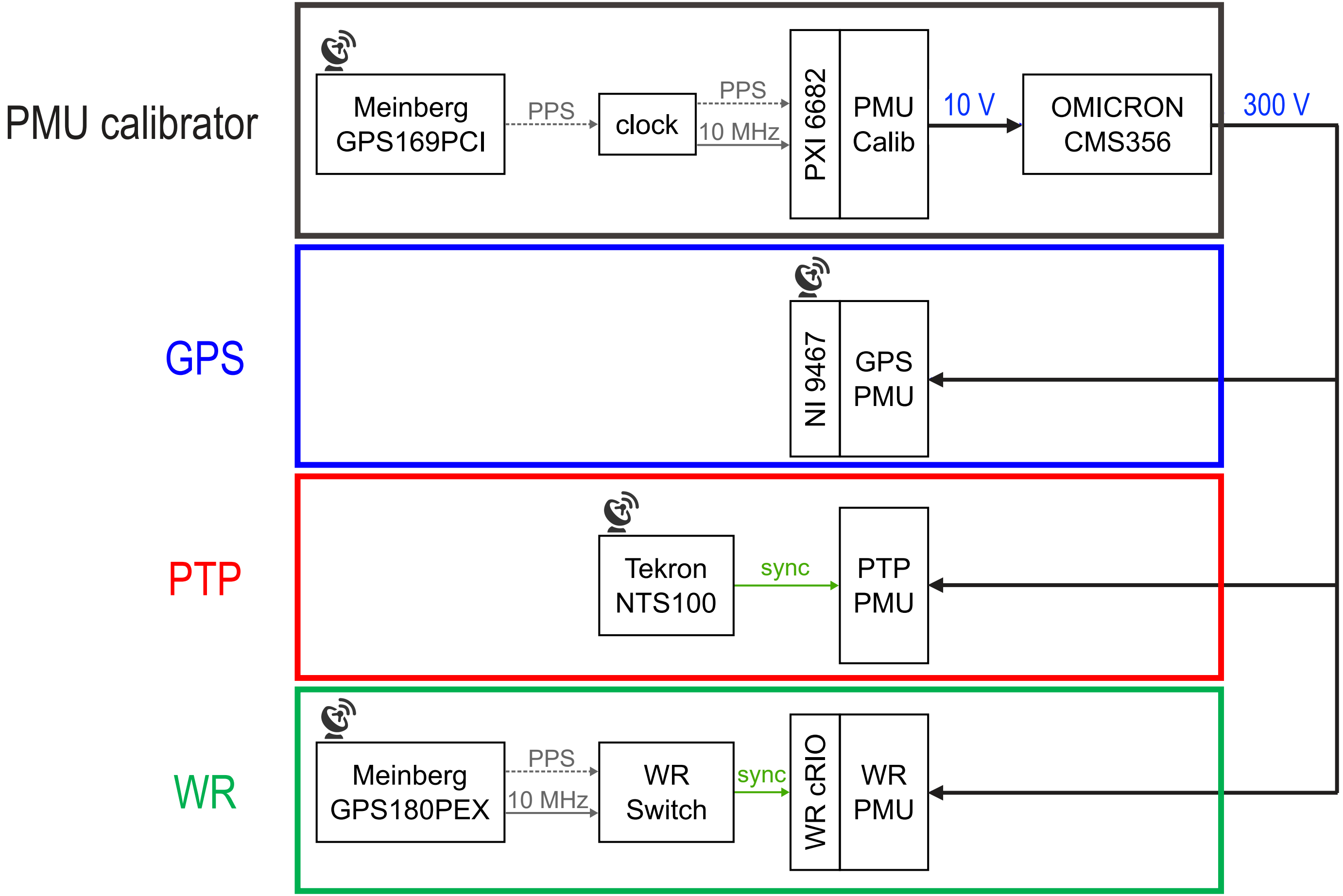


- Same hardware platform
- Same synchrophasor estimation ➔
- Only difference is the time sync

Any phase estimation difference is due to the time synch difference

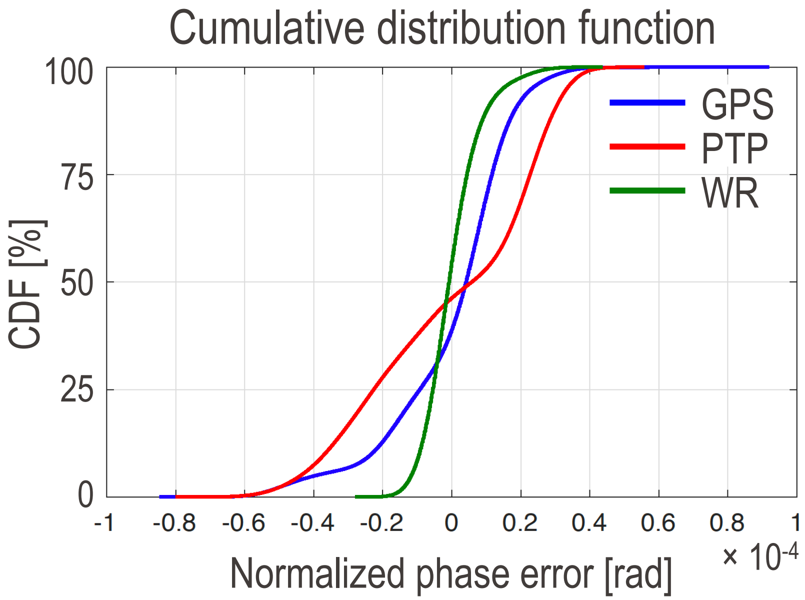
- i-IpDFT: T = 60 ms, Fr = 50 fps, Fs = 50 kHz ➔ phase error ε_{alg} < 5 µrad

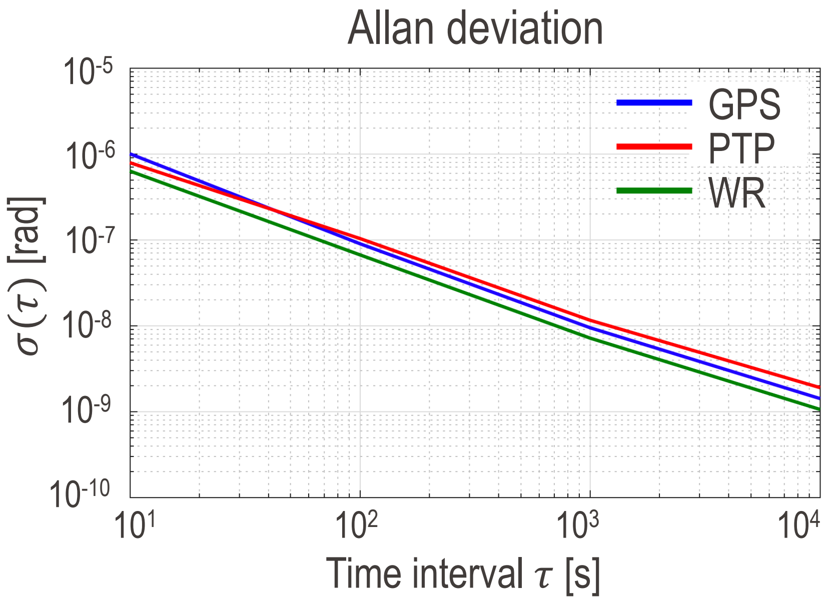
The Measurement Setup



Performance Assessment – Phase Error

- Worst-case scenario: 24 h – single-tone voltage 50 Hz, 300 V, 0 rad





Standard deviation		
	GPS	18.1 µrad
	PTP	25.9 µrad
	WR	8.1 µrad

Conclusion

Time Dissemination Techniques for PMUs

- We discussed the uncertainty contribution of the time dissemination technology on the synchrophasor estimation for PMU applications
- We carried out a performance comparison using:
  - Same hardware platform (NI-cRIO)
  - Same synchrophasor estimator (i-IpDFT)
  - Different time synchronization sources: GPS, PTP and WR
- The WR-PMU is capable of minimizing the time dissemination uncertainty contribution and thus optimizing the performance of the synchrophasor estimation algorithm
- The WR-PMU produces a phase error always lower than 8 μs

DESL EPFL

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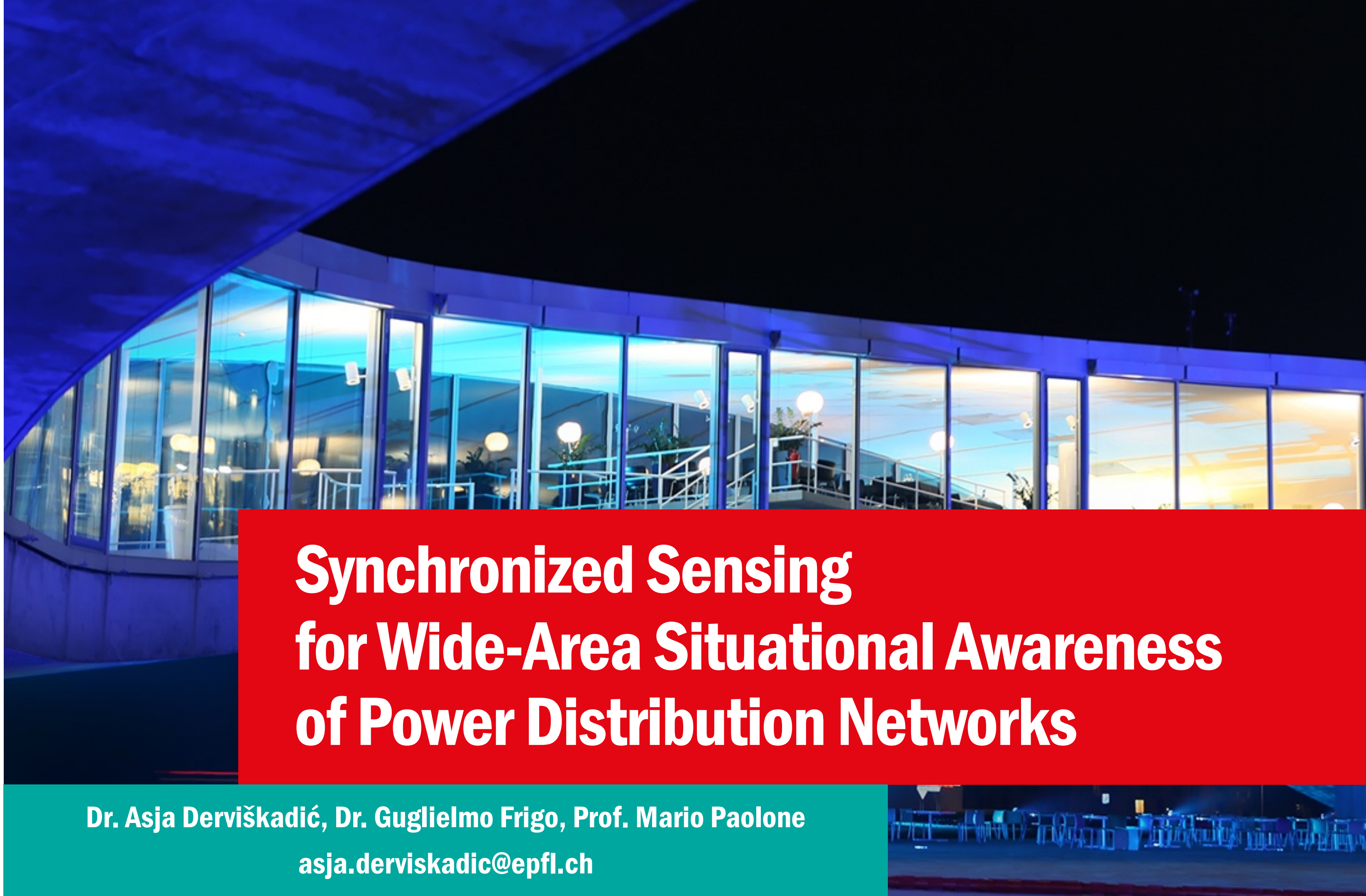

Synchronized Sensing for Wide-Area Situational Awareness of Power Distribution Networks

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