Zaphiro
Dynamic. Smart. Grid.

Paolo Romano
CEO and Co-founder

Demystifying Distribution Synchrophasors

Use Cases, Requirements, and Integration from Field Experience

About myself

Mar 2017 - Present

CEO and Co-founder @Zaphiro Technologies

- Product management
- Sales and Business development
- Fundraising and Company growth

Mar 2016 – Feb 2017

Post-doc @EPFL

- Responsible for industrial collaborations (NI, Intel)
- Management of projects with leading Swiss utilities (Romande Energie, SiL, etc.)

Nov 2011 – Feb 2016

PhD & Teaching assistant @EPFL

- PhD thesis: "DFT-based Synchrophasor Estimation Algorithms and their Deployment in Advanced Phasor Measurement Units for the Real-time Monitoring of Active Distribution Networks"
- Research interests: Phasor Measurement Units, Synchrophasor networks, Time synchronization

Dr. Paolo Romano
Co-founder and CEO
paolo.romano@zaphiro.ch

About Zaphiro

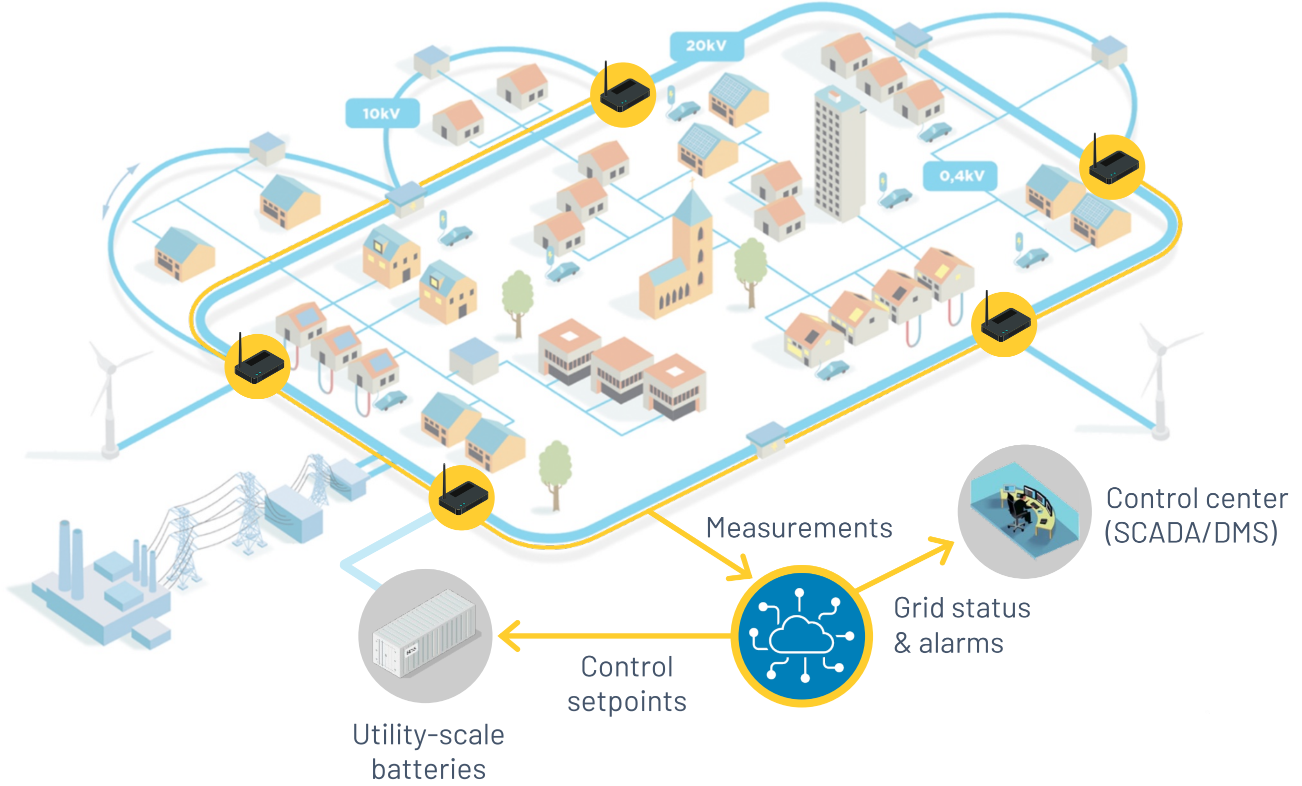
- Fast growing company based in **Switzerland**
- **Synchrophasor**-based solution to increase the resiliency, sustainability and efficiency of **distribution grids**
- Over **180** SynchroSense **D-PMU** devices installed in the field monitoring >**1600** grid assets, >**200** km of MV lines **24/7**

Customers

Partners

Distribution grid monitoring & automation system based on D-PMU technology

Distribution-Phasor Measurement Unit (D-PMU) device:
- Time-synchronized + high speed measurements
- Ideal for substation retrofitting



Modular and scalable Software Platform:
- Full interoperability with 3rd party devices
- Empowered by patented algorithm

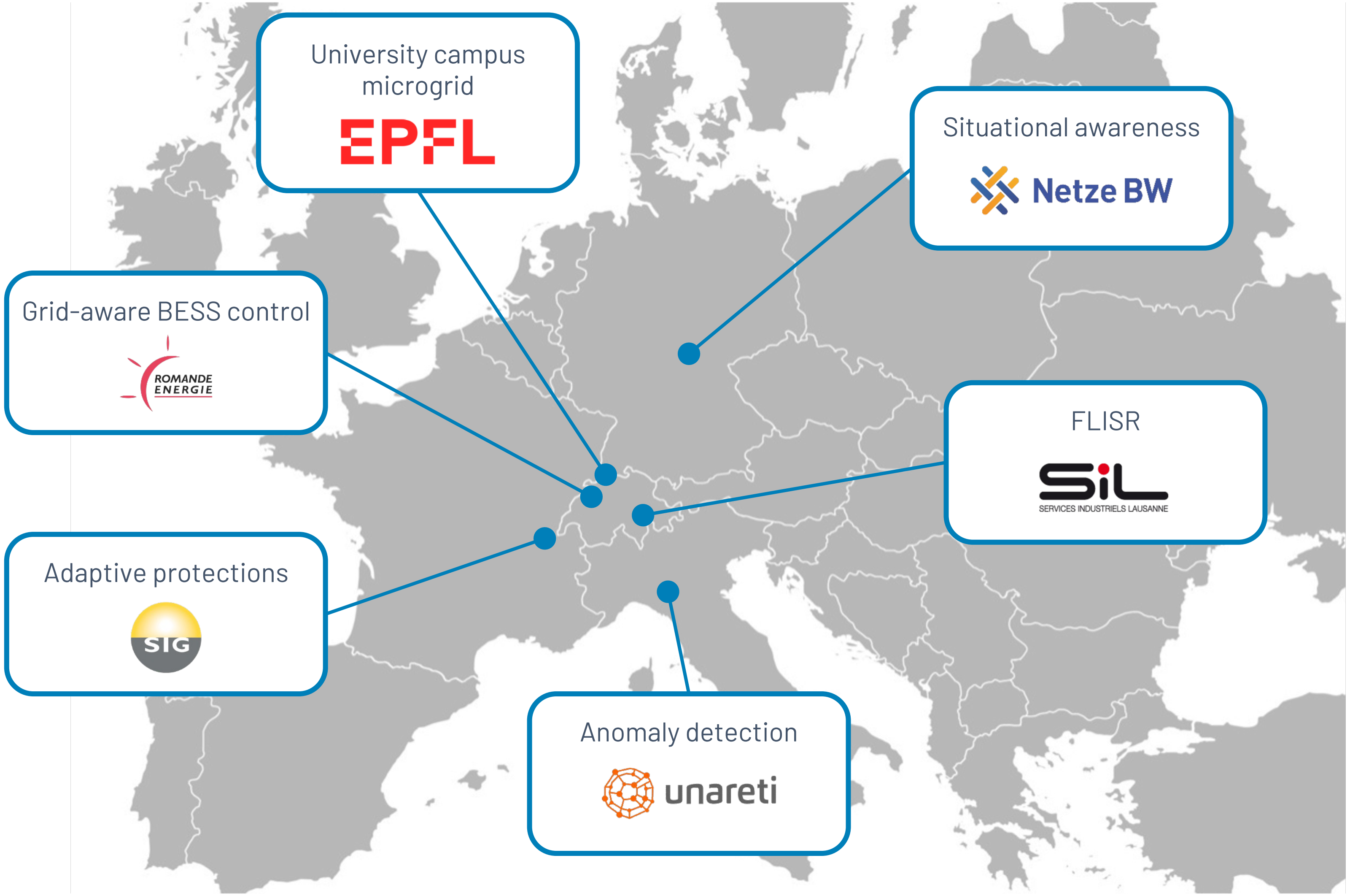
Real-time grid monitoring
→ Full grid visibility with as little as 10% of measurement coverage

Accurate fault location
→ Automated fault location to reduce the duration or even prevent blackouts

DER integration and control
→ Automatic control of utility-scale batteries to always guarantee grid stability

Offline grid analytics
→ Advanced grid analytics for optimal grid planning and predictive maintenance

Relevant D-PMU projects with European utilities



Lessons learned and challenges experienced in our D-PMU deployments

Challenge #1: The IEC/IEEE 60255-118-1 Std. has not been designed around D-PMU use cases

4.1 Input and output quantities

As shown in Figure 1, the input quantities are the time and the power system voltage and current signals. The time signal shall provide UTC time with sufficient accuracy that the PMU can meet the specified performance requirements. The time signal shall meet the input requirements specified by the PMU manufacturer. Annex A reviews common formats.

Voltage and current signals shall be supplied to the PMU as analog quantities over wire or as data packets over communication circuits as specified by the manufacturer. These signals represent the AC power system signals.

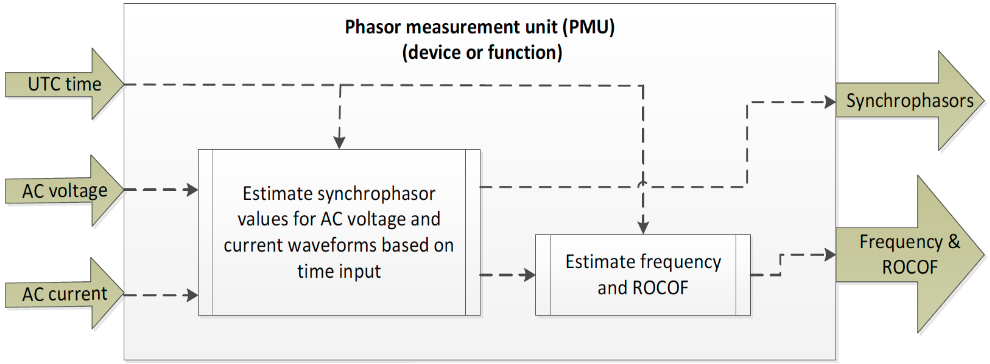


Figure 1 – Input and output quantities

Conventional vs non-conventional (low-power) VTs and CTs

- The current standard assumes analog inputs from conventional VTs/CTs outputing high voltage (100-300 V) and current (1-5 A) signals
- Less than 10% of distribution substations in EU are today instrumented
- Initial D-PMU rollouts will be based on "retrofit" solution which typically adopt non-conventional instrument transformers that output low-voltage signals (from 22.5/225 mV to few V), due to their lower costs, dimensions and improved performance

Challenge #1: The IEC/IEEE 60255-118-1 Std. has not been designed around D-PMU use cases

5.4.1 Performance classes

Compliance with the requirements shall be evaluated by class of performance. This document defines two classes of performance: P class and M class.

In general, P class has shorter measurement latency time, narrower frequency range, and lower harmonic signal rejection requirements than M class as well as no out-of-band signal rejection requirement. M class allows for longer latencies, allowing more filtering for a wider frequency range requirement and increased harmonic and out-of-band signal rejection requirements.

P class is intended for applications requiring fast response such as protection applications. As an example, the P-class reference model filter (Annex D) has a step response that is monotonic (free of over and undershoot) and fully settled within one cycle.

M class is intended for applications which could be adversely effected by aliased signals caused by out-of-band interference yet do not require low measurement reporting latency or short step response time. As an example, the M-class reference model filters (Annex D) have step responses with some overshoot and ringing, and significantly more measurement reporting latency than the P class model.

These two class designations do not indicate that either class is adequate or required for a particular application. The user shall choose a performance class that matches the requirements of each application. The user should consider the inherent trade-off between frequency domain and time domain performance.

All compliance requirements are specified by performance class. A PMU shall meet all the requirements as specified for a class, in order to be considered as compliant with this document for that class. If the vendor provides both P and M class performance, these shall be user selectable.

Performance classes

- The current standard defines P (Protection) and M (Measurement) performance classes
- Both classes, as defined today, are irrelevant for D-PMU applications
  - P-class cannot be used during fault conditions due to the currently limited voltage (80-120% V_{nom}) and current (10-200% I_{nom}) measurement range
  - M-class: the longer window length is not compatible with faster distribution grid dynamics
- Also, while both monitoring (measurement) and fault location (protection) applications are relevant for D-PMUs, the purchase of 2 separate devices for 2 different set of applications is not feasible

Challenge #1: The IEC/IEEE 60255-118-1 Std. has not been designed around D-PMU use cases

For the harmonic distortion test, the input signals shall be represented by Equation (15), Equation (16), and Equation (17):

$$X_a = X_m \cos(2\pi f_0 t) + X_m k_x \cos(2\pi n f_0 t) \quad (15)$$

$$X_b = X_m \cos(2\pi f_0 t - 2\pi/3) + X_m k_x \cos(2\pi n f_0 t - 2\pi n/3) \quad (16)$$

$$X_c = X_m \cos(2\pi f_0 t + 2\pi/3) + X_m k_x \cos(2\pi n f_0 t + 2\pi n/3) \quad (17)$$

where

X_m is the amplitude of the input signal;

f_0 is the nominal power system frequency in Hz;

k_x is the harmonic amplitude factor, and n is the harmonic order.

See Table C.1 for the harmonic phase sequence.

Table 2 – Steady-state synchrophasor measurement requirements

Influence quantity	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		Performance – P class		Performance – M class	
		Range	Max. TVE %	Range	Max. TVE %
Harmonic distortion (single harmonic)	< 0,2% (THD)	1 %, each harmonic up to 50th	1	10 %, each harmonic up to 50th	1

Testing conditions

- The current testing conditions are not completely representative of distribution grid operating conditions
- Harmonic distortion test assumes 1 harmonic at a time, whilst D-PMUs are typically processing very complex spectra characterized by the presence of multiple harmonics simultaneously
- Step test are characterized by low amplitude (10%)/phase steps (18 deg), and are not representative of typical step seen during fault events in voltage/current signals

Recommendations for a revision of the current PMU standard

IEC/IEEE 60255-118-1

Edition 1.0 2018-12

INTERNATIONAL STANDARD

Measuring relays and protection equipment –

Part 118-3: Synchrophasor for distribution systems - Measurements

Recommendations

1. Contemplate the possbility to interface PMUs to non-conventional instrument transformers
   - Update input signal ranges and measurands
2. Deinfition of a new PMU performance class for distribution applications (D-class) with new set of testing conditions
   - Wider amplitude ranges for steady state conditions
   - Step test with higher amplitude/phase steps
   - Complex harmonic spectra
3. Allow the possibility to certify PMUs for "extended accuracies" both under steady-state and dynamic conditions
   - For certain applications it is not sufficient to say "this PMU is Std. compliant"

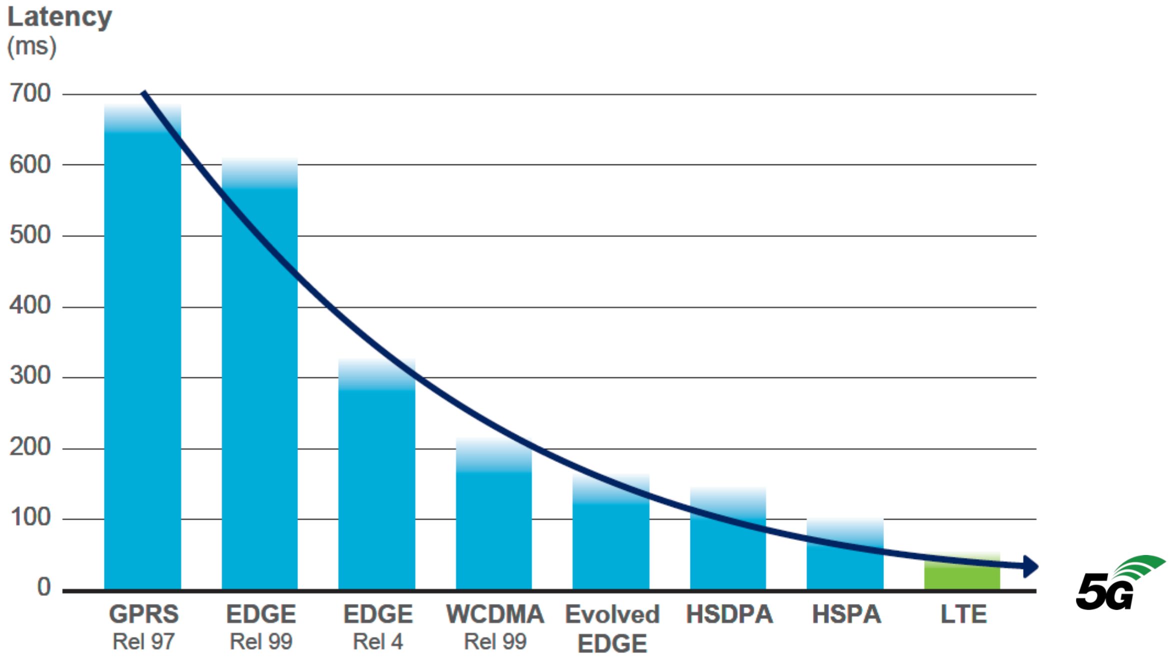
Join IEEE WG C41 for a new D-PMU Std!

Challenge #2: Power utilities are rolling-out their private networks, but it takes time

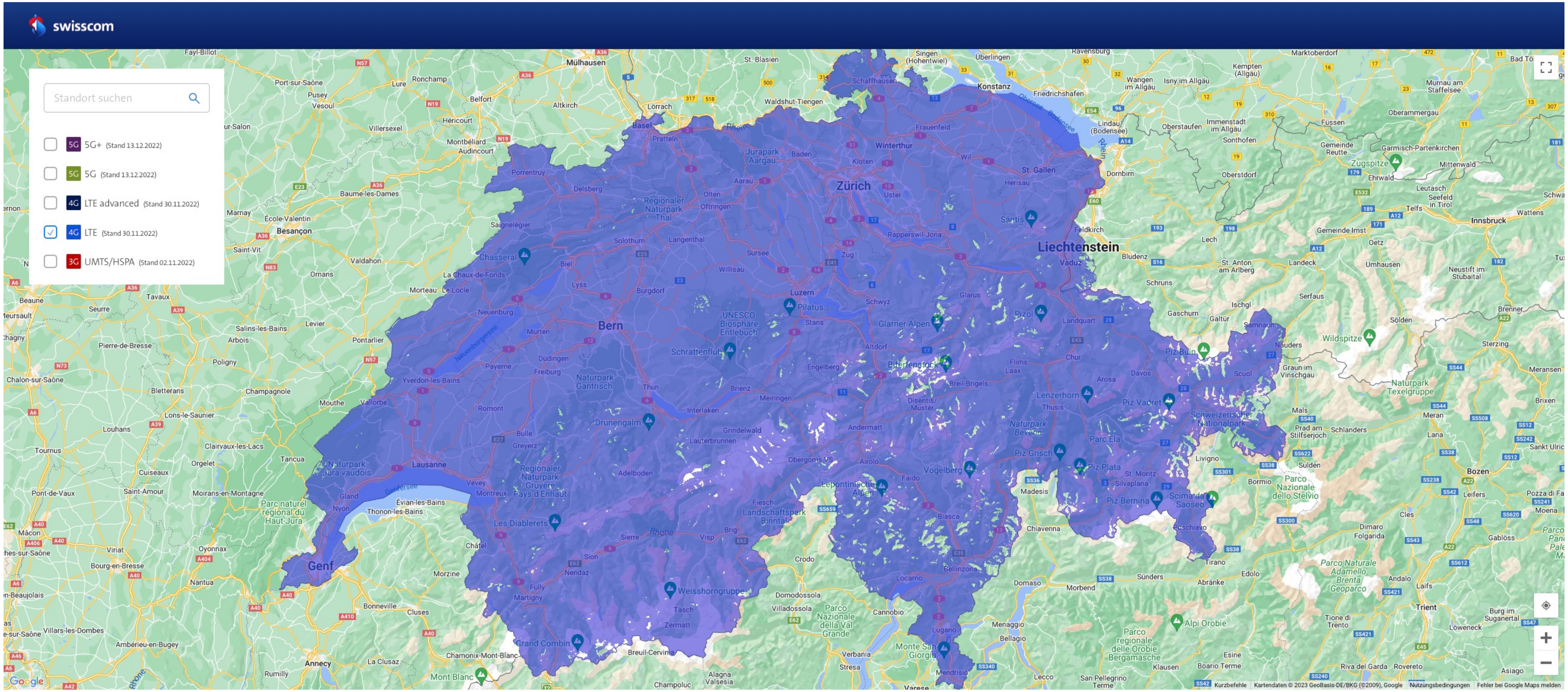
- Fiber networks are still the favorite options for many utilities, due to their higher security and performance, but their deployment inherently takes time
- Utilities that need to accelerate their grid digitization strategy have started looking/implementing public/private LTE networks due to their lower TCO and faster rollout times (e.g., AMI)
- **But are LTE networks compliant with the more demanding PMU requirements (latency, bandwidth)?**

LTE network are a viable solution for distribution synchrophasors

- **Coverage**: Public LTE networks guarantee complete coverage in most countries
- **Performance**: Average LTE latency (30-40ms) allows to cope with most PMU uses cases under consideration (see next slides)
- **Flexibility**: LTE networks can be used for a variety of use cases, from highly data intensive ones (e.g., D-PMUs) to less demanding applications (e.g., AMI)
- **Power-backup**: LTE base stations usually integrate a power backup making them suitable for use during faults/blackouts (e.g., FLISR)
- **Costs**: Public LTE networks are characterized by very low startup costs

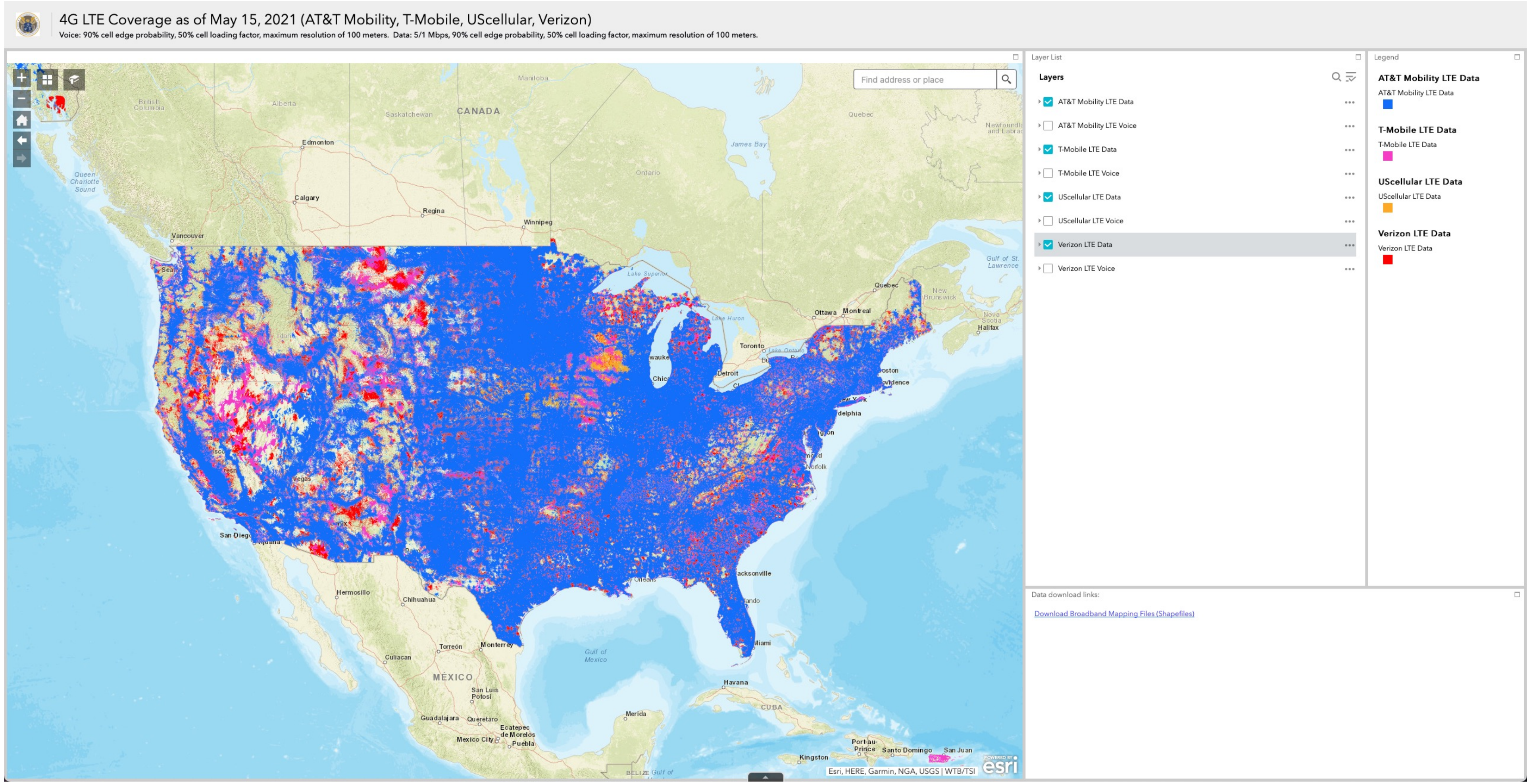


A view on public LTE coverage in Switzerland



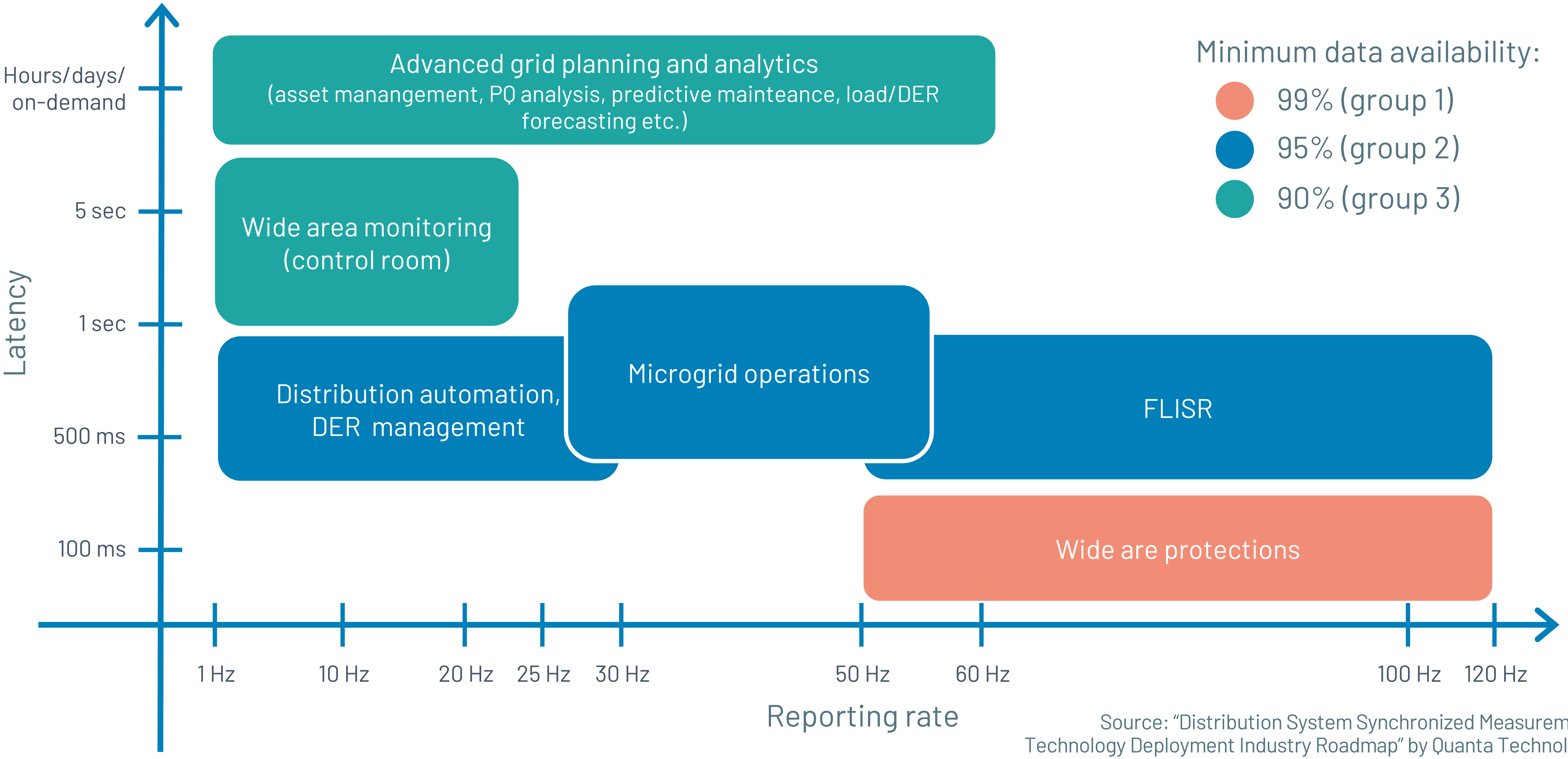
Source: "Mobile Coverage" by Swisscom
https://scmplc.begasoft.ch/plcapp/pages/gis/netzabdeckung.jsf?netztyp=lte

A view on public LTE coverage in US



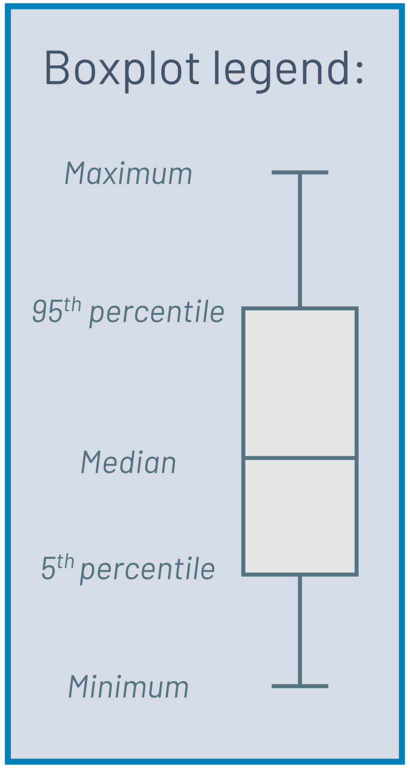
Source: "Mobile LTE Coverage Map" by FCC
https://www.fcc.gov/BroadbandData/MobileMaps/mobile-map

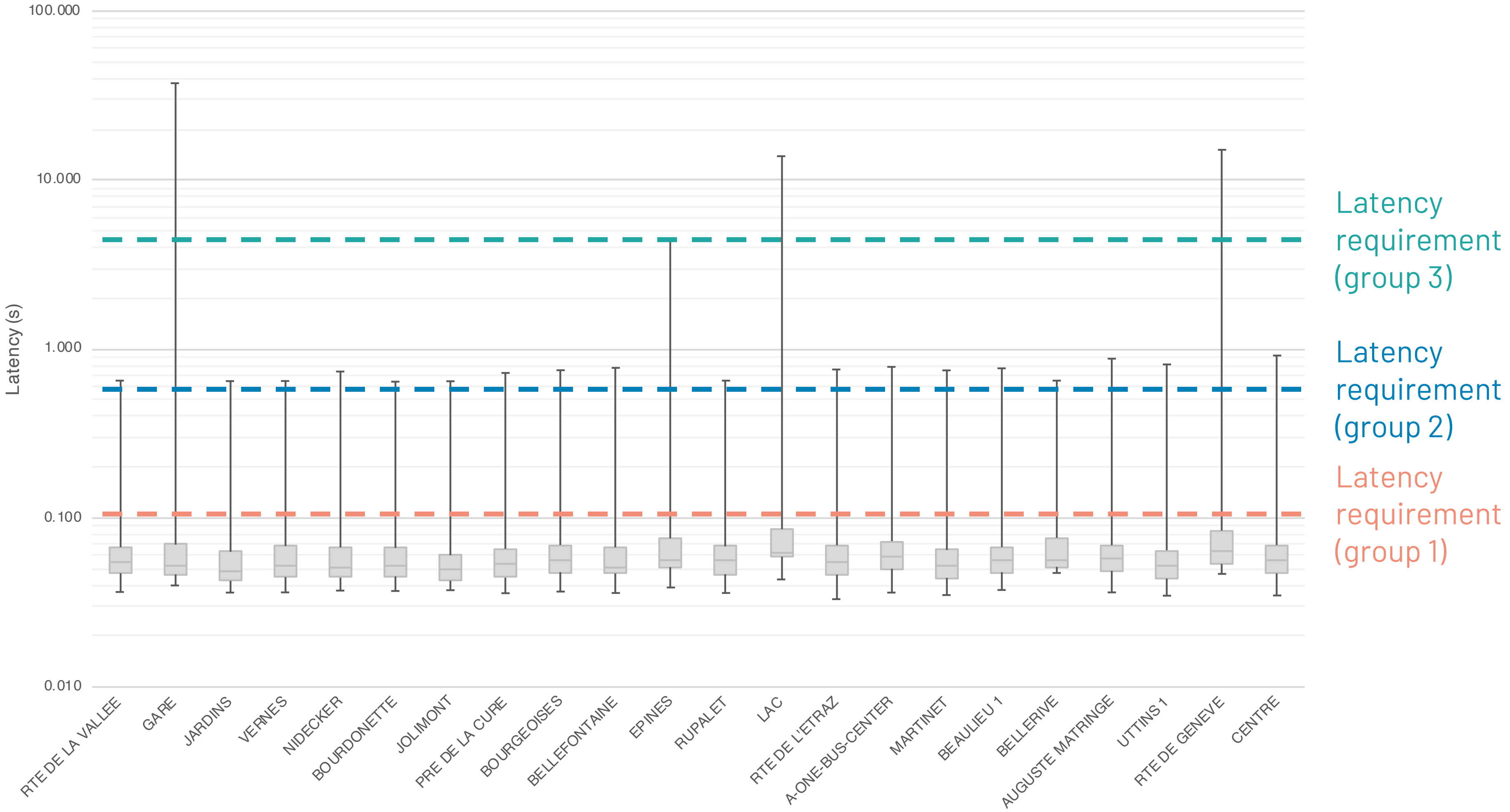
D-PMU application infrastructure and process requirements



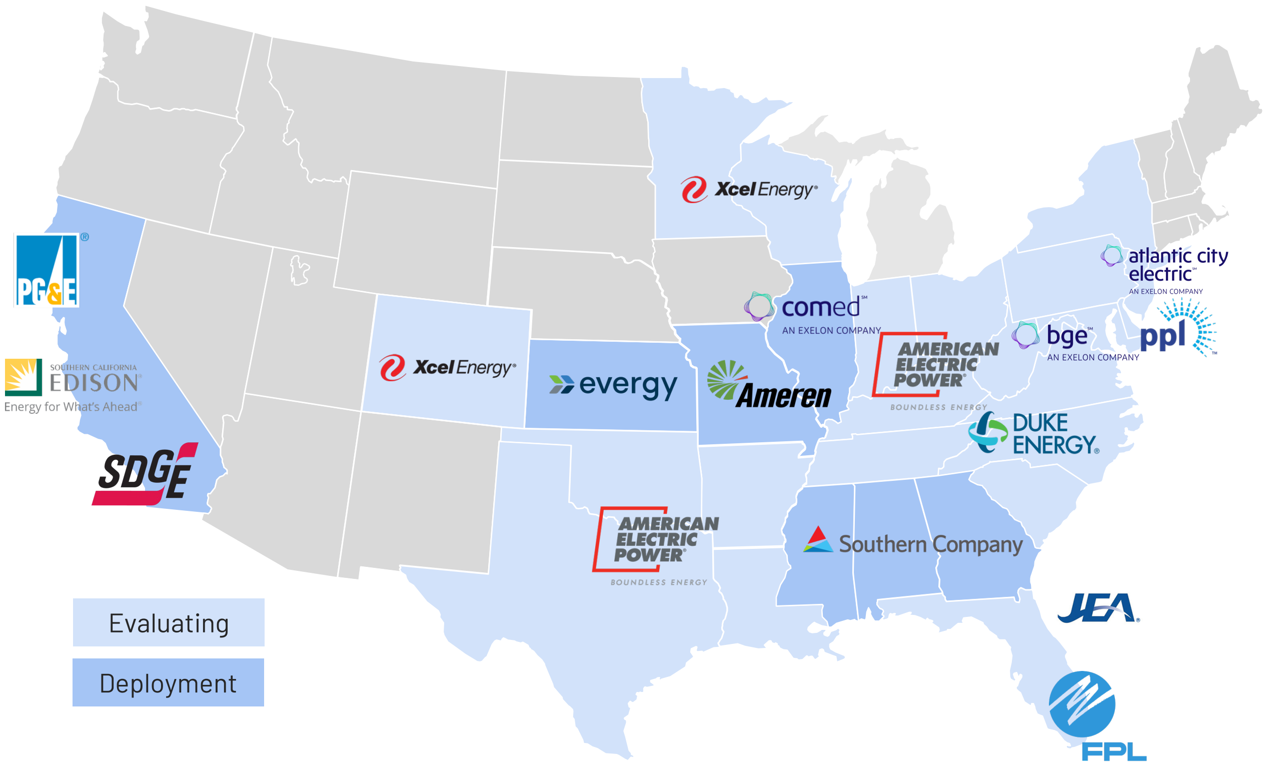
Source: "Distribution System Synchronized Measurement Technology Deployment Industry Roadmap" by Quanta Technology

Public LTE networks can satisfy the performance requirements of application groups 2-3





US Utility Private LTE Programs



Benefits of private LTE networks

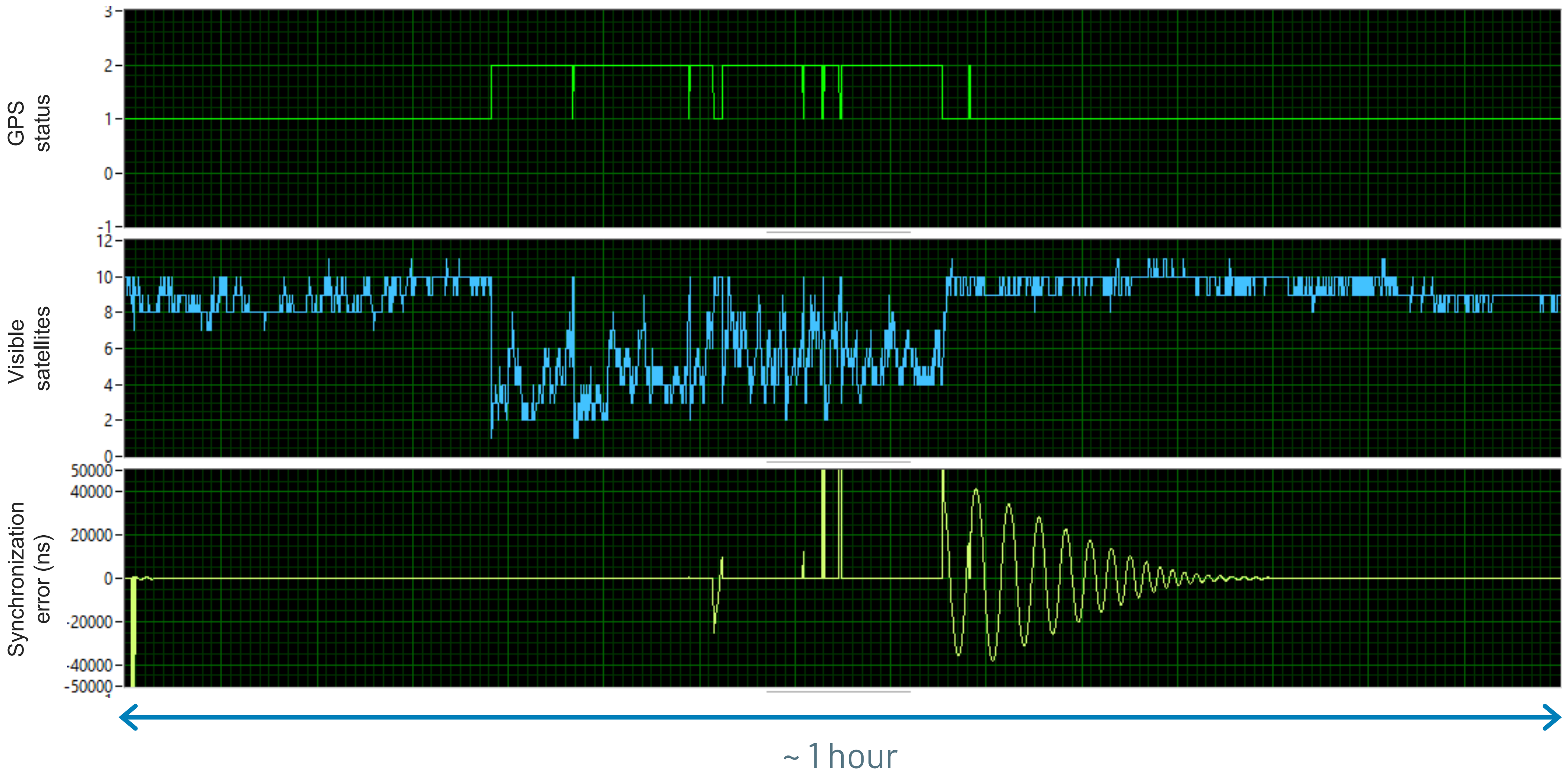
- Guaranteed **performance** (SLA)
- Higher **availability** than fiber networks with a lower rollout effort
- Higher **reliability** and **resiliency** during extreme events
- Higher **security** standards than public LTE networks
- Faster **restoration** compared to public LTE networks
- More appelaing **economics** for utility companies than OPEX-intensive public LTE networks

Source: Utility Broadband Alliance (UBBA)
https://www.ubba.com

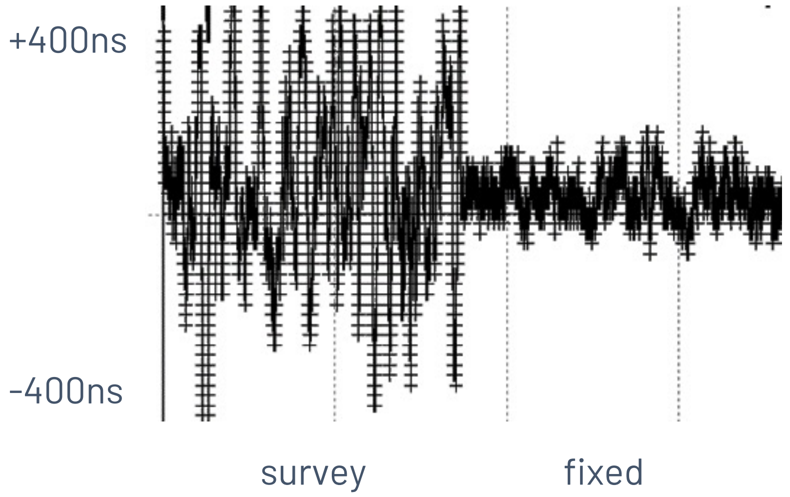
Challenge #3: GPS is not the ideal time synchronization solution, particularly in congested urban environments

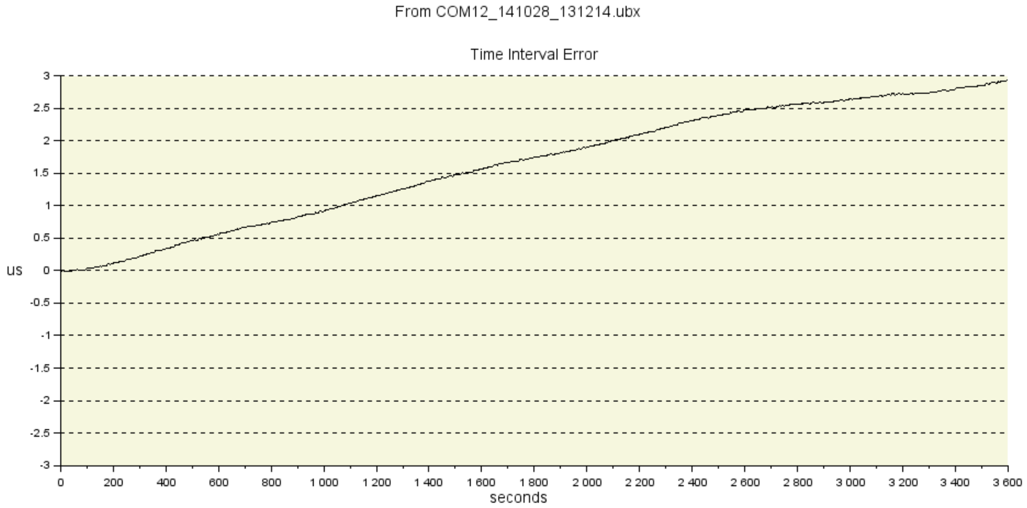
- Limited sky visibility in congested urban environments limits the applicability of standard GPS receivers for accurate PMU time synchronization
- It is challenging from a feasibility perspective, connecting a D-PMU installed in an underground distribution substation to an outdoor GPS antenna
- GPS antenna are more prone to vandalism, as distribution substations are more accessible to the public

GPS data logging by a PMU installed in Hong Kong



Multi-constellation GNSS receiver with stable clock for reliable free-running operations





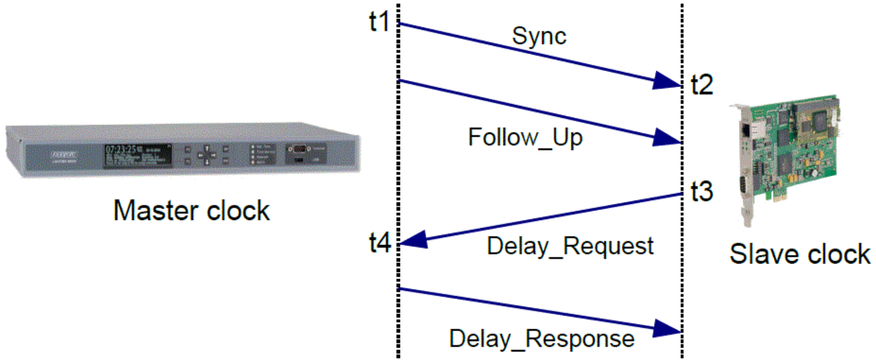
- Weak-signal start-up with aiding and single satellite capability support severe signal environments
- Survey-in provides error-free, self-determination of fixed position
- Fixed-position mode offers timing stability even in poor signal conditions

- <3 microseconds 1-hour internal oscillator holdover (lab measurement)
- Relibale free running operations also in temporary absence of GNSS satellites

Wide-area PTP time-synchronization

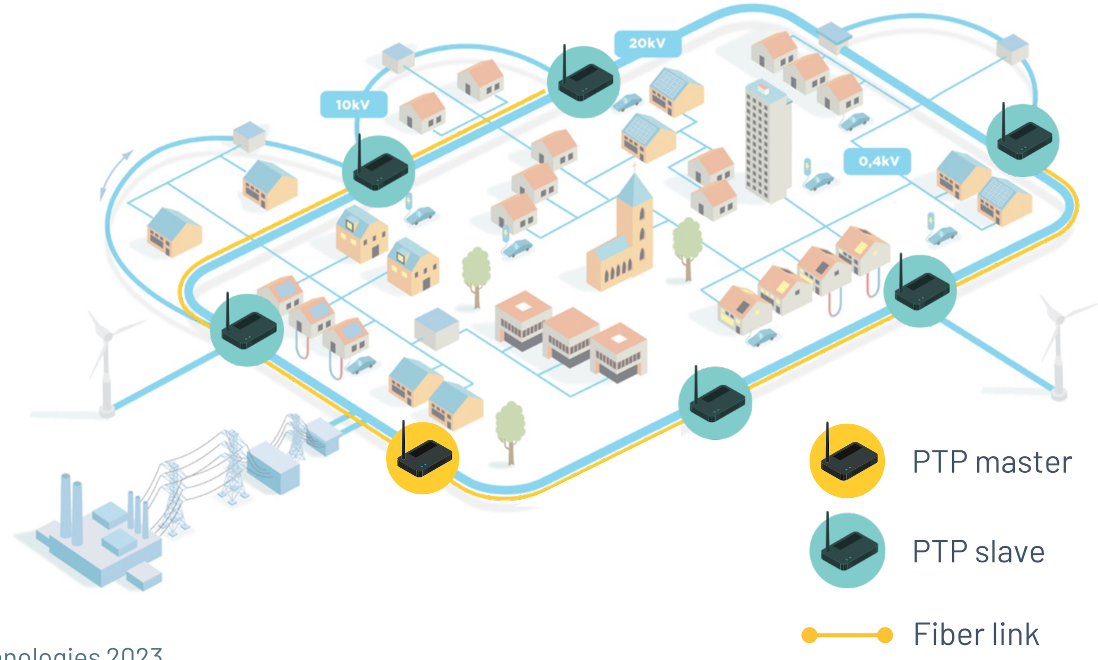
Precision Time Protocol (PTP)

- Protocol used to synchronize clocks throughout a computer network (IEEE 1588)
- Master-slave synchronization scheme (automatic master selection)
- Devices share synchronization packets to calculate propagation/internal delay and adjust/steer their internal clocks to stay in sync



Wide area PTP synchronization

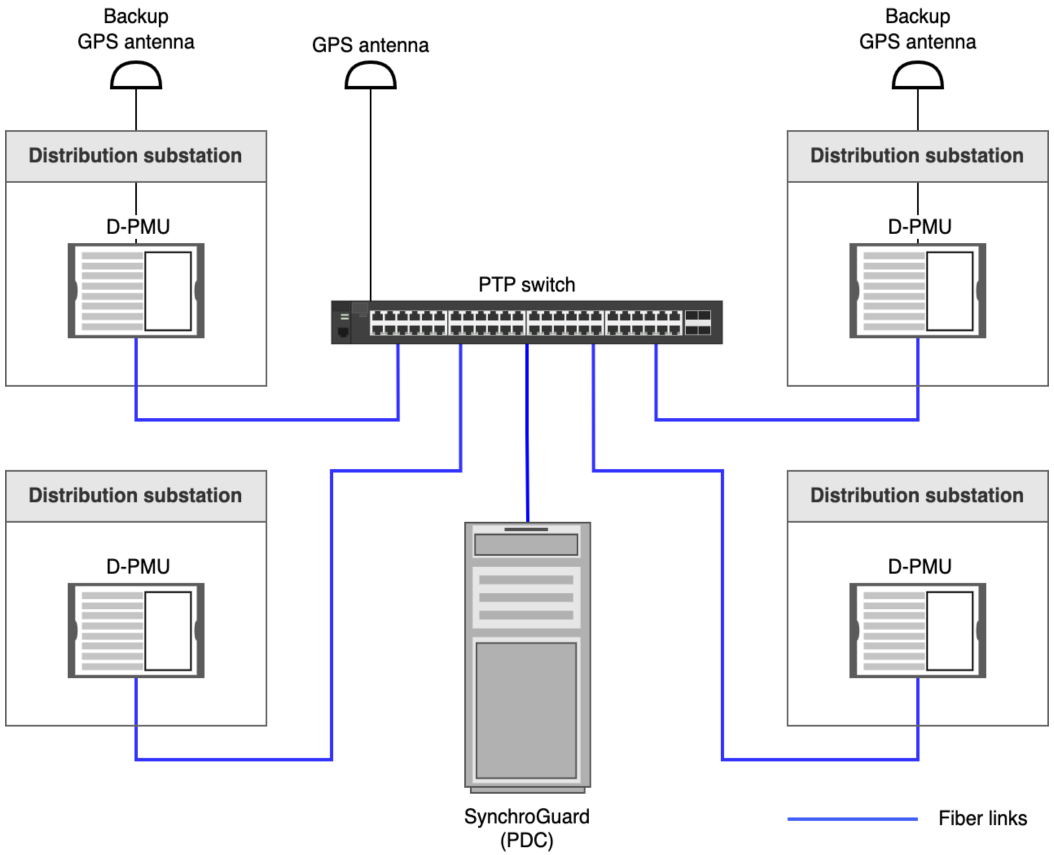
- Requires availaybility of fiber network
- Single GNSS-referenced clock (master)
- Simplified installation
- Increased timing reliability



Wide-area PTP time-synchronization

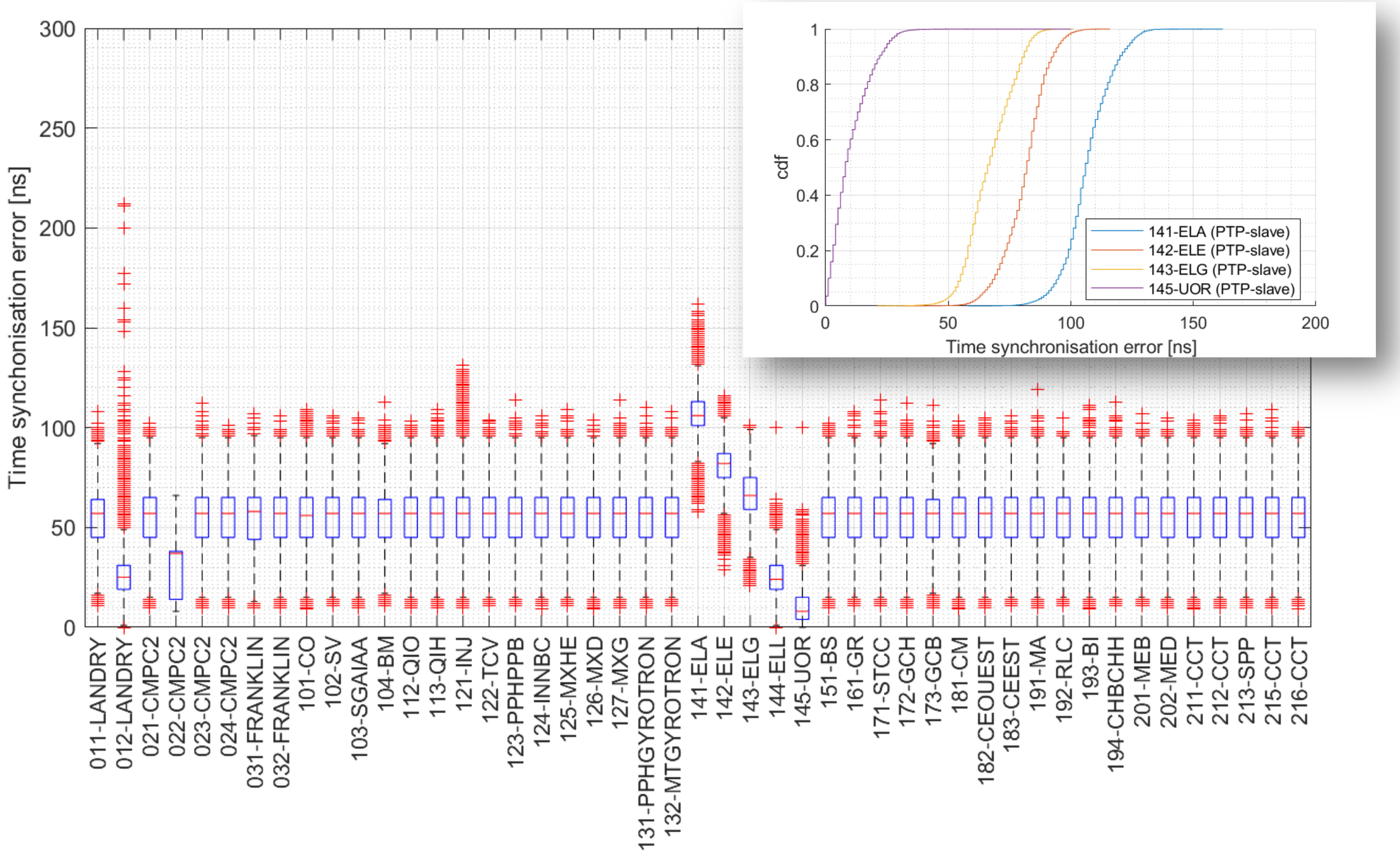
Field implementation example

- PMU data communication and time-synchronization via already available fiber network
- Fully PTP-compliant network:
  - Fiber network in “star” topology, with fiber links up to 2 km long
  - Cisco Catalyst C9407R PTP-compatible switch located in central switching substation
  - 5 PMUs equipped with GPS antenna acting as potential PTP grandmaster clocks
  - Election of best master clock via IEEE 1588 BMCA, based on clock accuracy
  - Rest of PMUs acting as PTP slave clocks
- PTP synchronization accuracy assessment via 1588 protocol and via reference GPS antenna in 4 substations



Wide-area PTP time-synchronization

Time synchronization accuracy



Challenge #4: Distribution grid size and complexity requires a different PMU deployment and architecture

Portion of Single Line Diagram of Swiss Utility Romande Energie

- A medium-voltage distribution grid is composed by 100-500x more nodes than the corresponding high-voltage transmission grid (a typical DSO in EU manages between 1'000-100'000 distribution substations)

  D-PMU solutions (hardware and software) must be able to cope with 1000s of measurement points/grid nodes

- At the same time due to budget constraints and to align with the overall digital strategy of a power utility, a D-PMU rollout will happen gradually, with typical initial D-PMU coverage <10%

  D-PMU solution (hardware and software) must integrate optimal placement tools able to cope with diverse D-PMU coverages

Optimal PMU placement

Netze BW

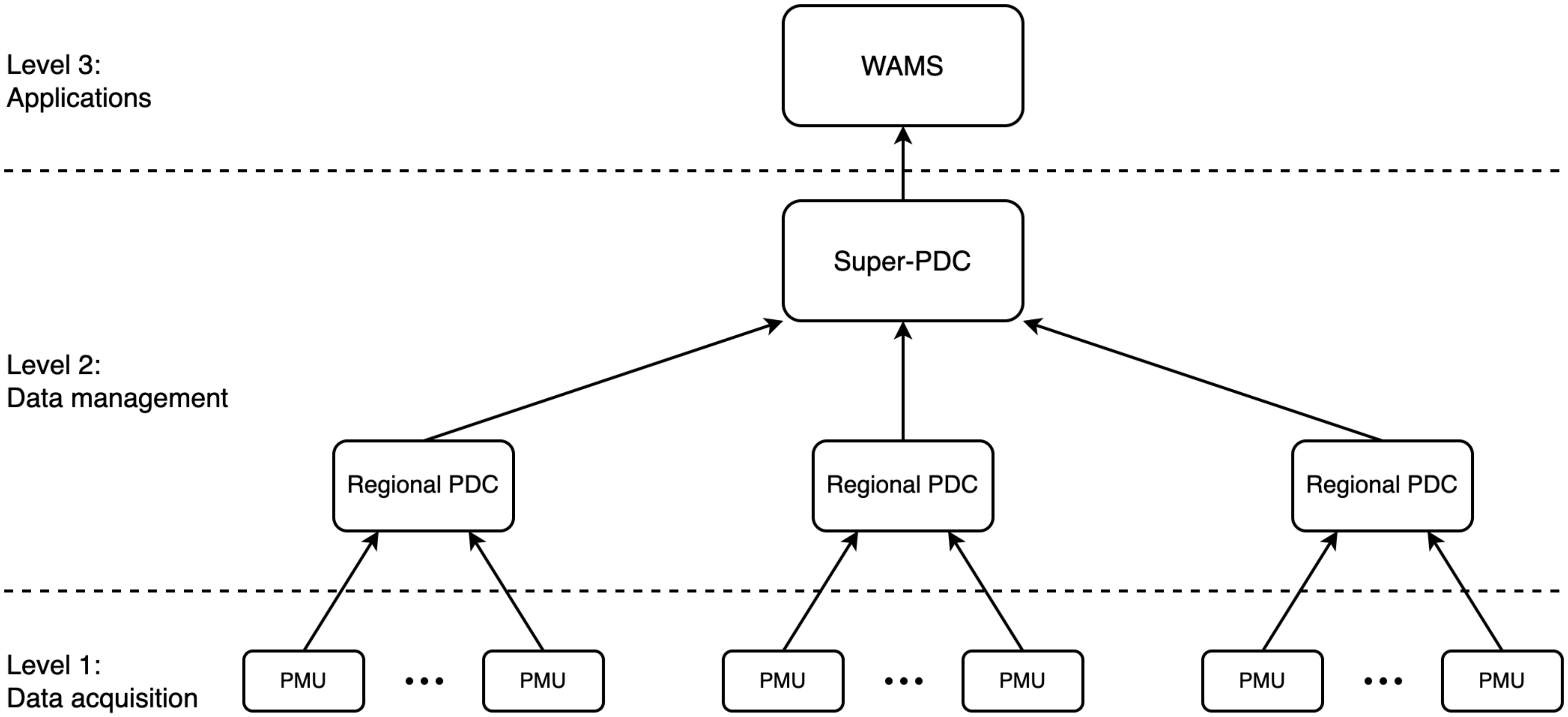
Problem statement

- Customer does not allow/foresee installation of PMUs in more than 10% of grid nodes, both because of budget limitations and lack of resources able to maintain such a device fleet
- Optimally place 7 D-PMU devices, taking into account
    - Grid size (80 nodes) and topology
    - Loads characterized by different unpredictability levels (e.g., residential vs commercial vs industrial loads)
    - Presence of distributed generation (solar, wind, CHP units, hydro)
    - Installation constraints (e.g., private distribution substations)
    - Target applications/use cases
    - Budget limitations

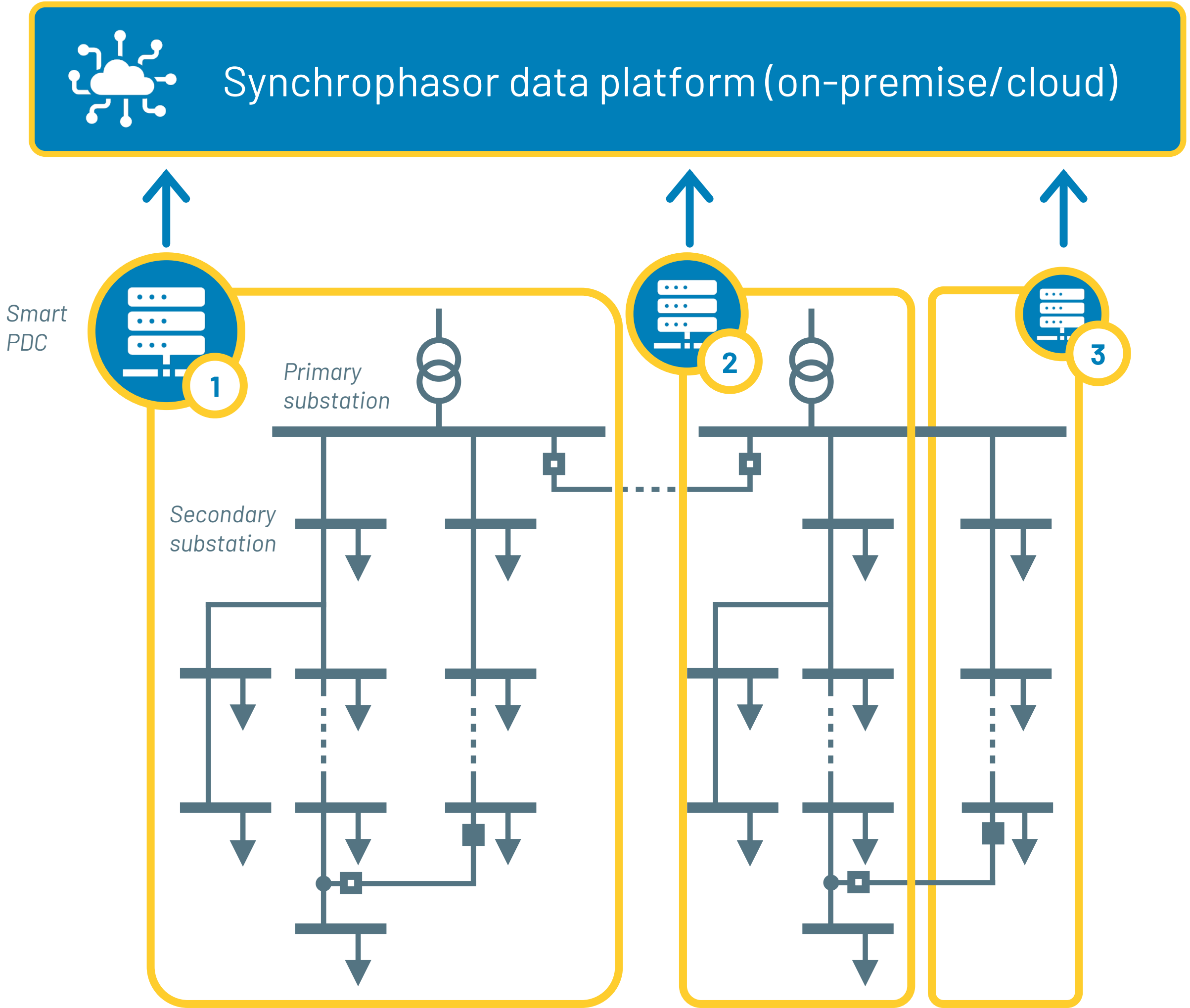
Solution

- Optimal PMU placement toolbox solely based on grid “digital twin” concept, which can operate with different level of details of the grid model

From a centralised architecture based on distributed physical systems and a central software application...



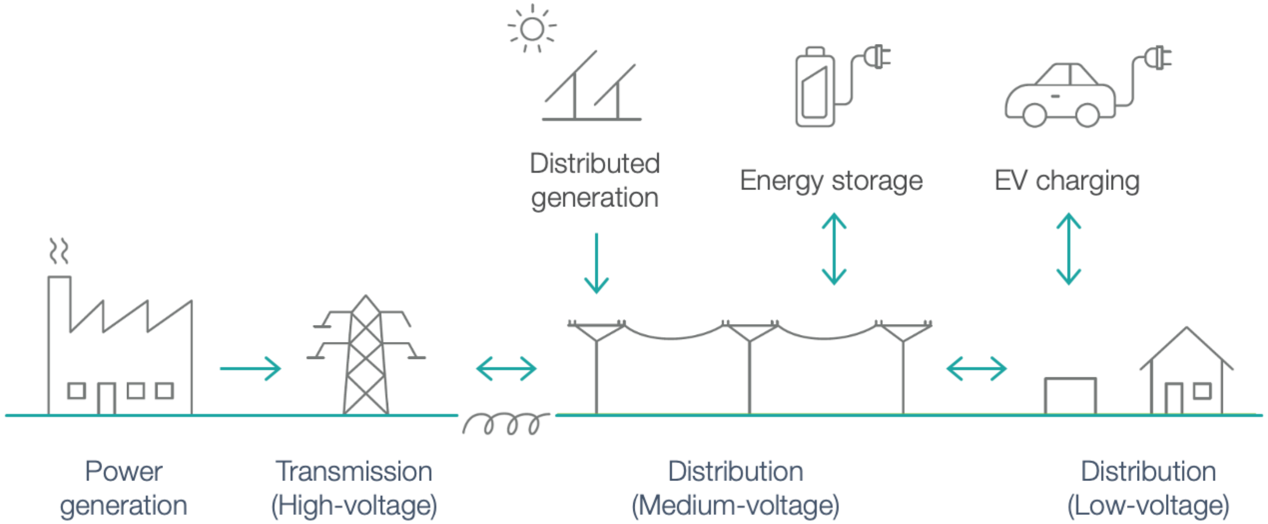
… to a fully virtualized solution based on optimally distributed "smart-PDC" and a central data platform



Requirements for a DSO-ready distribution synchrophasor platform

- From PDC to smart-PDC: automatic extraction of actionable insights/value added information from synchrophasor measurements
- Local phasor data concentration and processing for real-time closed-loop automation schemes requireing faster response times
- Optimal system segmentation in multiple (local) smart-PDC instances based on underlying grid topology and available resources
- Virtualized solution, able to run on different platforms (on-premise/cloud) and environents (substation/data center) depending on the specific customer needs
- Centralized synchrophasor platform (utility data center/cloud system) for global grid state reconciliation and long-term data storage

Challenge #5: When it comes to PMU's, DSOs and TSOs have different needs and expectations



Major DSOs challenges today:

1. Grid observability
2. Security of supply
3. DER integration

- Aging grid infrastructure, extreme weather events and massive DER integration are putting increasing pressure on DSOs to invest in digital tool to safeguard the security of electricity supply and unlock new services required by their new role
- DSOs will be hesitant to invest in synchrophasor (1) if they are not able to tackle their core problems/strategic developments and (2) if they do not integrate with their existing IT/OT environment

A proposal to integrate distribution synchrophasor in the current IT/OT environment of a utility company

Typical data sources (IEDs):

Remote Terminal Units (RTUs)

Fault Passage Indicators (FPIs)

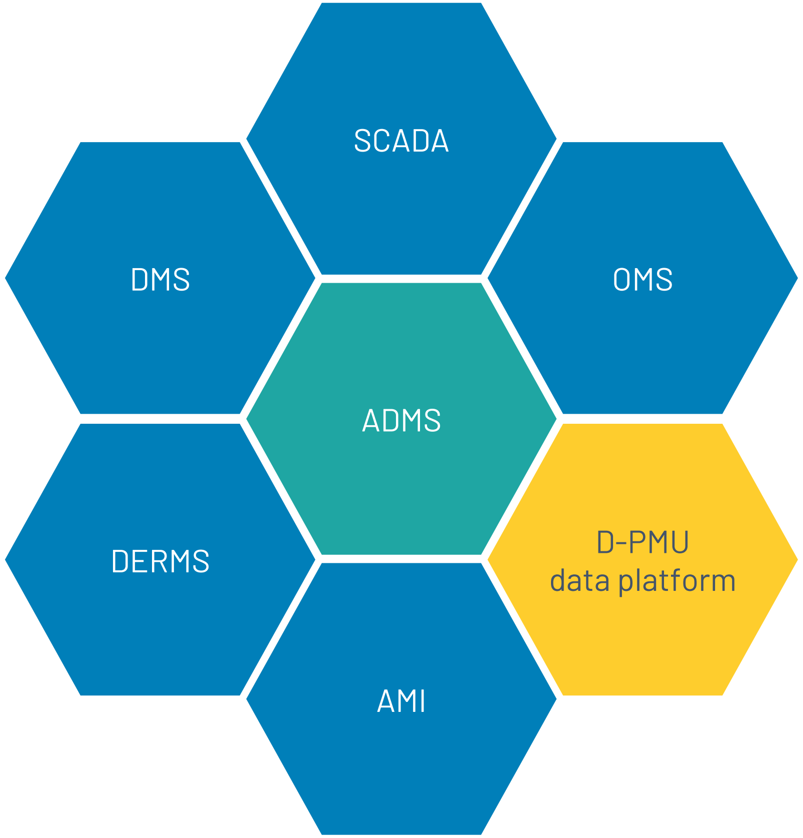
Protection relays

Energy (smart) meters

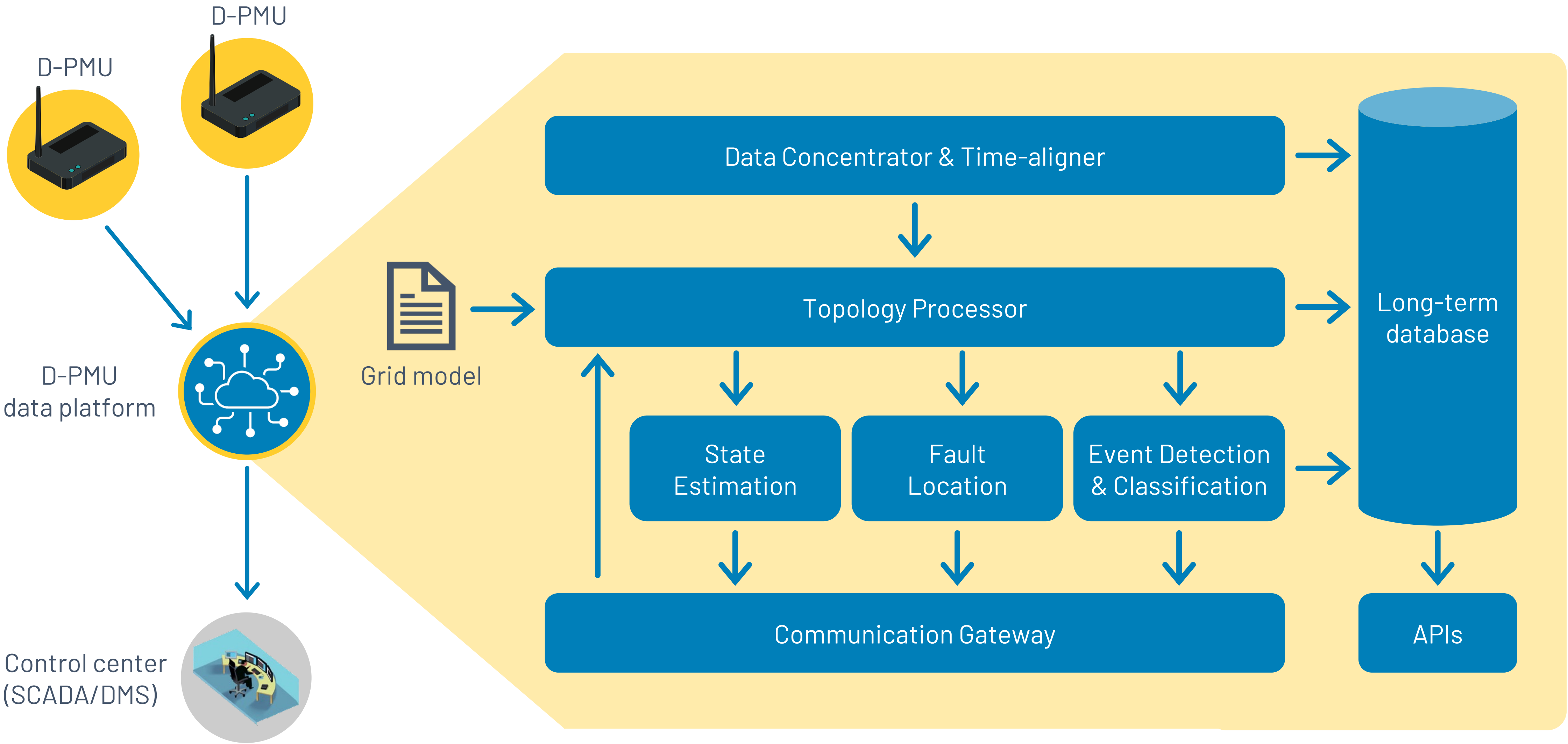
Power Quality (PQ) meters

Distribution Phasor Measurement Unit (D-PMU)

Control room integration



Must-have features for a D-PMU data platform



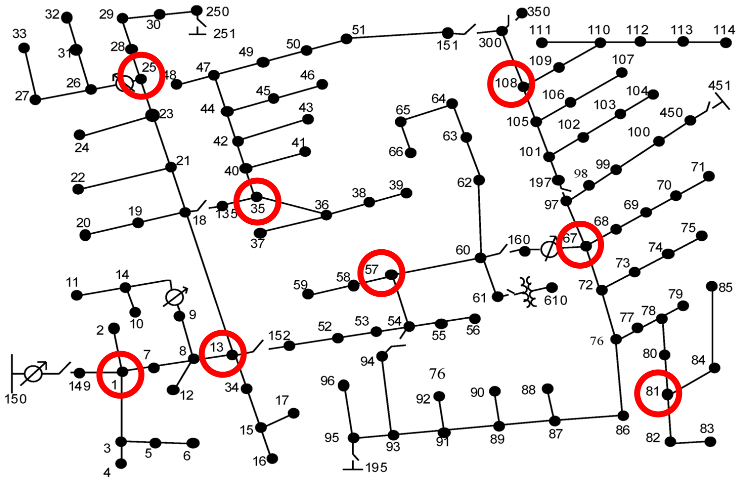
Two core D-PMU applications and related use cases

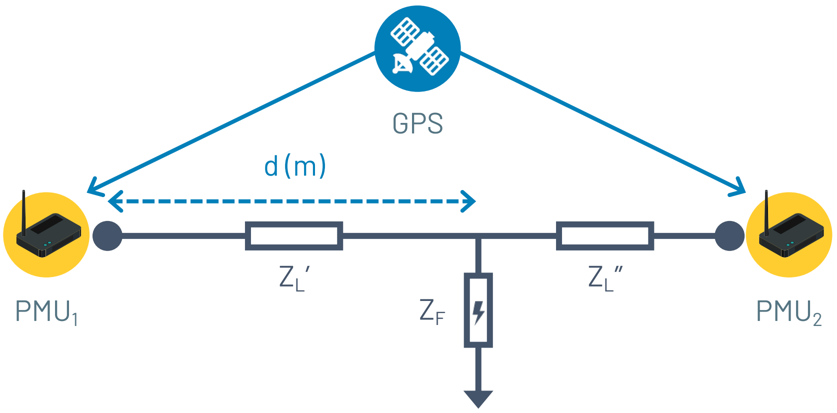
1. Distribution system state estimation

Benefits: Full-grid visibility on voltages/current/ power flows with as little as 10-20% measurement coverage.

2. PMU-based fault location

Benefits: Automatic identification and location of permanent/ incipient faults, blackout prevention, enhanced SAIDI/SAIFI.

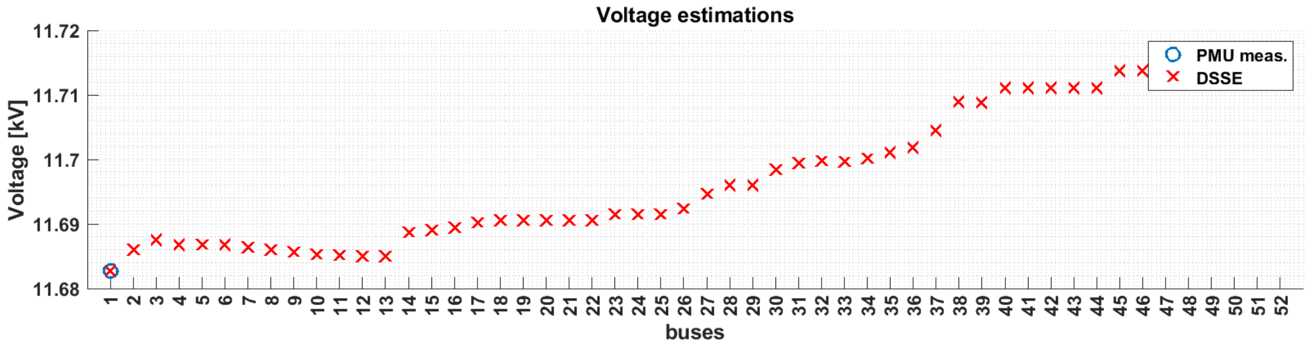


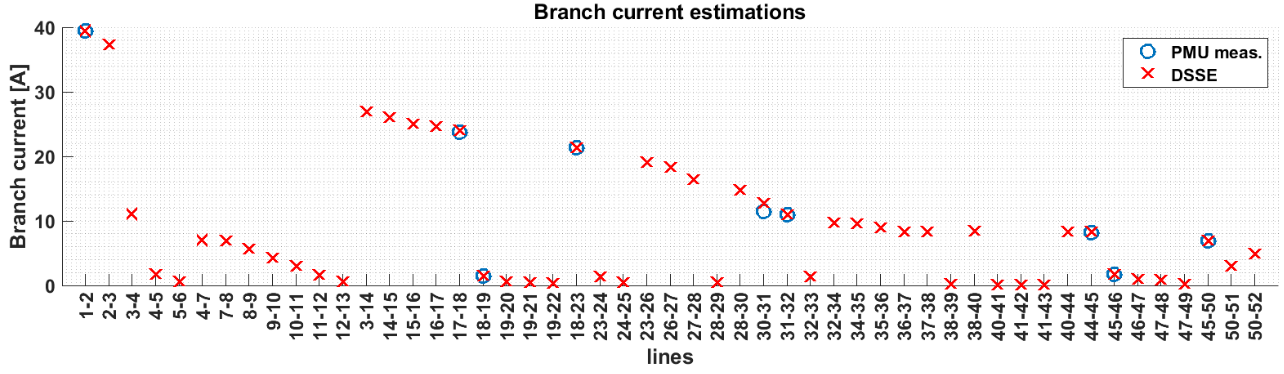


Distribution System State Estimation (DSSE)

Experimental validation in an active distribution grid in Germany

Netze BW

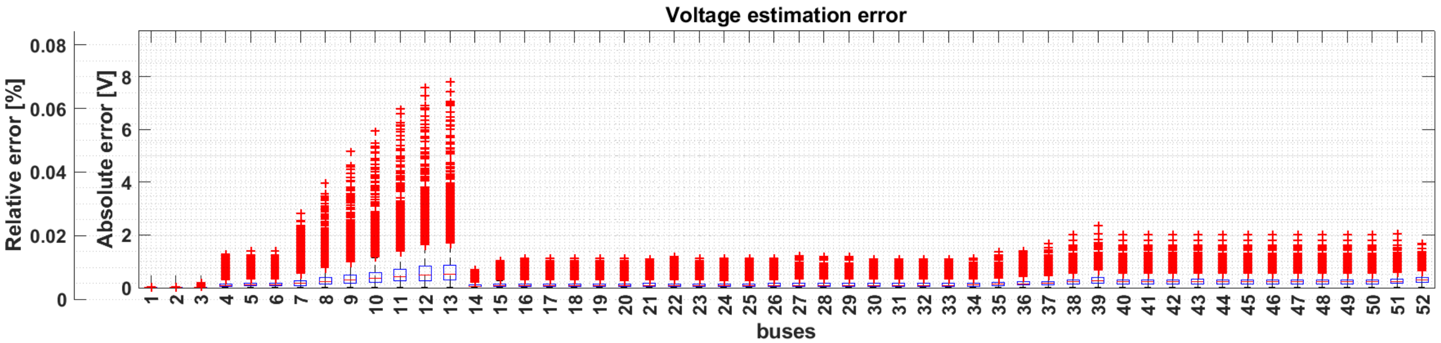


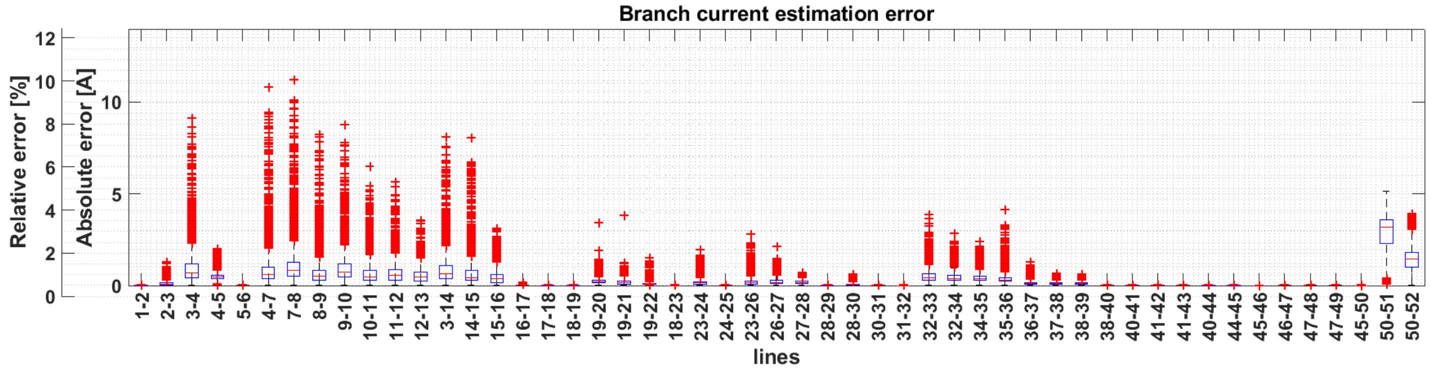


→ Full grid visibility (estimation of nodal voltages, nodal/branch currents and active/reactive power flows) based on a limited number of high-quality measurements from D-PMUs

Distribution System State Estimation (DSSE)

Accuracy assessment

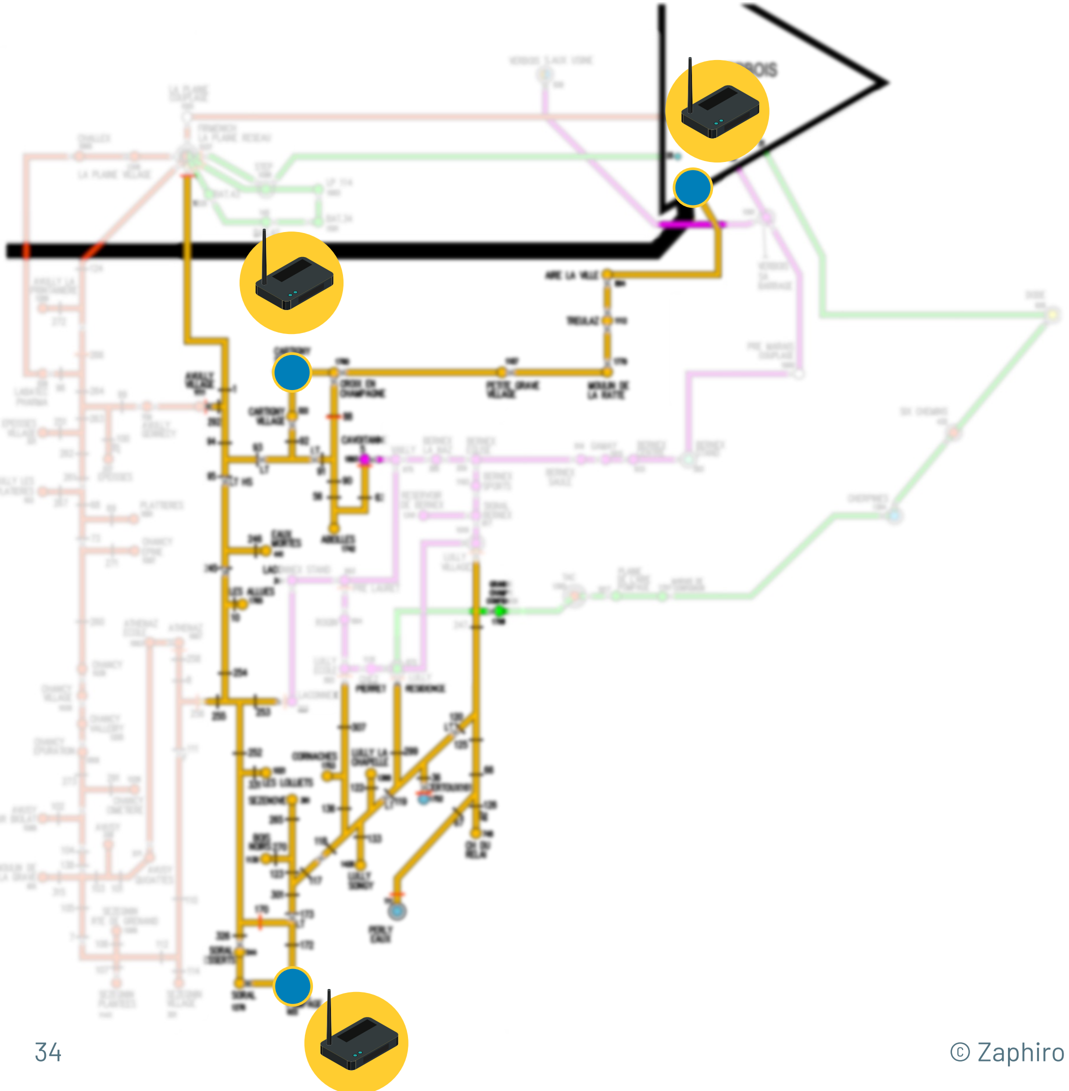




- → Negligible voltage estimation errors (<0.01%)
- → Limited branch current estimation error (95th percentile <1.4 A) for accurate line/transfomer congestion monitoring

PMU-based fault location

Real fault example in an overhead MV grid in Switzerland

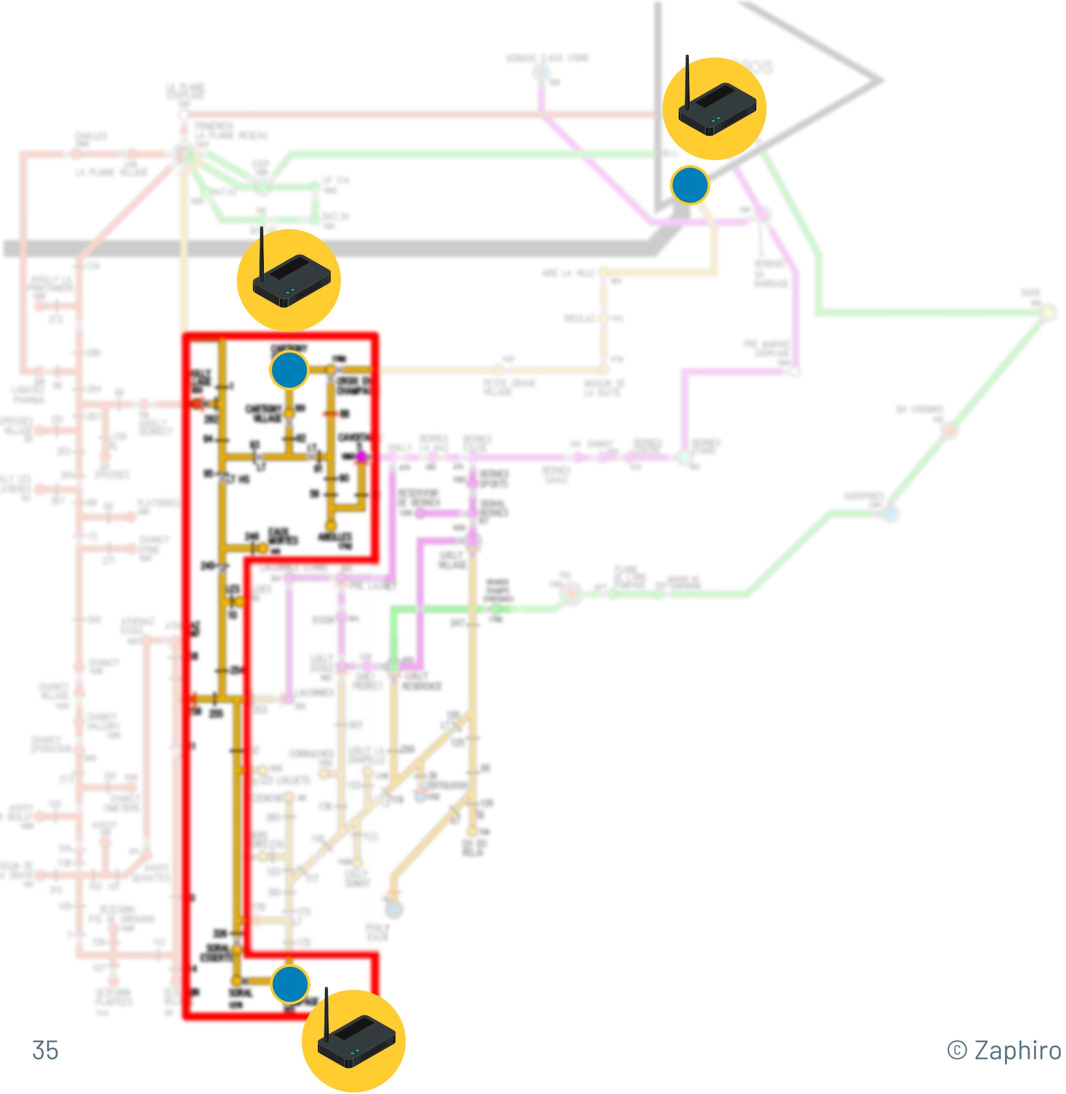


Grid characteristics:

- Feeder length: 21.5 km (radial topology)
- Neutral treatment: compensated (with Petersen coil)
- Nominal voltage: 20 kV L-L

PMU-based fault location

Faulted area identification



Benefits of D-PMU based faulted area identification

- **Sensitivity**: detection of low current faults
- **Reliability**: no false alarms raised
- **Speed**: immediate (<100 ms) faulted area identification

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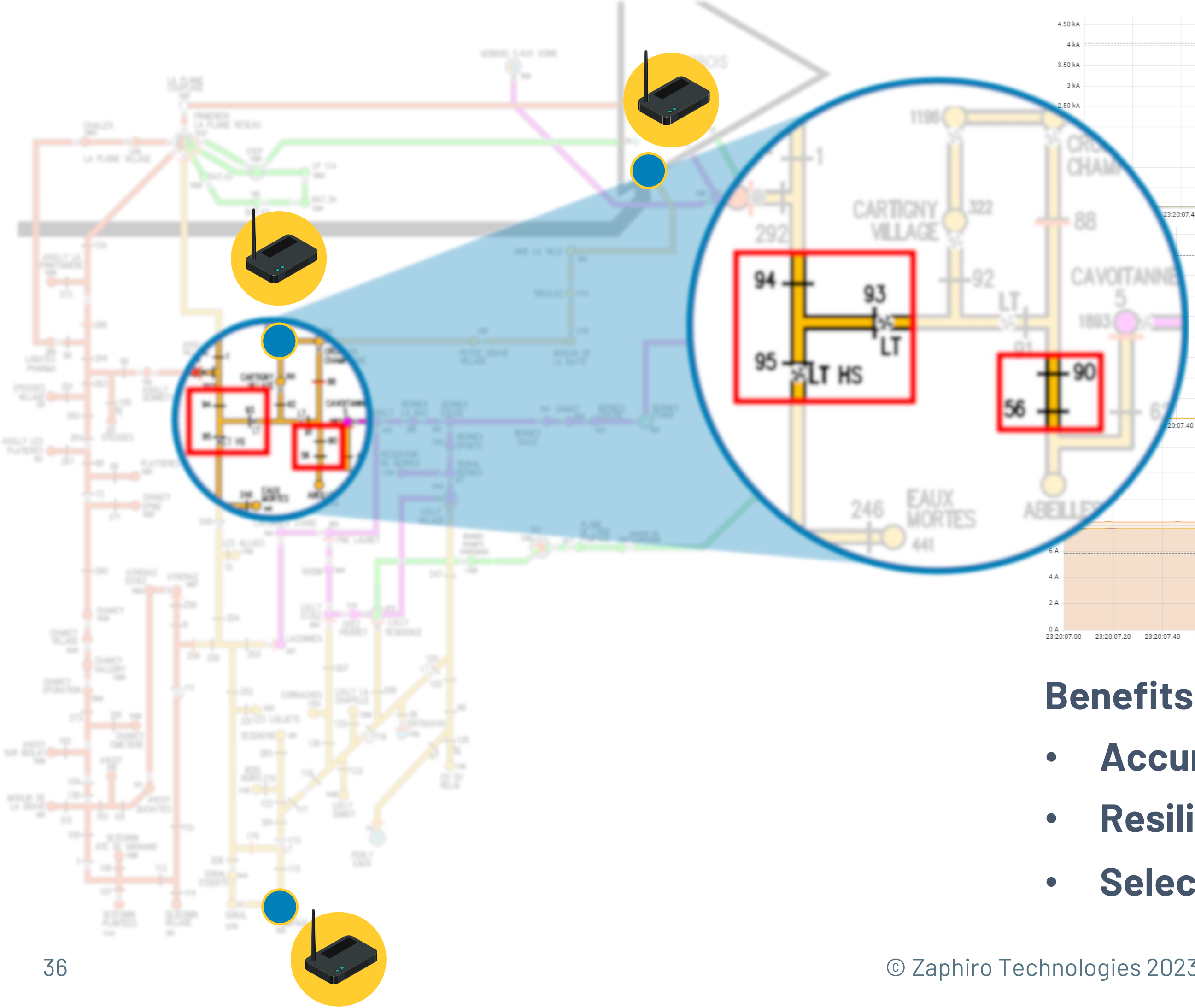
PMU-based fault location

Fault location within the faulted area

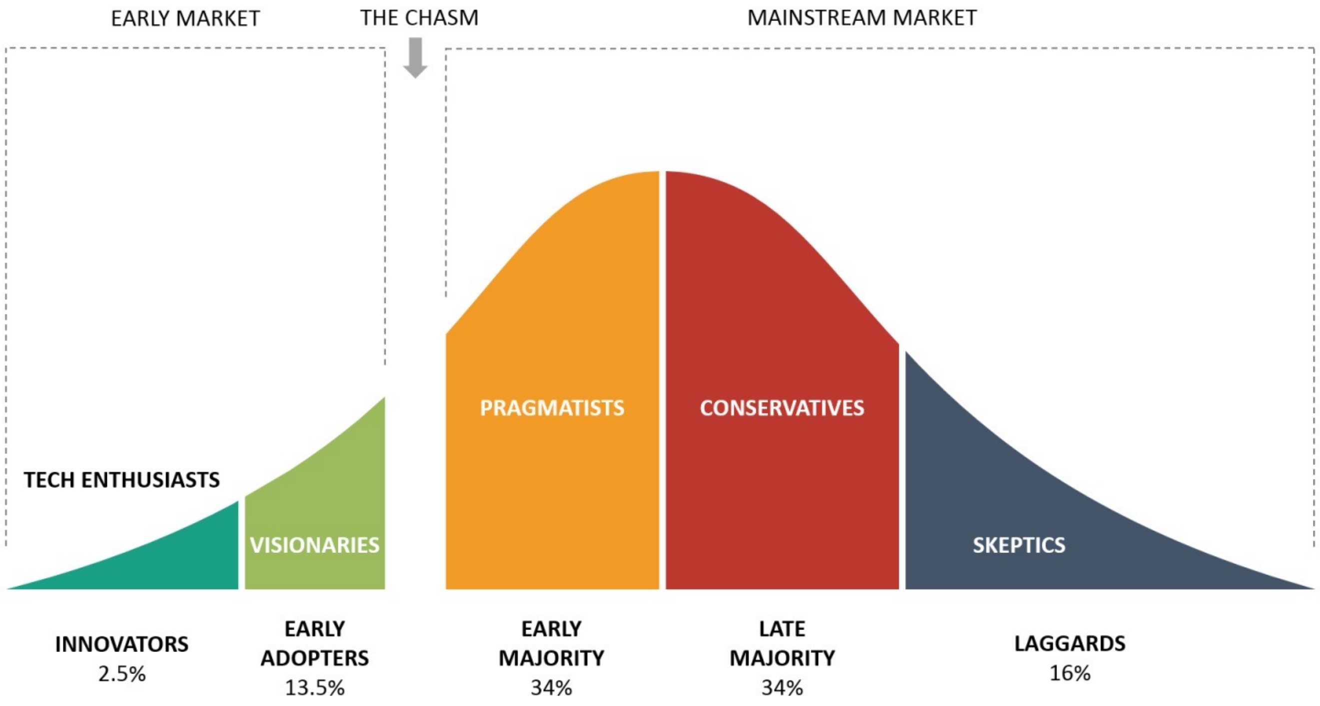


Benefits of D-PMU based fault location

- **Accuracy**: thanks to D-PMU time synchronization
- **Resiliency**: against DER/load infeed
- **Selectivity**: identification of the faulted component(s)

D-PMUs: what do we need to “cross the chasm”?

1. A new D-PMU Std. designed around the core D-PMU use cases and applications, able to clarify the requirements and ambiguity around D-PMU technology
2. More industry involvment to increase the amount of D-PMU vendors and cut-down the costs of today’s D-PMU devices
3. A research community focused on the development of novel and impactufl D-PMU applications able to justify the investment on D-PMU technology



Unlock your grid potential!

Contact us:

Dr. Paolo Romano
Co-founder and CEO
paolo.romano@zaphiro.ch
www.zaphiro.ch

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