Redundant Sensor Data Consolidation and Verification

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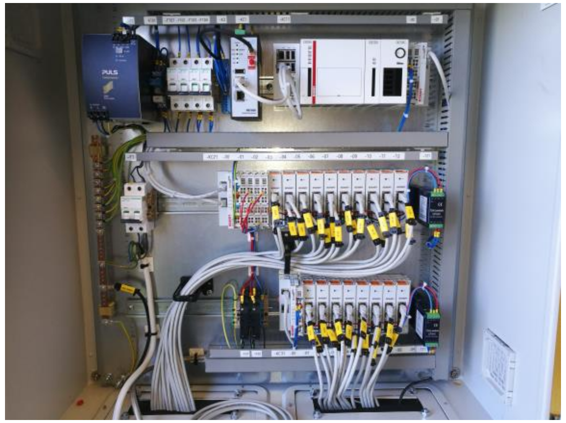
Background dLab

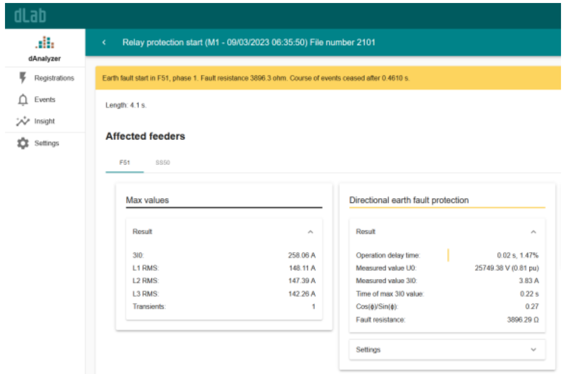
- dLab started as a research project at LTH (Lund Institute of Technology), funded by the E.ON (Swedish TSO/DSO division) in 2007
  - Starting 2005, extensive replacement of MV overhead lines with cables was carried out in rural areas, resulting in new grid topologies with long cables and large capacitive earth fault currents
  - The purpose was to study earth faults in these MV networks to overcome new challenges regarding protection equipment requirements, earth fault detection and relay setting strategies
  - The project needed data acquisition to capture real earth faults regardless of the substation equipment (ranging from electromechanical to static to numerical protection relays) and automated analysis of the gathered data
- This data handling concept was commercialized through dLab, founded in 2010 and commercially active since 2015

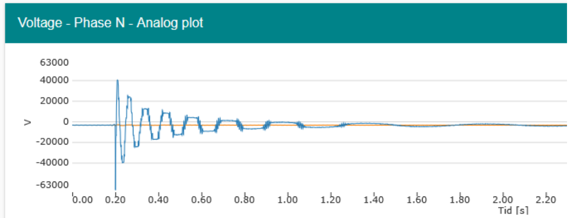
The dLab Concept

- Hardware
  - Automation equipment for data acquisition in the substation
  - Robust, versatile and reliable
  - Adaptive triggering for recording high resolution data
  - Continuous measurements for other uses (power quality, load flow etc.)

- Software
  - Centralized data storage and analysis
  - Early warnings for upcoming potential faults
  - Extensive disturbance recording with automatic analysis
  - Power quality measurement and evaluation
  - Load and power flow measurement for statistics, planning etc.



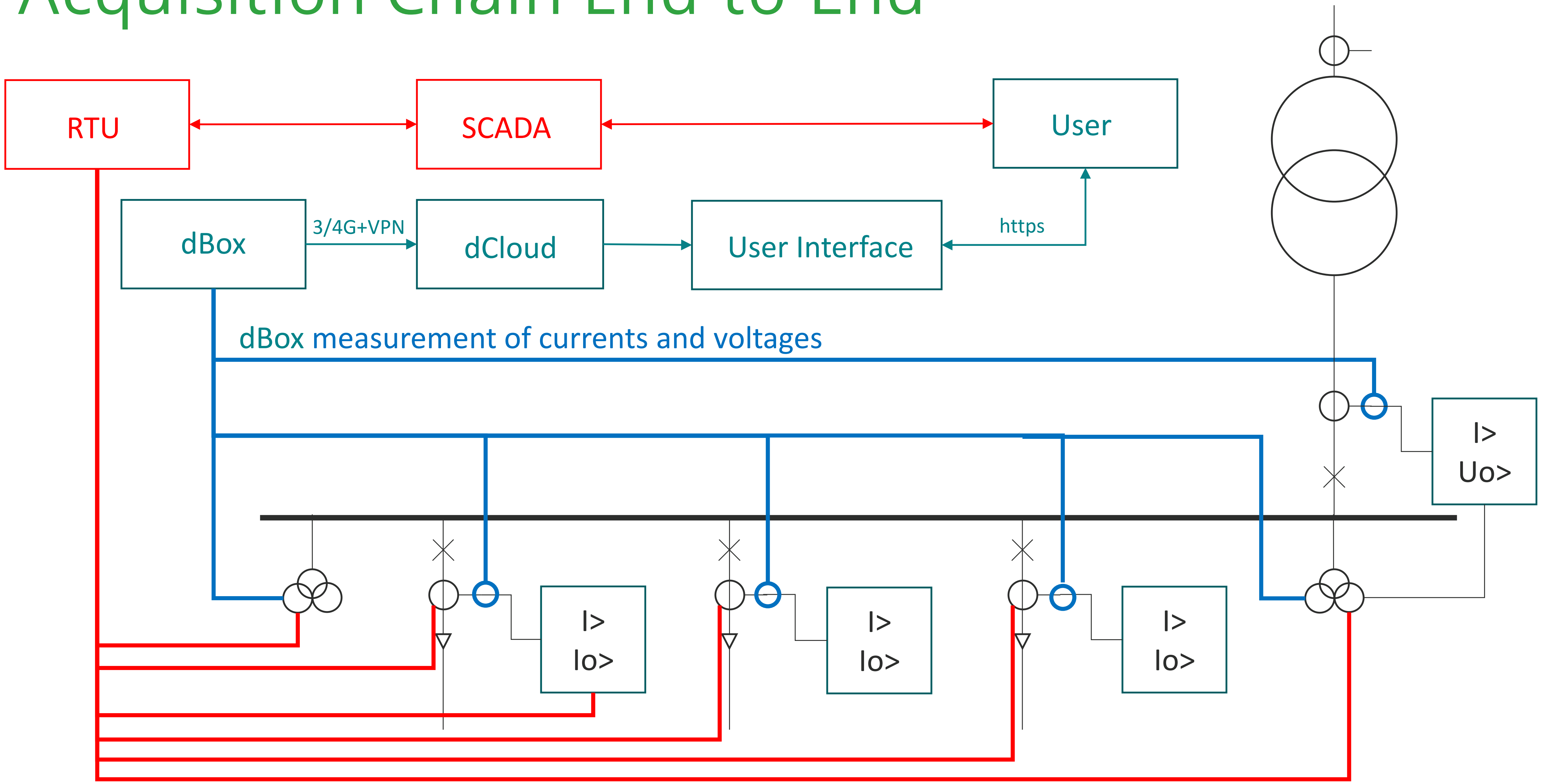




dLab and RESili8

- The dLab solution is independent from other substation equipment (historically because there was no or very limited other data sources in older substations)
- This means that in a modern substation, there are multiple ways to gather the same data (through IEDs, RTU etc.)
- The redundancy can be useful in multiple ways
- Since the dLab hardware uses the same sensors/data sources on a low (physical) level, the complete chain of data handling can be monitored for deviations and/or manipulation

Completely Separated Data Acquisition Chain End-to-End



Use Cases Involving dLab

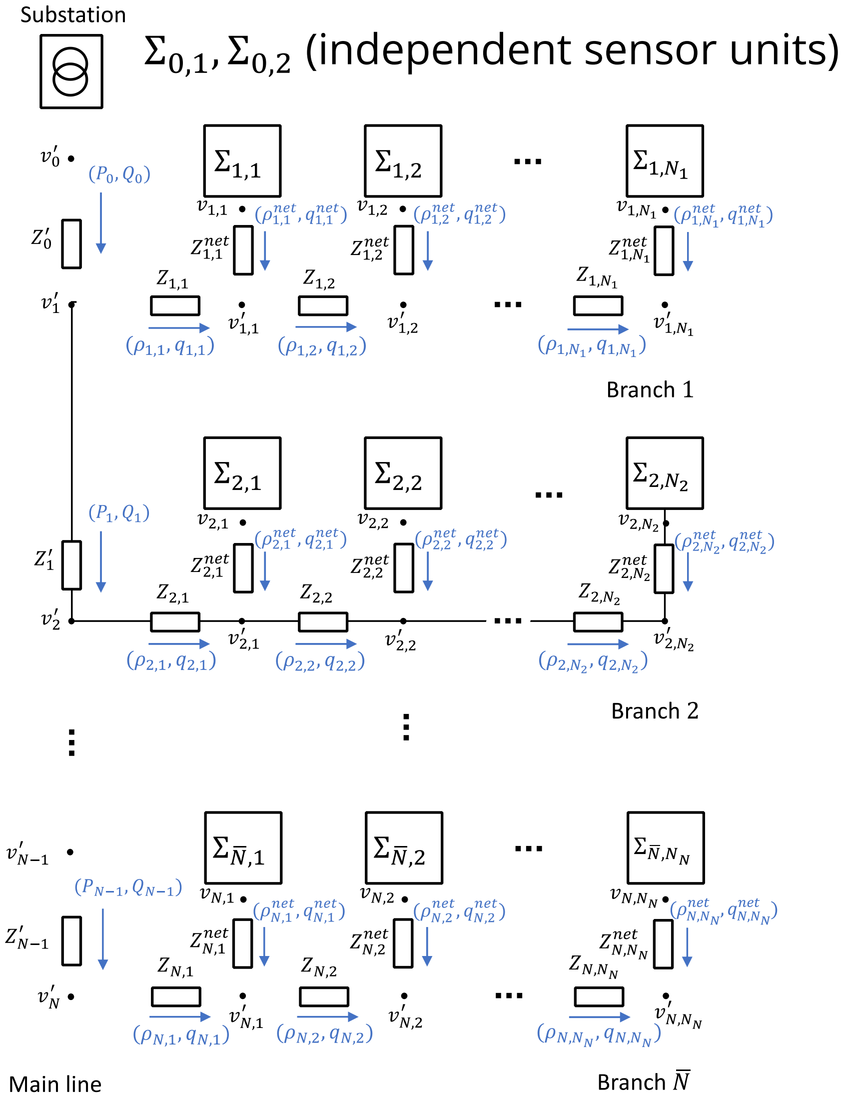
- Data integrity verification
  - Well in line with the cyber security-focused part of RESili8
  - Monitoring of protection and control system behaviour
  - Monitoring of measurement values

- Earth fault distance calculation
  - Related to the resilience of the grid on a more physical level
  - dLab provides high quality recorded data from real-world earth faults
  - One of dLab's DSO customers have been very helpful with providing known fault locations and grid data for comparison
  - Comparison to simulated faults to verify the model used for investigating the possibilities of calculating the fault location

Data Integrity Verification

- As mentioned, since the dLab concept is independent of other substation equipment, there are redundant ways of gathering the same data in the substation
- However, the data acquisition is done in different ways depending on its main purpose and is not synchronized
- This means the data cannot be compared bit-by-bit, so some other method is required to detect data corruption and anomalies
- KTH has done some work in this field in other projects that we hope to further develop in this scenario

State Estimation Using Redundant Sensors in Distribution Power Network



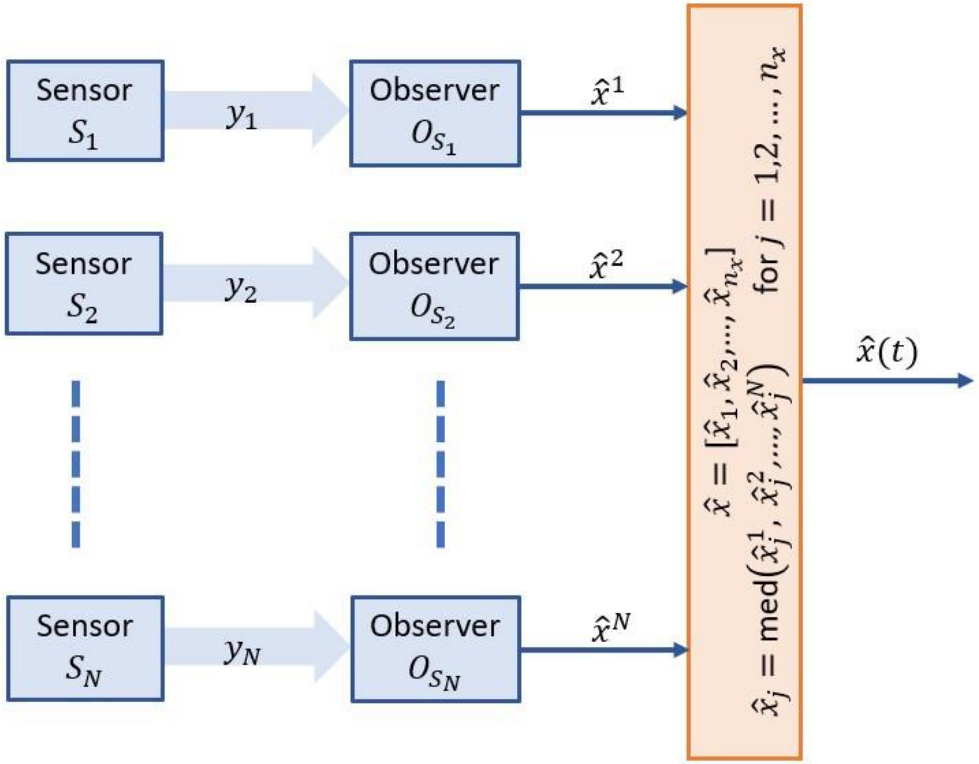
Setup:

- Substation and each branch have (power, voltage, current) sensor units $\Sigma_{i,j}$
- Unknown subset of sensor units subject to attack or other anomalies

Problems:

- (P1) How to detect and correct anomalous and corrupted measurement data in real time?
- (P2) Can (P1) be solved if sensors have different measurement rates $r_{i,j} > 0$?
- (P3) Can (P1)-(P2) be solved using a distributed algorithm?

(P1) Resilient Nonlinear State Estimation



$$
\begin{aligned}
\dot{x} &= f(x, z, w, d), \qquad z = (z_1, z_2, \dots, z_N), \\
z_i &= h_i(x, w, d), \qquad i \in \mathbb{N}_{[1,N]}, \\
y_i &= z_i + a_i
\end{aligned}
$$

- Assume:
  - Network state is observable from each sensor $\Sigma_{i,j}$ (*relaxed next);* and
  - At most M sensor corrupted/anomalous
- For each measurement $y_i(t)$ compute state estimate $\hat{x}^i(t)$ using dynamical state observer

$$\dot{\hat{x}}^i = \hat{f}(\hat{x}^i, y_i, w), \qquad i \in \mathbb{N}_{[1,N]}$$

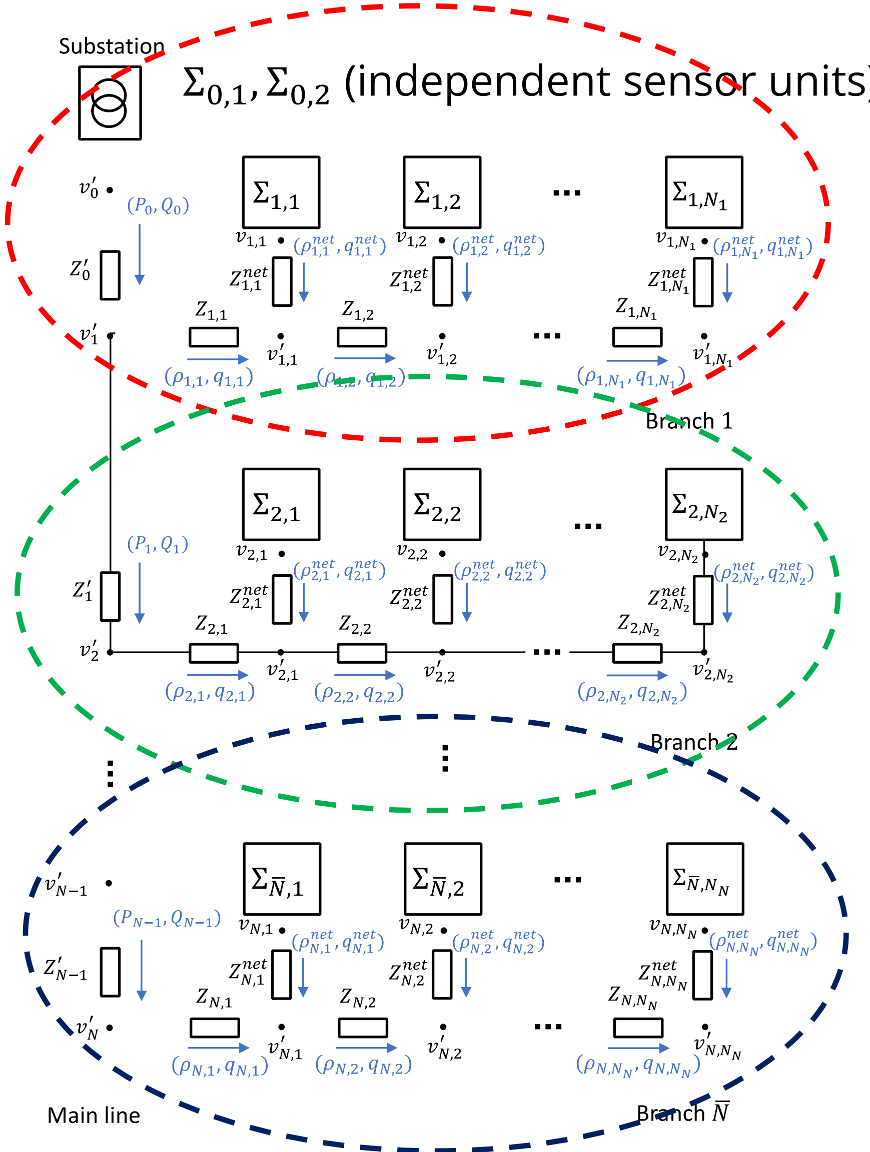
- Compute combined state estimate using median operation

$$
\begin{aligned}
\hat{x} &= (\hat{x}_1, \hat{x}_2, \dots, \hat{x}_{n_x}), \\
\hat{x}_j &= \text{med}(\hat{x}_j^1, \hat{x}_j^2, \dots, \hat{x}_j^N), \qquad j \in \mathbb{N}_{[1,n_x]}
\end{aligned}
$$

- Property: If $2M < N$ and no noise/disturbances, then anomalous/attacked sensors have no effect on $\hat{x}(t)$

[van der Horst, Kim, Chong, S., 2022]

(P1) Resilient Nonlinear State Estimation

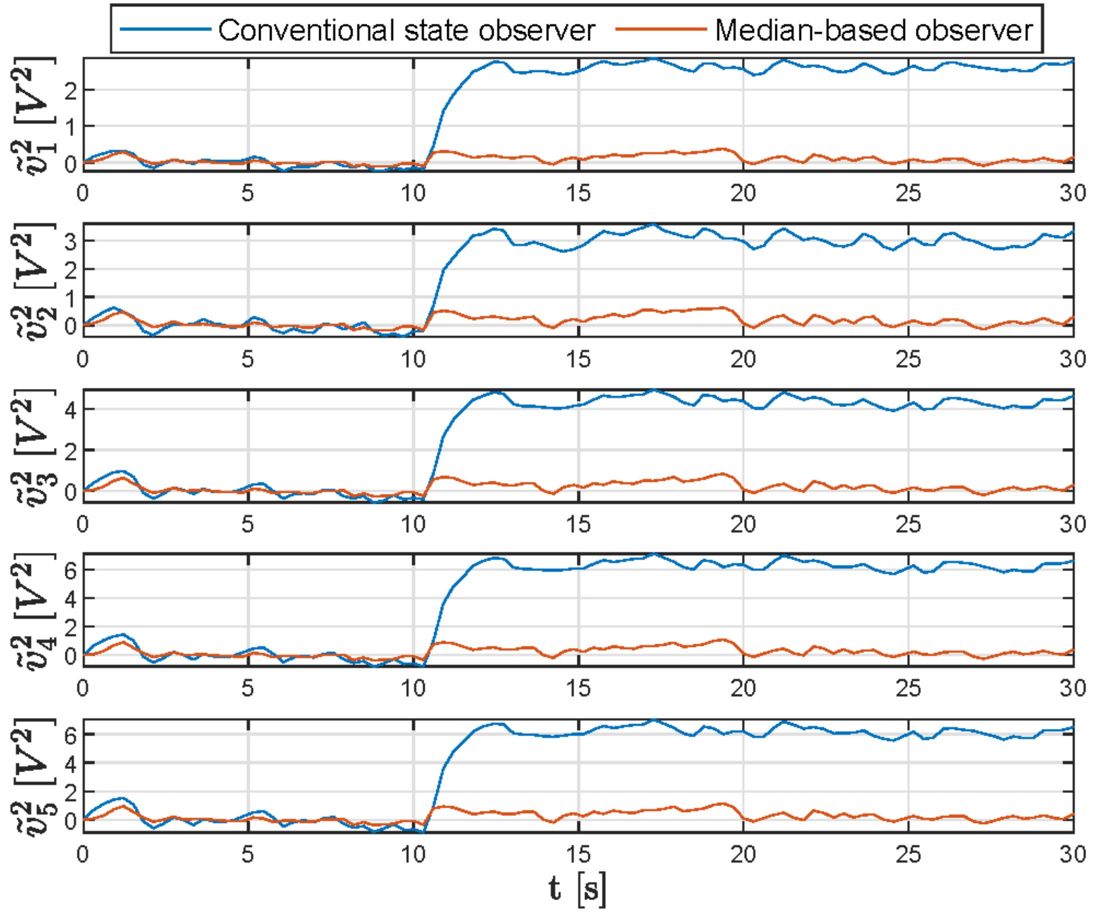


- Assume:
  - Network state is observable from each sensor $\Sigma_{i,j}$; and
  - At most M sensor corrupted/anomalous

- Relaxation: Each state variable is observable from at least three independent sensors
  - If state x_i observable by N_i sensors, up to $\lfloor (N_i - 1)/2 \rfloor$ of them can be attacked/anomalous

(P1) Example: Inverter-based power distribution network

State Estimation Errors

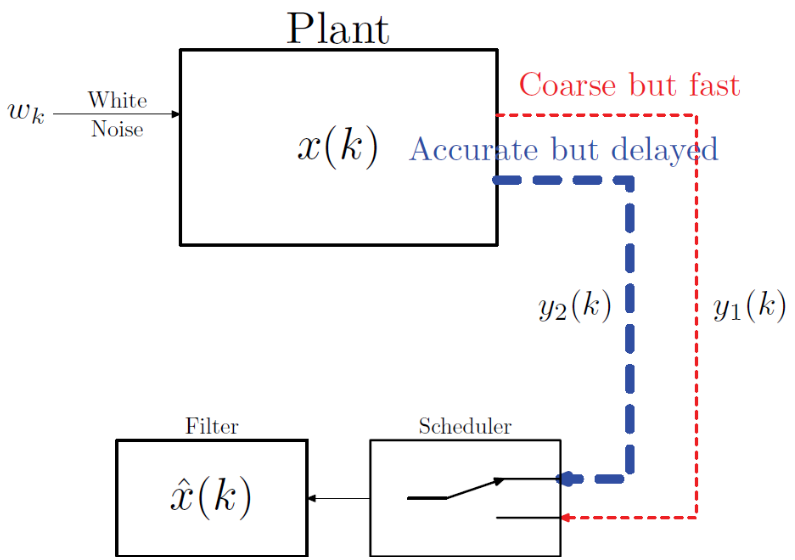


- Simulation of a benchmark residential European LV distribution network [Strunz *et al.*, 2009]
- Number sensors $N = 5$
- Number attacked sensors $M = 2$
  - $a_1(t) = a_4(t) = 0$ V, for $t < 10.5$ s
  - $a_1(t) = a_4(t) = 30$ V, for $t \geq 10.5$ s
- $2M = 4 < N = 5$

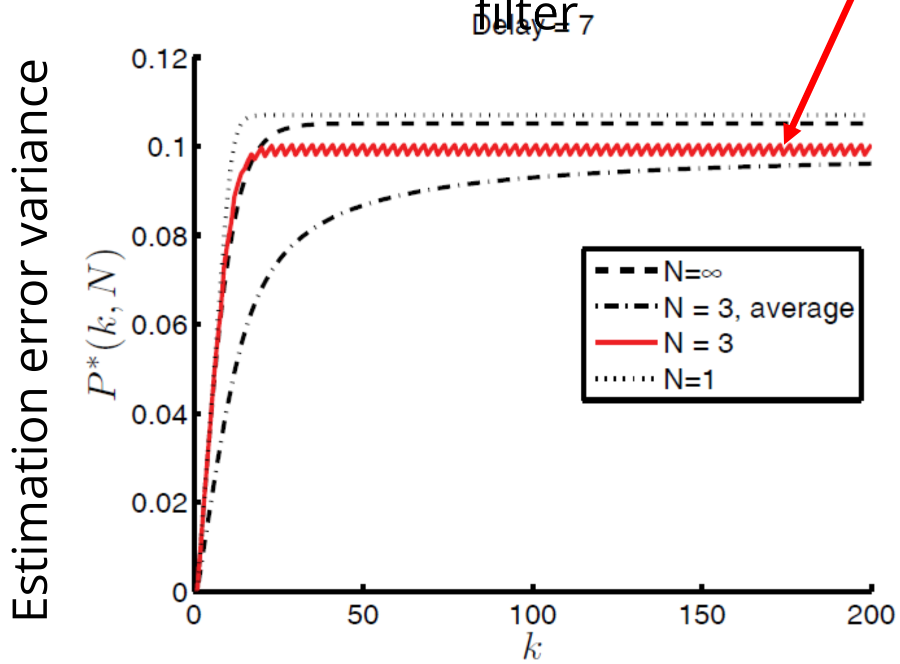
[van der Horst, Kim, Chong, S., 2022]

(P2) Asynchronous State Estimation

- Multi-rate (Extended) Kalman Filter
- Time-periodic Kalman Filter



Optimal time-periodic Kalman filter



$$
\begin{aligned}
x(k+1) &= Ax(k) + Bw(k), && k \geq 0, \\
y_1(k) &= C_1 x(k) + v_1(k), && k \in T_{lq}(N), \\
y_2(k) &= C_2 x(k-d) + v_2(k), && k \in T_{hq}(N),
\end{aligned}
$$

$$
\begin{aligned}
T_{hq}(N) &= \{N-1, 2N-1, 3N-1, \dots\} \\
&= \{k \geq 0 \mid (k+1) \mod N = 0\}, \\
T_{lq}(N) &= \{1, 2, \dots, N-2, N, \dots\} \\
&= \{k \geq 0 \mid (k+1) \mod N \neq 0\},
\end{aligned}
$$

[S., Rabi, Skoglund, Johansson: “Estimation over heterogeneous sensor networks,” IEEE CDC, 2008]

Summary

- dLab provides a versatile data acquisition and analysis platform
- The separated data flow from sensor to user can be utilized to detect data corruption and anomalies
- KTH studies models and methods for comparing unsynchronized data on different formats

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