Robust Recovery of PMU Signals under Corruption: Approaches and Guarantees

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CPS: Small: Fusion of Sensory Data and Expansivity of System Dynamics for Detection and Separation of Signature Anomaly in Energy CPS Wide-Area Monitoring and Control

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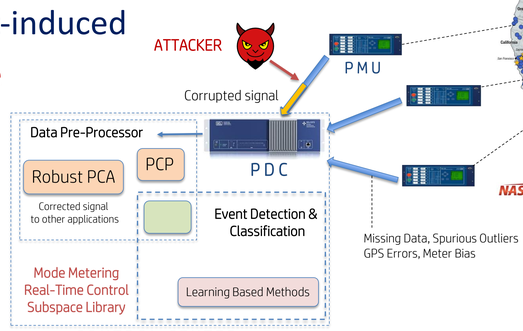
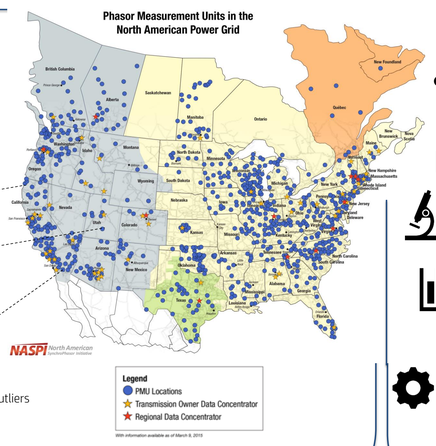
Spurious or maliciously injected outliers in PMU data – Need for anomaly correction – To distinguish between event-induced outliers and bad data – recover clean PMU data

A moving window Kernel PCA-based metric proposed for detecting event-induced outliers in presence of corruptions in PMU data -- A data-driven recursive Bayesian framework adopted for selecting the most appropriate subspace from the library for use in post-event signal recovery

Proposed approaches part of RPCA-based Robust Anomaly Correction and PMU Data Recovery scheme



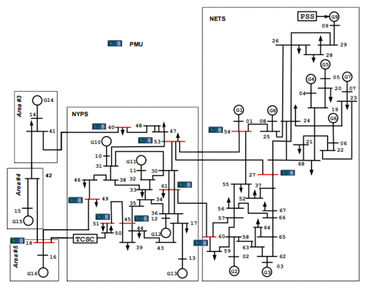


SCIENTIFIC Impact

- Fusion of sensory data with the dynamic properties of the physical system
- Fundamental insight into the coupling between the cyber and the physical layer of Energy CPS
- Better visualization of dynamic events
  Real time monitoring and event detection
- Quantify the effect of PMU signature anomalies on Principal Components in the higher versus lower dimensional subspaces
- Can potentially benefit a wide range of CPS- process control, oil and gas, energy, robots and future transportation systems employing autonomous vehicles
- Protect critical infrastructures from cyber-attacks and facilitate improved system diagnosis, lower downtime, better service, and higher resiliency

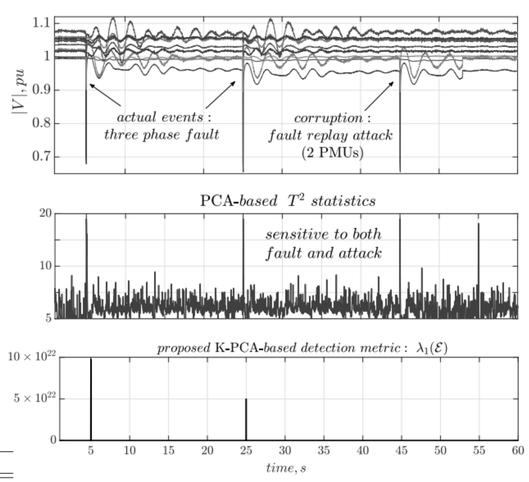
CASE STUDIES

IEEE 5-area 16-machine NY-NE Test System

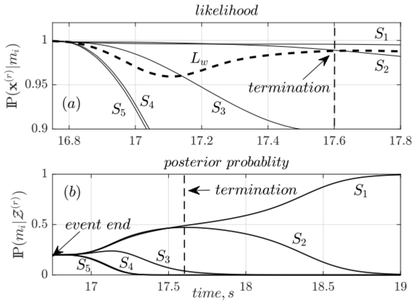


Subspace Library

S_1	S_2	S_3	S_4	S_5
$18-42$ out[1]	$18-49$ out[1]	$40-41$ out[1]	$53-54$ out[1]	Nominal Condition

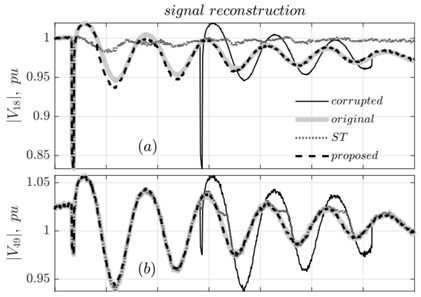


K-PCA-based detection of event-induced outlier: Data recovery is suspended in event window



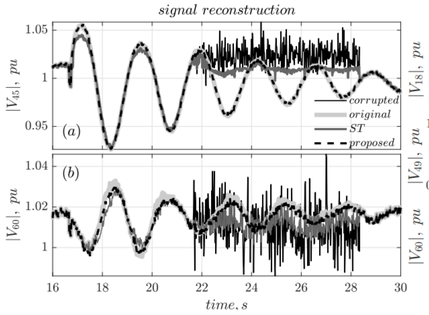
Recursive Bayesian Approach for Subspace Selection: Likelihood and Posterior probabilities of a subspace being the true subspace given a set of PMU observations

Selection accelerated with a suitable termination criteria

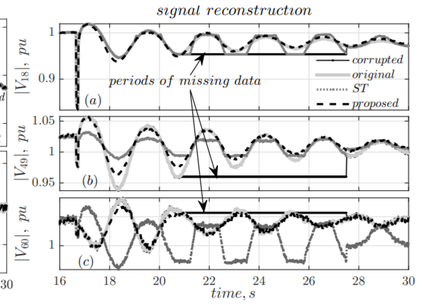


Signal recovery under fault resembling attack in 2 PMUs – also shown, no recovery during actual event (fault)

Subspace selection is accurate, therefore, reconstruction quality is good



Signal recovery under noise injection attack in 2 PMUs



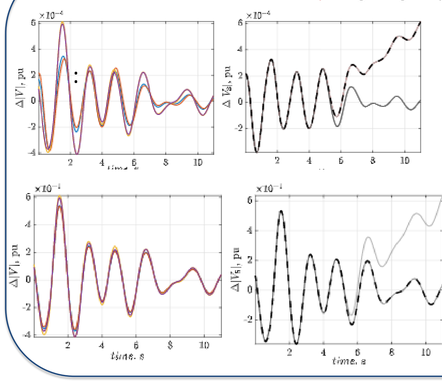
Signal recovery under missing data attack in 3 PMUs

Broader Impact on EDUCATION & OUTREACH

To include the outcome of our research as a module of one course EE 488: Power Systems Analysis at Penn State through Problem-based Learning (PBL).

To integrate the proposed research into iTech: Summer Technology Camp for Teens - a free week-long interactive day camp, coordinated through Penn State's College of Information Sciences and Technology (IST), designed to introduce high school students (9th-12th grades) to information technology.

Guarantees for Data Recovery: Signal grouping to ensure that for a given set Restricted Isometry Constant is below a threshold



Signal set I : poor RIC -- recovery not guaranteed -- shows incorrect reconstruction

Signal set II : RIC below threshold-- recovery guaranteed -- shows correct reconstruction

Publications from this Award

1. Mahapatra, Kaveri and Chaudhuri, Nilanjan Ray. "Malicious Corruption-Resilient Wide-Area Oscillation Monitoring using Principal Component Pursuit," *IEEE Transactions on Smart Grid*, 2018. doi:10.1109/TSG.2017.2778054
2. Mahapatra, Kaveri and Chaudhuri, Nilanjan Ray and Kavasseri, Rajesh G. and Brahma, Sukumar M.. "Online Analytical Characterization of Outliers in Synchrophasor Measurements: A Singular Value Perturbation Viewpoint," *IEEE Transactions on Power Systems*, v.33, 2018. doi:10.1109/TPWRS.2017.2771782
3. Chatterjee, Kaustav and Mahapatra, Kaveri and Chaudhuri, Nilanjan Ray. "Robust Recovery of PMU Measurements with Outlier Characterization and Stochastic Subspace Selection." Submitted to IEEE Transactions on Smart Grid
4. Chatterjee, Kaustav and Chaudhuri, Nilanjan Ray. "Corruption-Resilient Detection of Event-Induced Outliers in PMU Data: A Kernel PCA Approach", IEEE Power and Energy Society General Meeting, Atlanta, GA, USA, Aug 2019.
5. Chatterjee, Kaustav and Chaudhuri, Nilanjan Ray. "Grouping PMU Signals with Guaranteed Recovery under Corruption: Insights and Recommendation", Submitted to IEEE Power and Energy Society General Meeting, Montreal, Canada, Aug 2020.

2019 NSF Cyber-Physical Systems Principal Investigators' Meeting

November 21-22, 2019 | Crystal City, Virginia

Award ID#: 1739206

School of Electrical Engineering and Computer Science