Corruption-Resilient Online Event Detection in Energy CPS: A Kernel PCA Approach
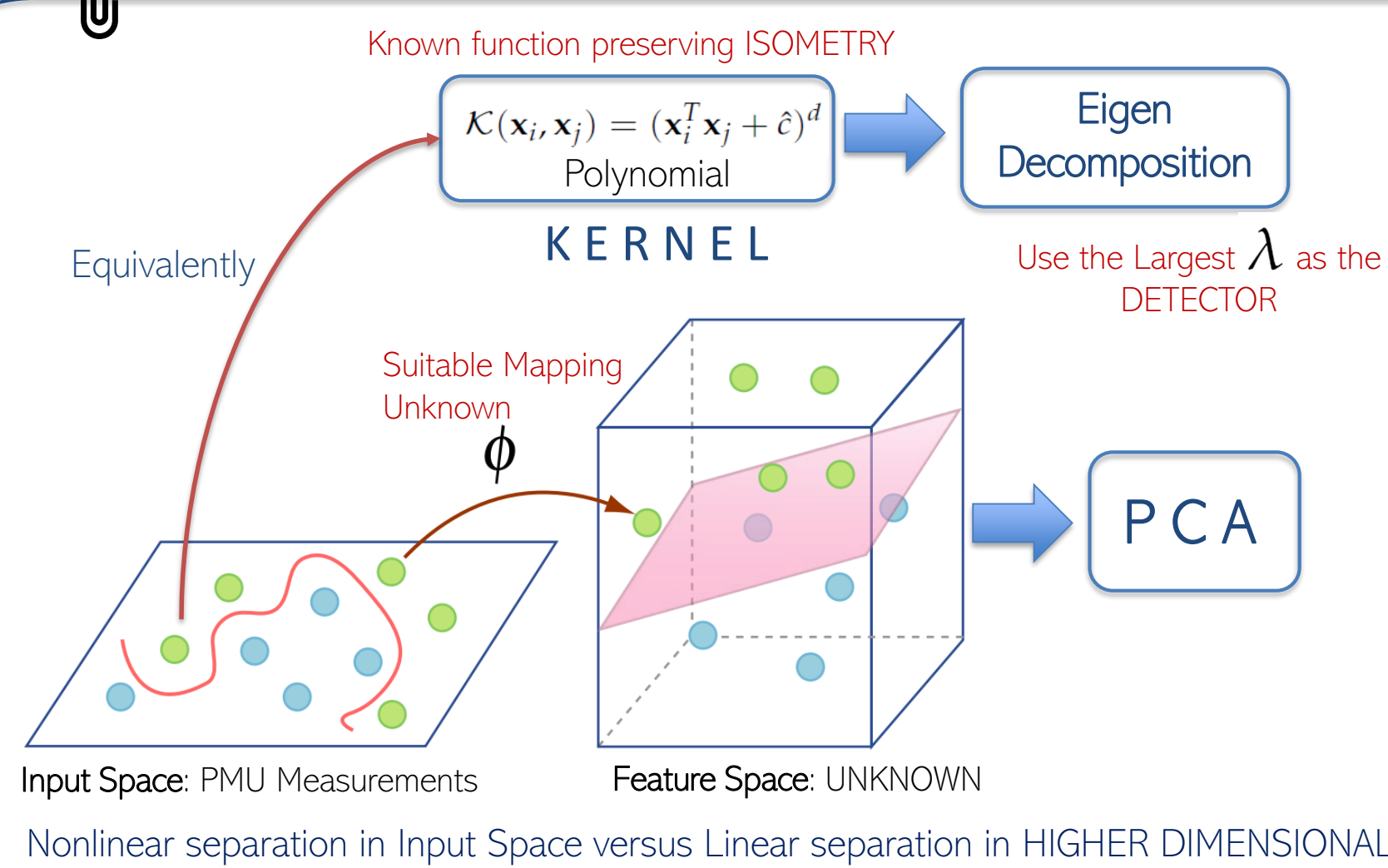
Kaustav Chatterjee, Graduate Research Assistant

Dr. Nilanjan Ray Chaudhuri, PI, Assistant Professor

The Pennsylvania State University

MOTIVATION | Spurious or maliciously injected sensor data can jeopardize the monitoring and wide-area stabilizing control of power grids | Need for attack-resilient monitoring strategy

OBJECTIVES | Development of analytical methods for Bad Data Detection and Correction understanding the underlying physics of the system | Event Detection and Classification robust to Bad Data
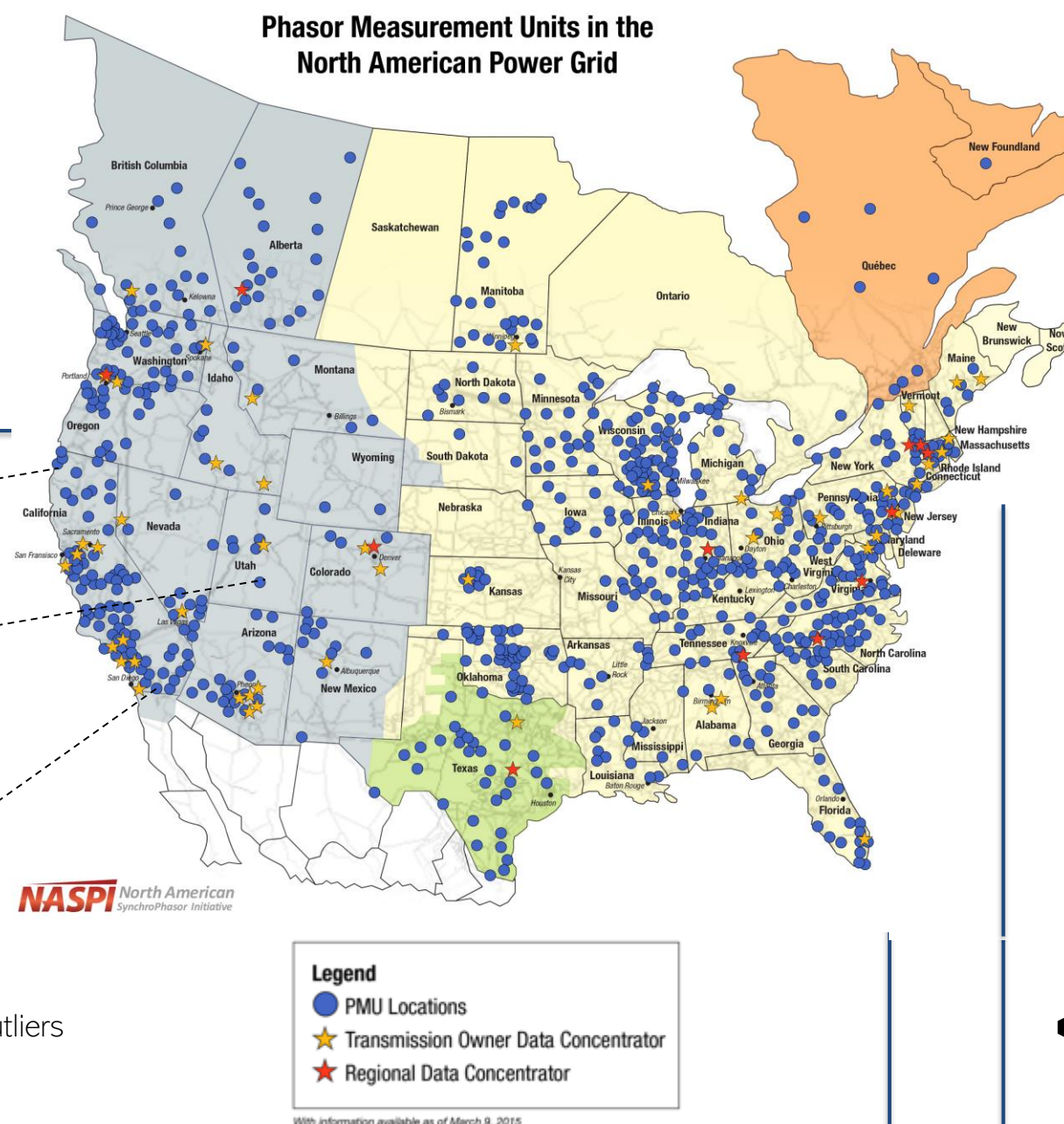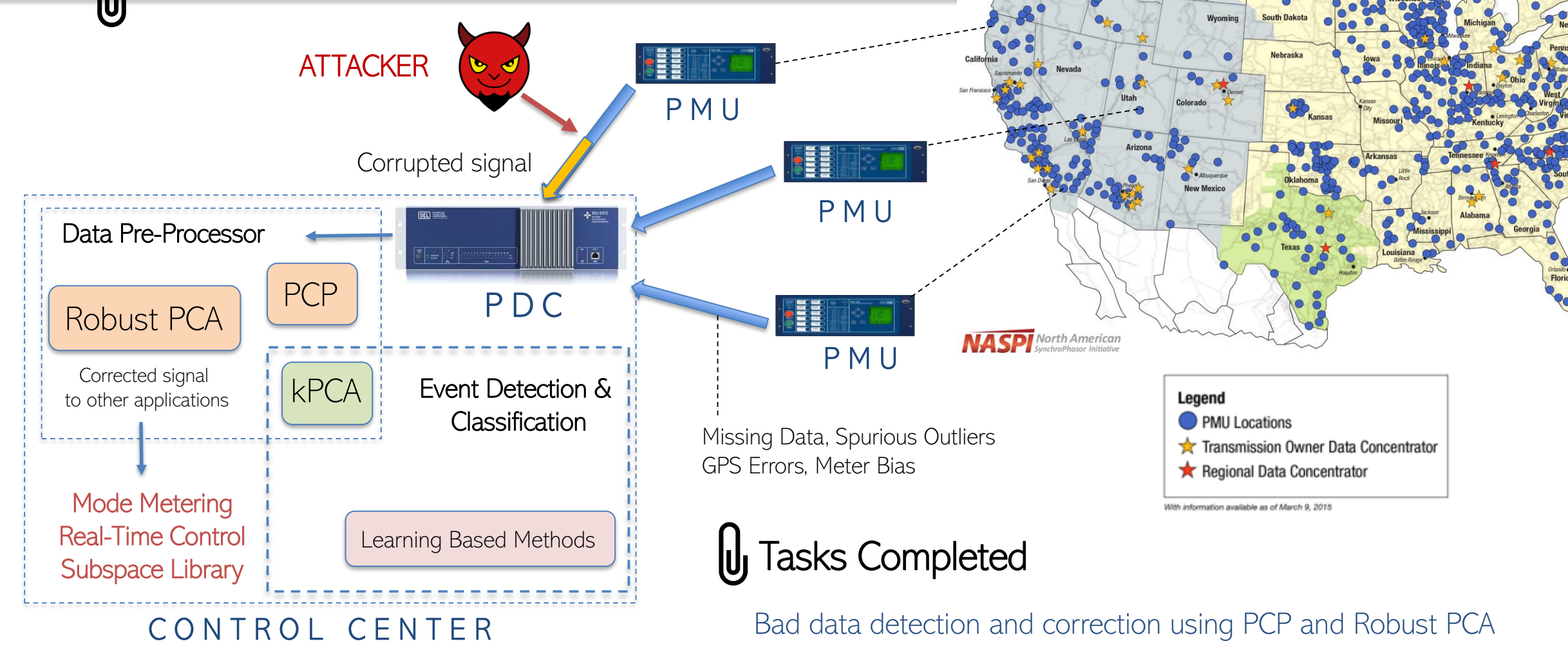
Phasor Measurement Units in the North American Power Grid

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

Kernel PCA based Event DETECTION

Known function preserving ISOMETRY

$$\mathcal{K}(\mathbf{x}_i, \mathbf{x}_j) = (\mathbf{x}_i^T \mathbf{x}_j + \hat{c})^d$$
Polynomial

KERNEL → Eigen Decomposition

Use the Largest λ as the DETECTOR

Equivalently

Suitable Mapping Unknown ϕ

PCA

Input Space: PMU Measurements
Feature Space: UNKNOWN

Nonlinear separation in Input Space versus Linear separation in HIGHER DIMENSIONAL Feature Space

Comparison with PCA based Methods

- Captures the inherent non-linearity in the dynamic data
- Robust to spurious bad data outliers
- Resilient to malicious corruption (when in limited % of channels)
- Can work with lesser information: sub-second window size
- Computationally intensive- But compensated by ability to work on small windows

Challenges and Tasks Ahead

- Complete Data-driven KERNEL from learning
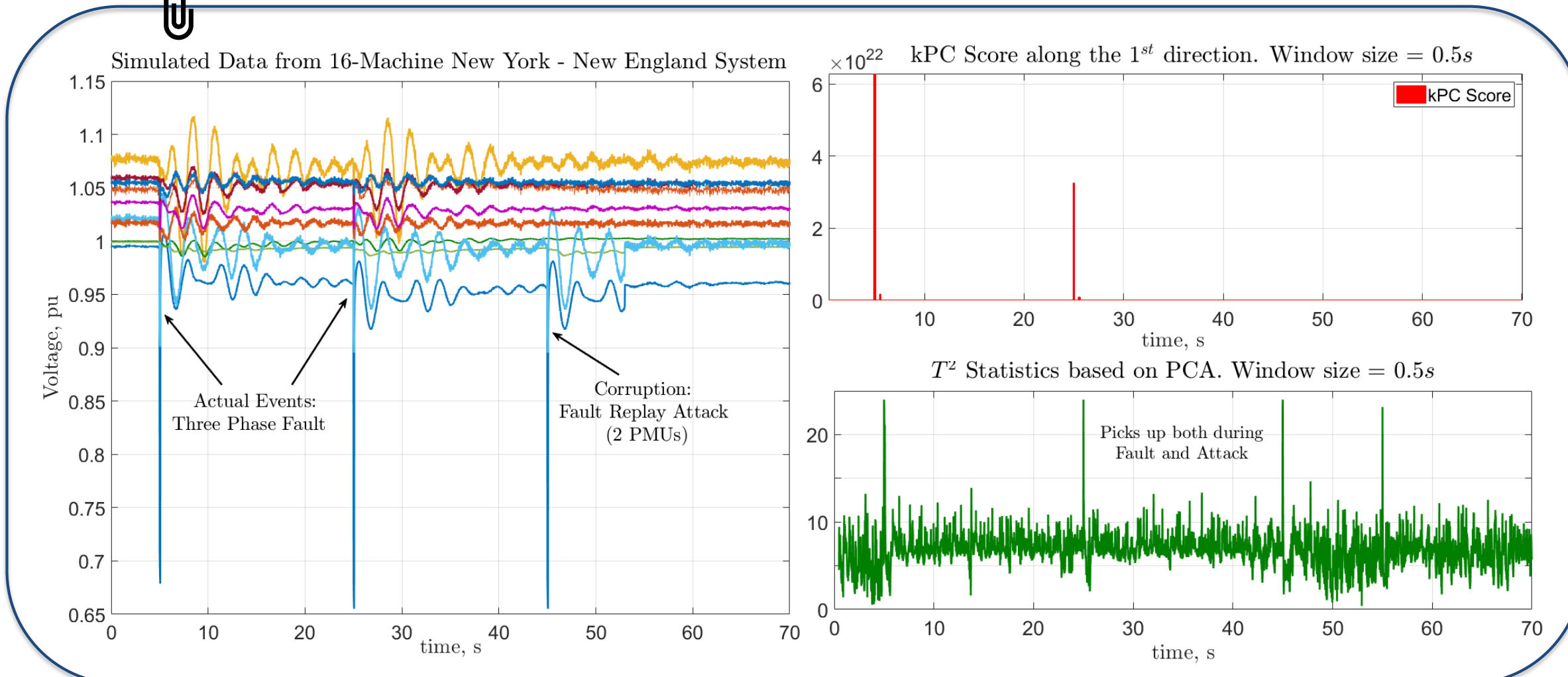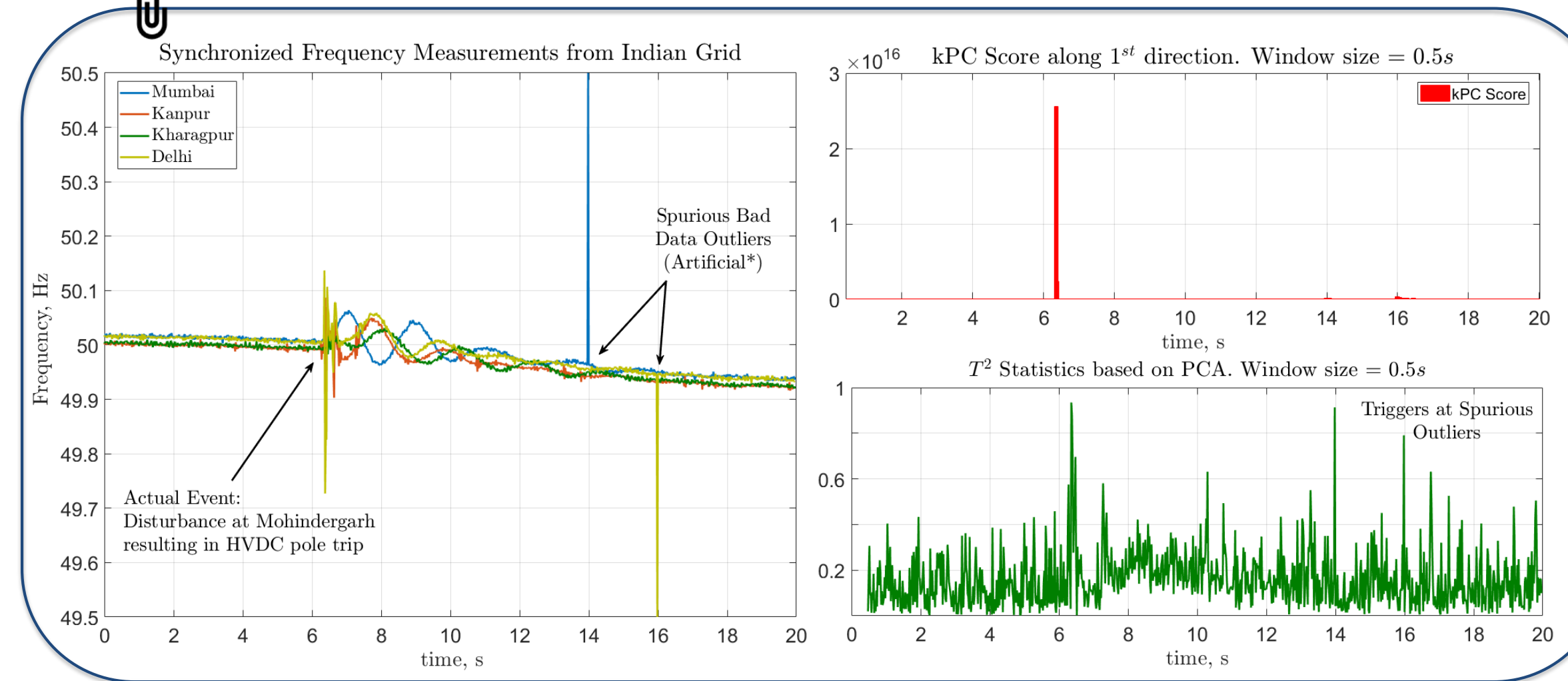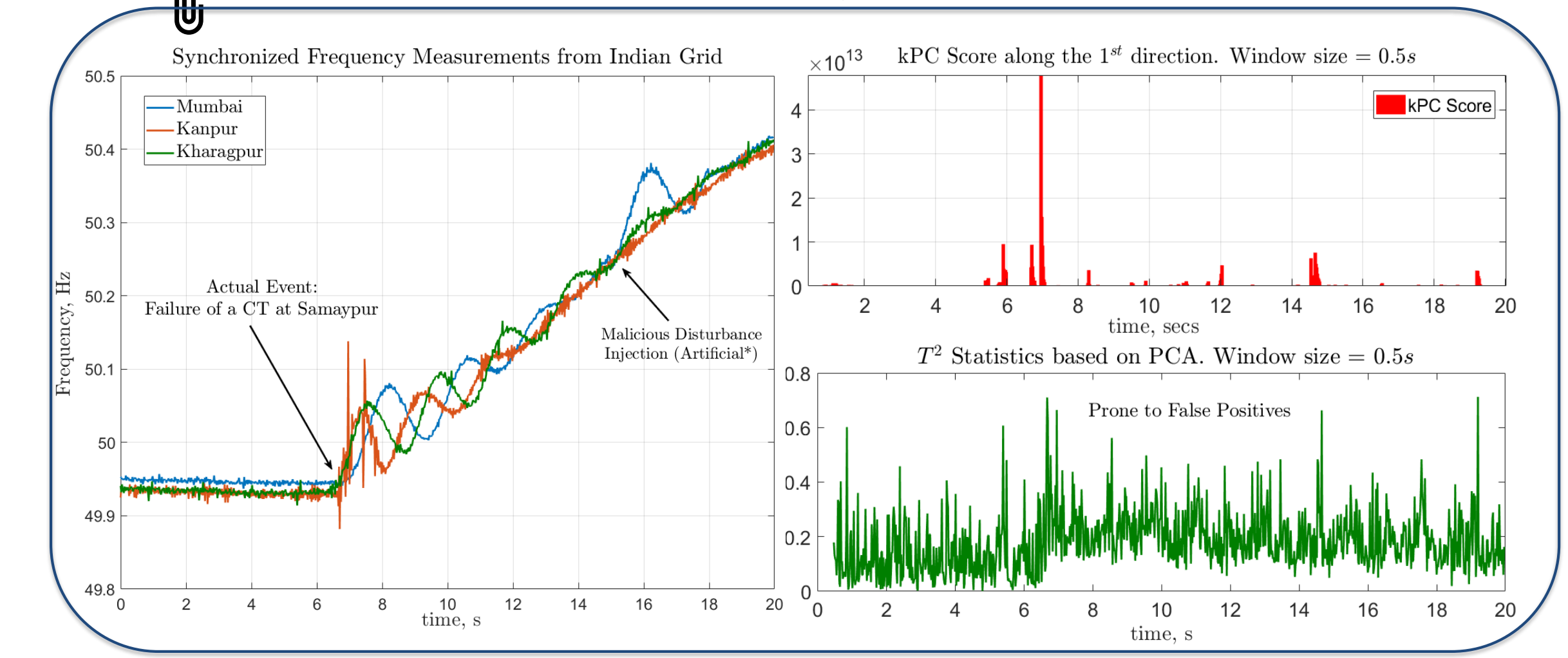- Data-manifold information + kPCA based Event CLASSIFIER

The BIGGER Picture !

ATTACKER

PMU

Corrupted signal

Data Pre-Processor
- Robust PCA
- PCP
- kPCA

PDC

Corrected signal to other applications

Event Detection & Classification
- Learning Based Methods

Mode Metering Real-Time Control Subspace Library

Missing Data, Spurious Outliers GPS Errors, Meter Bias

CONTROL CENTER

Tasks Completed

Bad data detection and correction using PCP and Robust PCA

Legend
- PMU Locations
- Transmission Owner Data Concentrator
- Regional Data Concentrator

NASPI North American

Event Detection from Bus Voltage Measurements (Simulated Data)

Simulated Data from 16-Machine New York - New England System

kPC Score along the 1st direction. Window size = $0.5s$ ×10²²

Actual Events: Three Phase Fault

Corruption: Fault Replay Attack (2 PMUs)

T^2 Statistics based on PCA. Window size = $0.5s$

Picks up both during Fault and Attack

Event Detection from Bus Frequency Measurements (Field Data)

Synchronized Frequency Measurements from Indian Grid
- Mumbai
- Kanpur
- Kharagpur
- Delhi

kPC Score along the 1st direction. Window size = $0.5s$ ×10¹⁶

Spurious Bad Data Outliers (Artificial*)

Actual Event: Disturbance at Mohindergarh resulting in HVDC pole trip

T^2 Statistics based on PCA. Window size = $0.5s$

Triggers at Spurious Outliers

Event Detection from Bus Frequency Measurements (Field Data)

Synchronized Frequency Measurements from Indian Grid
- Mumbai
- Kanpur
- Kharagpur

kPC Score along the 1st direction. Window size = $0.5s$ ×10¹³

Actual Event: Failure of a CT at Samaypur

Malicious Disturbance Injection (Artificial*)

T^2 Statistics based on PCA. Window size = $0.5s$

Prone to False Positives

Broader Impact on SOCIETY

Better visualization of system dynamics can help the operator understand the precursors to cascading failures and potential blackouts – saving millions of dollars of revenue.

Resilience from cyber attacks- followed by detection and localization can arrest the unholy nexus of cyber terrorists and enemy nations from causing havoc.

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. Mahapatra, Kaveri and Chaudhuri, Nilanjan Ray. "Malicious Corruption-Resilient Wide-Area Oscillation Monitoring using Online Robust PCA," 2018 IEEE PES General Meeting, Portland, OR, 2018

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).
- Develop specific team projects in EE 488 to solve challenging ill-structured problems in this area that require students to work together in teams to explore topics and issues beyond textbook-approaches.
- 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.
- To make resilient smart grids as the thrust of iTech 2019. The hands-on activities will include smart grids and cyber-attacks against power grids.

BROADER Impact
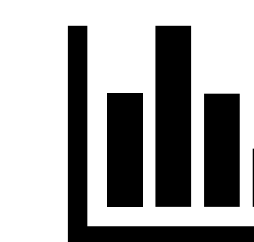
The proposed research leverages 'big data' for real-time monitoring and control of CPS.

In today's world of 'Industrial Internet' where sensory data is being utilized for system health monitoring and controls, the proposed ideas can make significant stride in understanding data quality and anomaly

The key contribution comes from the proposed derivation of fundamental connection between classical Singular Value Perturbation theory and Principal Component Analysis (PCA) with the physical system's expansive dynamical properties to establish bounds on deviations in the Principal Component scores in terms of the state matrices.

Concepts developed in the arena of anomaly detection and attack resilience can be adapted to other Cyber-Physical Systems, like- process control, oil and gas, and future transportation systems, with suitable modifications capturing the physics of the systems.