

Networked Information Gathering and Fusion of PMU Measurements

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Background

- For smart grid in the making, a key step is to modernize its cyber-infrastructure , where real-time, lightweight, and adaptive algorithms are developed for three core functionalities, namely measurement, communication, and fusion
- Existing supervisory control and data acquisition (SCADA) systems provide only the static states or the quasi-static states of the power grid
- The synchrophasor technology is emerging as an enabling technology to facilitate both information interaction and energy interaction between providers and customers
- It is critical to develop reliable and secure communication systems for synchrophasor data

Outline

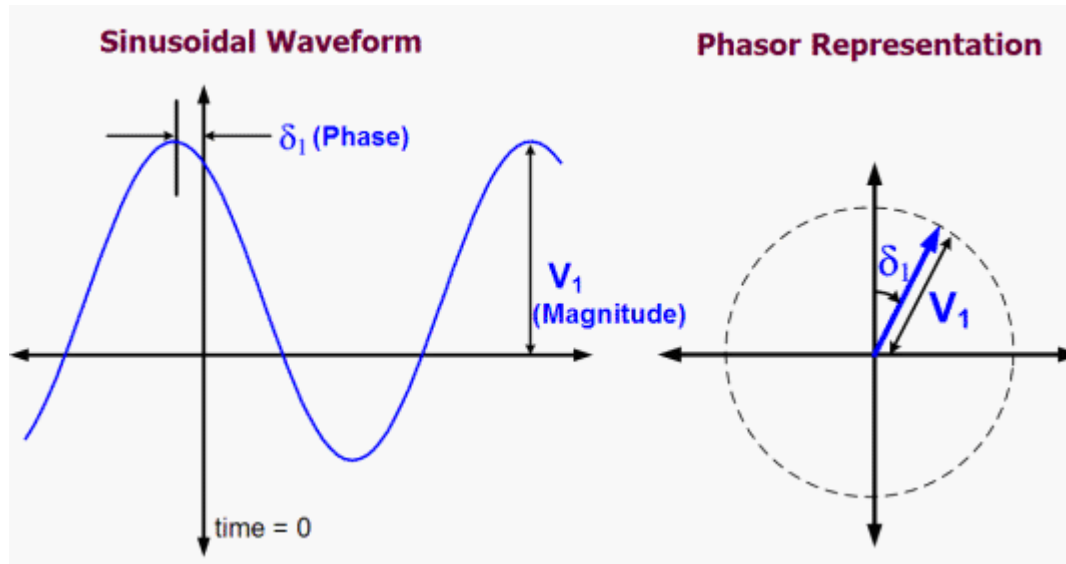
- I) Networked communications of synchrophasor data
- II) Networked computation and fusion of synchrophasor data
- III) Robust architecture for smart grids

I) Networked Communications of Synchrophasor Data

- Deregulation of the power industry has moved the operations of power grids from vertically integrated centralized management to coordinated decentralized management
- The North American SynchroPhasor Initiative (NASPI) plays a critical role in coordinating the information management

Phasor Measurement

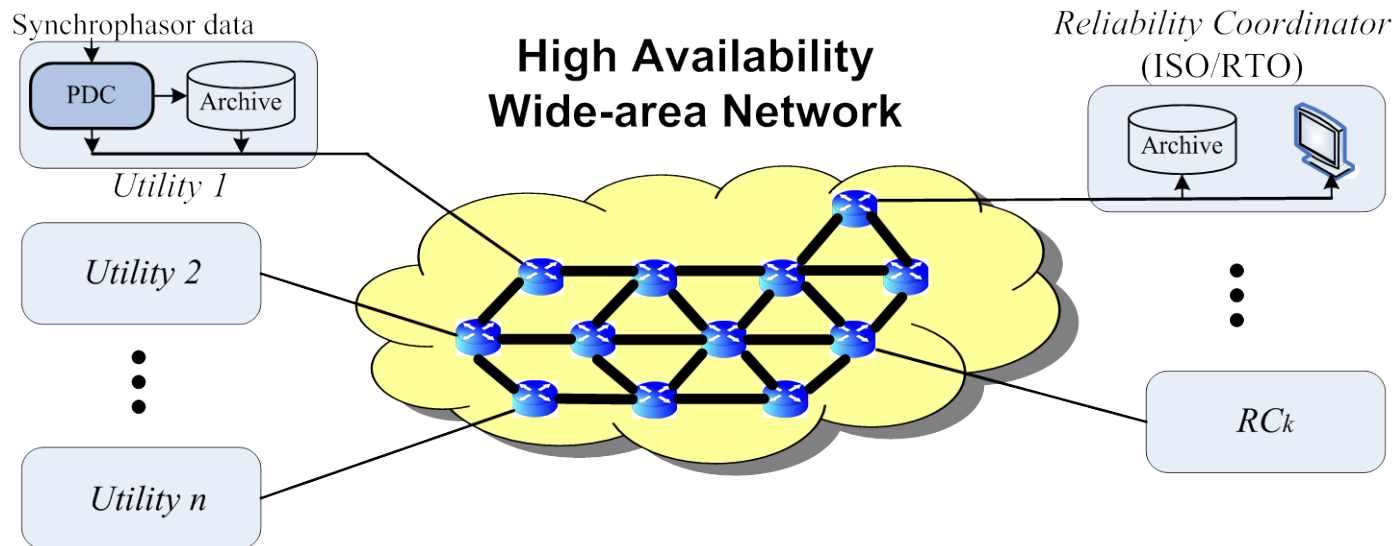
- Phasor: an electrical quantity with magnitude and angle



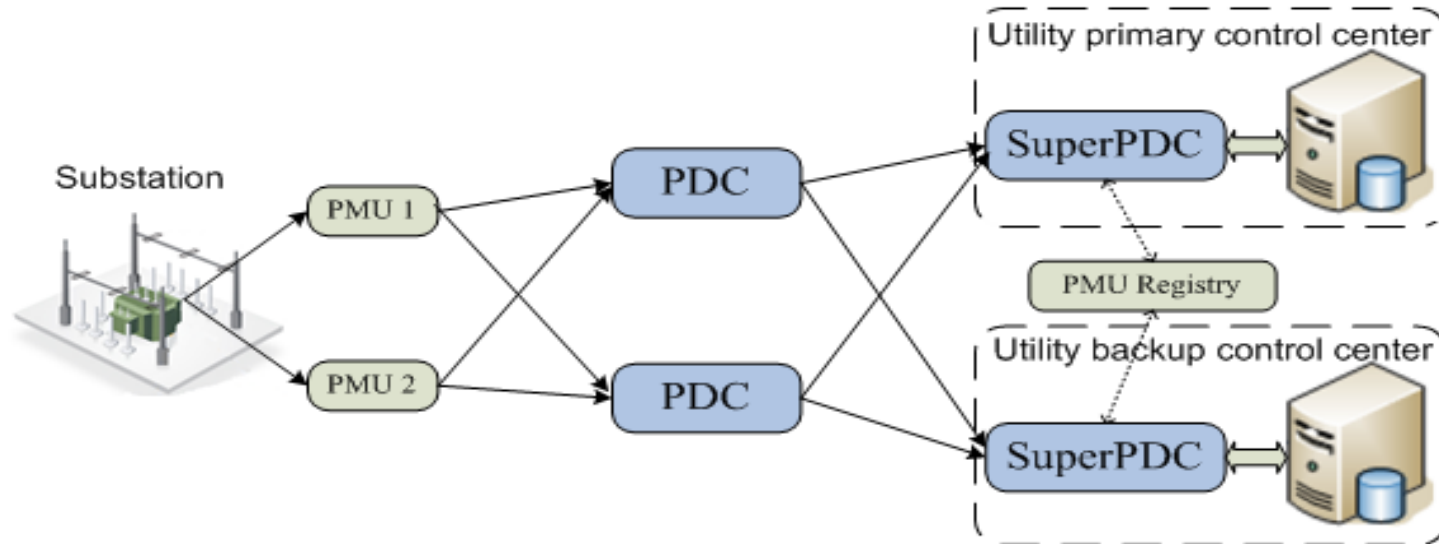
- A PMU is a device measuring fundamental-frequency **voltage and current phasors** up to 60 samples per sec
- Synchronized by GPS time stamps

Hierarchical Information Architecture

- Intra-utility level communications
 - synchrophasor data **gathering and archiving**: PDCs gather and align measurements from PMUs, and then submit them to utility control centers for archiving
- Inter-utility level communications
 - ensures **the high availability** of synchrophasor data (both real-time data and historical data) to support different **wide-area applications**



Redundant Configuration of Intra-utility Level Communication Systems



- PMUs and PDCs in redundant pairs
- redundant communication links
- primary and backup control centers
- PMU registry ensures that only one copy of the redundant measurements is archived

Inter-utility Level Data Delivery

Synchrophasor-based applications can be classified into three categories:

- wide-area monitoring

e.g., visualization, state measurement and estimation, load model synthesis

- wide-area protection and control

e.g., dynamic security assessment (DSA), voltage stability detection and correction, islanding control

- post-event analysis

e.g., fault detection and localization, model validation

QoS Requirements of Synchrophasor Data Communications

	Monitoring	Protection and Control	Post-event Analysis and Research
Latency	<1000 ms	< 5ms	$10^4 - 10^6$ ms
Updating frequency	1-120 Hz	30-120 Hz	< 1Hz
Priority	medium - high	High	Low

Source: [Bakken'11]

Off-the-shelf Technologies: Good Enough?

- transmission control protocol (TCP)
 - not designed for smart grid applications with diverse latency requirements
 - can incur relatively long delays (on the order of seconds)
 - lacks the provisioning for priorities
- bandwidth reservation technologies
 - inflexible
 - can result in low network utilization

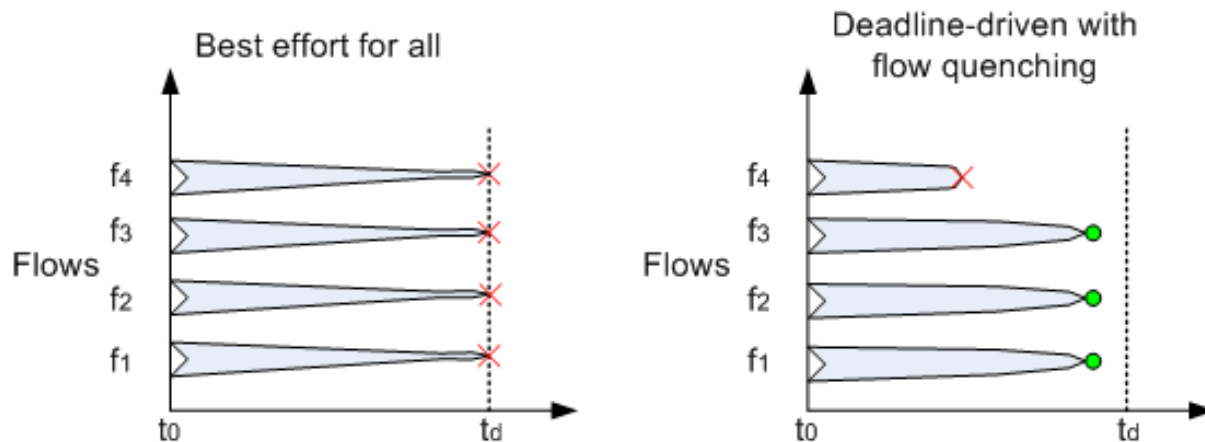
Towards Deadline-driven Flexible Synchronphasor Data Delivery (1)

Several promising techniques (originally proposed for data center communications [Wilson'11]):

- dynamic rate allocation
 - transmitters make rate requests on a slot basis
requested rate = data size / deadline
 - given the received rate requests, each router dynamically allocate resources to the flows: a multi-objective optimization problem
 - minimize the number of flows which fail to meet their deadlines
 - Maximize network utilization

Towards Deadline-driven Flexible Synchronphasor Data Delivery (2)

- queue management
 - routers maintain multiple queues for synchronphasor data
 - queues with higher priorities are allocated resources first
- dynamic flow quenching
 - “load-shedding” under congestion so as to spare resources for the rest of data flows to meet their deadlines



II) Networked computation and fusion of synchrophasor data

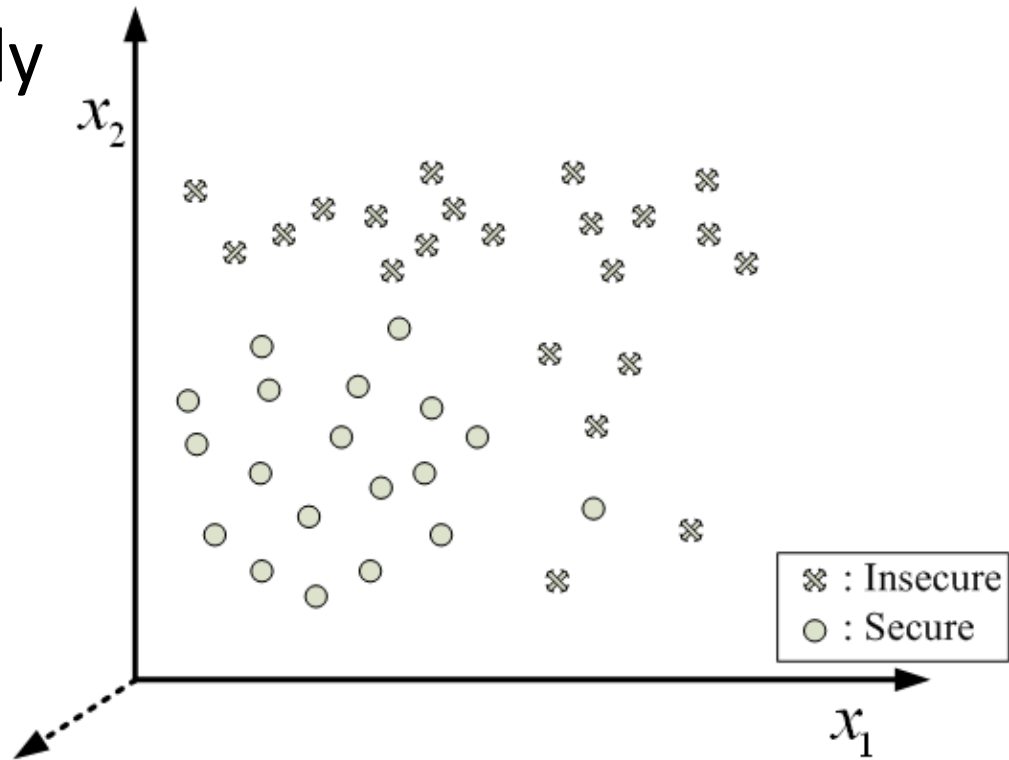
- Synchrophasor data fusion for online DSA
 - A data-mining framework for online DSA
 - Online DSA with missing PMU data
 - Modeless assessment
- Synchrophasor data fusion for fault detection and localization
 - A GMRF model for synchrophasor data
 - Decentralized network inference using synchrophasor data

Dynamic Security Assessment

- Dynamic Security Assessment (DSA)
 - assess the impact of N-k contingencies: transient, voltage, and thermal instability
- Online DSA
 - use **real-time** measurements
 - security decision for **impending** system events
 - challenges:
 - a large number of contingencies
 - real-time processing of high-dimensional data

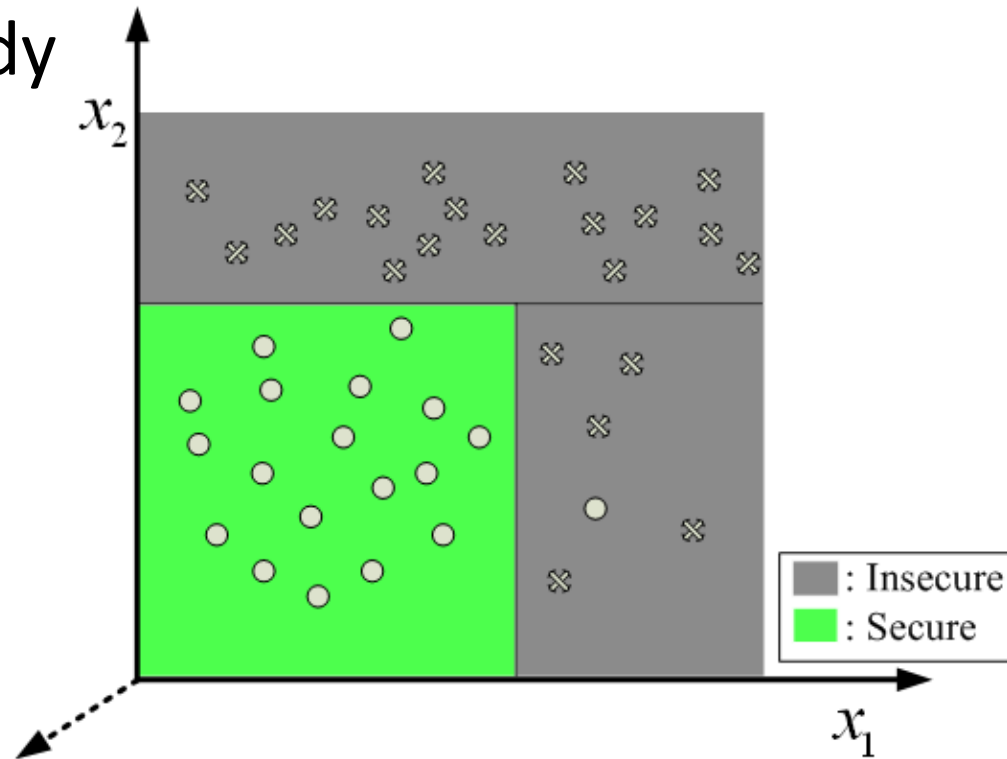
Data-mining for DSA

- Exhaustive offline study
 - knowledge base



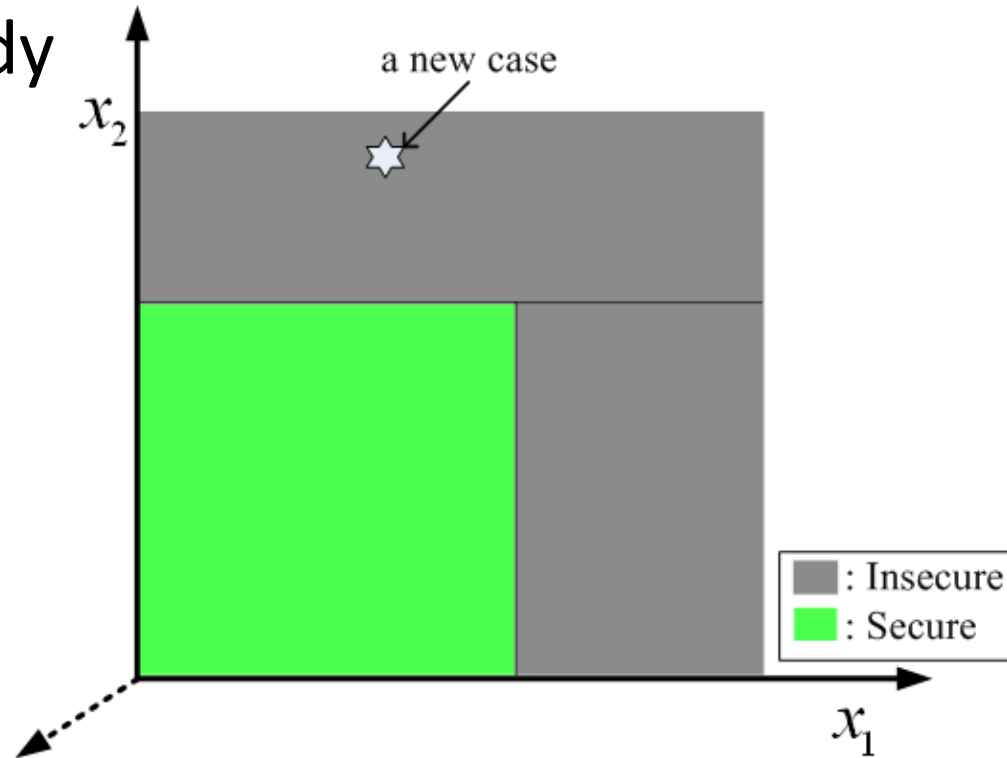
Data-mining for DSA

- Exhaustive offline study
 - knowledge base
- Data mining
 - classifier
 - decision regions



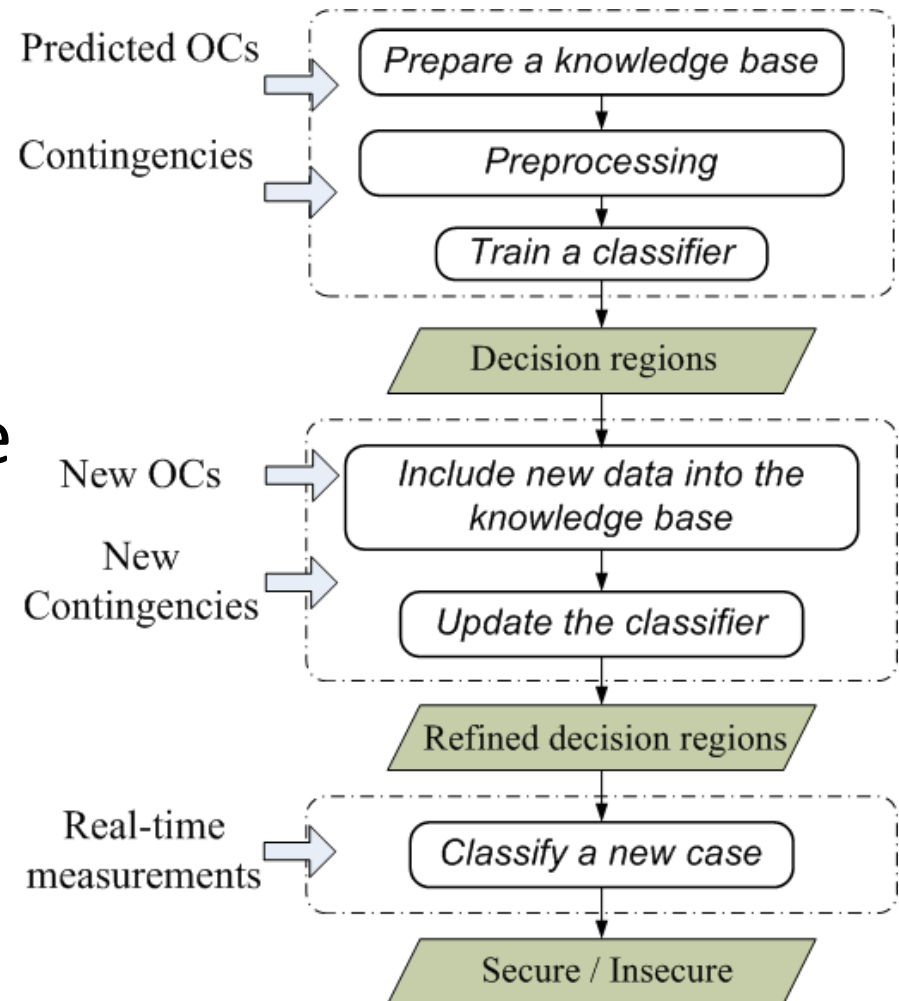
Data-mining for DSA

- Exhaustive offline study
 - a knowledge base
- Data mining
 - a classifier
 - decision regions
- Classify a new case
 - detailed analysis (power flow analysis, time-domain simulations) can be avoided



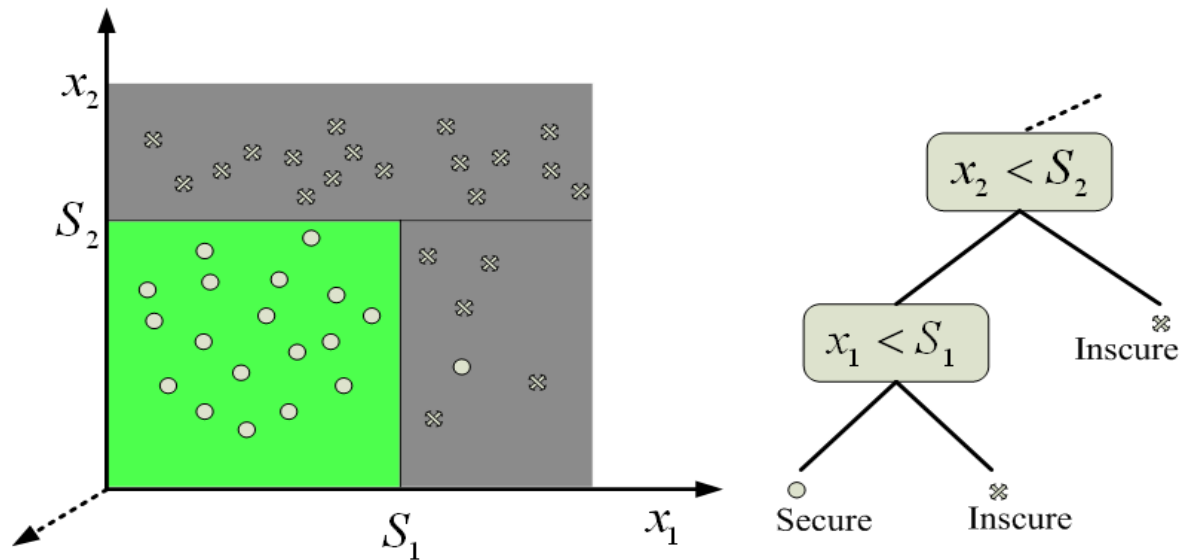
A Data-mining Framework for Online DSA

- Offline training
(day/hours ahead)
- Near real-time update
- Online DSA



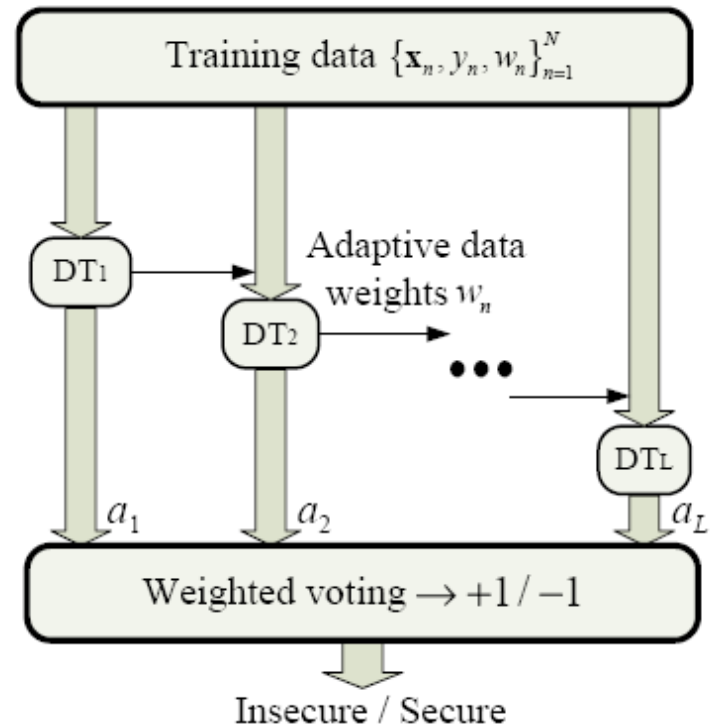
Offline Training (1)

- Classifier via boosting simple decision trees
 - decision tree (DT): a tree-structured model that maps an observation on the attributes to a binary decision
 - decision regions are characterized by several critical attributes and thresholds



Offline Training (2)

- Simple DTs (DTs with a smaller height) are more **robust to noise**, compared to a fully-grown DT
- “Boost” the accuracy
 - build multiple simple DTs sequentially, using adaptive data weights
 - subsequent DTs assign higher weights to cases misclassified by previous DTs
 - a weighted voting among the simple DTs



Near Real-time Update

- A low-complexity algorithm for updating the classifier
 - simple DTs are gracefully updated, without rebuilding
 - new cases are incorporated into the simple DTs one at a time
 - a simple DT remains unchanged if it classifies the new case correctly
 - otherwise, only the nodes which misclassify the new cases are updated
 - the voting weights of the simple DTs are recomputed for accuracy assurance

Online DSA with Missing PMU Data

- In online DSA, critical measurements could be unavailable due to
 - random failures of PMUs and PDCs
 - large communication latency
- Initial case study suggests that traditional surrogate method of DTs does not work well
- Online DSA with randomly missing PMU data is still an **open** problem

Modeless Assessment

- Another possible approach to security assessment is the “modeless” approach, where Thevenin Equivalents as seen by key lines are computed from PMU data and used to estimate the margins to (thermal, voltage and angles) security violations
- With PMU data being the primary source of creating the equivalents, the assessment would be able to track the margins to critical values in real-time

Synchrophasor Data Fusion for Fault Detection and Localization

- Fault diagnosis of transmission lines is challenging, due to the complex system uncertainty and measurement errors
- In light of the stochastic nature of power systems, the bus injections and branch flows could be variable across various time scales
- Probabilistic graphical models to model the spatially correlated data from PMUs, and use statistical hypothesis testing for the task of fault diagnosis

DC Power Flow Model

- Branch flow

$$P_{ij} = b_{ij} (\theta_i - \theta_j)$$

θ_i, θ_j : phasor angles at buses

P_{ij} : branch flow

- Bus injection

$$P_i = \sum_{j \neq i} P_{ij} = \sum_{j \neq i} b_{ij} (\theta_i - \theta_j)$$

- The phasor angle at bus i

$$\theta_i = \sum_{j \neq i} c_{ij} \theta_j + \frac{1}{\sum_{j \neq i} b_{ij}} P_i, \text{ where } c_{ij} = b_{ij} / \sum_{j \neq i} b_{ij}$$

A GMRF Model for Phasor Angles

- Phasor angle

θ_i could be modeled as a Gaussian random variable truncated within $[0, 2\pi)$

- Conditional distribution

$$\theta_i | \boldsymbol{\theta}_{-i} \sim N\left(u_i + \sum_{j \neq i} r_{ij} (\theta_j - u_j), 1\right)$$

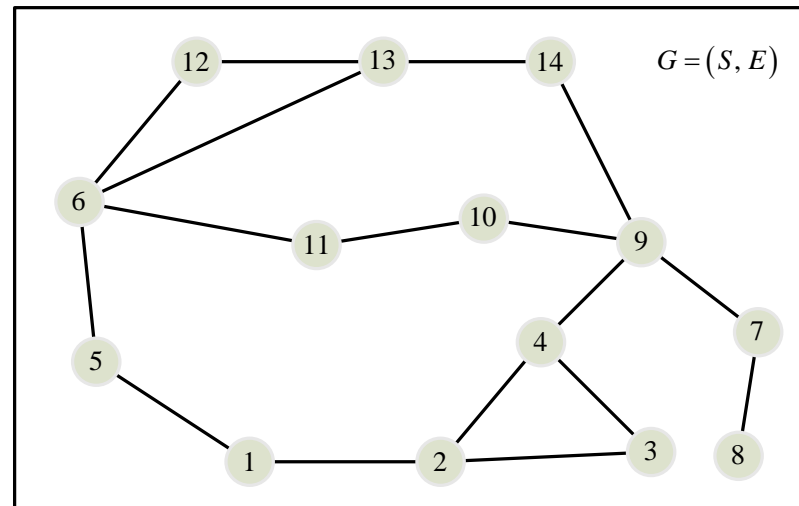
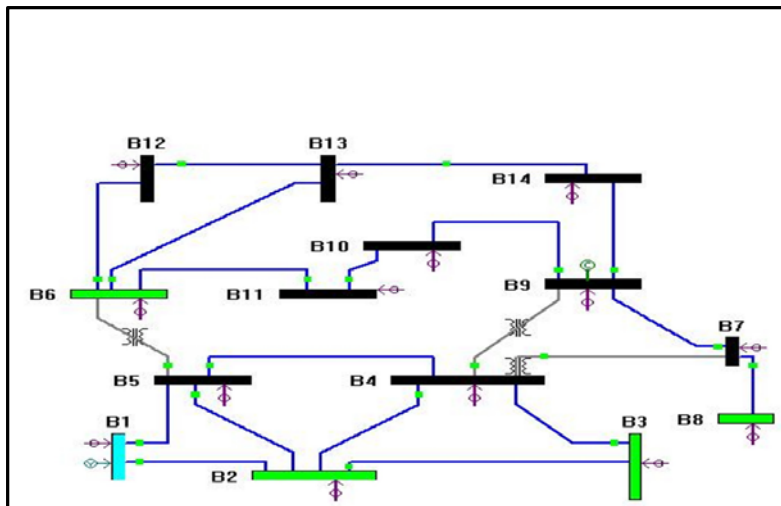
- Joint distribution

$$\boldsymbol{\theta} \sim N(\mathbf{0}, \mathbf{J}^{-1}), \quad \mathbf{J} = \mathbf{I} - \mathbf{R}$$

- partial correlation matrix $\mathbf{R} = [r_{ij}]$
- for θ_i , r_{ij} is proportional to b_{ij}

Example: GMRF Model

IEEE 14-bus system and the dependency graph of phasor angles



Intuition behind dependency graph: given the phasor angles at neighbor buses, the phasor angle is independent of all the other phasor angles

Fault Detection and Localization

- Fault detection through hypothesis testing on the change of partial correlation coefficients

$$\begin{cases} \mathcal{H}_0 : r_{ij} = r'_{ij} & \forall \{i, j\} \in E' \\ \mathcal{H}_1 : r_{ij} \neq r'_{ij} & \exists \{i, j\} \in E' \end{cases}$$

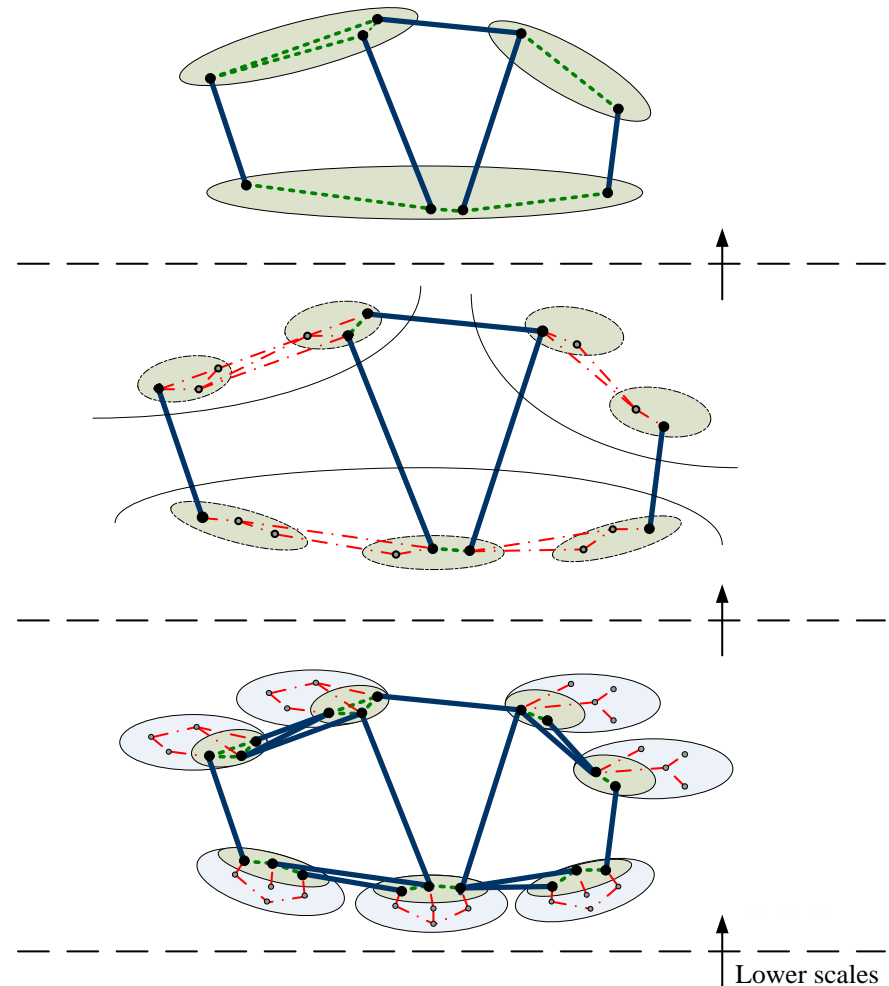
where, \mathbf{R}' , E' are the partial correlation matrix and the line set under normal condition

- Fault localization: a line is faulted if the partial correlation of the phasor angles of the two terminal buses is changed

$$\delta_{ij}(d_{ij}, \varepsilon) = \begin{cases} 0 & \text{if } d_{ij} \leq \varepsilon \\ 1 & \text{o.w.} \end{cases} \quad \forall \{i, j\} \in E'$$
$$d_{ij} \triangleq \left| \frac{\hat{r}_{ij}}{r'_{ij}} - 1 \right|$$

III) Decentralized network inference using synchrophasor data

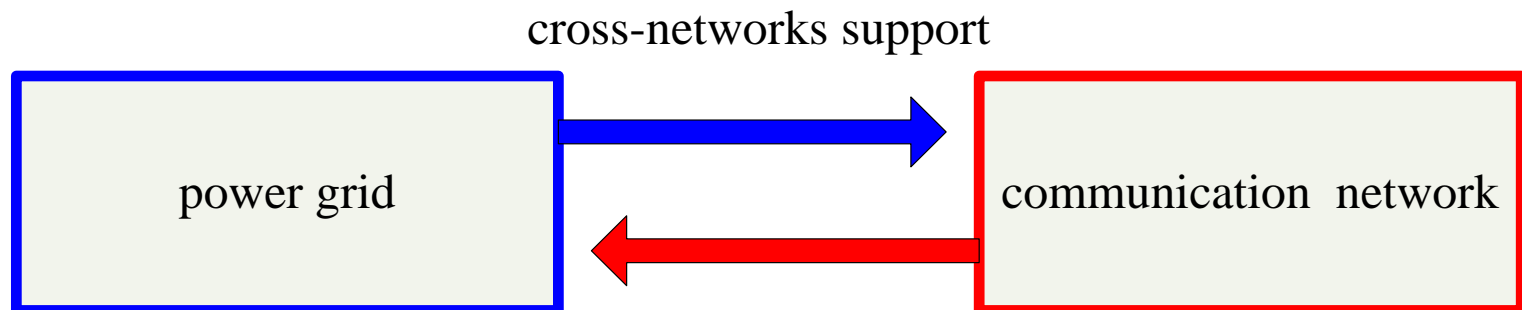
- multi-scale decomposition of GMRF
- subfields perform estimation based on local measurements
- The information matrix used for fault detection and localization is obtained through simple message passing



Robust architecture for smart grids

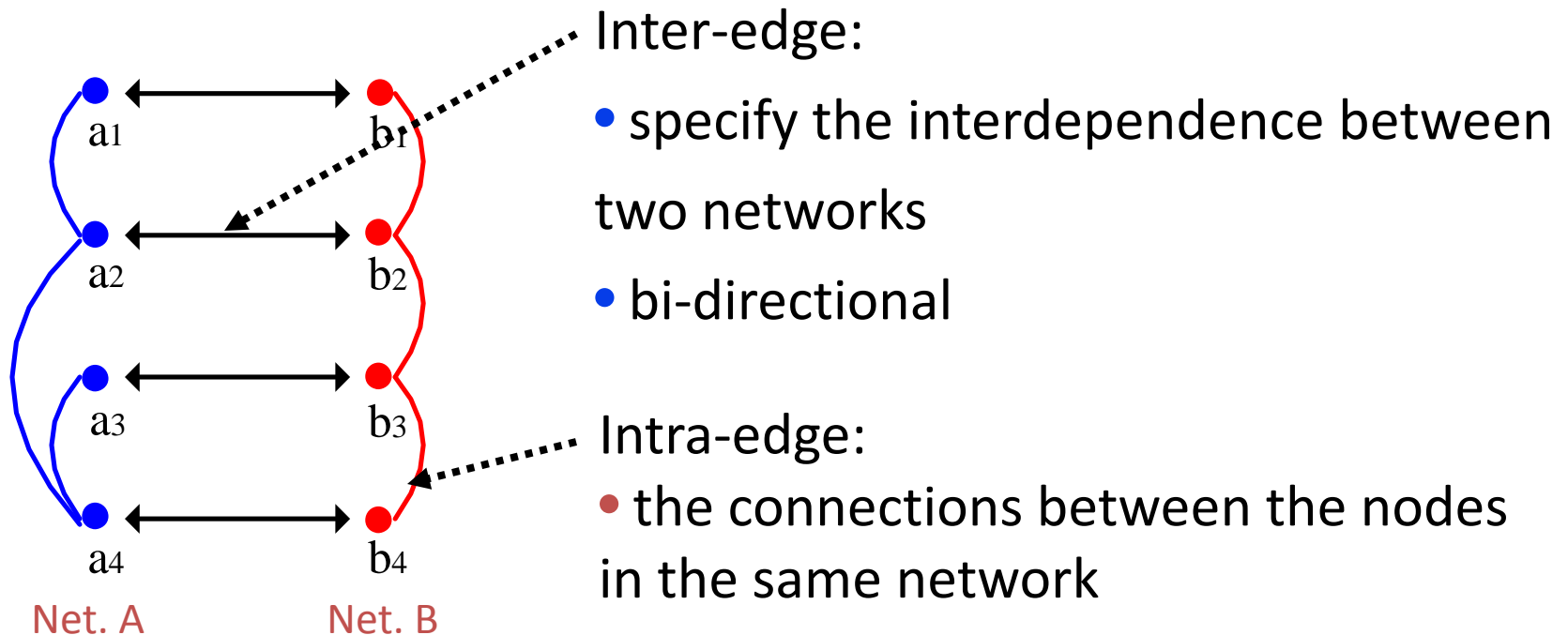
- Interdependence
 - power substation receive control signals through communication node
 - communication node relies on the power supply from power grid

power grid and communication network could be modeled as two interdependent networks



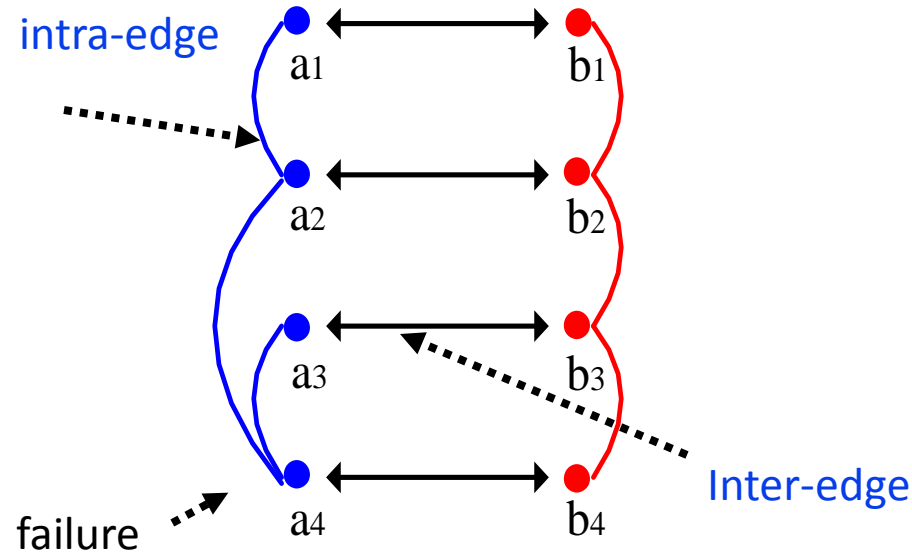
Interdependent Networks

Model of Interdependent Networks [Buldyrev'10]



Cascading Failures in Interdependent Systems: An Example

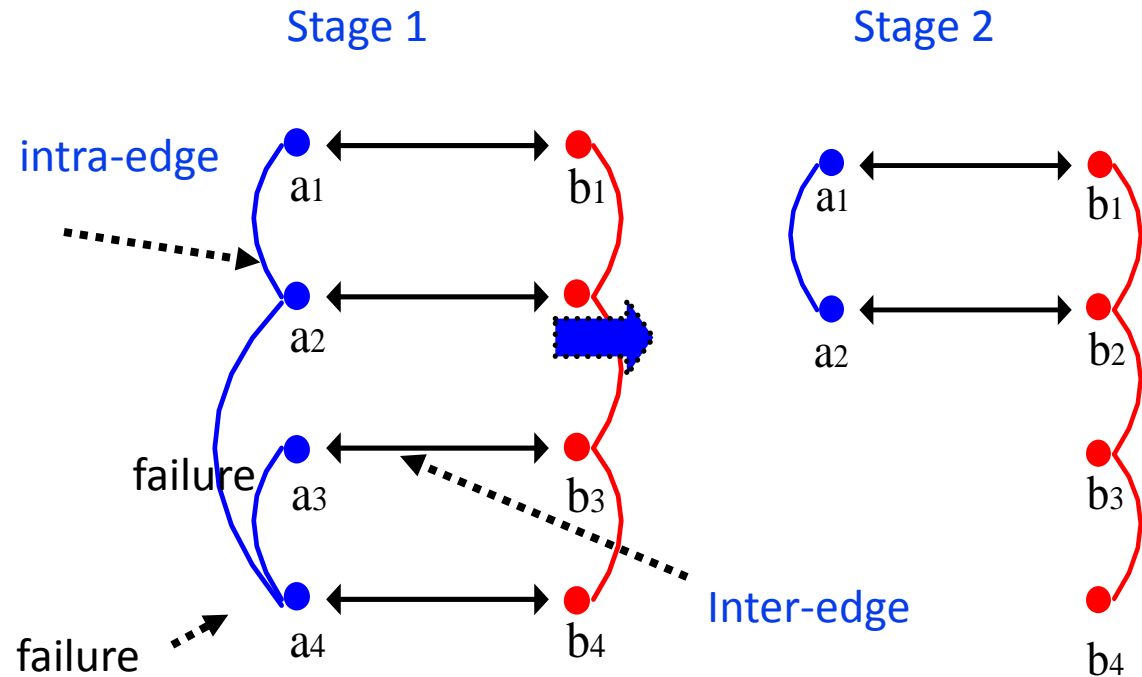
Stage 1



stage1

- After a4 is removed, a3 fails since it is no longer in the giant component in A
- The intra & inter edges associated with a3 and a4 will be removed

Cascading Failures in Interdependent Systems: An Example



stage 2

- b3 and b4 will be removed due to losing inter-edges from A

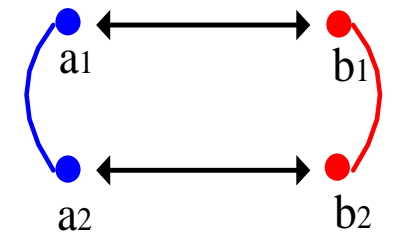
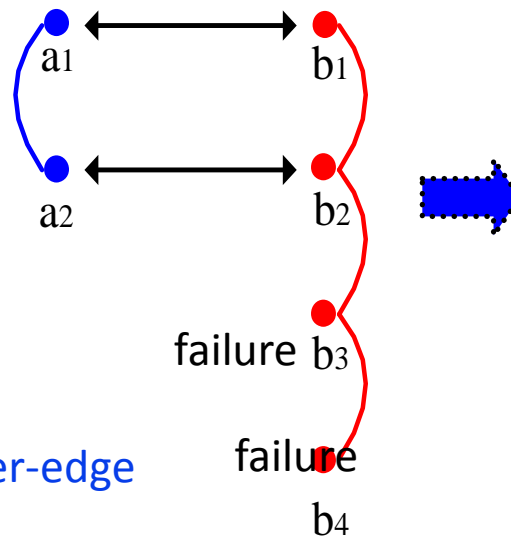
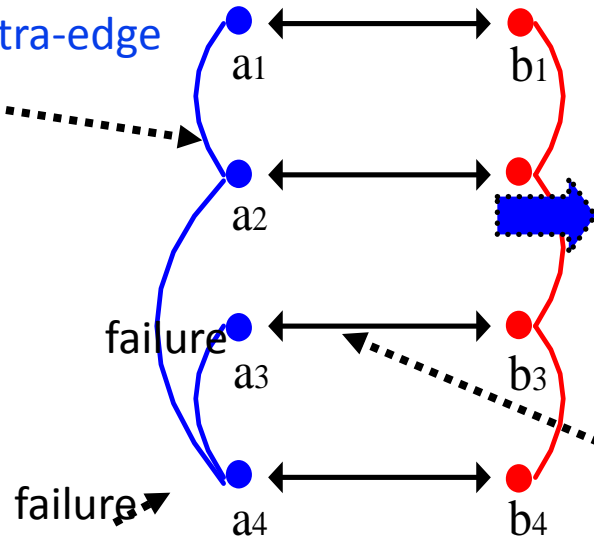
Cascading Failures in Interdependent Systems: An Example

Stage 1

Stage 2

Stage 3

intra-edge

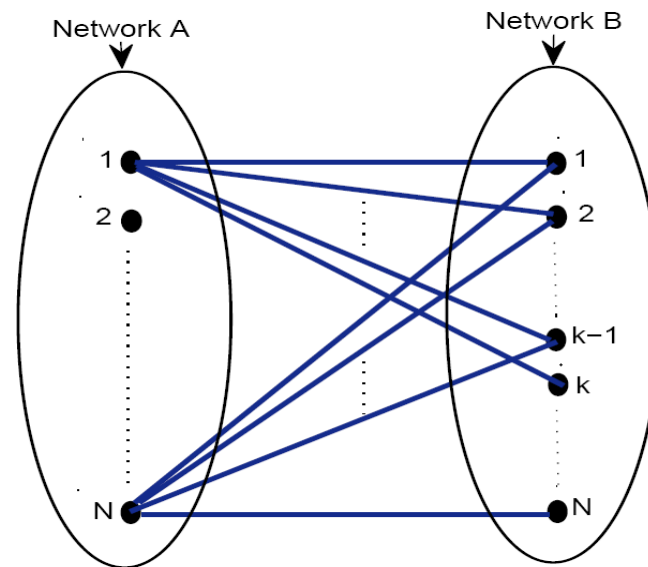


stage3

● Cascading failure stops

Inter-edge Allocation Strategy

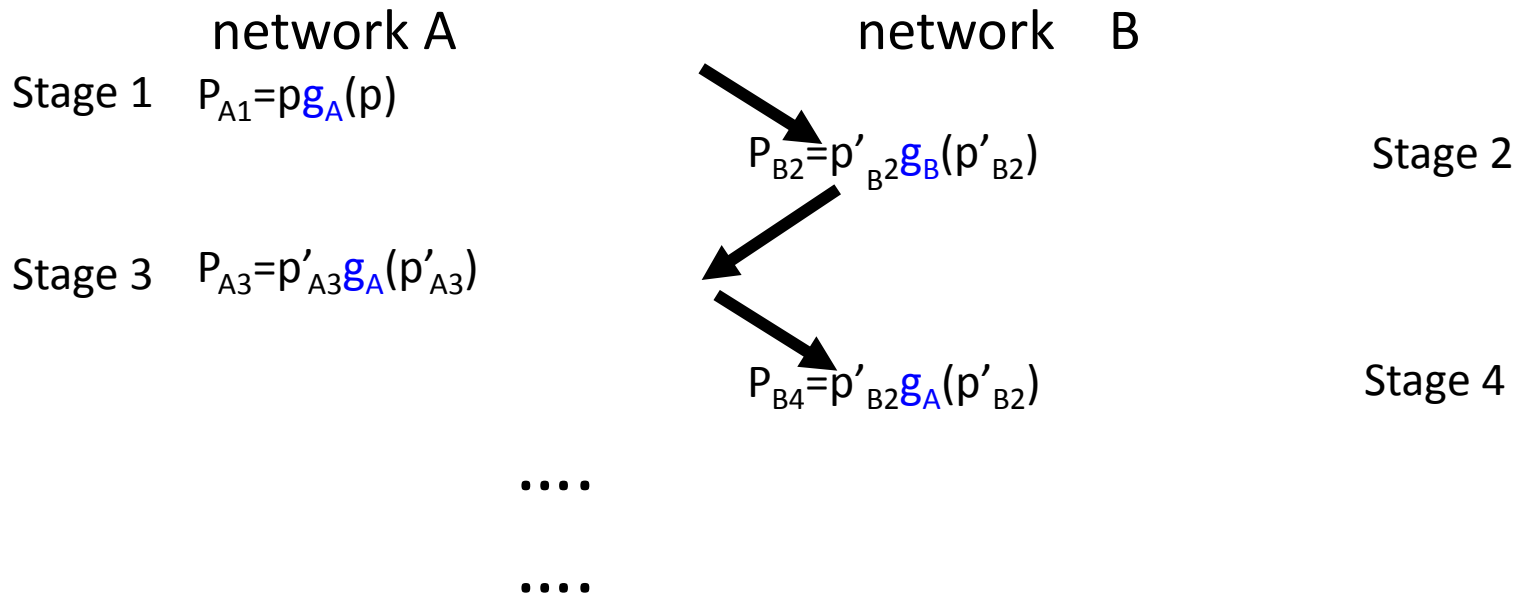
- Regular allocation:
each node in network A
and network B has
exactly k inter-edges.



- Regular allocation can lead to higher system robustness to cascading failures than random allocation

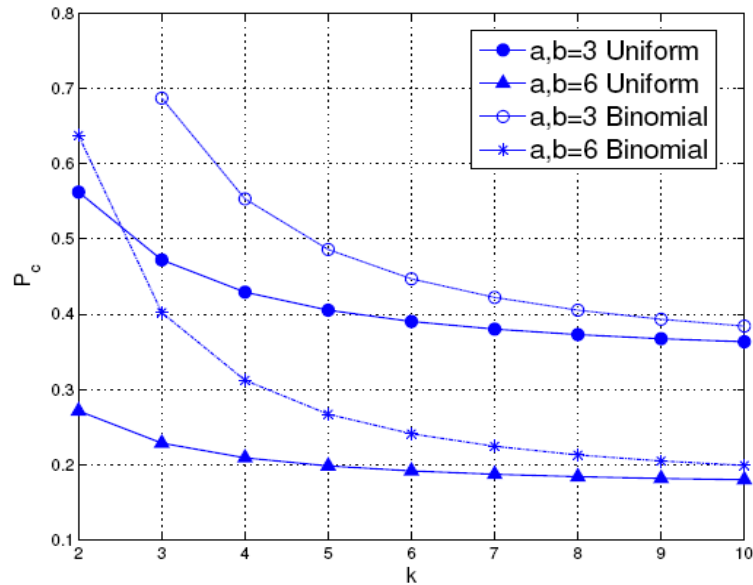
Analysis of Cascading Failures

The functioning giant component size in the dynamic of cascading failures

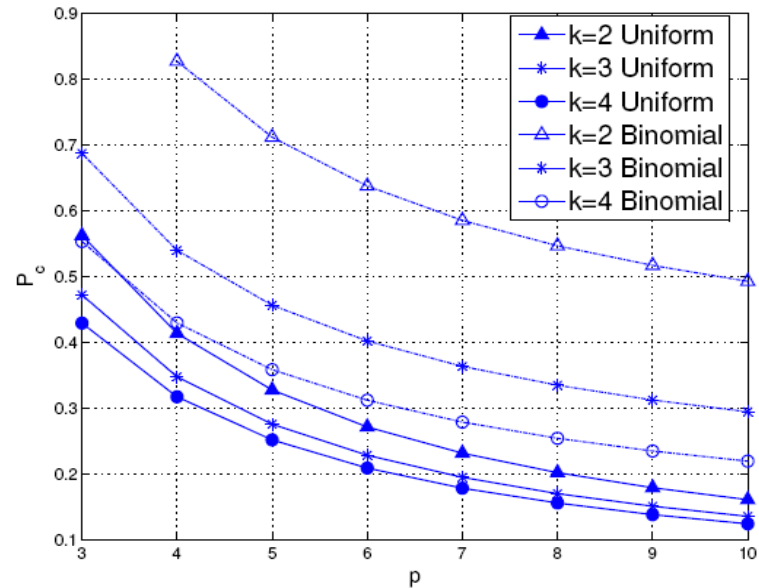


- Finally reach an equilibrium point (the end of cascading failures)
- By calculating the equilibrium point, the ultimate giant component size and *critical threshold* p_c could be obtained
- critical threshold p_c is defined as the critical value of p when the random removal of a fraction $(1-p)$ of the nodes in network A would lead to no giant component

Performance Comparison



(a)



(b)

- Two Erdos-Renyi network with average intra-degree $a=b$ at different value
- Regular (uniform) allocation strategy leads to lower p_c under various conditions
- Lower p_c indicates the higher robustness!

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Thank you!

Q&A?

