Geographically Correlated Failures in Power Networks – Survivability Analysis

Andrey Bernstein[1,2], Daniel Bienstock[3], **David Hay[4]**, Meric Uzunoglu[1], Gil Zussman[1]

[1] Electrical Engineering, Columbia University

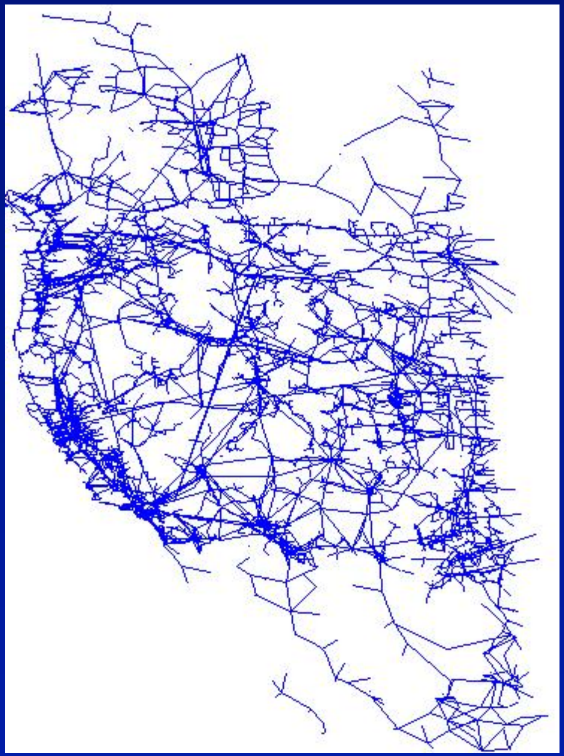
[2] Electrical Engineering, Technion

[3] Industrial Engineering and Operations Research, Columbia University

[4] Computer Science and Engineering, Hebrew University

The Power Grid

- A failure will have a significant effect on many interdependent systems - oil/gas, water, transportation, telecommunications
- Extremely complex network
- Relies on physical infrastructure
  - Vulnerable to physical attacks
- Failures can cascade

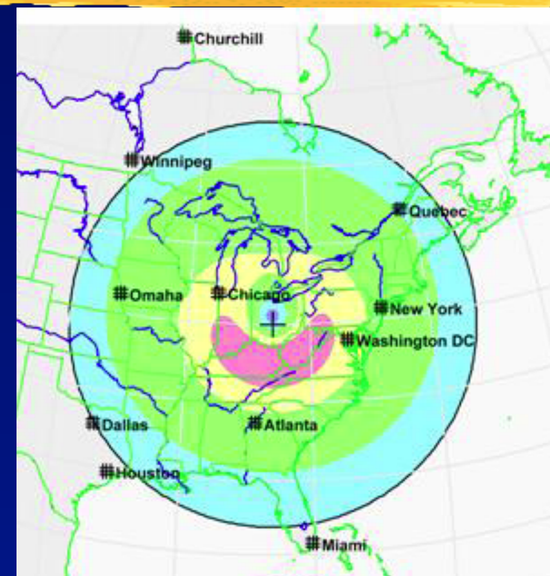


Large Scale Physical Attacks/Disasters

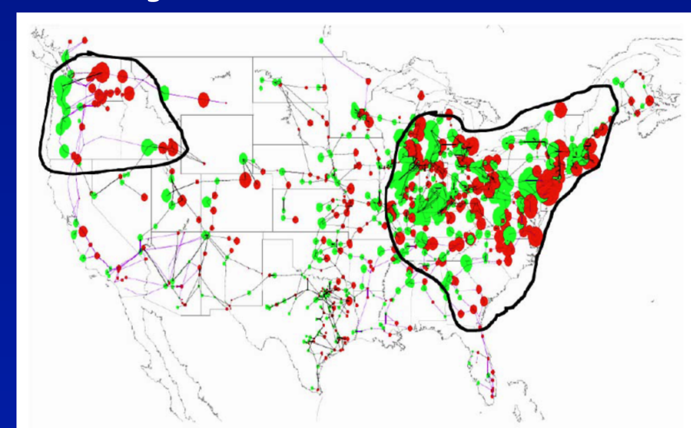
- EMP (Electromagnetic Pulse) attack
- Solar Flares - in 1989 the Hydro-Quebec system collapsed within 92 seconds leaving 6 Million customers without power

- Other natural disasters

- Physical attacks or disasters affect a specific *geographical area*



Source: Report of the Commission to Assess the threat to the United States from Electromagnetic Pulse (EMP) Attack, 2008



FERC, DOE, and DHS, Detailed Technical Report on EMP and Severe Solar Flare Threats to the U.S. Power Grid, 2010

Large Scale Physical Attacks/Disasters

Connect :

IEEE COMMUNICATIONS SOCIETY

IEEE

Hurricane Sandy Update:

The effects of Hurricane Sandy are profound throughout the eastern seaboard of the United States, including the New York City metro area and vast portions of New Jersey. Our thoughts and prayers are with our members and employees affected by this calamity.

IEEE is experiencing significant power disruptions to our U.S. facilities in New Jersey and New York. As a result, you may experience disruptions in service from IEEE. We apologize for any inconvenience and thank you for your patience.

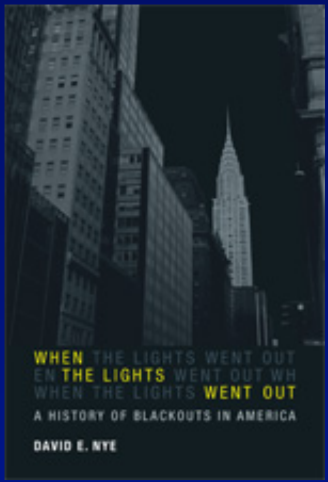
We share the mission of IEEE: To foster technological innovation and excellence for the benefit of humanity.

n

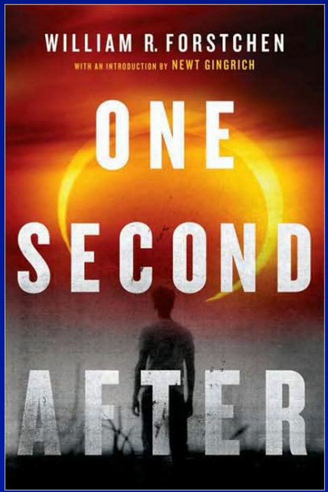
Power Grid, 2010

Related Work

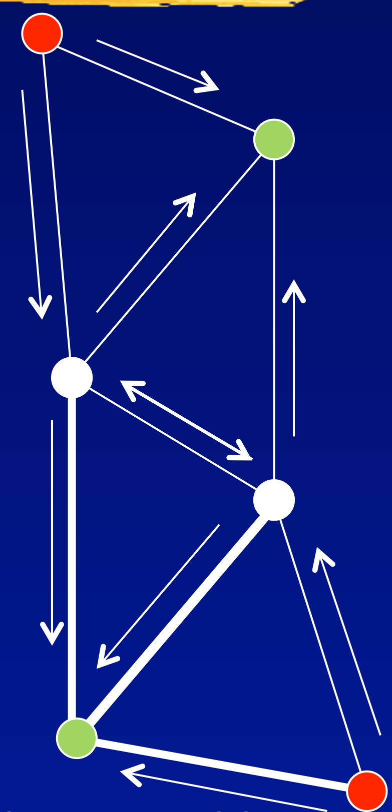
- Report of the Commission to Assess the threat to the United States from Electromagnetic Pulse (EMP) Attack, 2008
- Federal Energy Regulation Commission, Department of Energy, and Department of Homeland Security, Detailed Technical Report on EMP and Severe Solar Flare Threats to the U.S. Power Grid, Oct. 2010



- Cascading failures in the power grid
  - Dobson et al. (2001-2010), Hines et al. (2007-2011), Chassin and Posse (2005), Xiao and Yeh (2011), …
  - The N-k problem where the objective is to find the k links whose failures will cause the maximum damage: Bienstock et al. (2005, 2009)
  - Interdiction problems: Bier et al. (2007), Salmeron et al. (2009), …
  - Do not consider geographical correlation of initial failing links



Power Grid Vulnerability and Cascading Failures



- Power flow follows the laws of physics
- Control is difficult
  - It is difficult to "store packets" or "drop packets"
- Modeling is difficult
  - Final report of the 2003 blackout – cause #1 was "inadequate system understanding" (stated at least 20 times)
- Power grids are subject to **cascading failures**:
  - Initial failure event
  - Transmission lines fail due to overloads
  - Resulting in subsequent failures
- Large scale geographically correlated failures have a different effect than a single line outage
- Objectives:
  - Assess the vulnerability of different locations in the grid to **geographically correlated failures**
  - Identify properties of the cascade model

Outline

- Background
- Power flows and cascading failures
- Numerical results – single event
- Cascade properties
- Vulnerability analysis and numerical results

Power Flow Equations - DC Approximation

- Exact solution to the AC model is infeasible

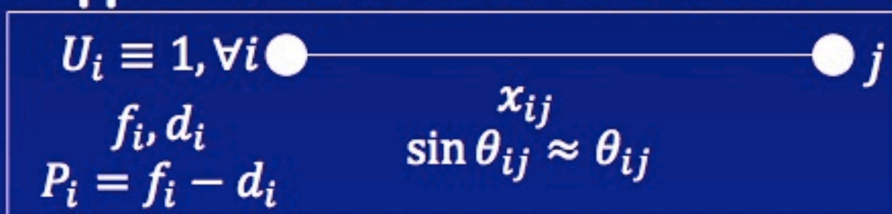
$$P_{ij} = U_i^2 g_{ij} - U_i U_j g_{ij} \cos\theta_{ij} - U_i U_j b_{ij} \sin\theta_{ij}$$

$$Q_{ij} = -U_i^2 b_{ij} + U_i U_j b_{ij} \cos\theta_{ij} - U_i U_j g_{ij} \sin\theta_{ij}$$

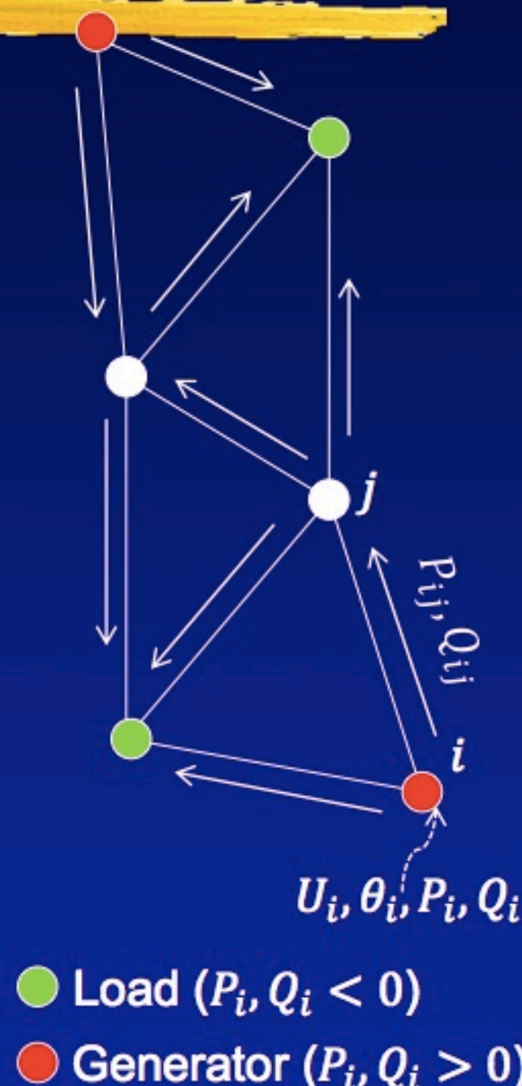
and $\theta_{ij} = \theta_i - \theta_j$.

  - Non -linear, non-convex, intractable,
  - May have multiple solutions

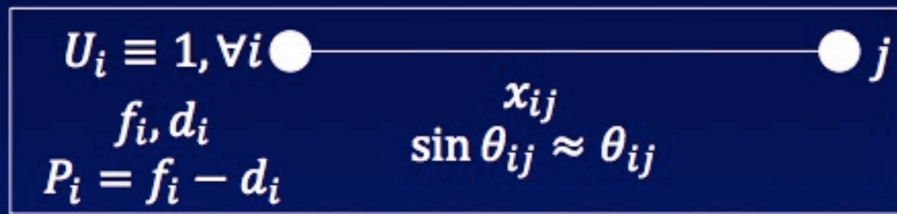
- We use **DC approximation** which is based on:

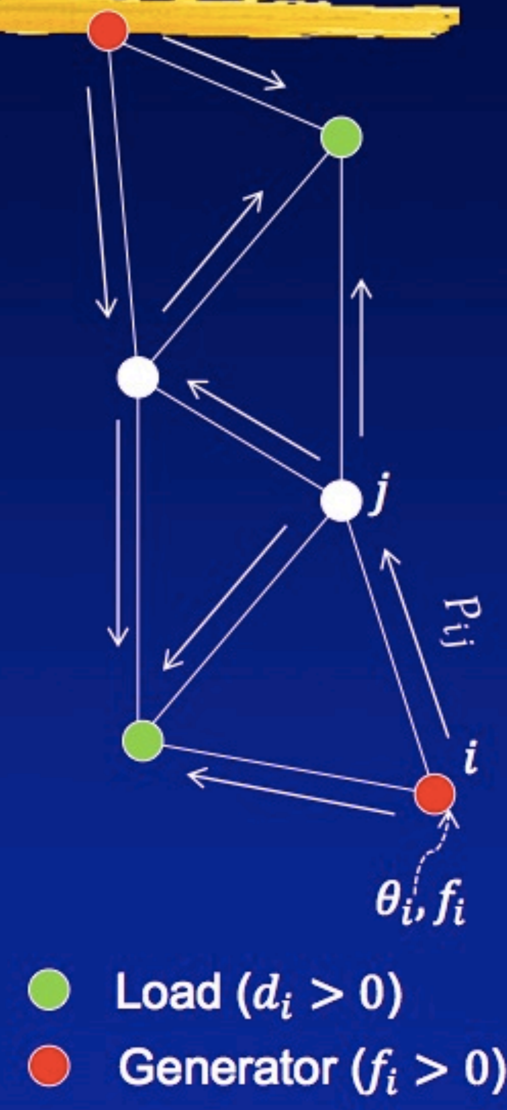


  - $U_i = 1\,p.u.$ for all i
  - **Pure reactive** transmission lines – each line is characterized only by its reactance $x_{ij} = -1/b_{ij}$
  - Phase angle differences are "small", implying that $\sin\theta_{ij} \approx \theta_{ij}$



Power Flow Equations - DC Approximation





- The active power flow P_{ij} can be found by solving:

  $f_i + \sum_{j:P_{ji}>0} P_{ji} = \sum_{j:P_{ij}>0} P_{ij} + d_i$ for each node i

  $P_{ij} = \frac{\theta_i - \theta_j}{x_{ij}}$ for each line (i, j)

- Lemma (Bienstock and Verma, 2010):
  Given the supply and demand vectors $\{f_i\}$ and $\{d_i\}$ with $\sum_i f_i = \sum_i d_i$ for each connected component of the network, the above equations have unique solution in $\{P_{ij}, \theta_i\}$

- Known as a good approximation
- Frequently used for contingency analysis
  - Do the assumptions hold during a cascade?

Line Outage Rule

- Different factors can be considered in modeling outage rules
  - The main is **thermal capacity** u_{ij}
- Simplistic approach: fail lines with $|P_{ij}| > u_{ij}$

  Not part of the power flow problem constraints

- More realistic policy:

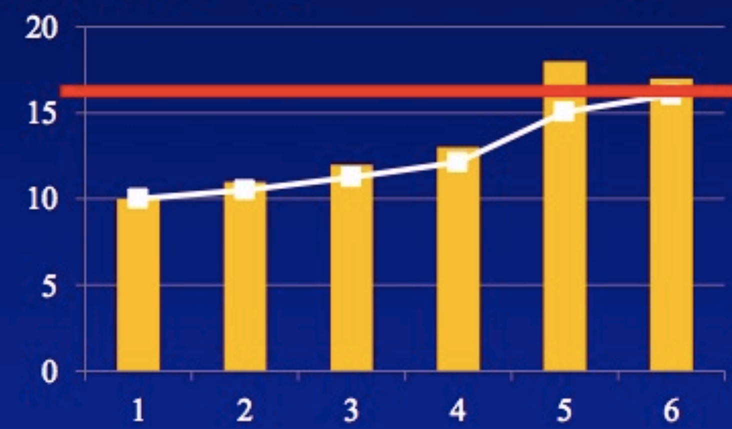
  Compute the moving average

  $\tilde{P}_{ij} \coloneqq \alpha|P_{ij}| + (1-\alpha)\tilde{P}_{ij}$

  ($0 \le \alpha \le 1$ is a parameter)

  Fail lines (possibly randomly)

  if $\xi_{ij} = \tilde{P}_{ij}/u_{ij}$ is close to or above 1



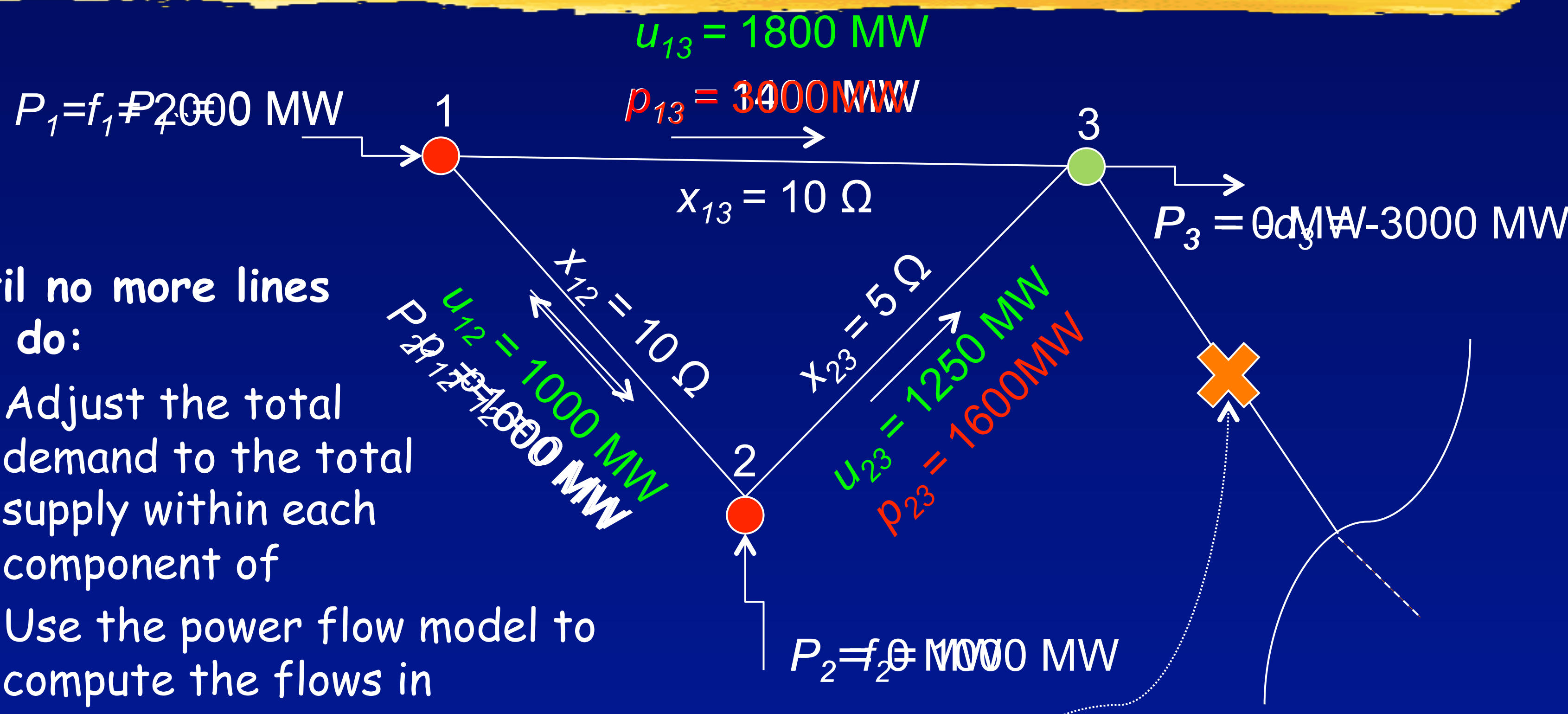
- In the following examples - **deterministic outage rule:**

  Fail lines with $\frac{\tilde{P}_{ij}}{u_{ij}} > 1$
- More generally:
  - Each line (i,j) is characterized by its state $\xi_{ij} = \tilde{P}_{ij}/u_{ij}$
  - An outage rule $O(\xi_{ij}) \in [0,1]$ specifies the probability that (i,j) will fail given that its current state is ξ_{ij}

Cascading Failure Model

- **Input:** Fully connected network graph G, supply/demand vectors with $\sum_i f_i = \sum_i d_i$, lines states ξ_{ij}
- **Failure Event:** At time step $t = 0$, a failure of a subset of lines occurs
- **Until no more lines fail do:**
  - Adjust the total demand to the total supply within each component of G
  - Use the power flow model to compute the flows in G
  - Update the state of lines ξ_{ij} according to the new flows
  - Remove the lines from G according to a given outage rule O

Example of a Cascading Failure



- **Until no more lines fail do:**
  - Adjust the total demand to the total supply within each component of
  - Use the power flow model to compute the flows in
  - Update the state of lines ξ_{ij} according to the new flows
  - Remove the lines from according to a given outage rule

Initial failure causes disconnection of load 3 from the generators in the rest of the network

As a result, line (2,3) becomes overloaded

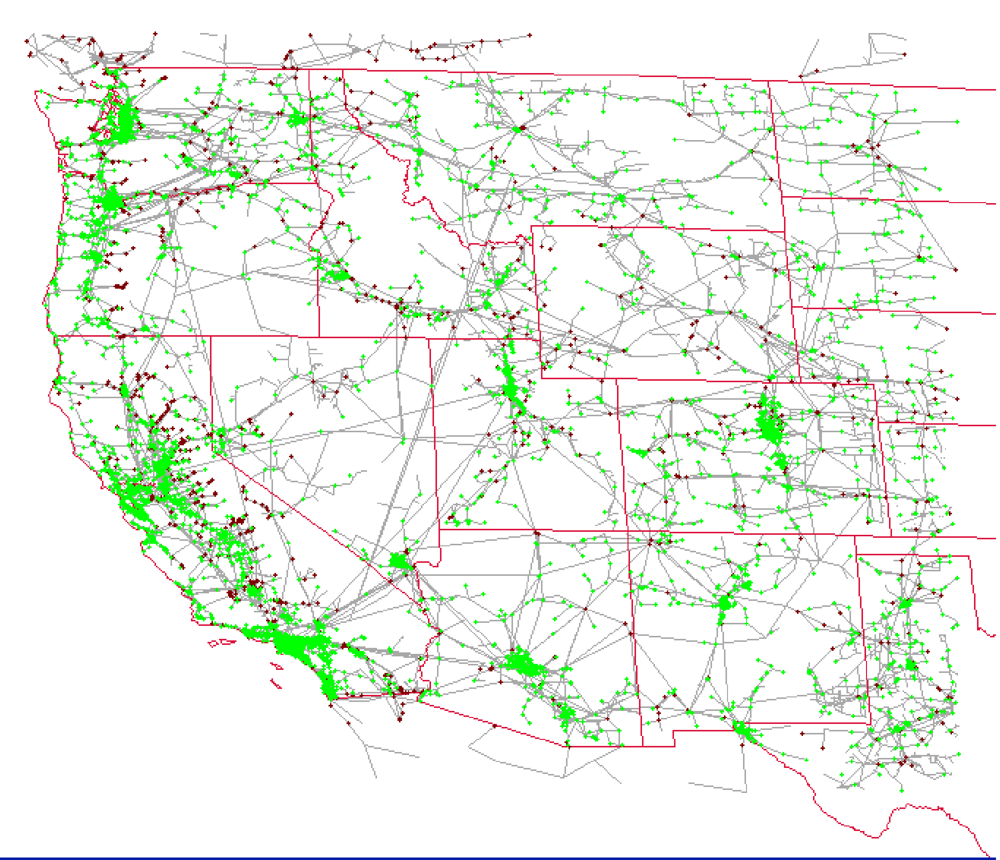
Outline

- Background
- Power flows and cascading failures
- Numerical results – single event
- Cascade properties
- Vulnerability analysis and numerical results

Numerical Results - Power Grid Map

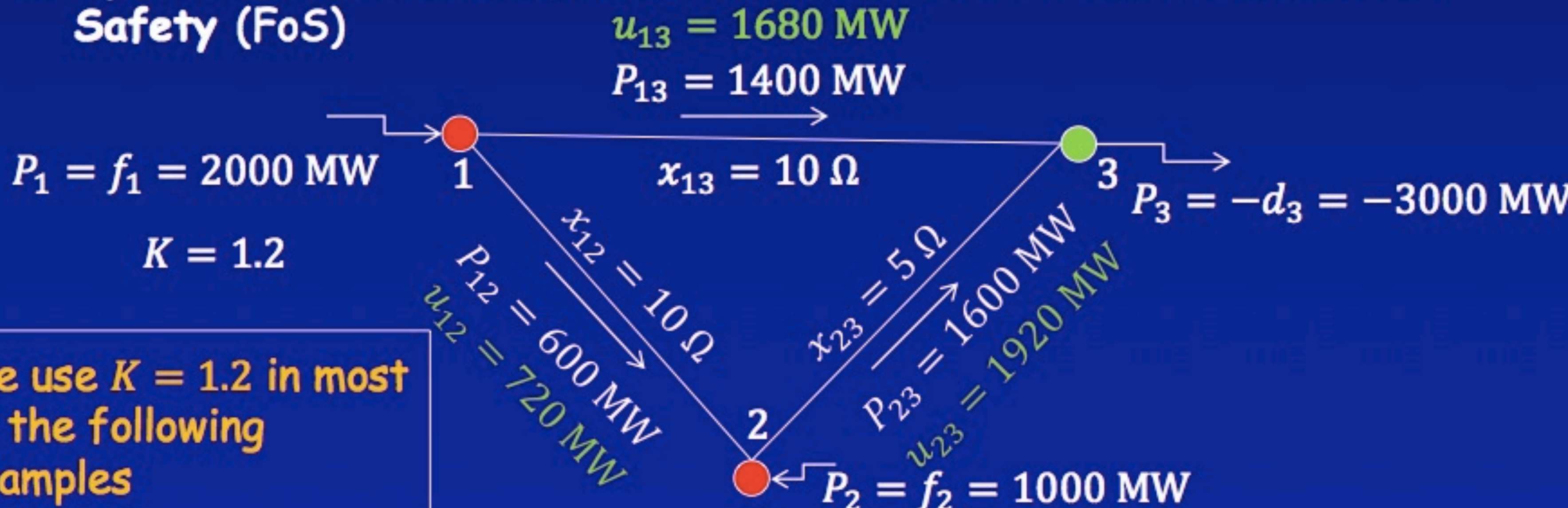
- Obtained from the GIS (Platts Geographic Information System)
- **Substantial processing** of the raw data
- Used a **modified** Western Interconnect system, to avoid exposing the vulnerability of the real grid

- 13,992 nodes (substations), 18,681 lines, and 1,920 power stations.
- 1,117 generators (red), 5,591 loads (green)
- Assumed that demand is proportional to the population size



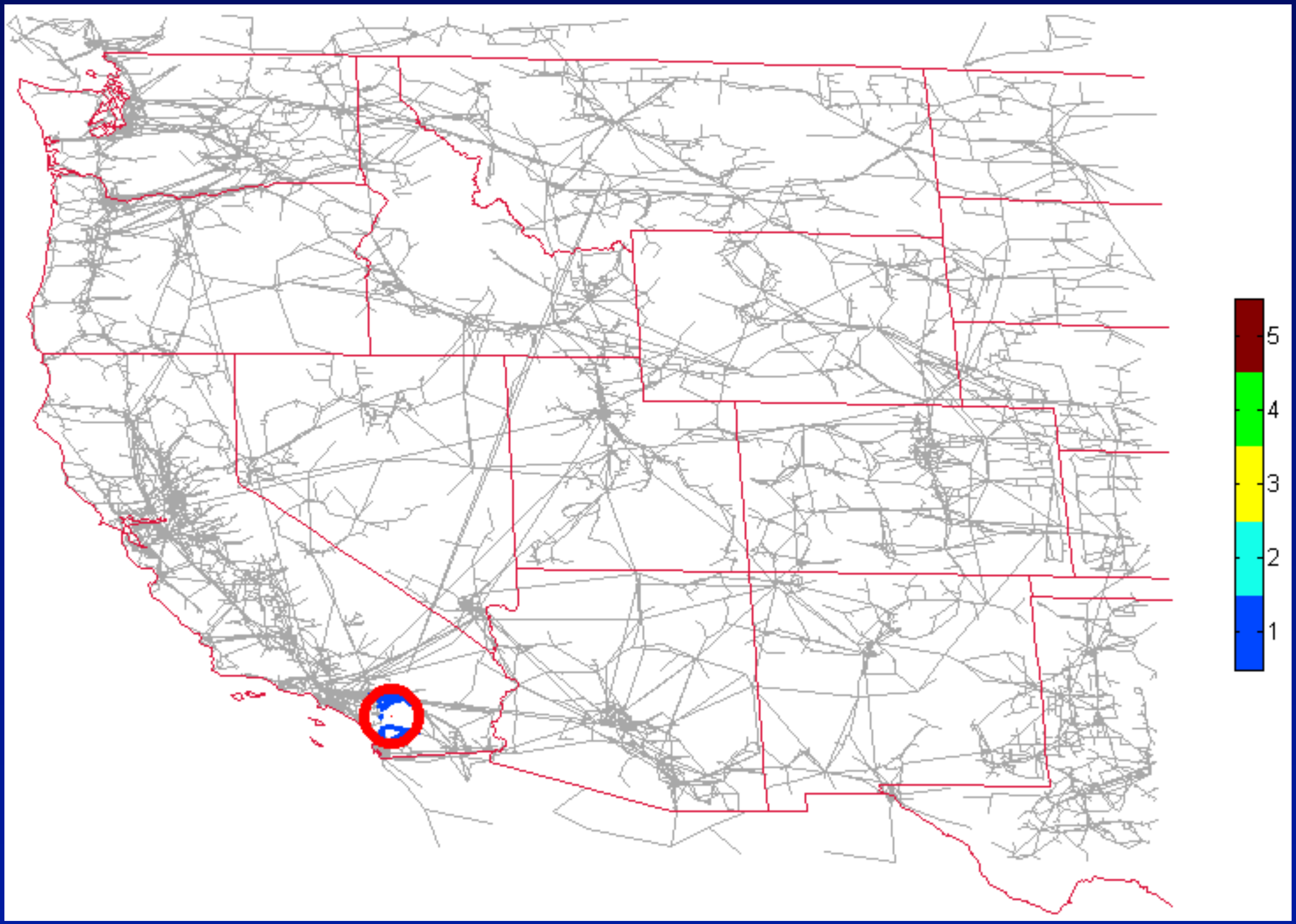
Determining The System Parameters

- The GIS does not provide the power capacities and reactance values
- We use the **length of a line** to determine its **reactance**
  - There is a linear relation
- We estimate the **power capacity** by solving the power flow problem of the original power grid graph
  - Without failures – N-Resilient grid
  - With all possible single failures – $(N\text{-}1)$-Resilient grid
- We set the power capacity $u_{ij} = KP_{ij}$
  - P_{ij} is the flow of line (i,j) and the constant K is the grid's **Factor of Safety** (FoS)



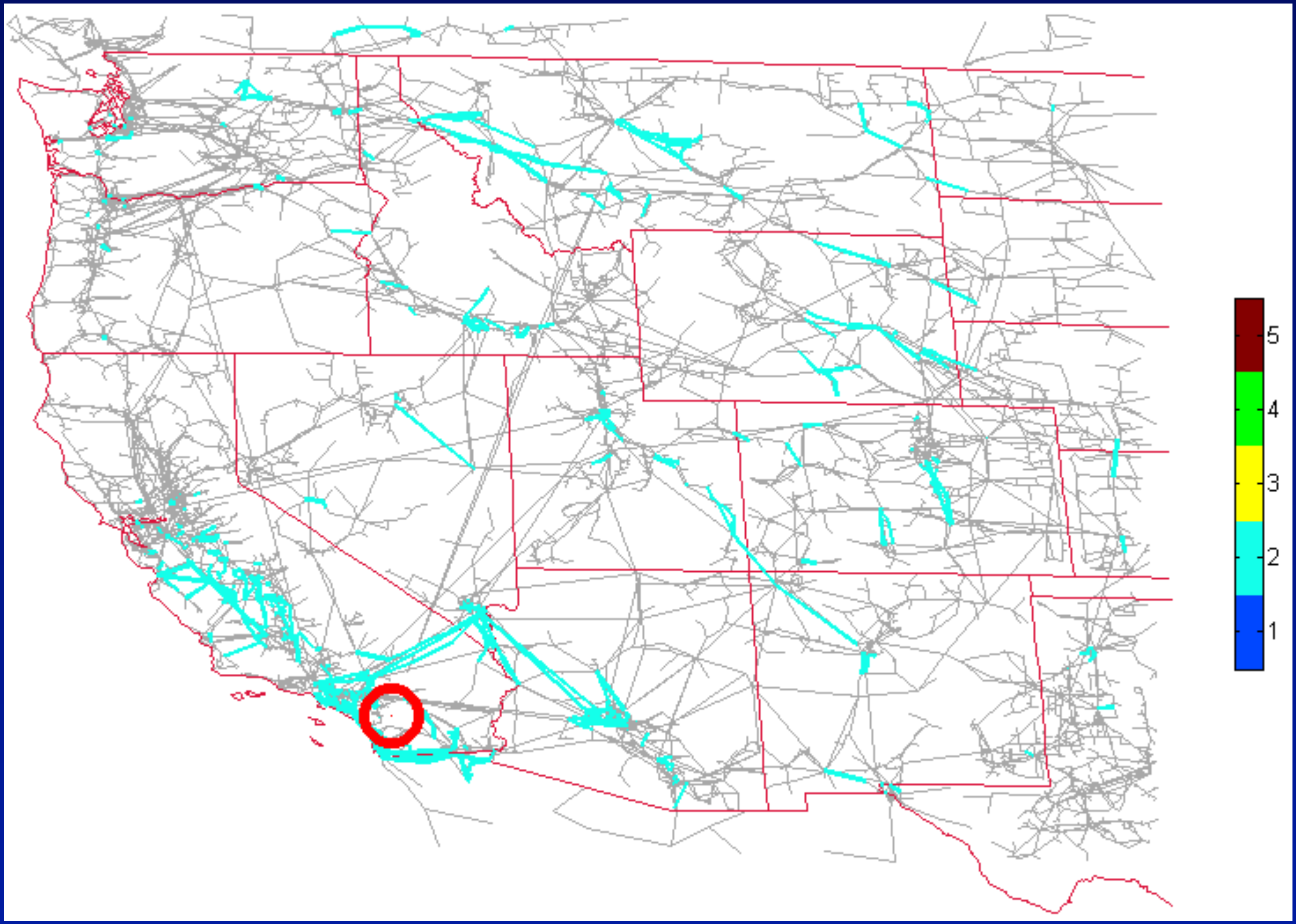
We use $K = 1.2$ in most of the following examples

Cascade Development – San Diego area

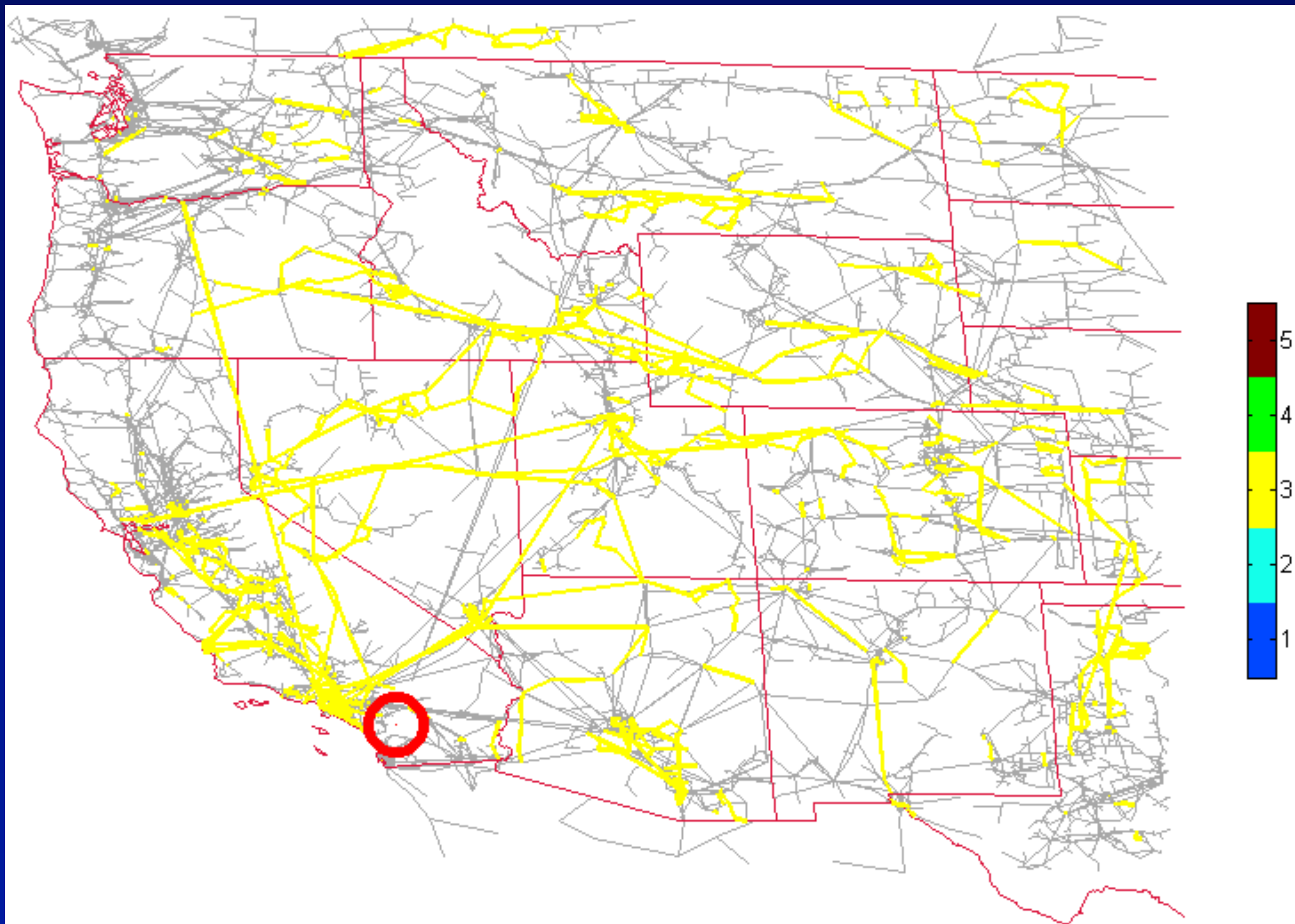


N-Resilient, Factor of Safety $K = 1.2$

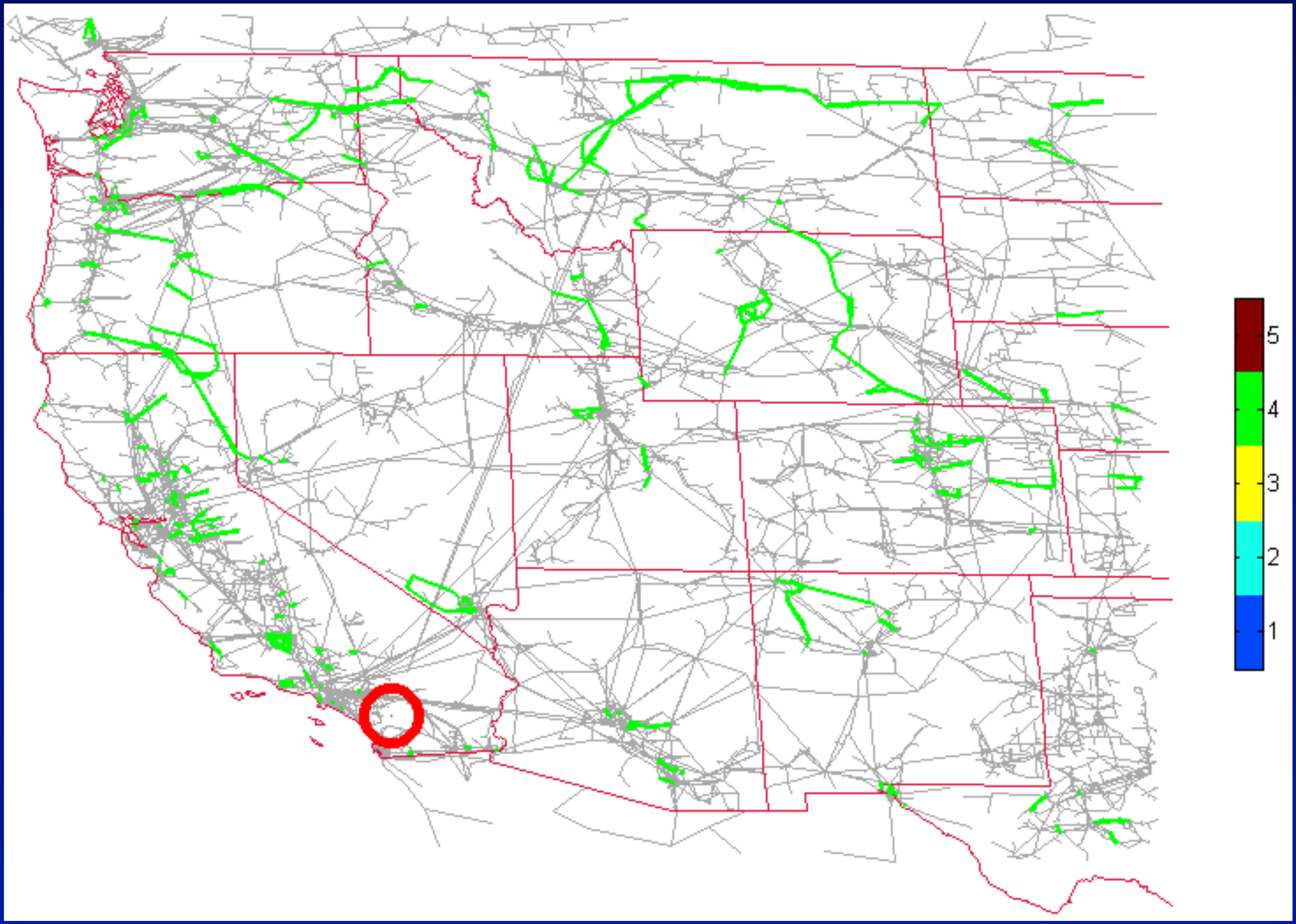
Cascade Development – San Diego area



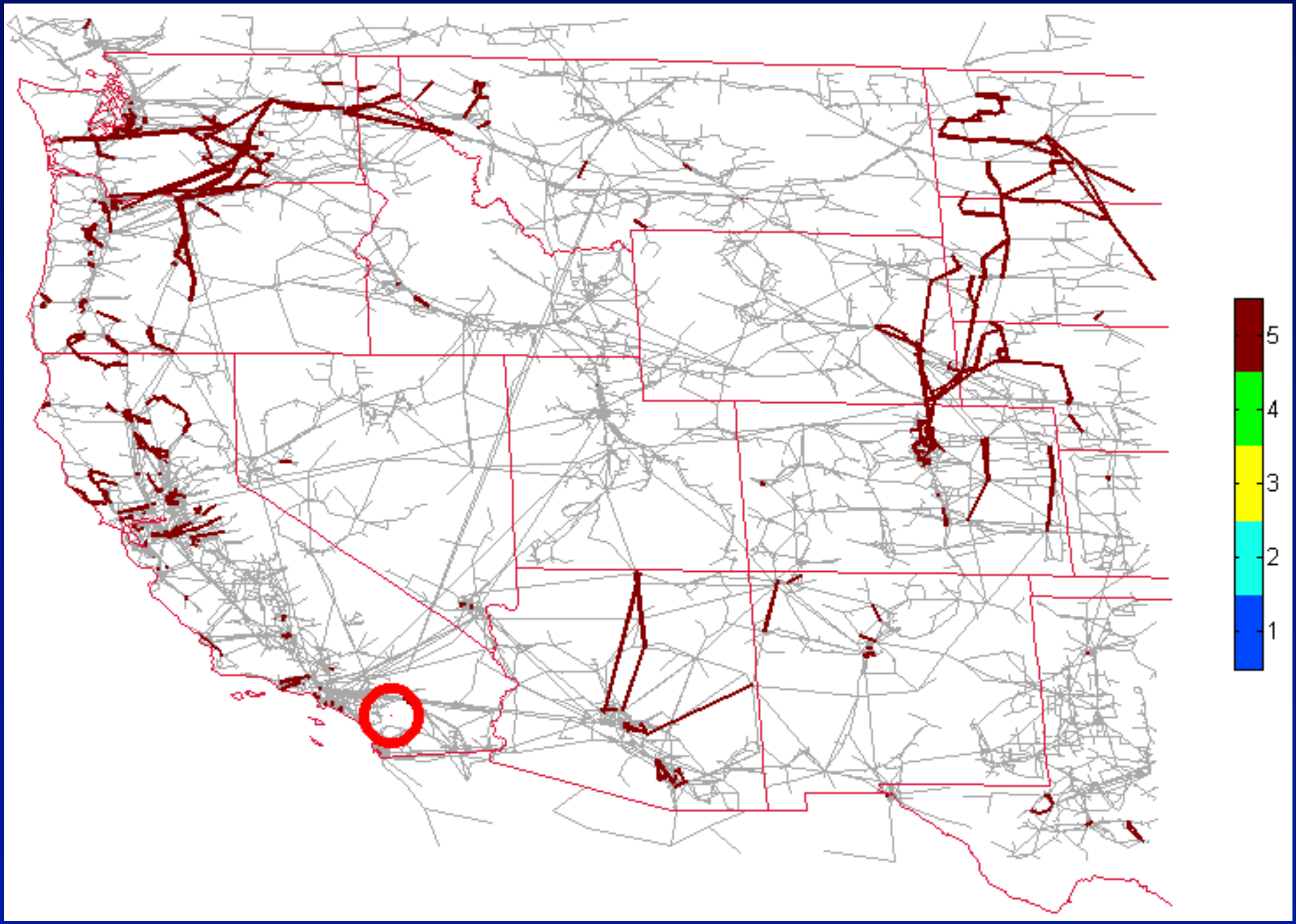
Cascade Development – San Diego area



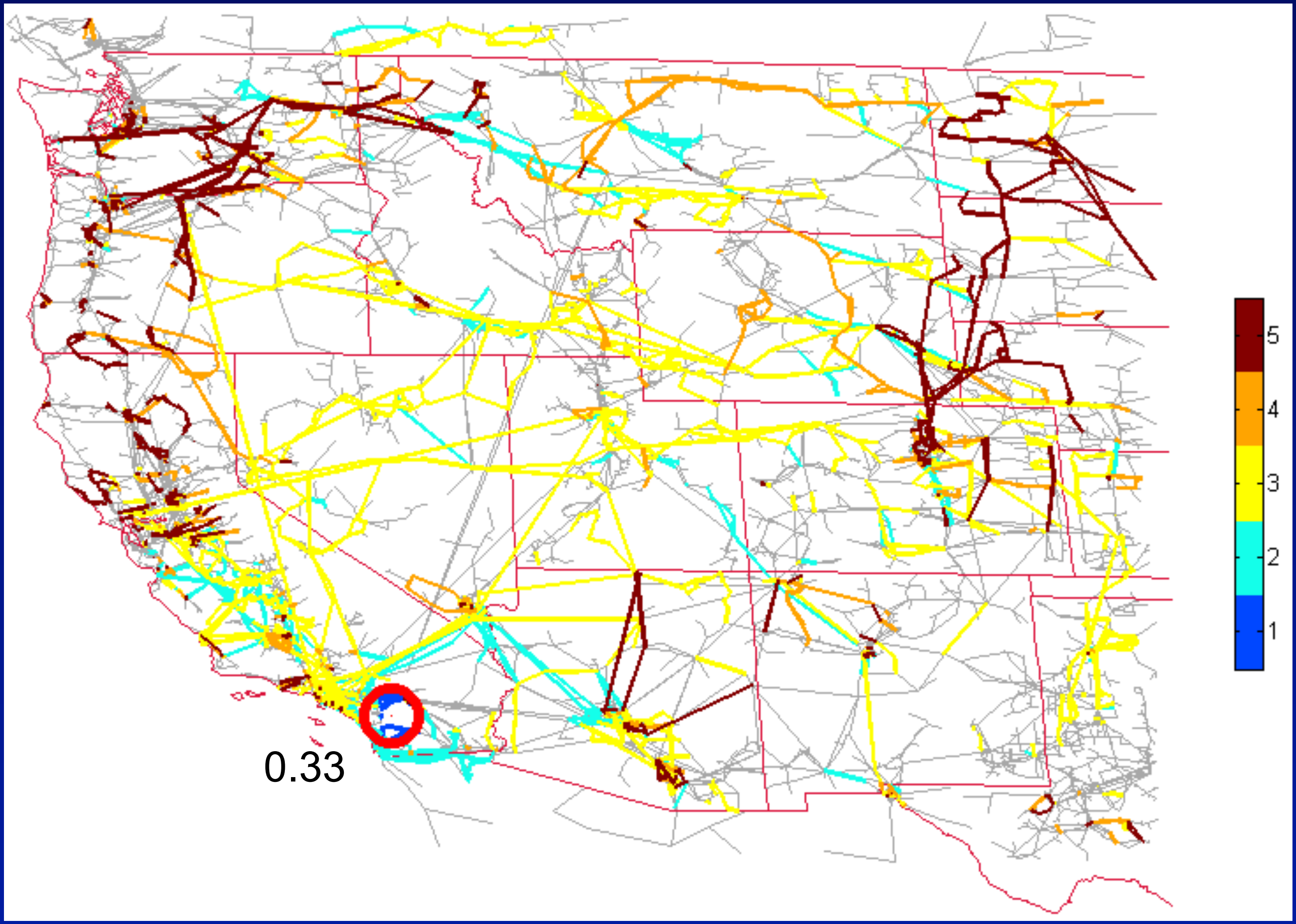
Cascade Development – San Diego area



Cascade Development - San Diego area



Cascade Development – San Diego area

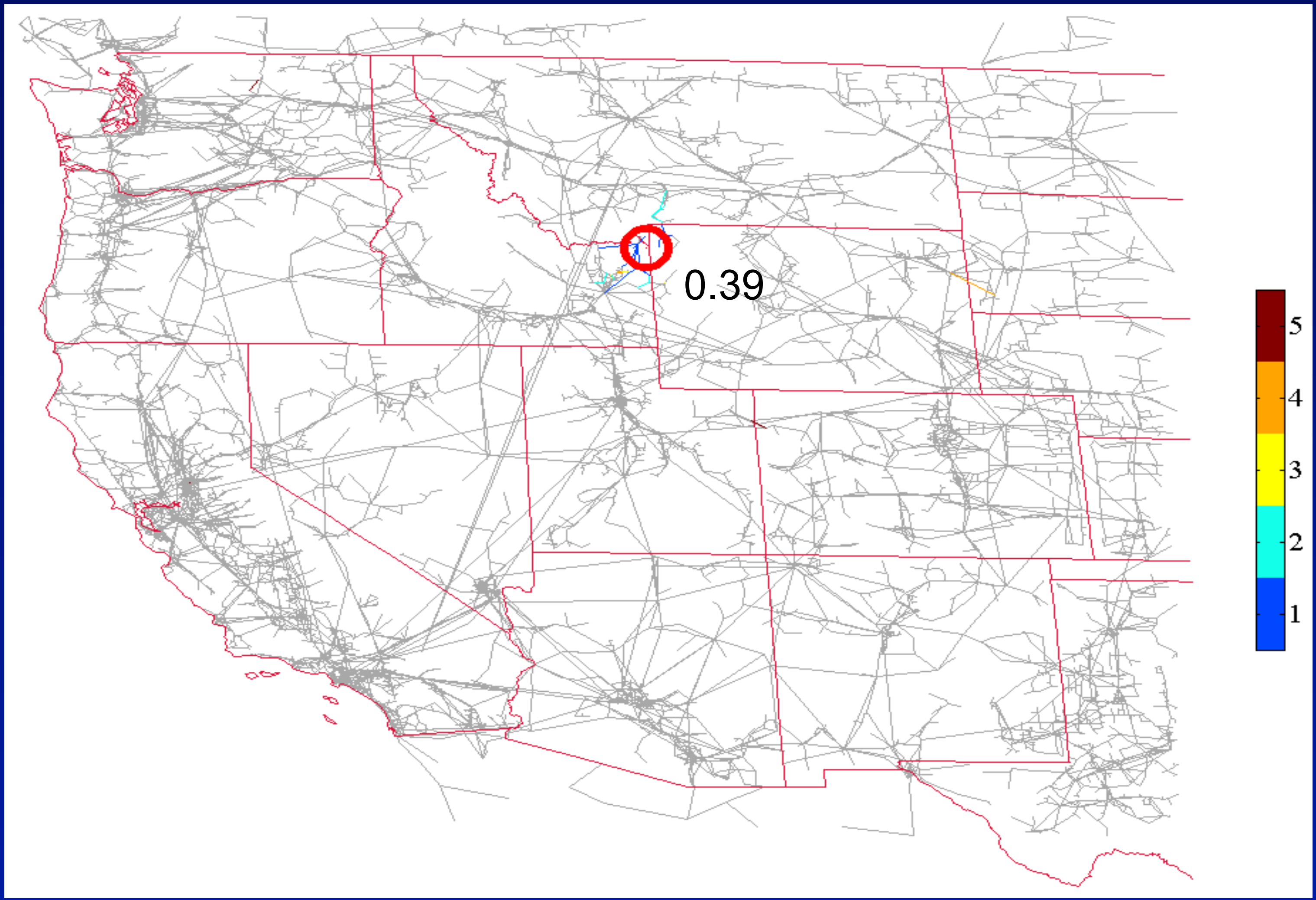


N-Resilient, Factor of Safety $K = 1.2 \rightarrow$ **Yield = 0.33**

For $(N\text{-}1)$-Resilient $\rightarrow$ **Yield = 0.35** For $K = 2 \rightarrow$ **Yield = 0.7**

(Yield - the fraction of the demand which is satisfied at the end of the cascade)

Cascade Development - 5 Rounds, Idaho-Montana-Wyoming border



N-Resilient, Factor of Safety $K = 1.2 \rightarrow$ **Yield = 0.39**

For (*N*-1)-Resilient → **Yield = 0.999** For $K = 2 \rightarrow$ **Yield = 0.999**

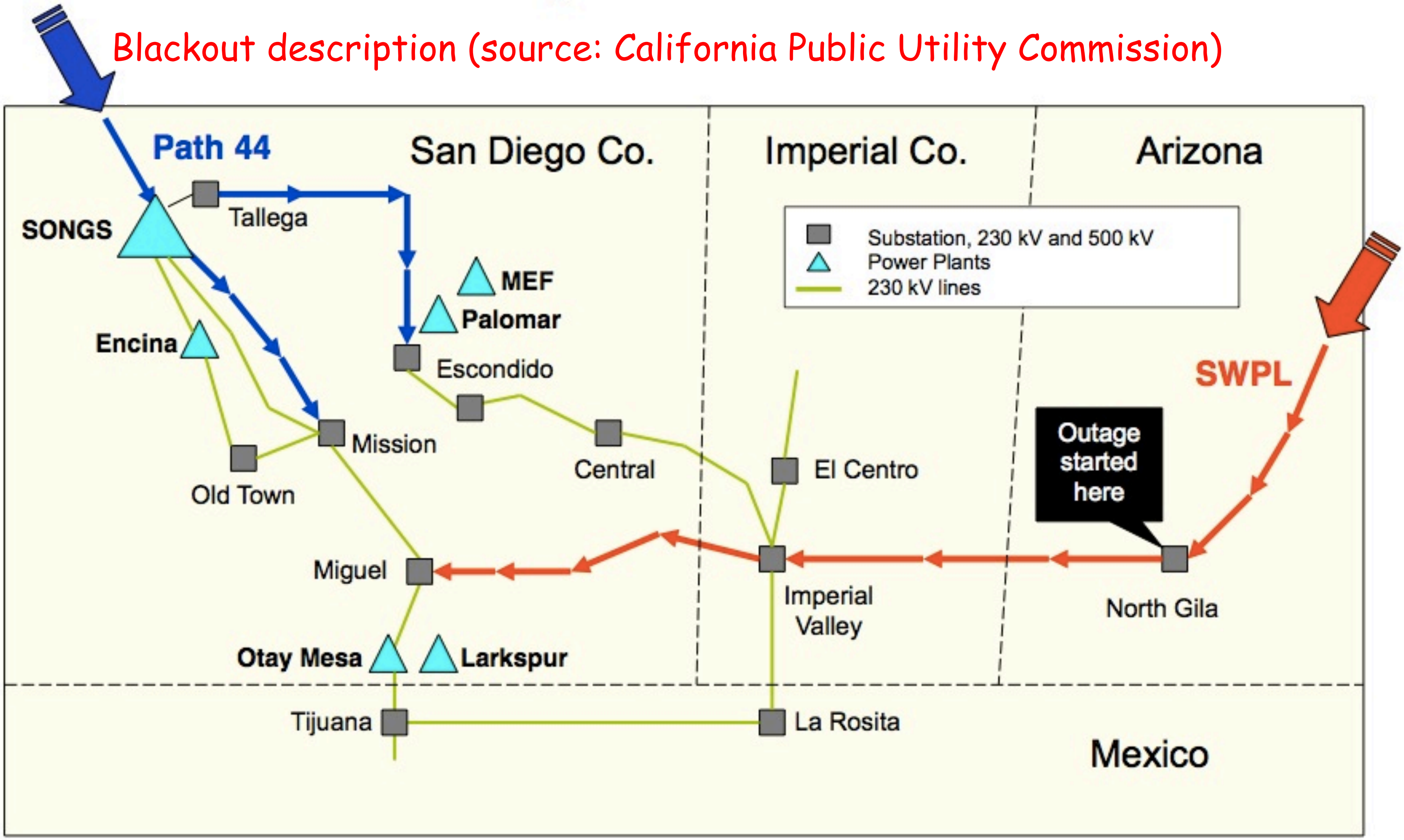
(Yield - the fraction of the demand which is satisfied at the end of the cascade)

Outline

- Background
- Power flows and cascading failures
- Numerical results – single event
- Cascade properties
- Vulnerability analysis and numerical results

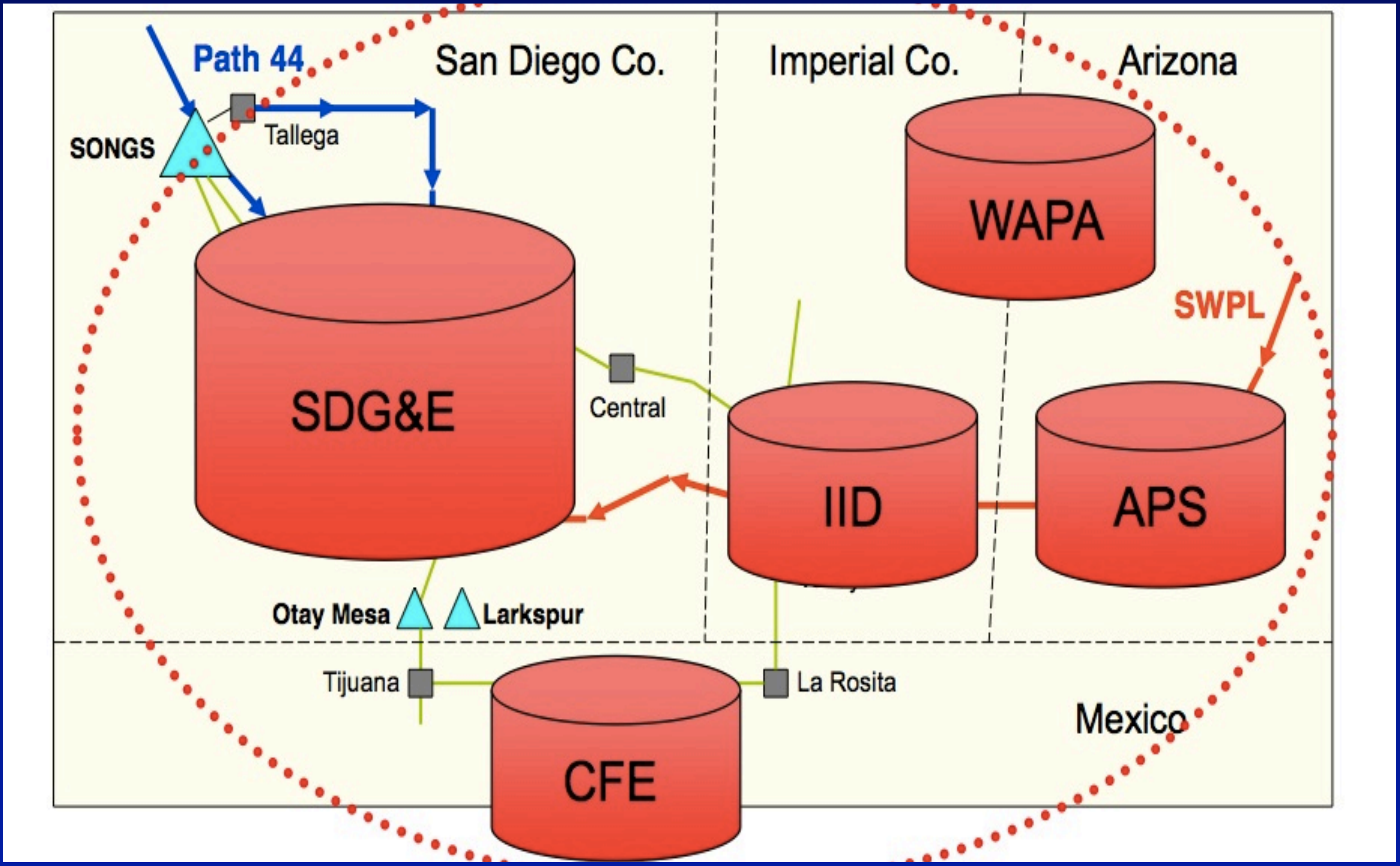
Latest Major Blackout Event: San Diego, Sept. 2011

Blackout description (source: California Public Utility Commission)



*Map not to scale

Pacific Southwest Balancing Authority



Blackout Statistics

Utility Company	Generation Lost (MW)	Demand Interrupted (MW)	Number of Customers Affected
SDG&E	2229	4293	1,387,336
SCE	2428	0	117*
CFE Comision Federal de Electricidad	1915	2205	1,157,000
IID Imperial Irrigation District	333	929	144,000
APS Arizona Public Service	76	389	69,694
WAPA Western Area Power Association	0	74	18,000
TOTAL	**6982 MW**	**7890 MW**	**2,776,147**

Event Timeline

Prior to start of events, SWPL delivering 1370 MW, and Path 44 delivering 1287 MW.

15:27:39 – 500kV Hassayampa-North Gila (SWPL) line trips at North Gila Substation.

SWPL lost. Increased flow on Path 44 to 2407 MW.

15:27:58 to 15:30:00 – CCM tripped in CFE area (needed emergency assistance of 158 MW). IID experienced problems with Imperial Valley-El Centro line resulting in 100MW swing.

Path 44 flow increased to 2616 MW.

15:32:00 to 15:33:44 – IID transformer bank and two units trip. Also two 161 kV lines trip at Niland-WAPA and Niland-Coachella Valley.

Flow from SDG&E to IID increased by 209 MW. Path 44 flow increased to 2959 MW.

15:35:40 to 15:36:45 – Two APS 161 kV lines to Yuma tripped and electrically separated from IID and WAPA. SDG&E now fed power into Yuma area.

Flow from SONGS to San Diego to Yuma. Path 44 flow increased to 3006 MW.

15:37:56 – IID's 161 kV tie to WAPA tripped. Import power into Yuma, Imperial Valley, Baja Norte, and San Diego wholly dependant on Path 44.

15:37:58 to 15:38:07 – El Centro Substation (IID) trip due to under frequency. Two units at La Rosita plant (CFE) trip resulting in a loss of 420 MW.

Path 44 flow increased to 3454 MW and 7500 Amps.

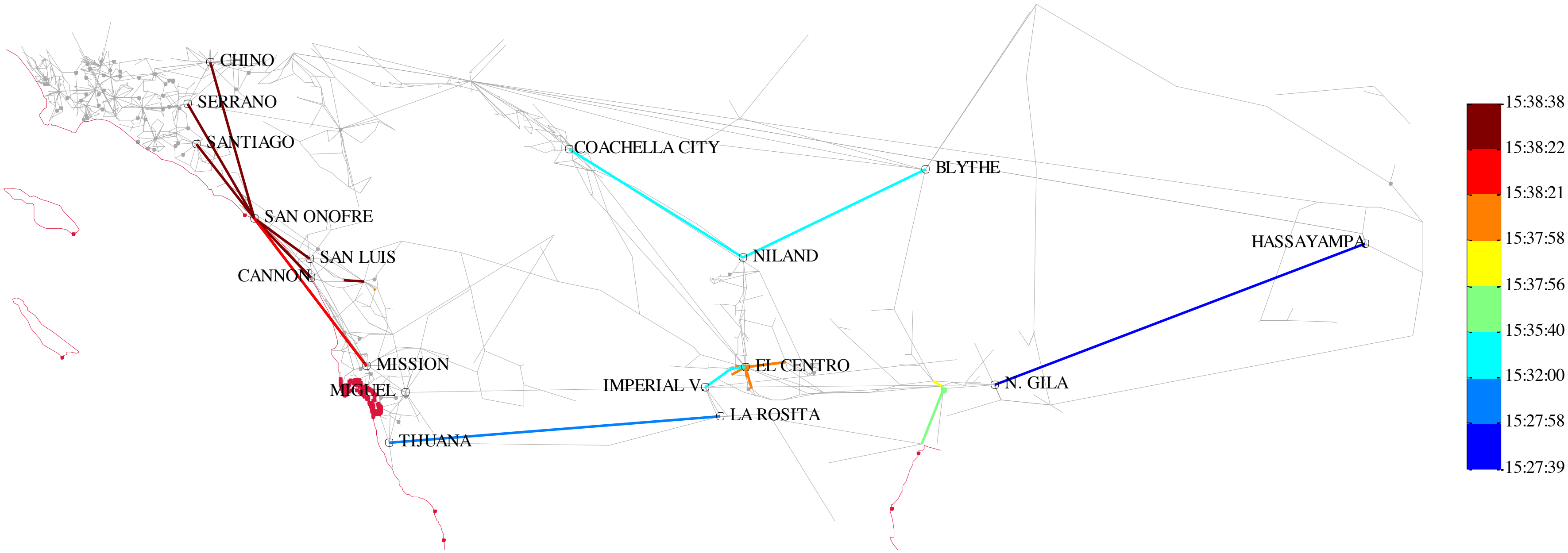
15:38:21 – Path 44 exceeded safety setting of 8000 Amps. Overload relay protection initiated to separate Path 44 between SCE and SDG&E at SONGS switchyard.

Path 44 reaches 9660 Amps, then drops to 8230 Amps.

15:38:22 to 15:38:38 – SONGS and local power plants trip. 230kV lines open.

15:38:38 – Blackout

Real Cascade

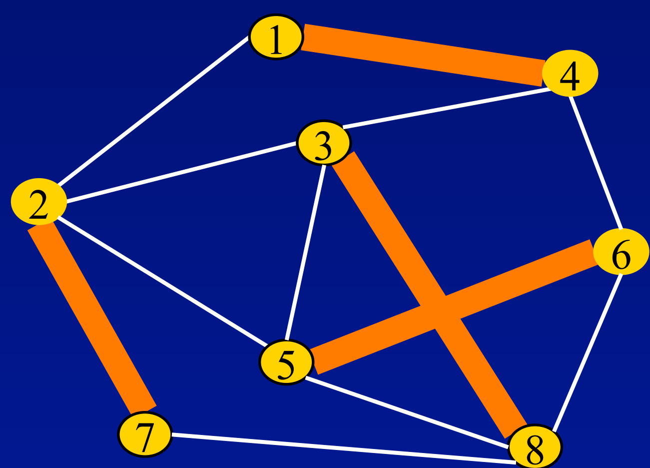


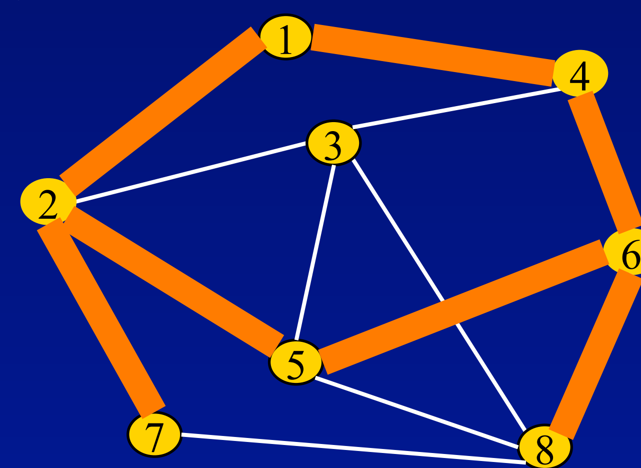
- Failures indeed “skip” over a few hops

Power Flow Cascading Failures Model*

The following properties hold:

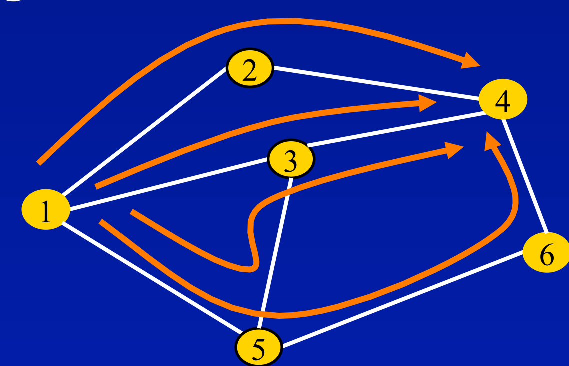
- Consecutive failures may happen within arbitrarily long distances of each other
  - Very different from the epidemic-percolation-based cascade models





- Cascading failures can last arbitrarily long time
- * Proofs for simple graphs
  - Based on the observation that for all

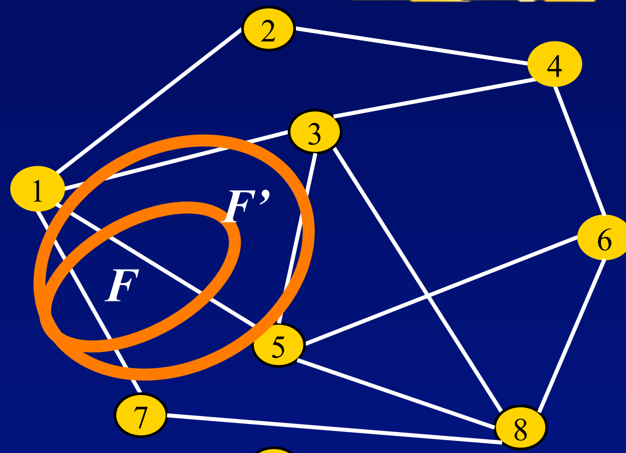
    parallel paths $\sum_{path\ 1} P_{ij}x_{ij} = \sum_{path\ 2} P_{ij}x_{ij}$



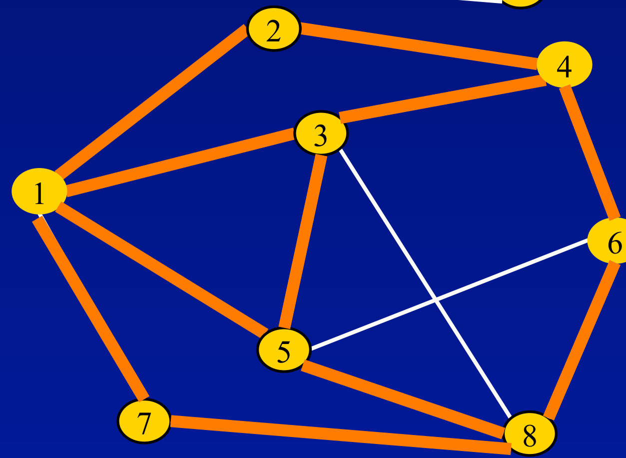
Power Flow Cascading Failures Model*

The following properties hold:

- Consider failure events *F* and *F'* (*F* is a subset of *F'*) - The damage after *F* can be greater than after *F'*



- Consider graphs *G* and *G'* (*G* is a subgraph of *G'*) - *G* may be more resilient to failures than *G'*



- Observation (without proof): In large scale geographically correlated failures we do not experience the slow start phenomena that follows single line failures

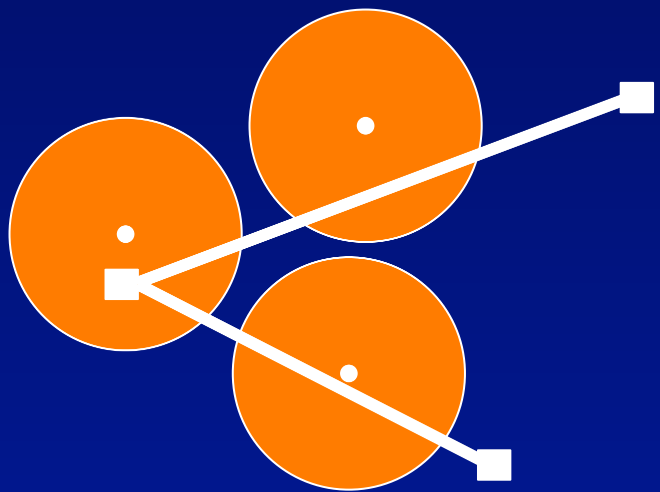
* Proofs for simple graphs

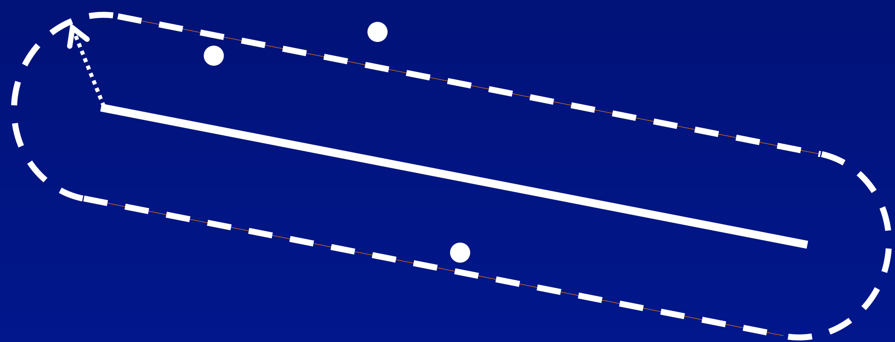
Outline

- Background
- Power flows and cascading failures
- Numerical results – single event
- Cascade properties
- Vulnerability analysis and numerical results

Identification of Vulnerable Locations

- **Circular and deterministic failure model:** All lines and nodes within a radius r of the failure's epicenter are removed from the graph (this includes lines that pass through the affected area)

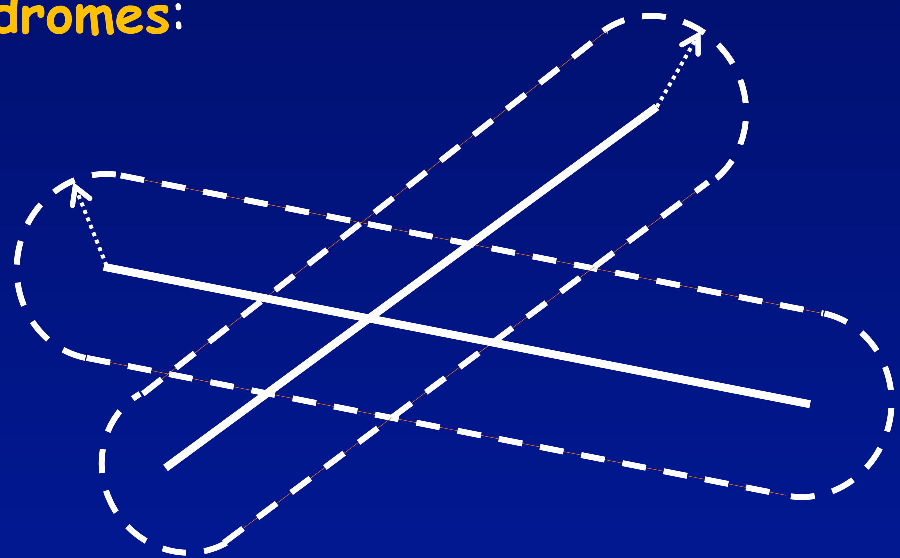




- Theoretically, there are infinite attack locations
- We would like to consider a finite subset

Identification of Vulnerable Locations

- Utilizing observations regarding the attack locations - $O(n^6)$
  - e.g., all attacks that affect only a single link are equivalent
- Candidates for the most vulnerable locations are **the intersection points of the hippodromes**:



- Identifying the intersections, using computational geometric tools - $O(m^2)$ (m - the number of faces in the arrangement)*
  - Can be extended to probabilistic attack models
- For r=50 km, ~70,000 candidate locations were produced for the part of the Western Interconnect that we used

* based on Agarwal, Efrat, Ganjugunte, Hay, Sankararaman, and Zussman (2011)

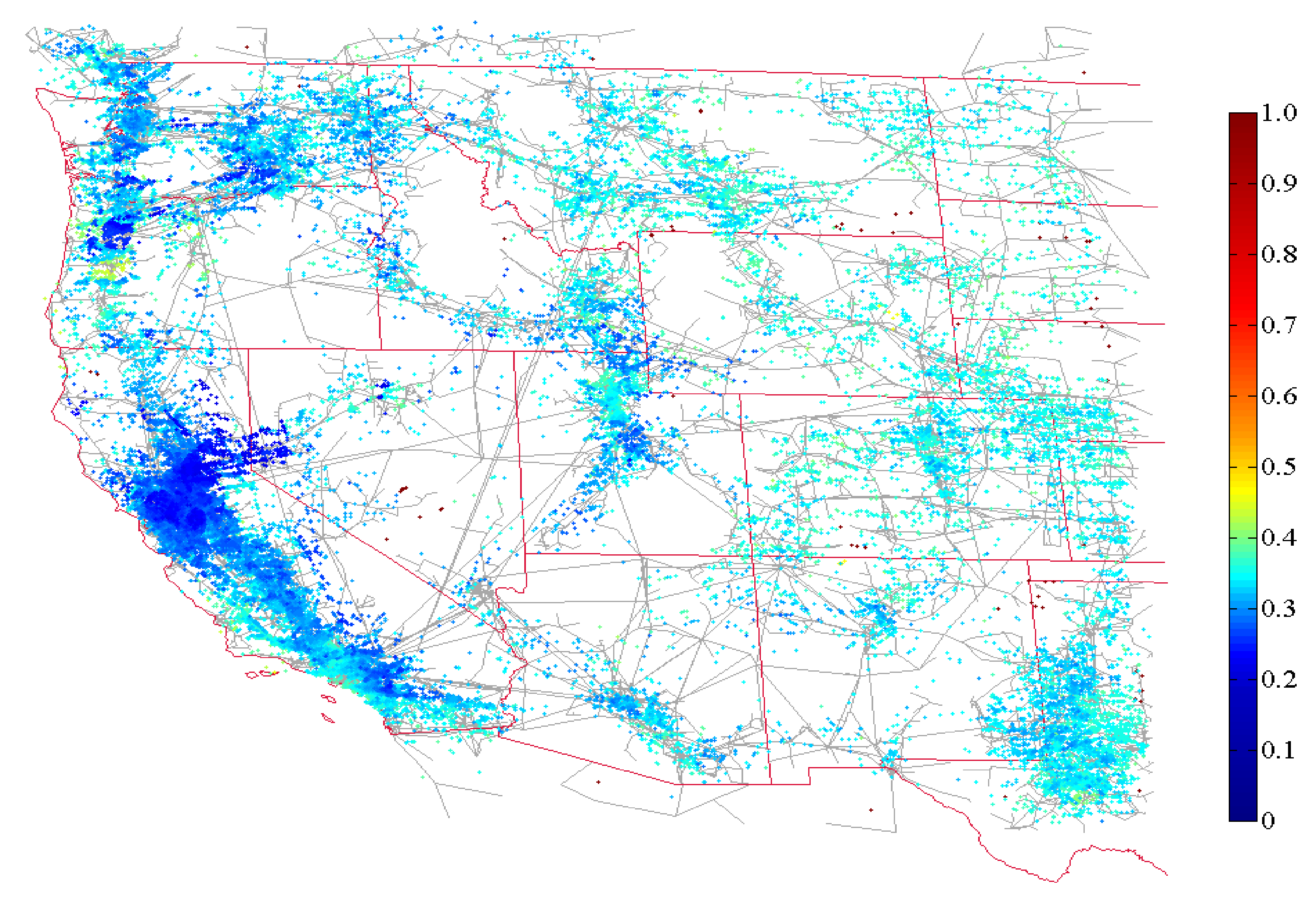
Computational Workload

- Eight core server was used to perform computations and simulations
- The identification of failure locations was performed in parallel, on different sections of the map
  - For a given radius - was completed in less than 24 hours
- The simulation of each cascading failure required solving large scale systems of equations (using the Gurobi Optimizer)
  - Completed in less than 8 seconds for each location
- When parallelized, the whole simulation was completed in less than 24 hours

Performance Metrics

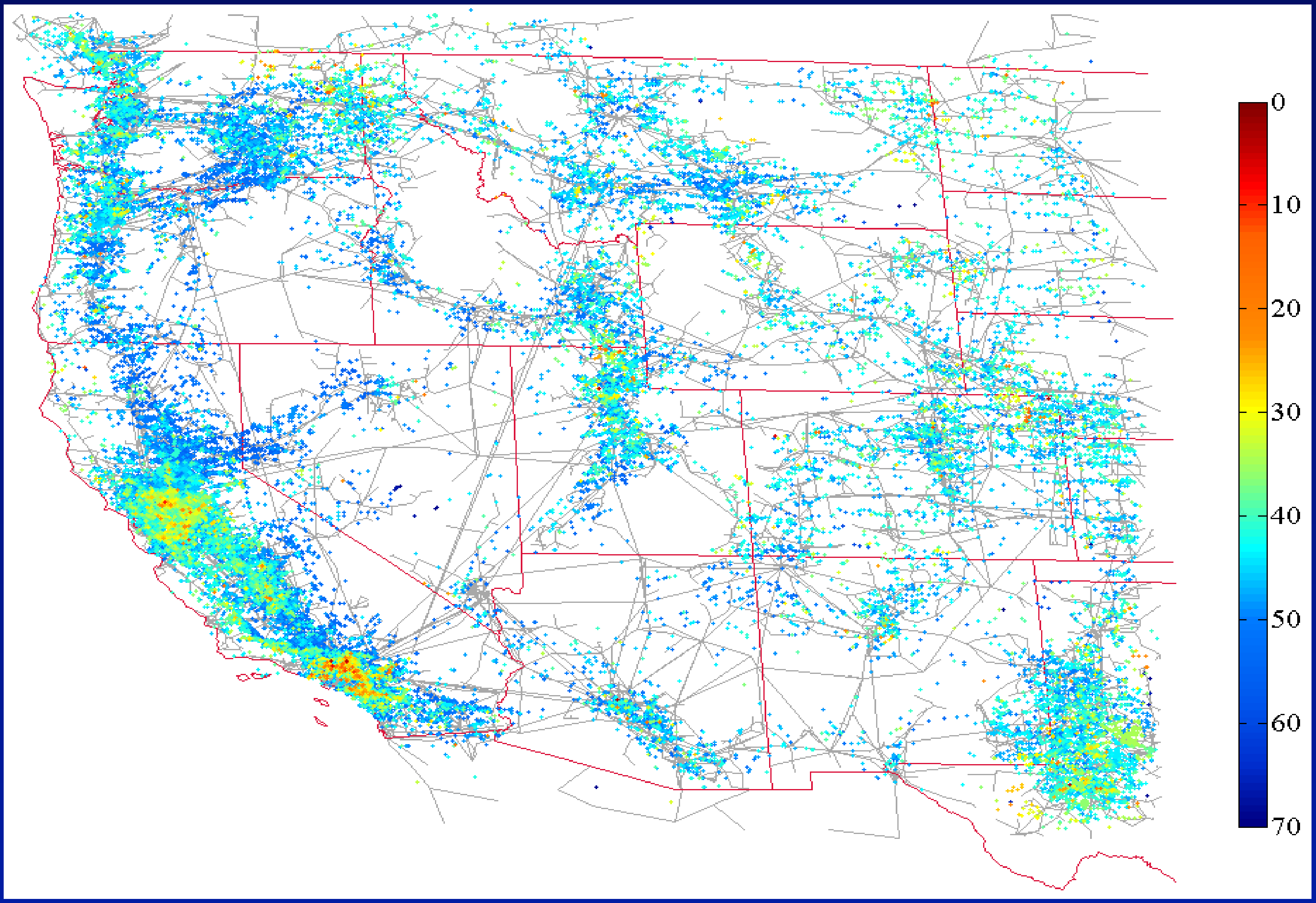
- **The yield:** the fraction of the original total demand which remained satisfied at the end of the cascading failure
- **The number of rounds until stability**
- **The number of failed lines**
- **The number of connected components in the resulting graph**

Yield Values, *N*-Resilient

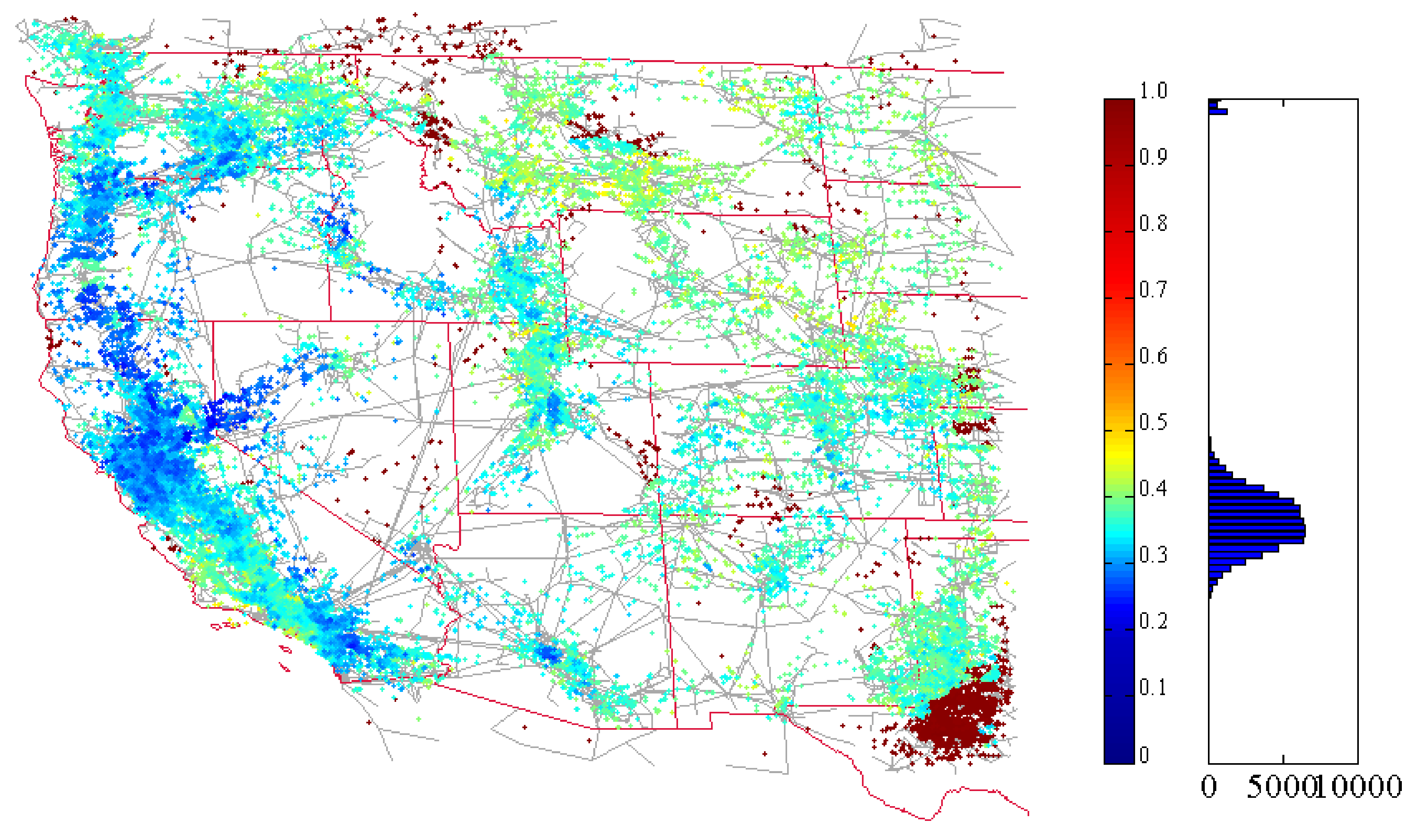


The color of each point represents the yield value of a cascade whose epicenter is at that point

Number of Rounds until Stability, *N*-Resilient

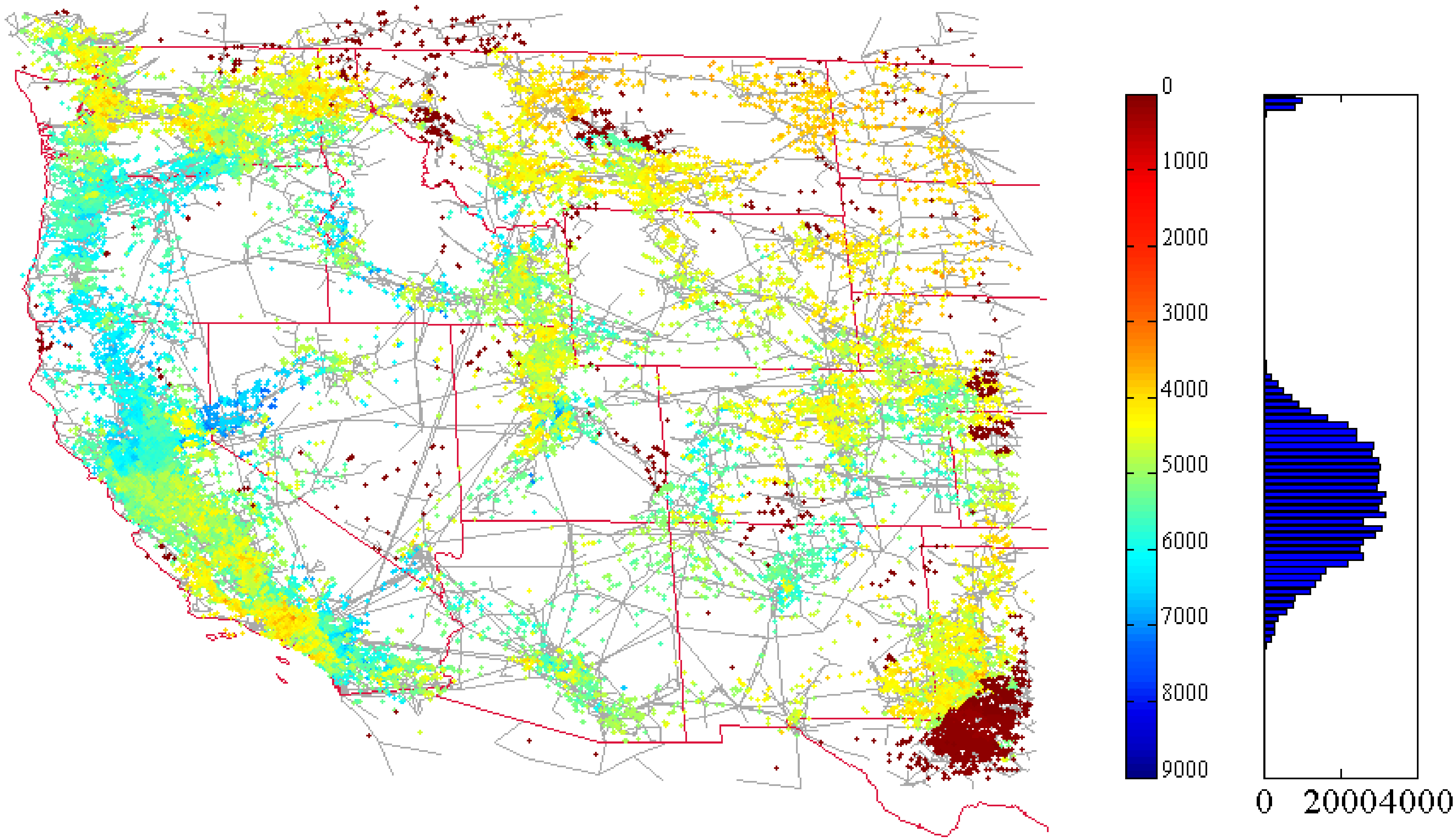


Yield Values, N-1 Resilient



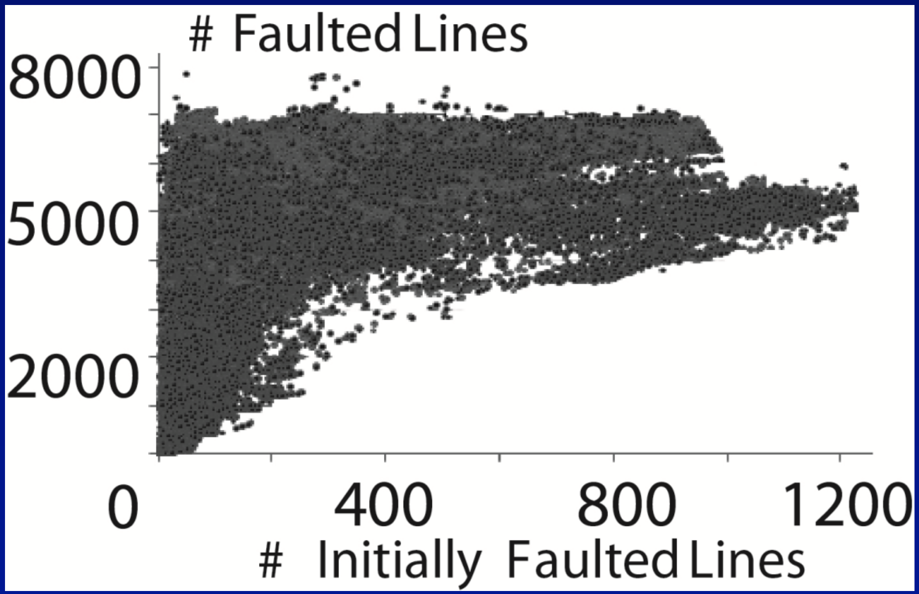
The color of each point represents the yield value of a cascade whose epicenter is at that point

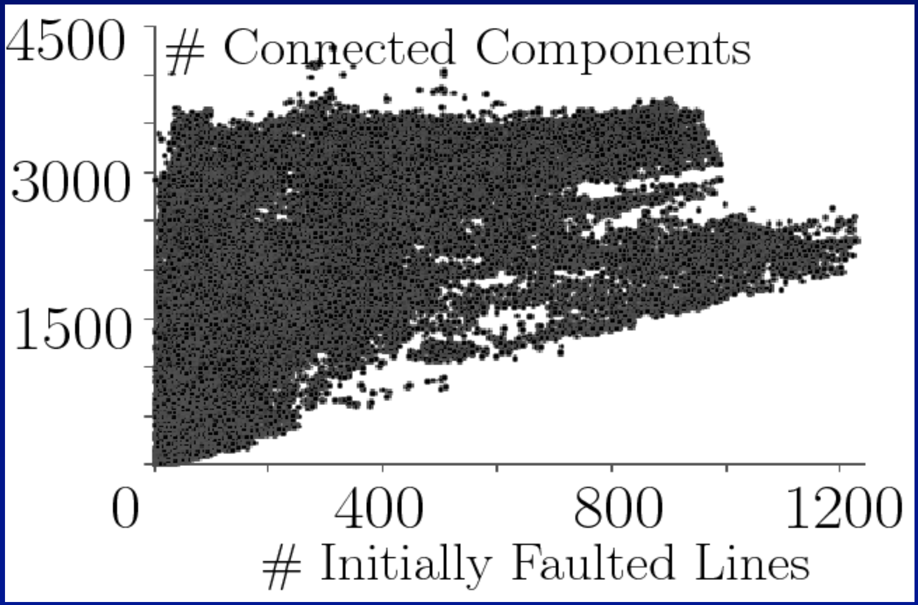
Number of Failed Lines, *N*-1 Resilient



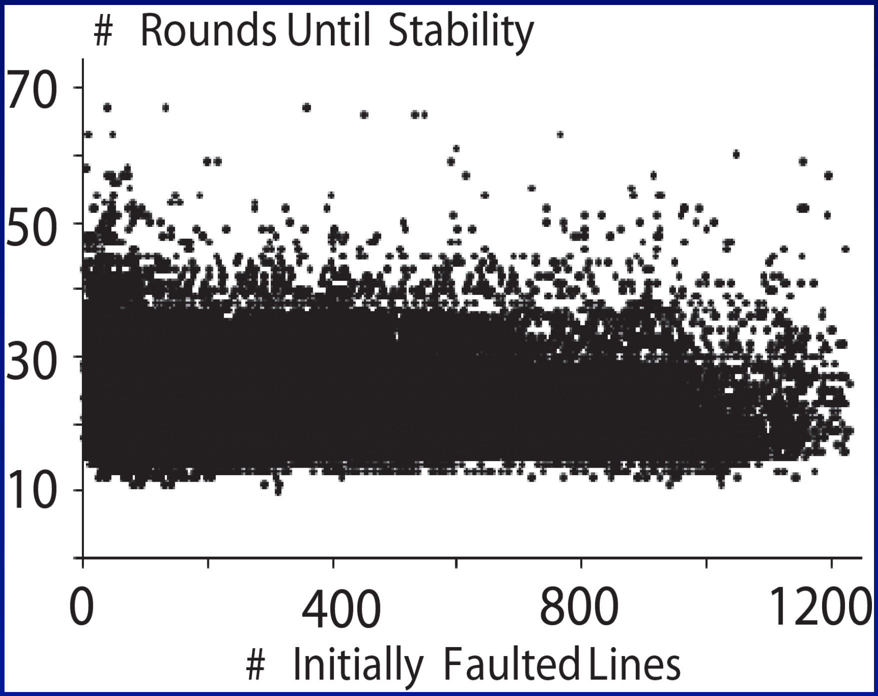
The color of each point represents the yield value of a cascade whose epicenter is at that point

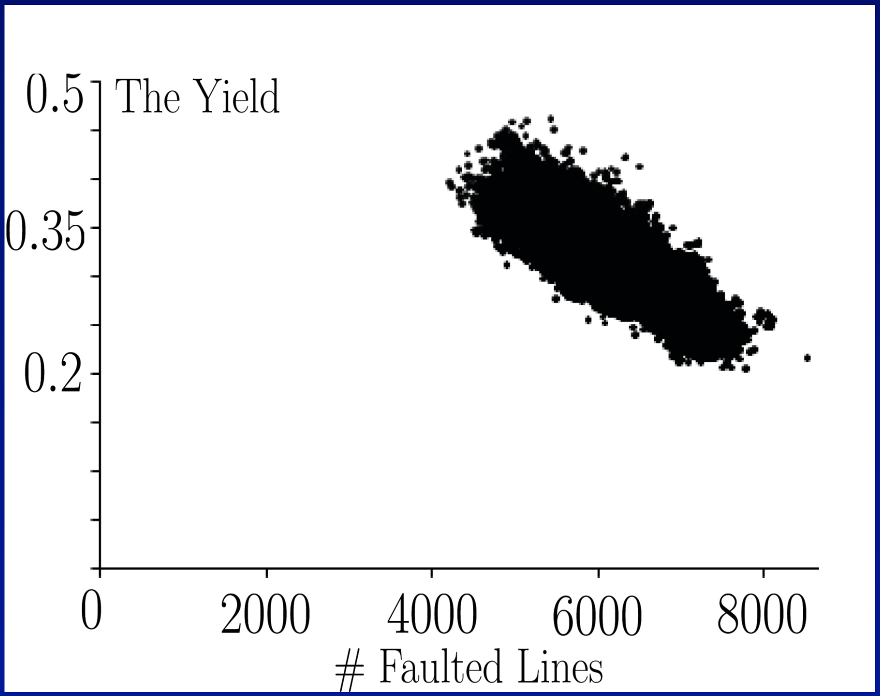
Scatter Graphs - after 5 Rounds





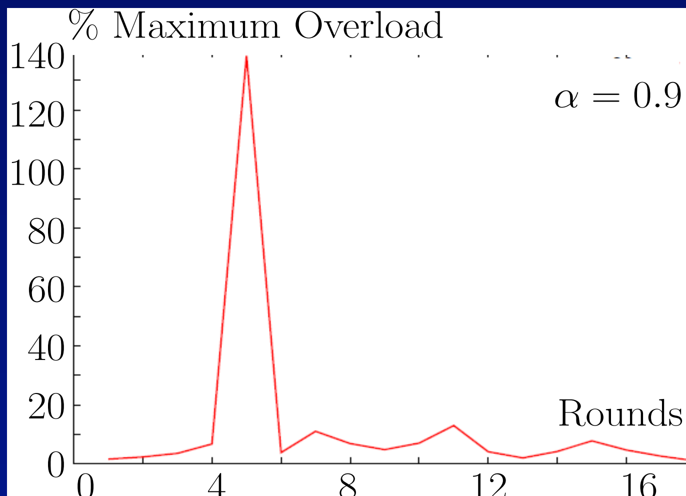
Scatter Graphs - Unlimited Number of Rounds

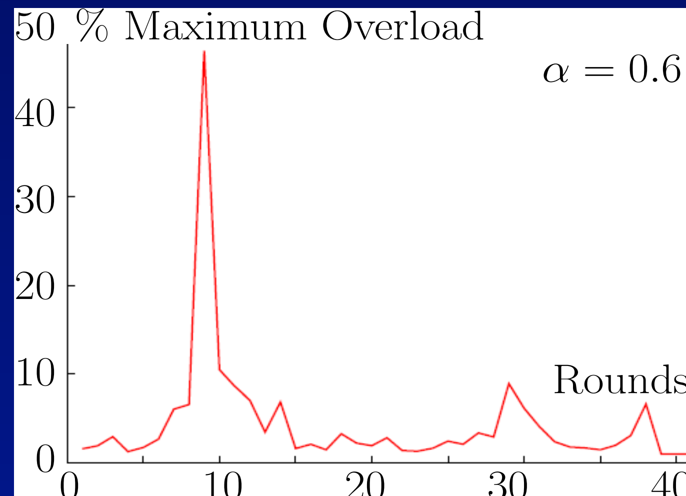


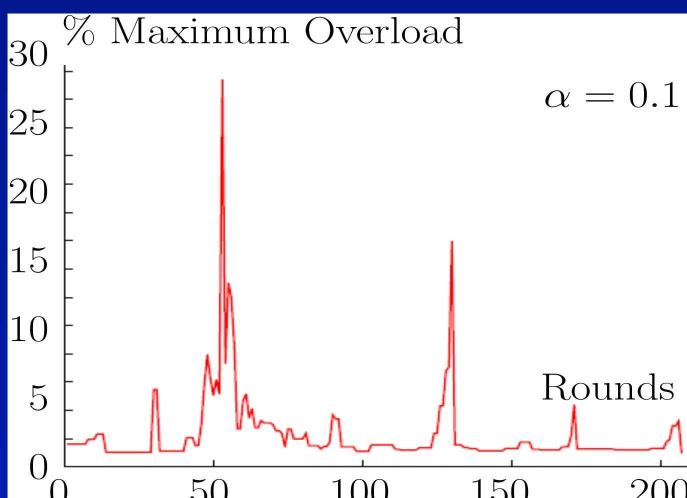


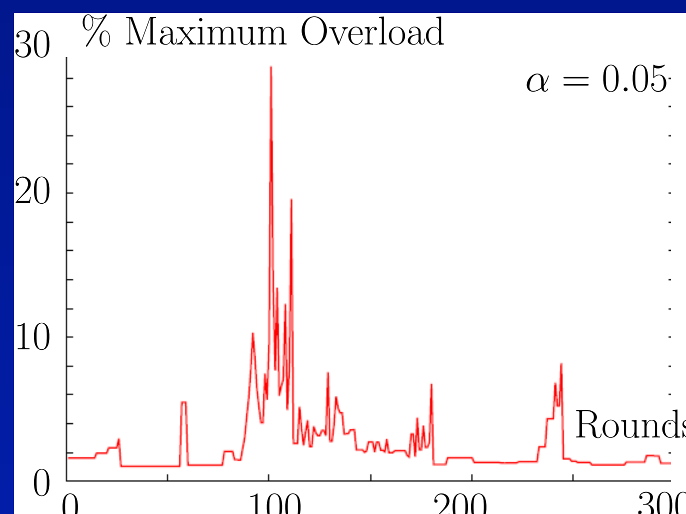
Sensitivity Analysis – Moving Average

- Compute moving average $\tilde{P}_{ij}=\alpha|P_{ij}|+(1-\alpha)\tilde{P}_{ij}$. Fail line if $\tilde{P}_{ij}>u_{ij}$.

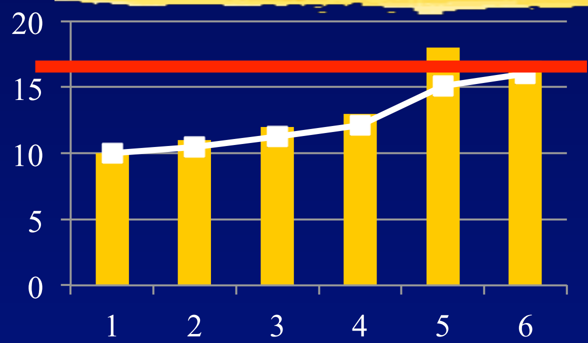




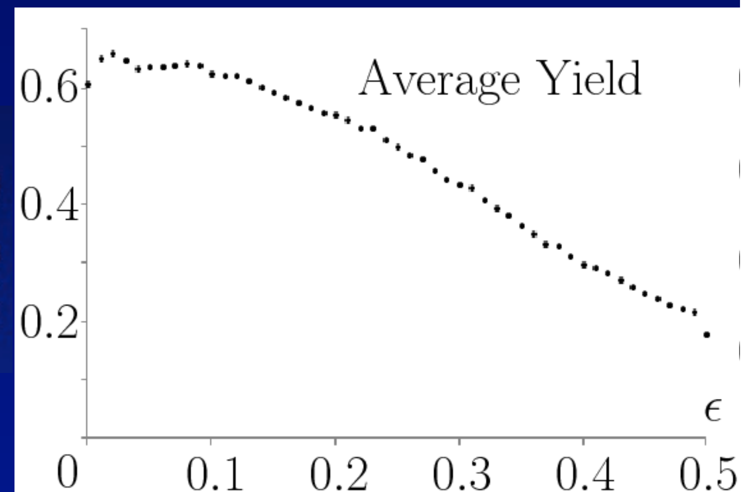




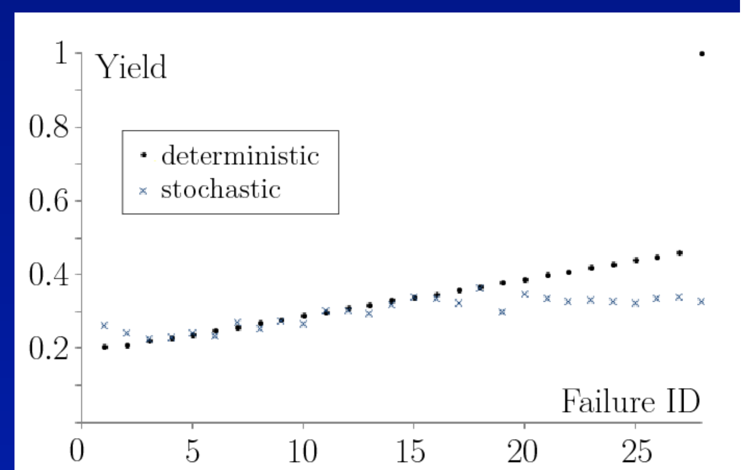
Sensitivity Analysis - Stochastic Rule



P{Line *(i,j)* faults at round *t* } = $\begin{cases} 1, & \tilde{P}_{ij}^t > (1+\epsilon)u_{ij} \\ 0, & \tilde{P}_{ij}^t \leq (1-\epsilon)u_{ij} \\ q, & \text{otherwise} \end{cases}$



- Specific attack - 100 repetitions for each ε, *q=1/2*



- 25 different attacks - comparison between deterministic and stochastic (ε = 0.04), *q=1/2*

Conclusions

- Using network survivability tools developed efficient algorithms to identify vulnerable locations in the power grid
  - Based on the DC approximation and computational geometry
- Showed that cascade propagation models differ from the classical epidemic/percolation-based models
- Performed an extensive numerical study along with a sensitivity analysis
  - Can serve as input for smart-grid monitoring and strengthening efforts