The Vulnerability of Fiber Networks and Power Grids to Geographically Correlated Failures

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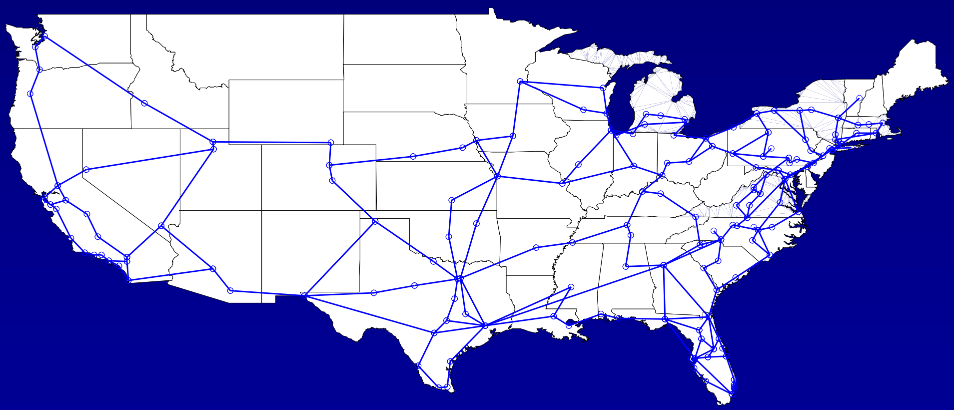
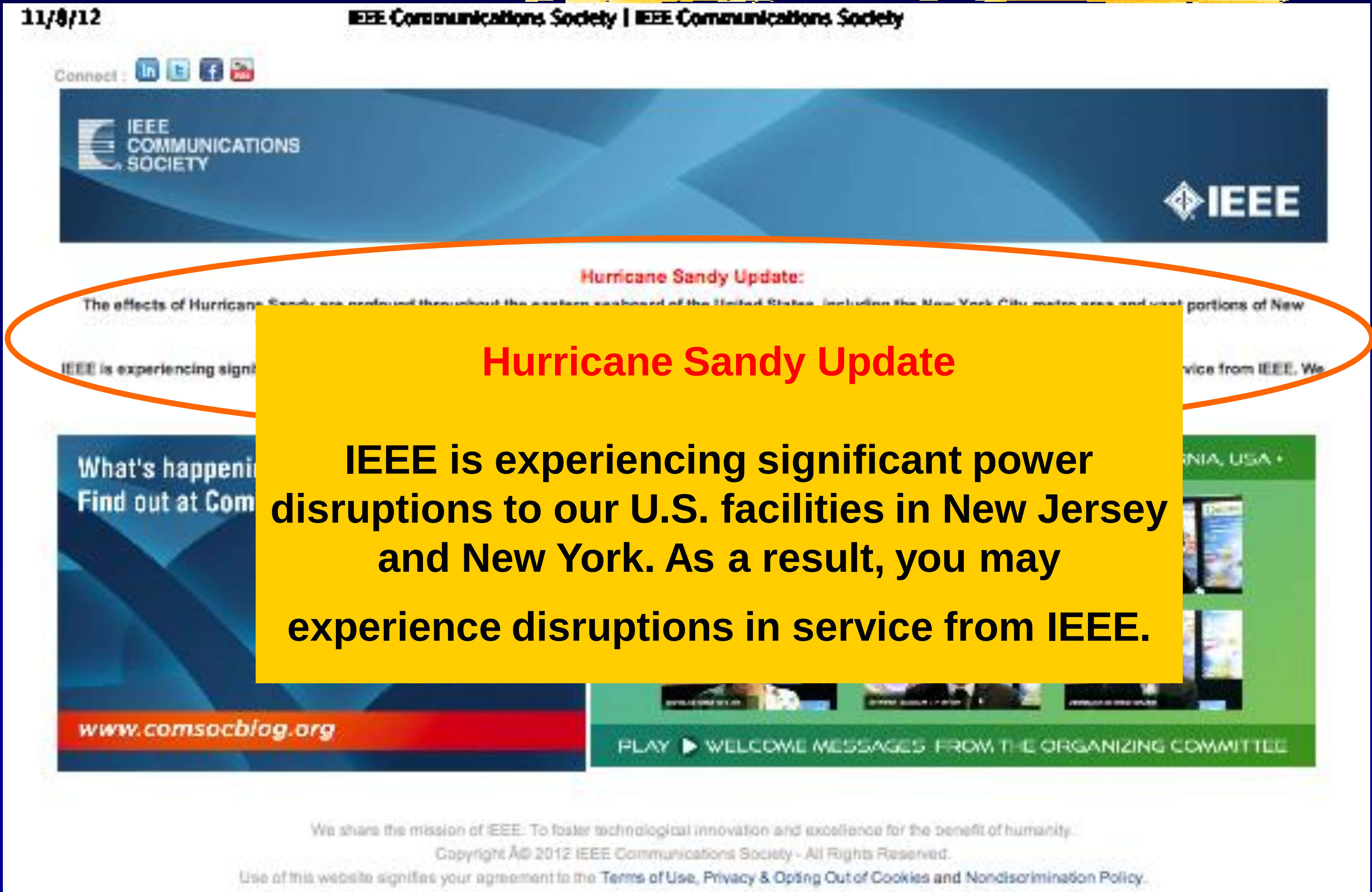
Telecommunications Networks and Power Grids

- An attack/failure will have a significant effect on many interdependent systems
- Rely on physical infrastructure ➡ Vulnerable to physical attacks/failures
- In the power grid, failures may cascade



The fiber backbone of Level3 Communications

Interdependent Networks

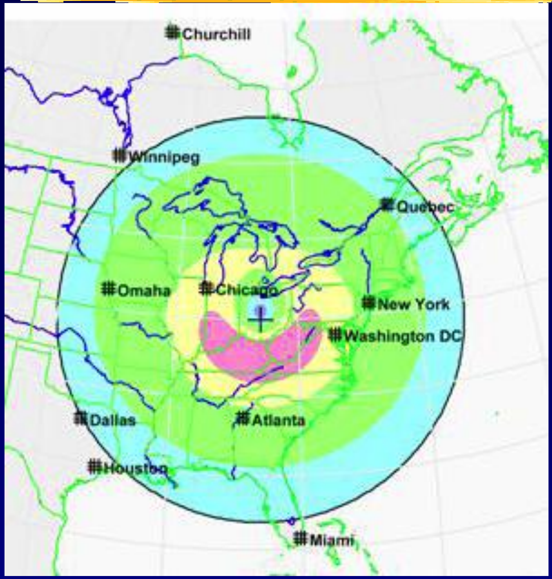


Hurricane Sandy Update

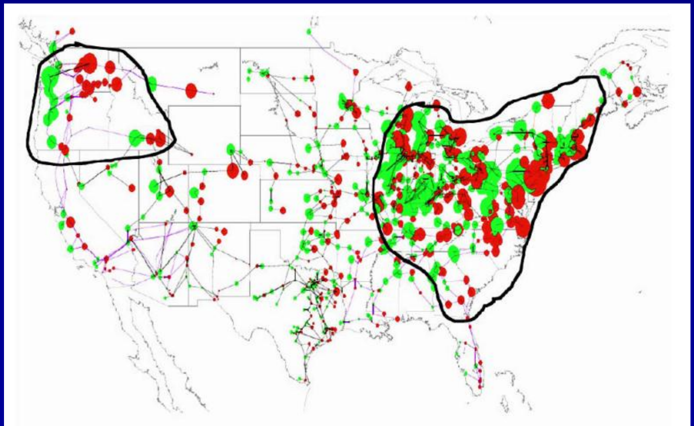
IEEE is experiencing significant power disruptions to our U.S. facilities in New Jersey and New York. As a result, you may experience disruptions in service from IEEE.

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



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

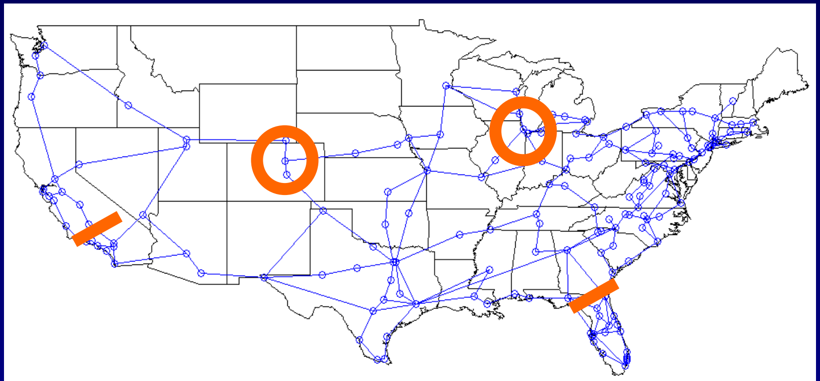


FERC, DOE, and DHS, Detailed Technical Report on EMP and Severe Solar Flare Threats to the U.S. Power Grid, 2010

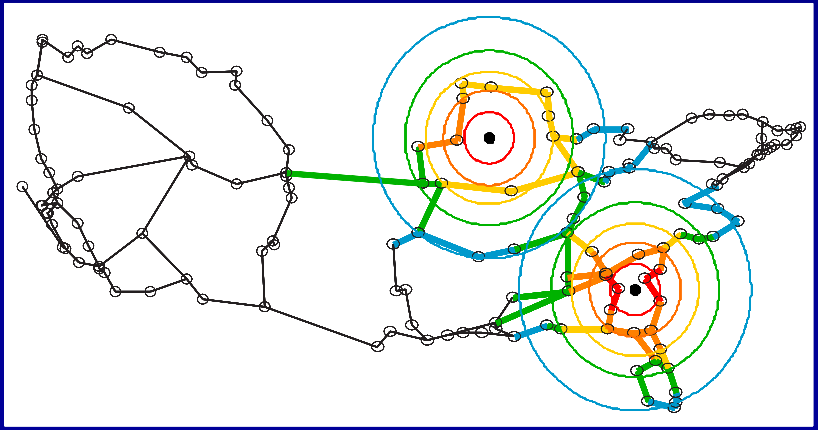
- Other natural disasters
- Physical attacks or disasters affect a specific *geographical area*

Geographically Correlated Failures in Networks

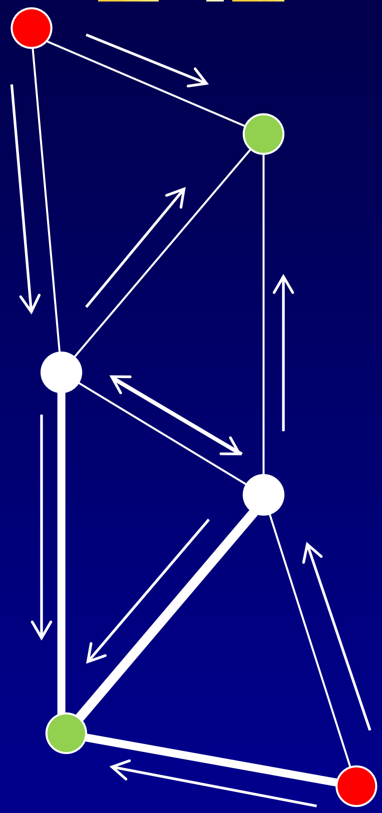
- Understand the effects of a **physical** attack/disaster on the bandwidth, connectivity, and reliability of the network
  - Identify locations that an adversary would select
- Deterministic Attacks
  (Neumayer, Zussman, Cohen, and Modiano, IEEE INFOCOM'09, IEEE Trans. Networking, 2011)
  - Line Segment and Circular cuts



- Probabilistic properties – realistic structures
  (Agarwal, Efrat, Ganjugunte, Hay, Sankararaman, Zussman, IEEE INFOCOM'11, IEEE Trans. Networking, to appear)
  - A number of simultaneous attacks
  - Take into account protection and restoration



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

Power Flow Equations - DC Approximation

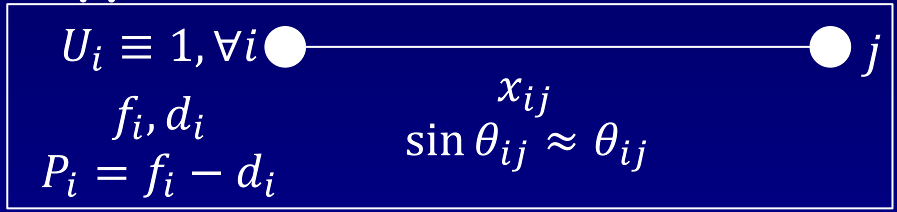
- Exact solution to the AC model is infeasible

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

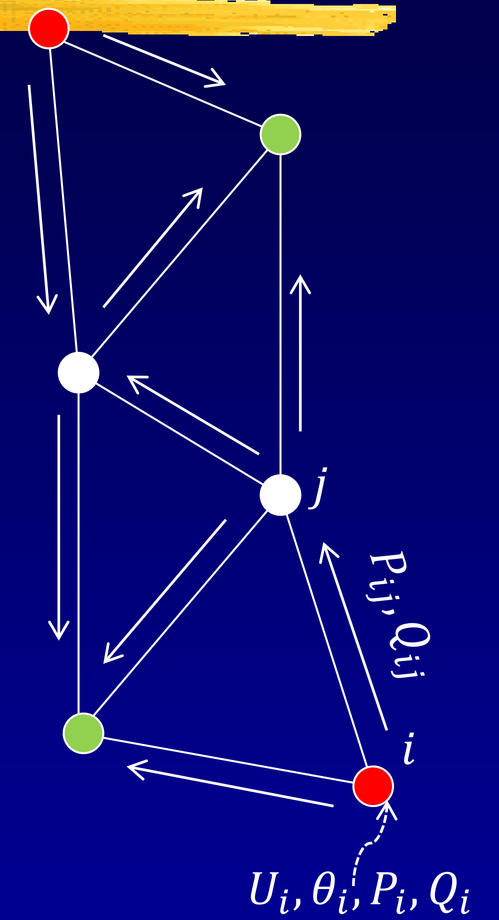
$$Q_{ij} = -U_i^2 b_{ij} + U_i U_j b_{ij} \cos\theta_{ij} - U_i U_j g_{ij} \sin\theta_{ij}$$

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

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

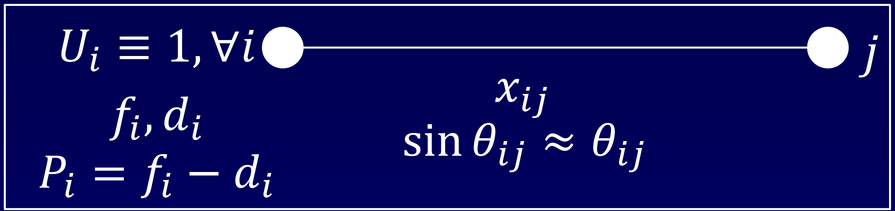


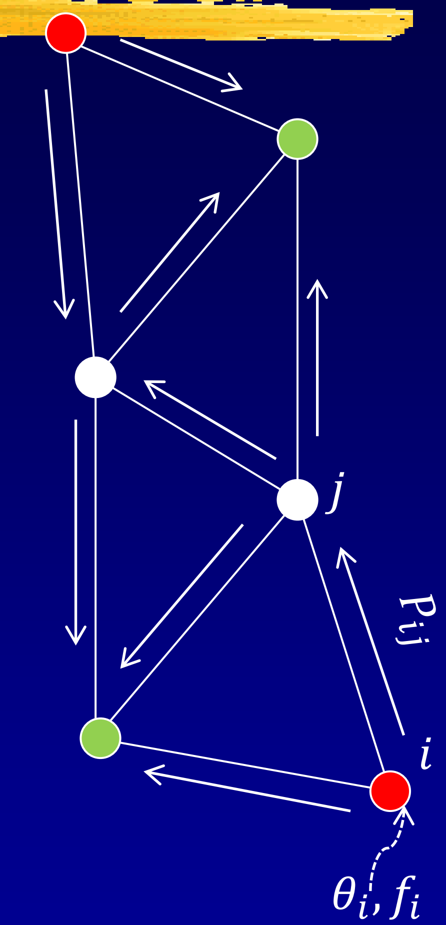
  - $U_i = 1\, p.u.$ for all i
  - **Pure reactive** transmission lines – each line is characterized only by its reactance $x_{ij} = -1/b_{ij}$
  - Phase angle differences are "small", implying that $\sin\theta_{ij} \approx \theta_{ij}$



Load ($P_i, Q_i < 0$)
Generator ($P_i, Q_i > 0$)

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)

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

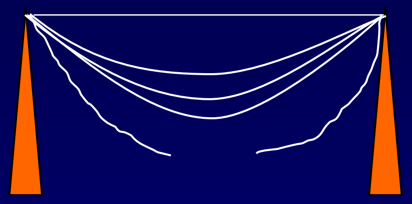
Load ($d_i > 0$)

Generator ($f_i > 0$)

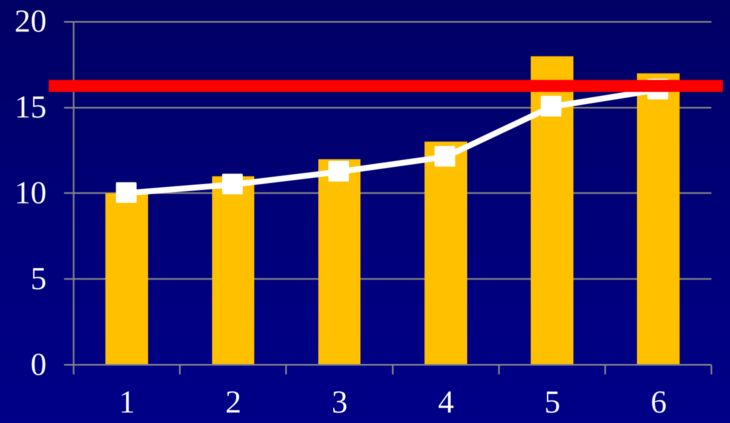
Line Outage Rule

- 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
  $\tilde{P}_{ij} := \alpha|P_{ij}| + (1-\alpha)\tilde{P}_{ij}$
  ($0 \le \alpha \le 1$ is a parameter)

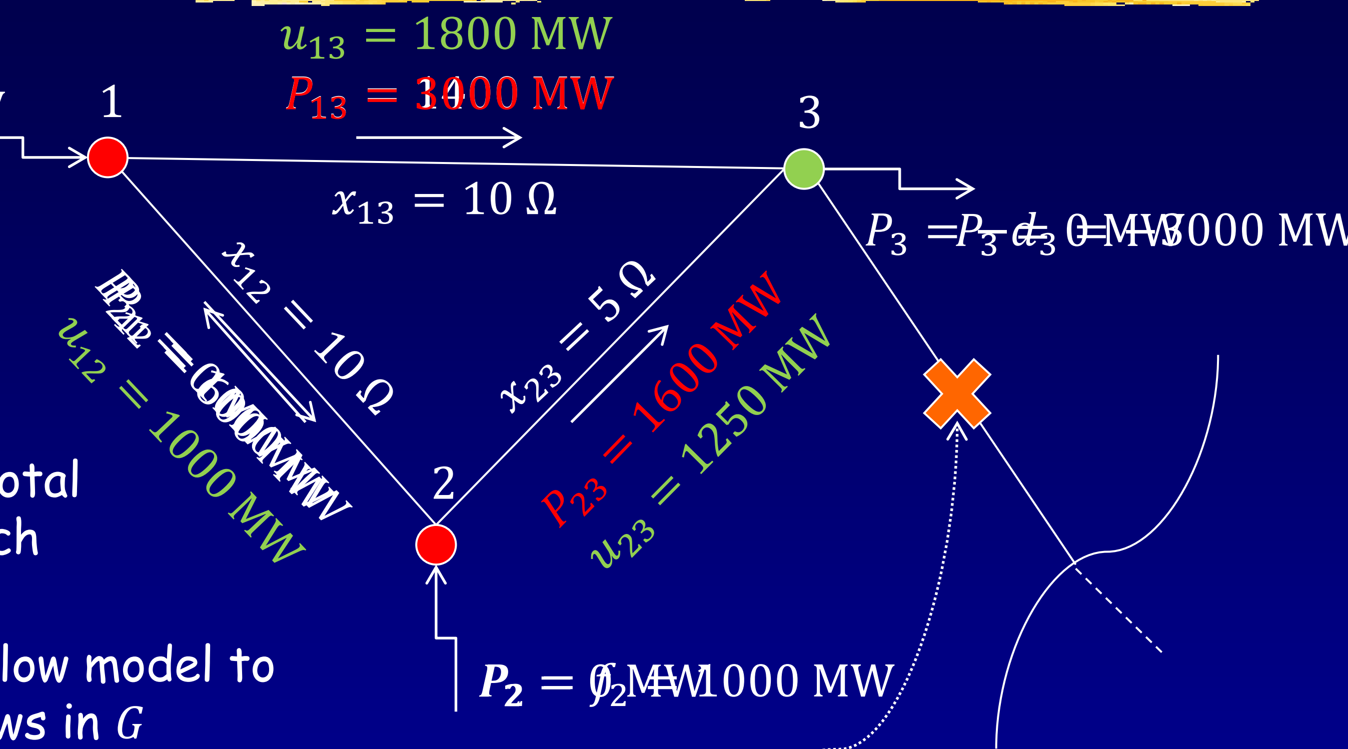


- **Deterministic outage rule:**
  Fail lines with $\tilde{P}_{ij} > u_{ij}$
- **Stochastic outage rule:**

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

Example of a Cascading Failure

- **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

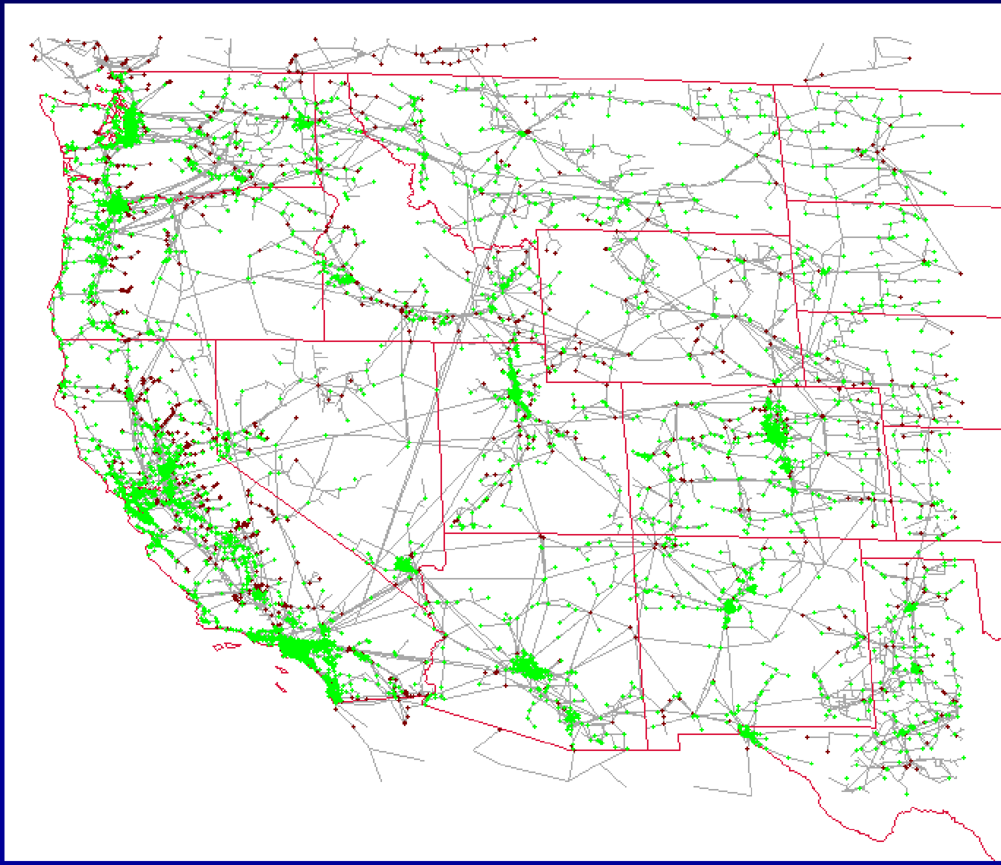


Initial failure causes disconnection of load 3 from the generators in the rest of the network

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

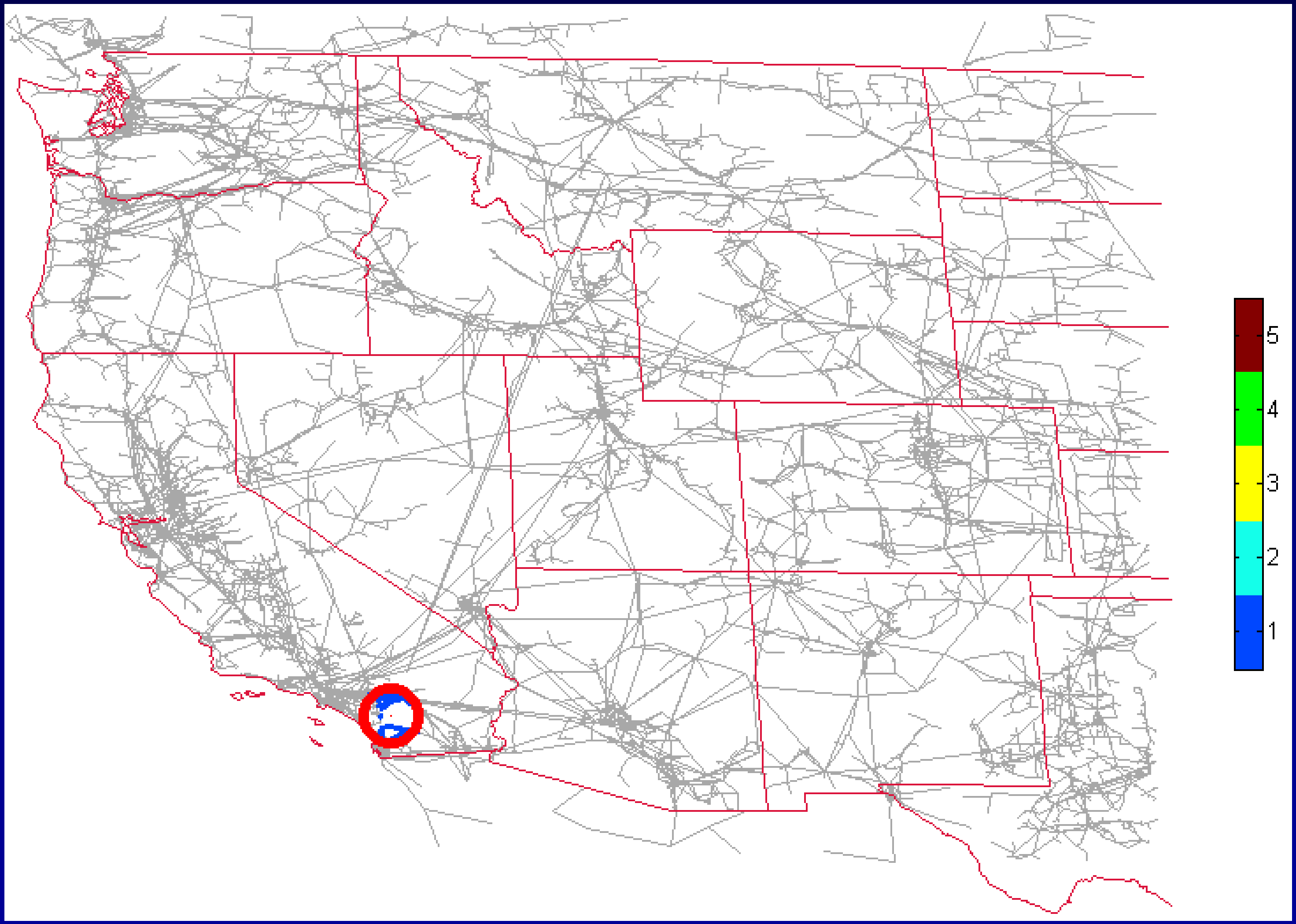
Numerical Results - Power Grid Map

- 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



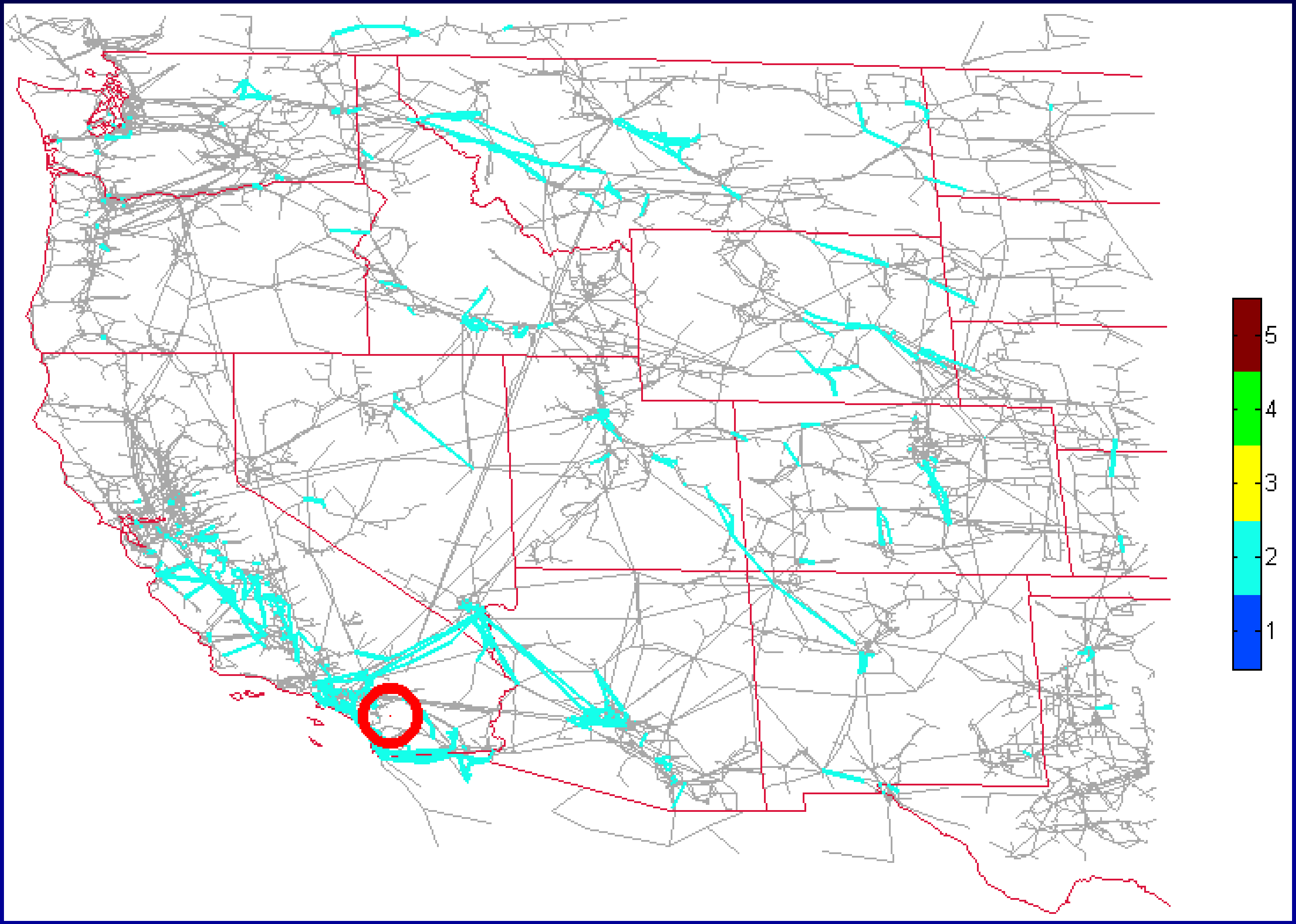
- 13,992 nodes (substations),
  18,681 lines,
  and 1,920 power stations.
- 1,117 generators (red),
  5,591 loads (green)
- Assumed that demand is proportional to the population size
- Determining capacities and reactance values – requires a lot of processing

Cascade Development – San Diego area

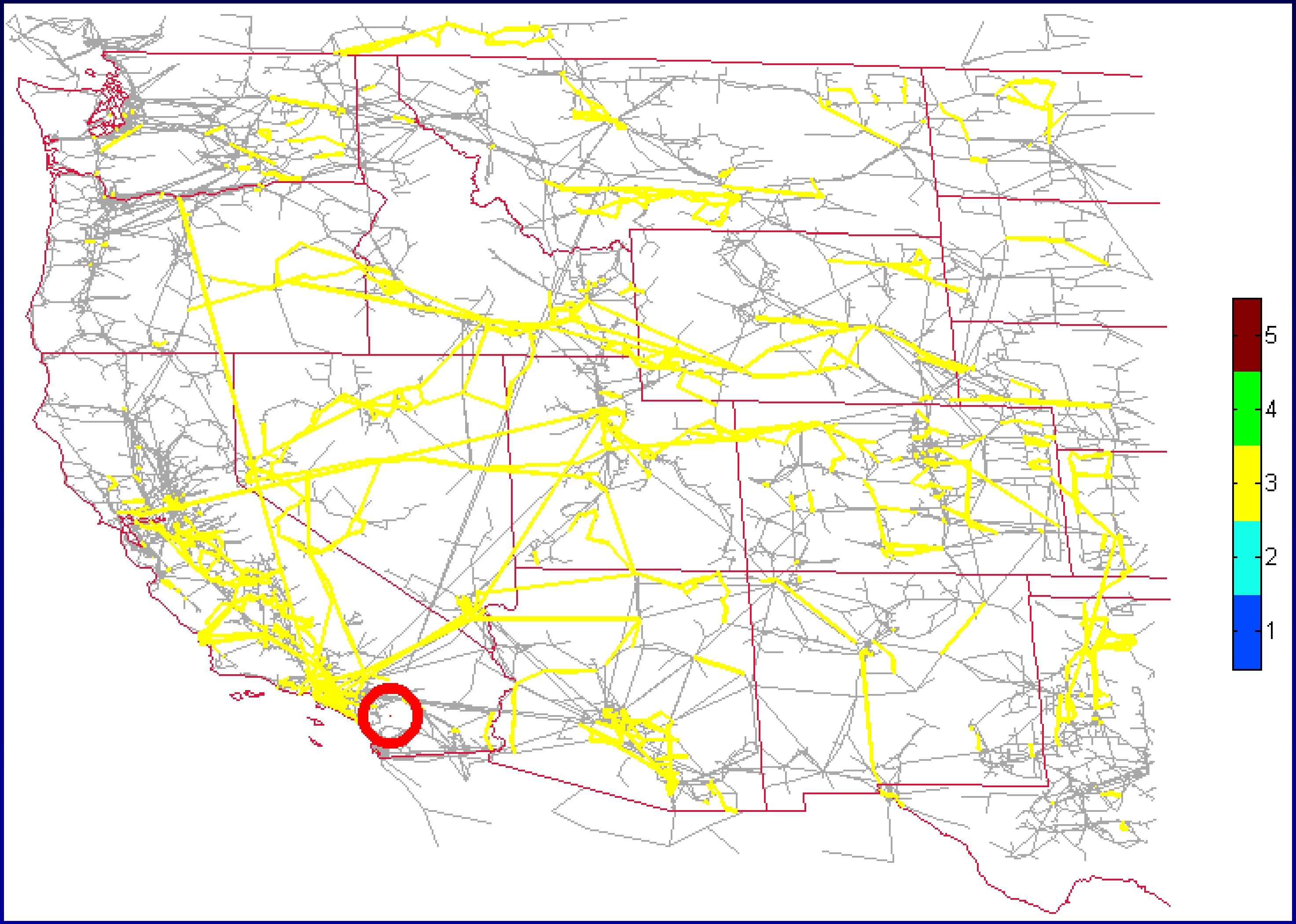


N-Resilient, Factor of Safety $K = 1.2$

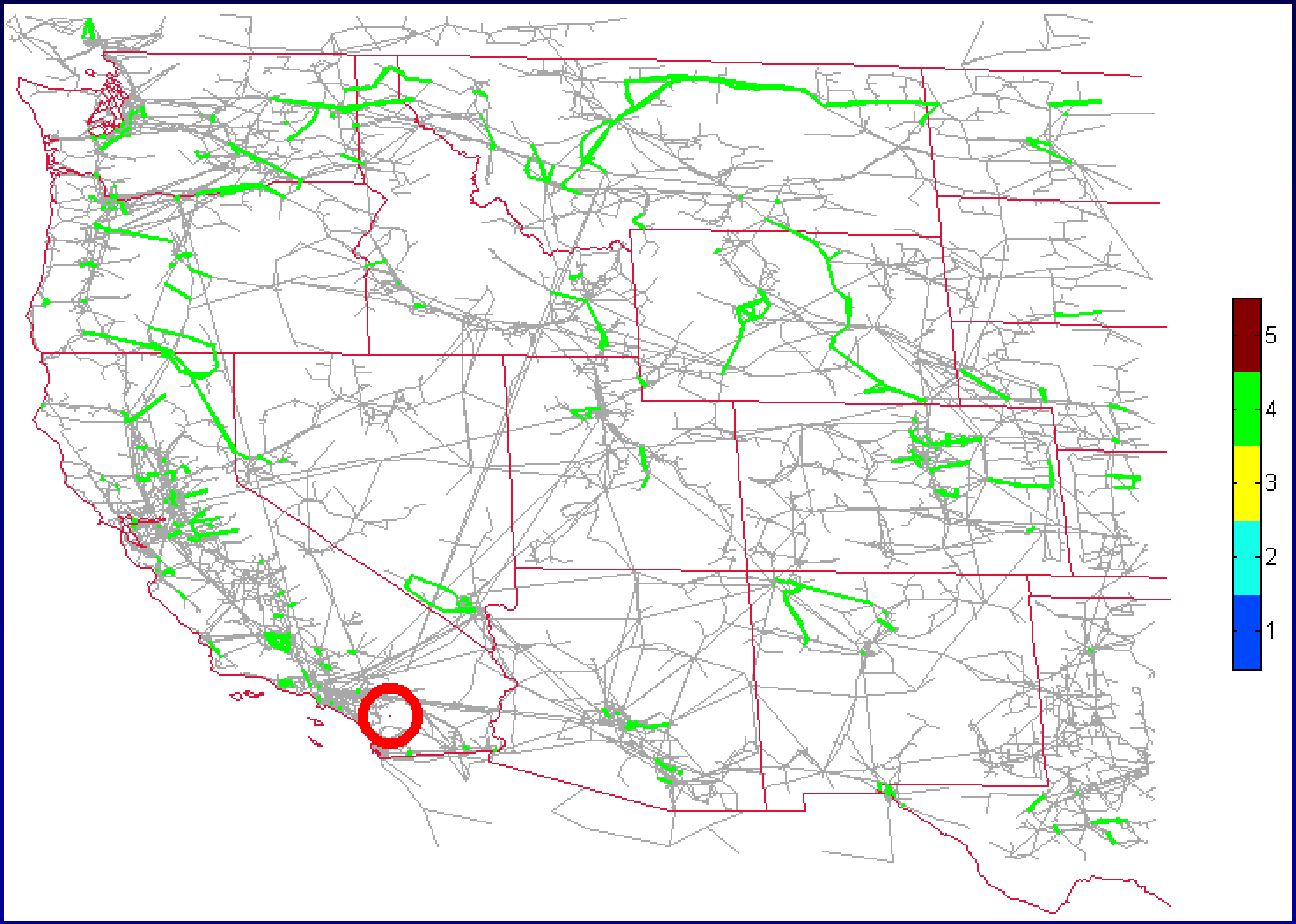
Cascade Development – San Diego area



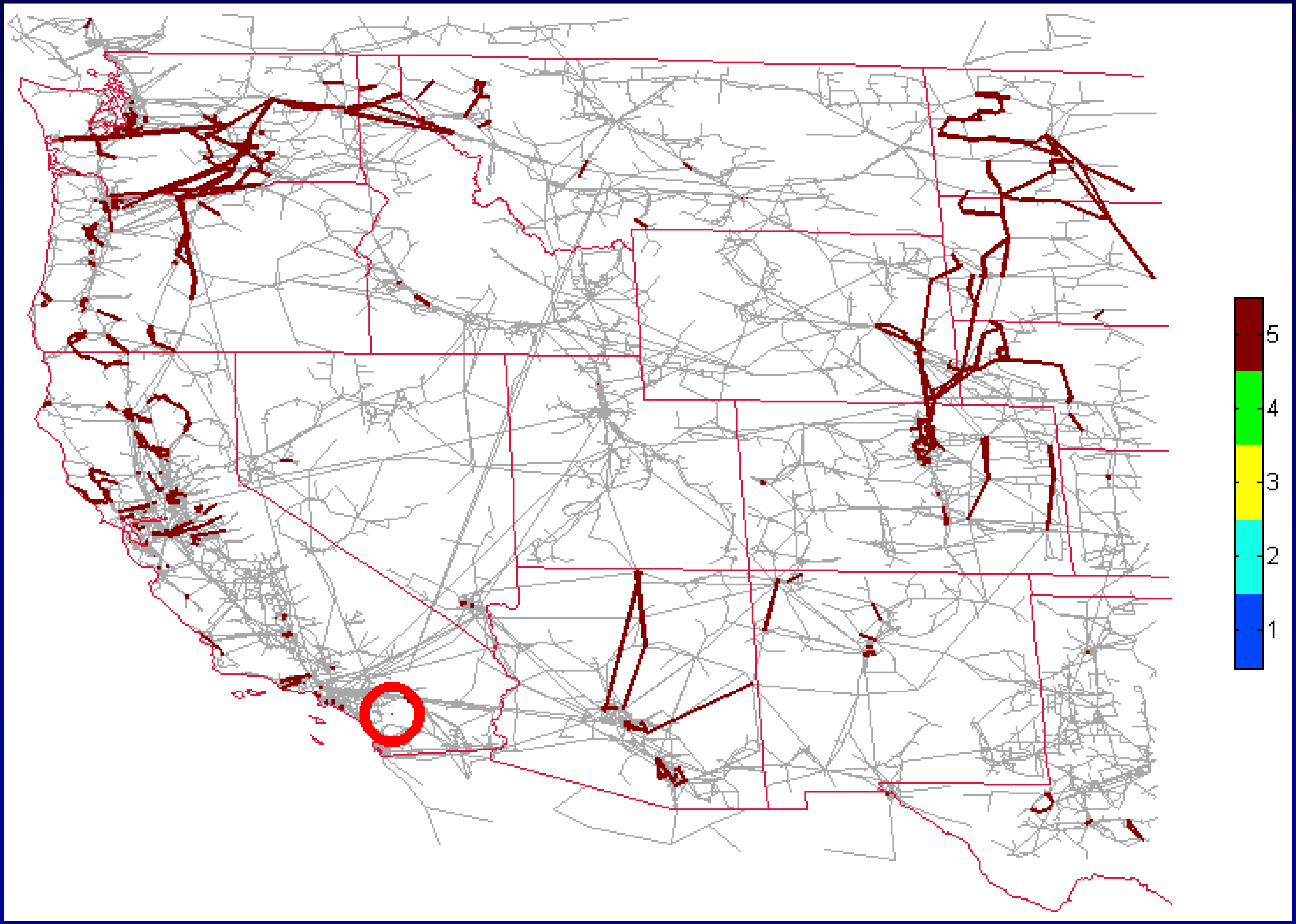
Cascade Development - San Diego area



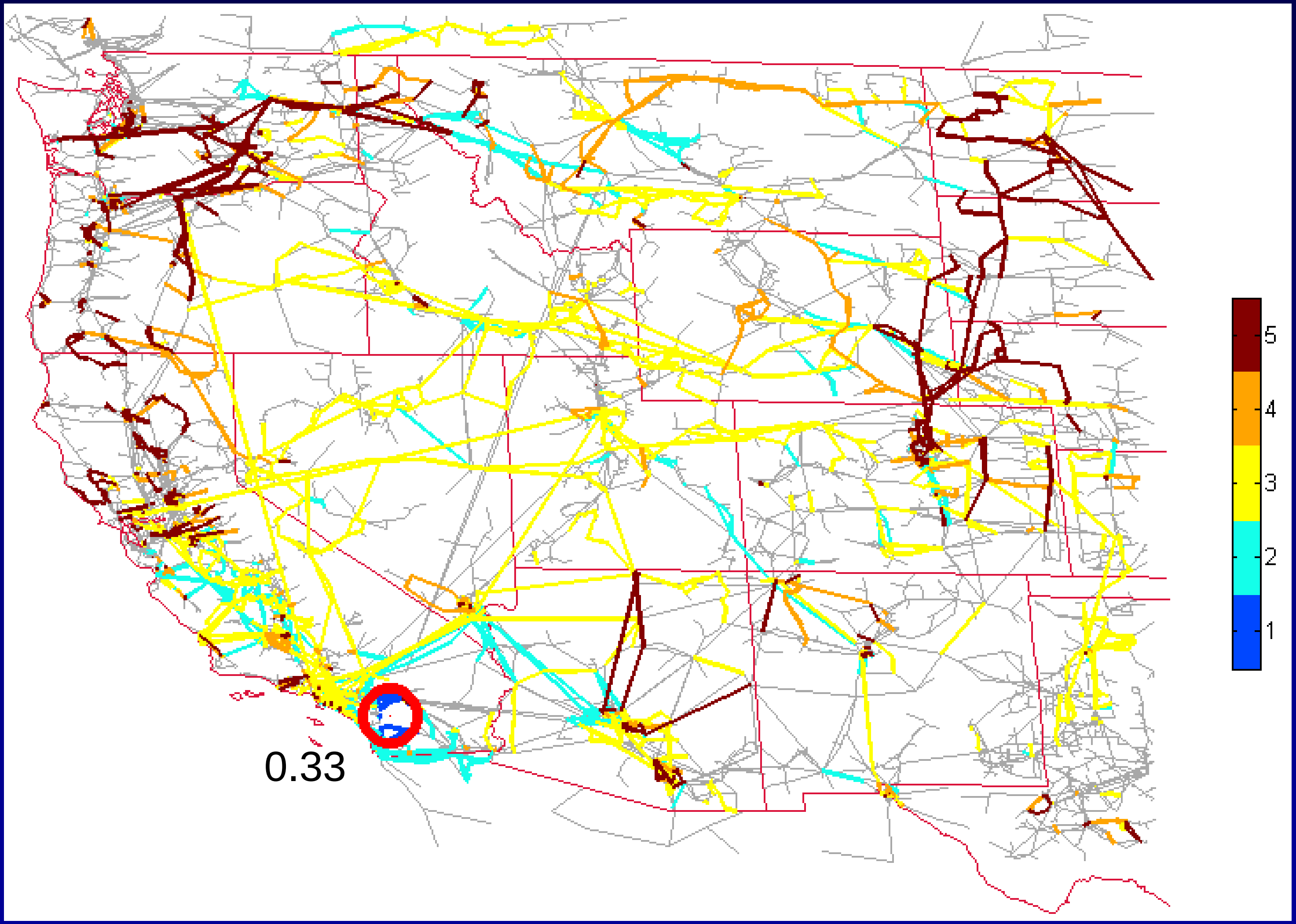
Cascade Development - San Diego area



Cascade Development – San Diego area



Cascade Development - San Diego area



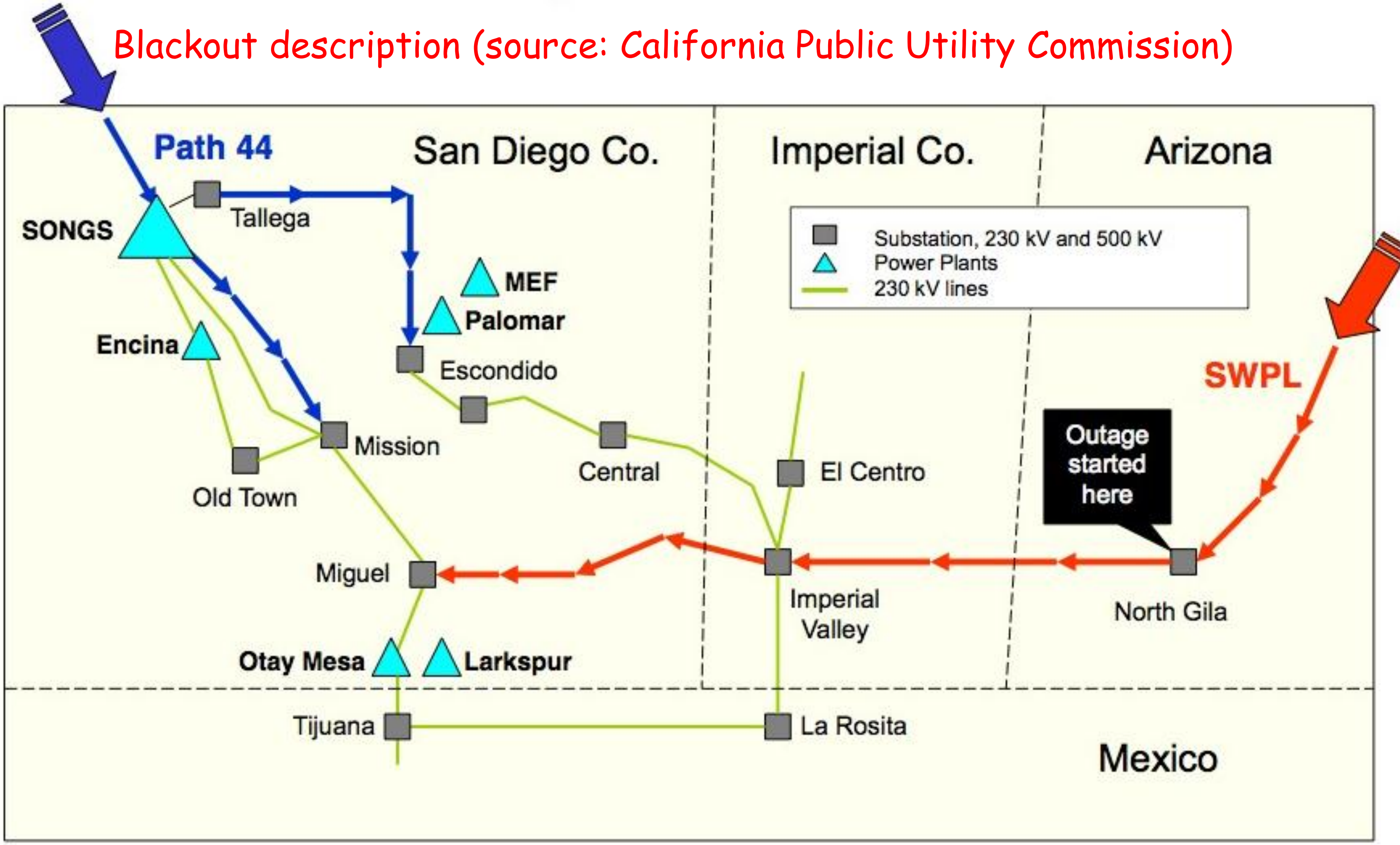
N-Resilient, Factor of Safety $K = 1.2 \rightarrow$ **Yield = 0.33**

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)

Latest Major Blackout Event: San Diego, Sept. 2011

Blackout description (source: California Public Utility Commission)



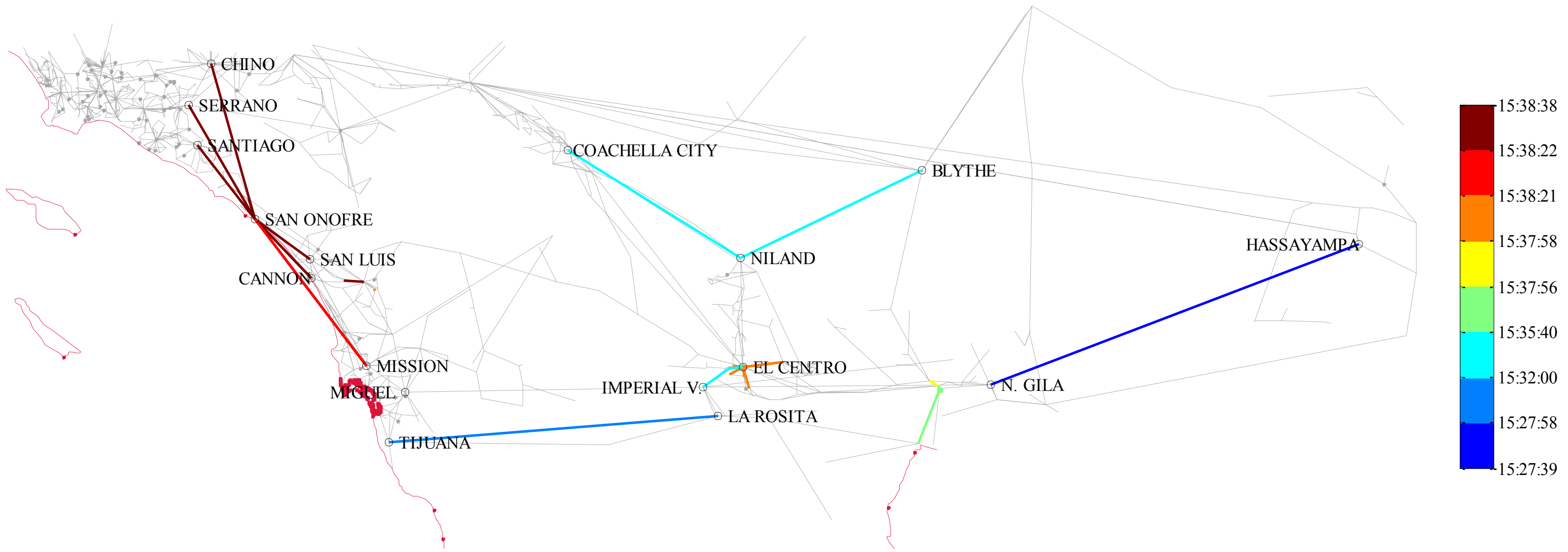
*Map not to scale

Event Timeline

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

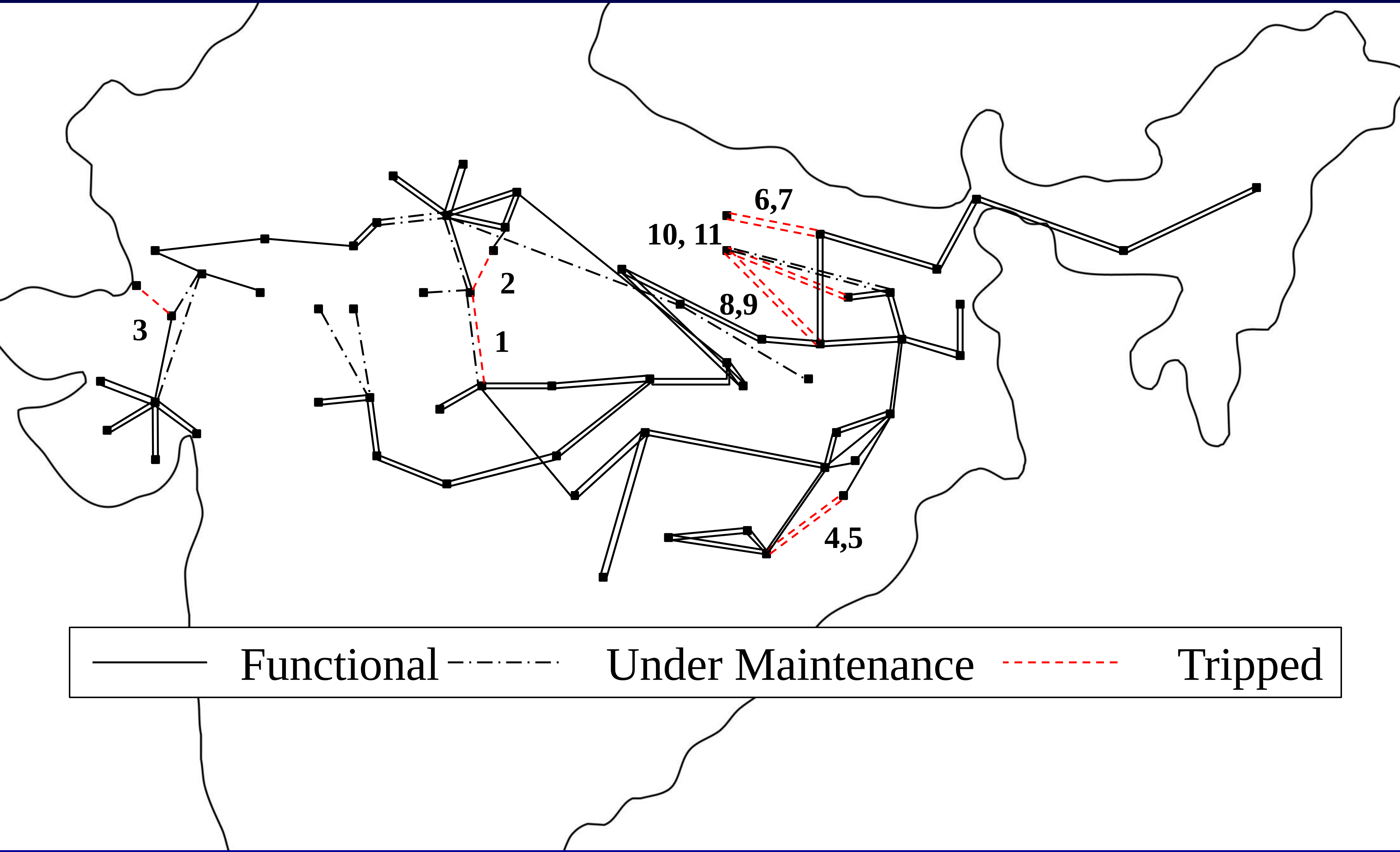
- **15:27:39** – 500kV Hassayampa-North Gila (SWPL) line trips at North Gila Substation.
  - SWPL lost. Increased flow on Path 44 to 2407 MW.
- **15:27:58 to 15:30:00** – CCM tripped in CFE area (needed emergency assistance of 158 MW). IID experienced problems with Imperial Valley-El Centro line resulting 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 – San Diego Blackout



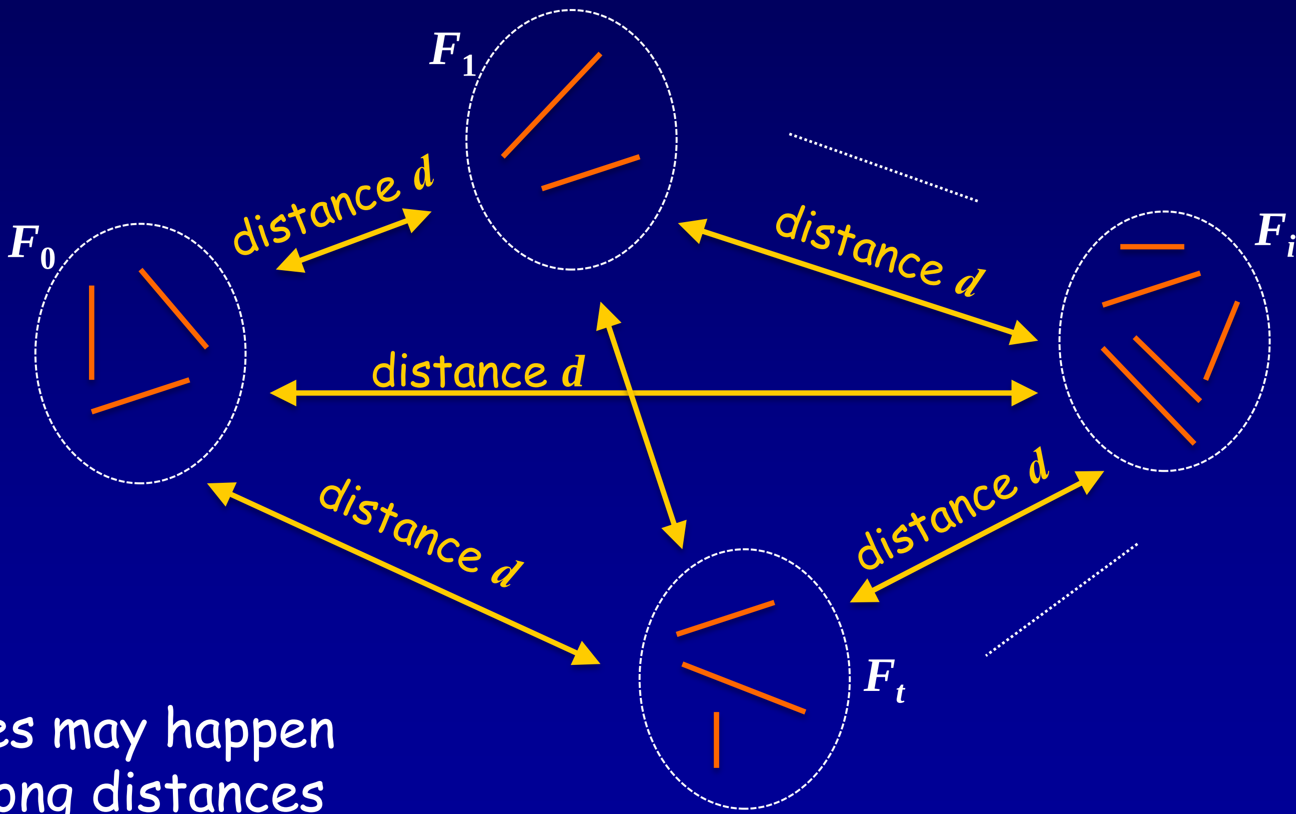
- Failures indeed “skip” over a few hops

India Blackout – July 30, 2012



Cascade Properties – Failures Distance and Duration

- For any $d > 0$, for any $t > 0$, there exists a graph $G = (V, E)$ s.t.:
  - The distance between any two sets F_i and F_j of edge failures is at least d
  - The number of rounds is at least t

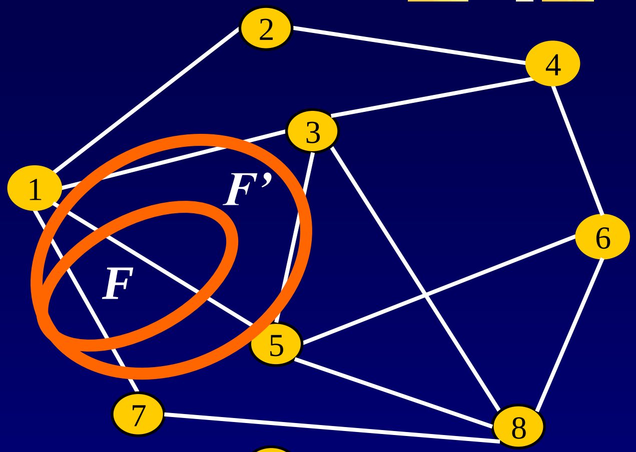


- Consecutive failures may happen within arbitrarily long distances of each other and may last a long time
- Very different from the epidemic-percolation-based cascade models

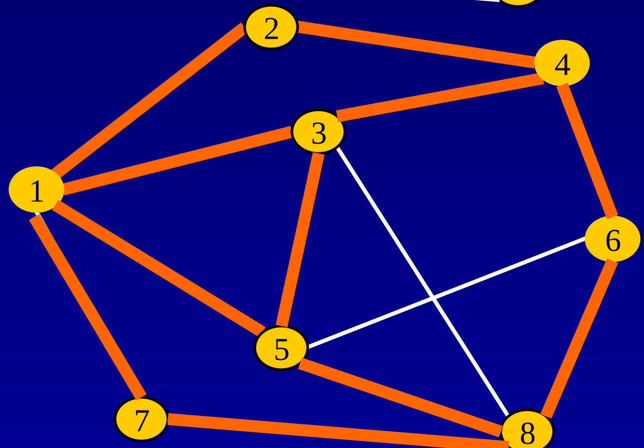
Power Flow Cascading Failures Model - Properties

There exist graphs in which 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'***

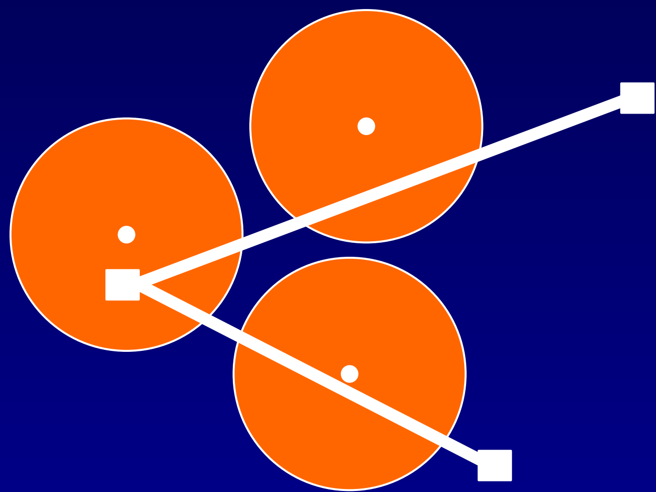


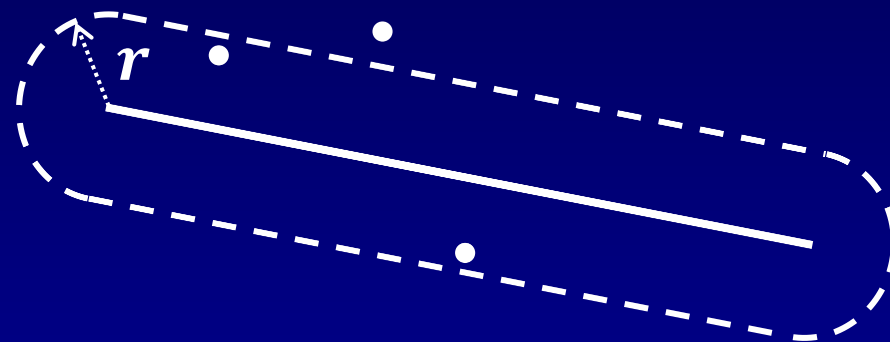
- Consider graphs ***G*** and ***G'*** (***G*** is a subgraph of ***G'***) - ***G*** may be more resilient to failures than ***G'***



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)

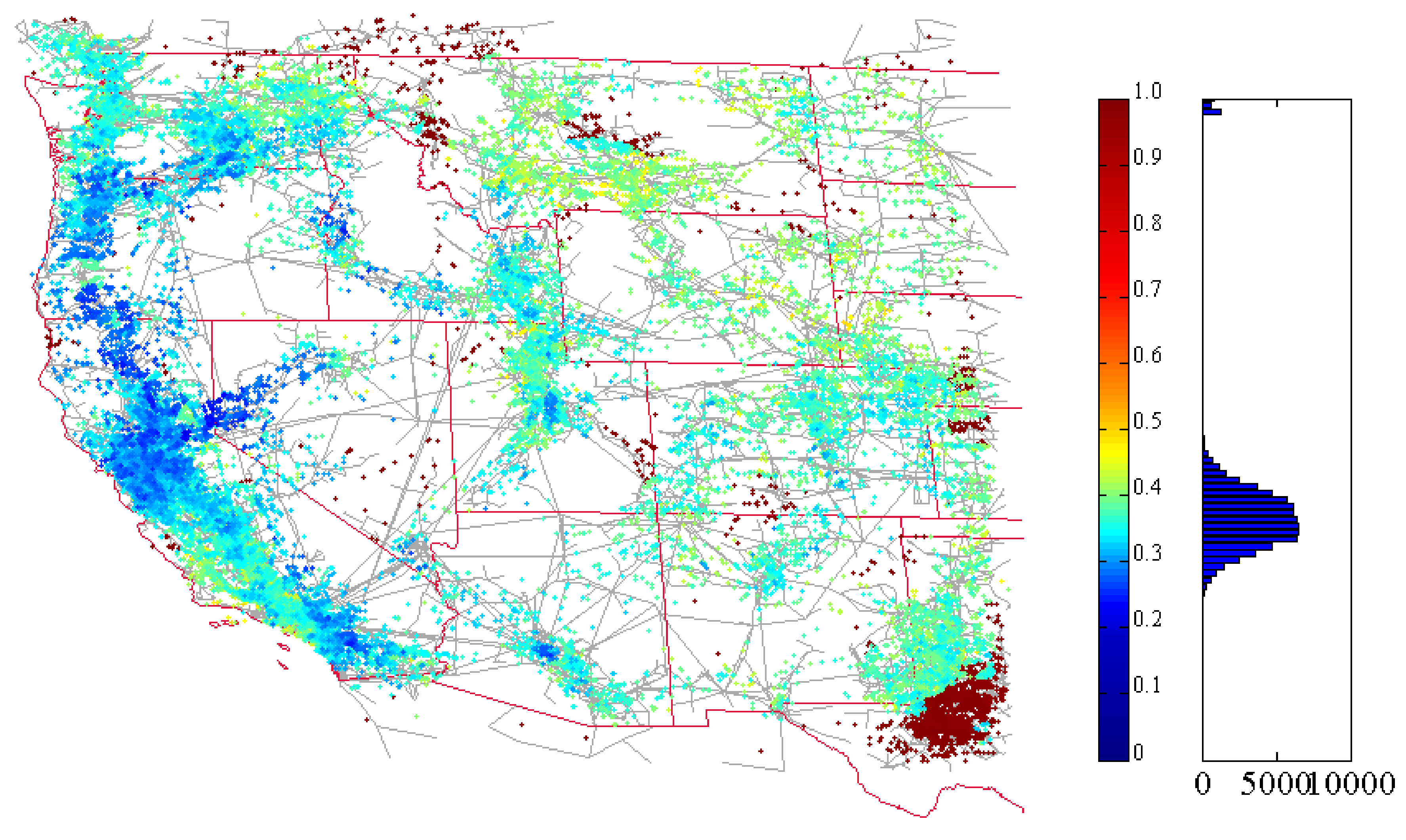




- Theoretically, there are infinite attack locations
- We would like to consider a finite subset
- We use computational geometric tools to efficiently find the subset*
- For $r = 50\ km$, ~70,000 candidate locations were produced for the part of the Western Interconnect that we used

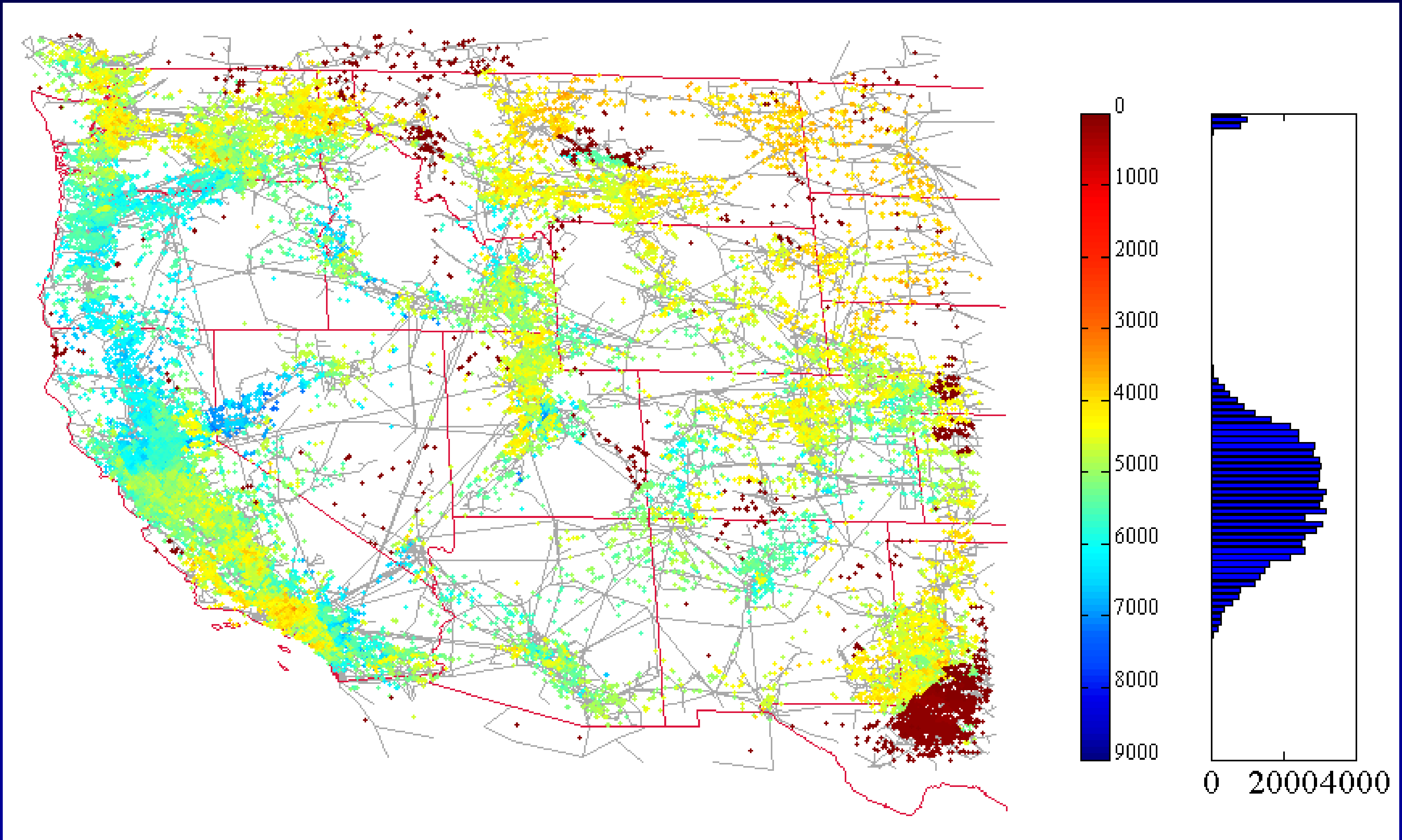
* based on Agarwal, Efrat, Ganjugunte, Hay, Sankararaman, and Zussman (2011)

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

Conclusions

- Studied the vulnerability of fiber and power networks to geographically correlated failures
- For power grids, showed that cascade propagation models differ from the classical epidemic/percolation-based models
- Developed efficient algorithms to identify vulnerable locations in the power grid
  - Based on the DC approximation and computational geometry
- Performed an extensive numerical study along with a sensitivity analysis
  - Can serve as input for smart-grid monitoring and strengthening efforts