https://sites.google.com/site/antonioscalaphys

Statistical Physics for Power Grids

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Physics Seminars, Federico II

NA april 2015

Overview

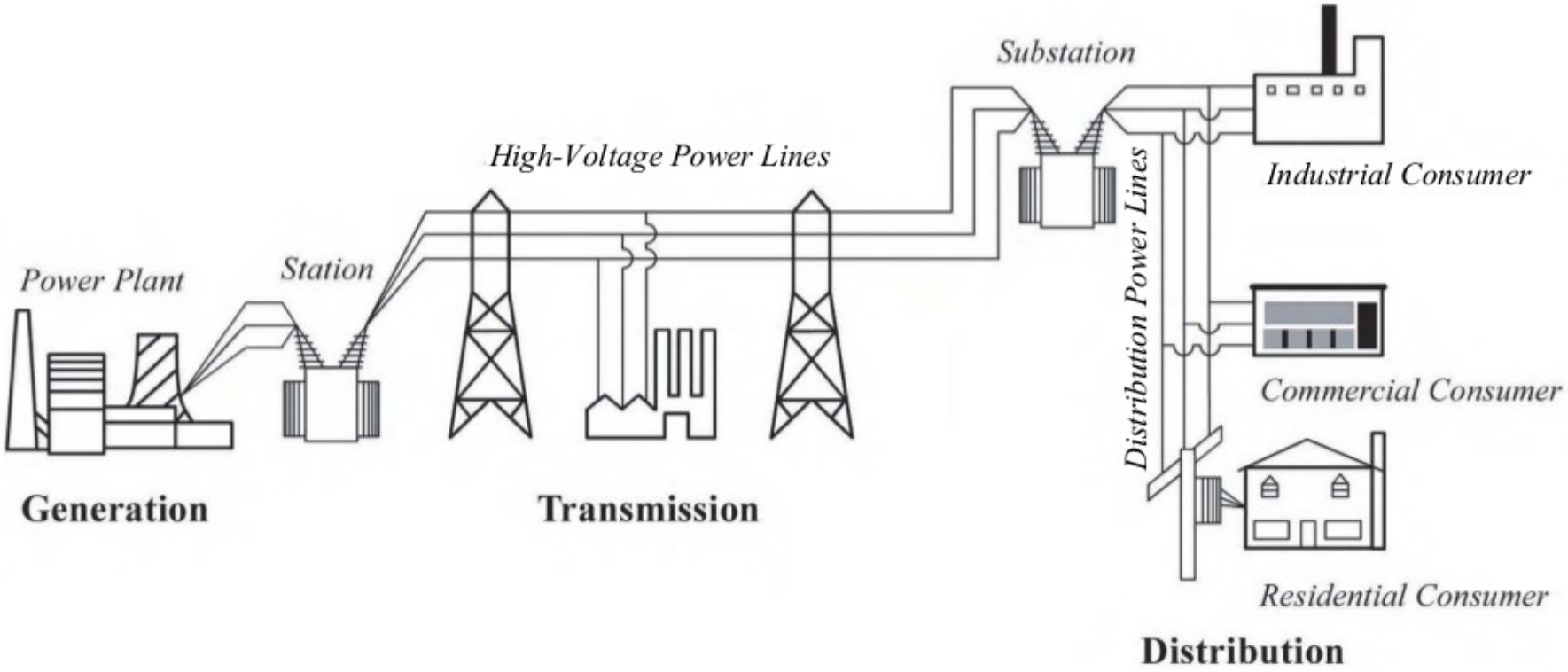
- Power System

- Blackouts
  - Stress from Increasing loads
  - Fluctuations from Renewable Sources

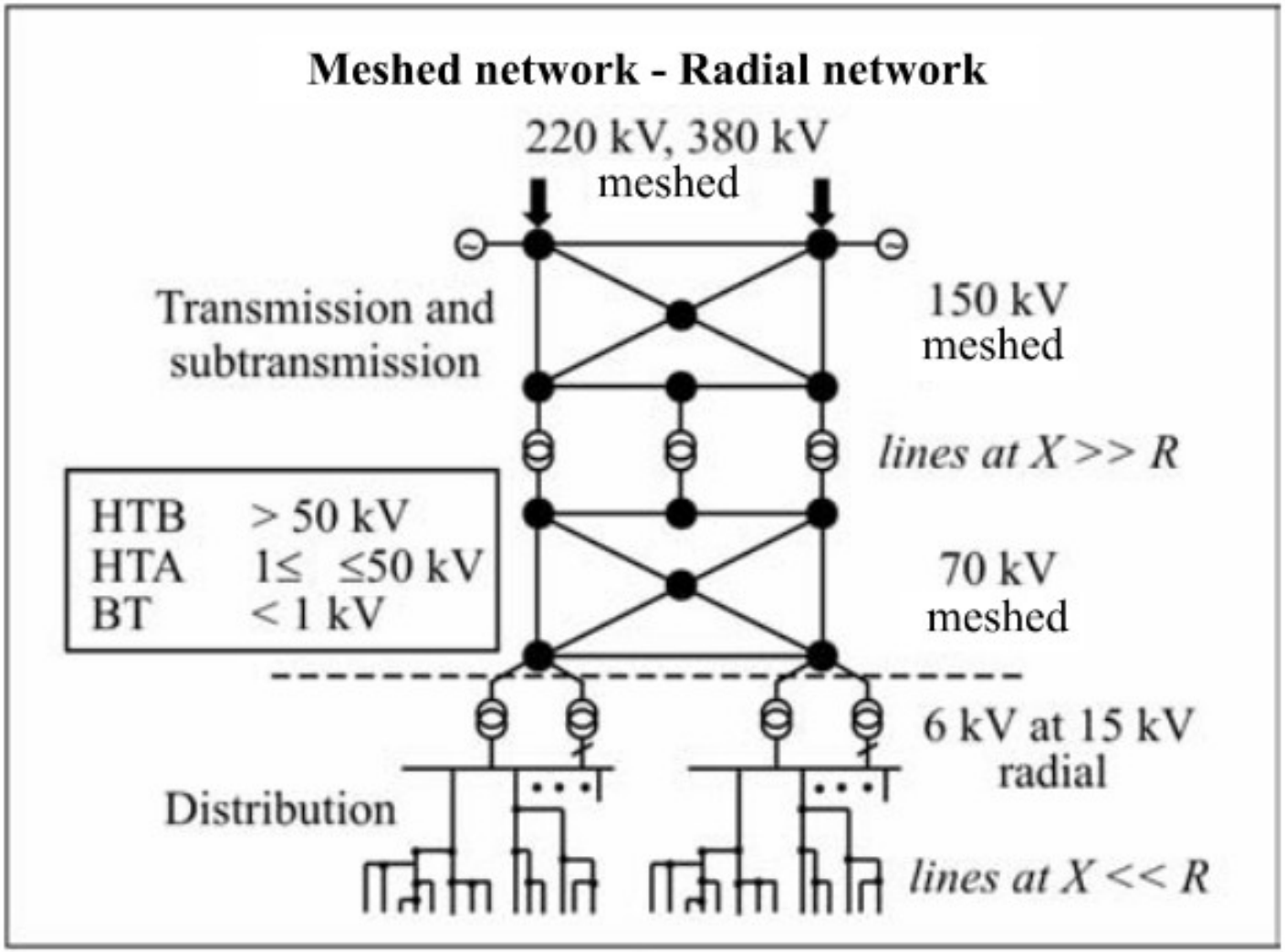
- Self-healing Networks
  - Simulations
  - Cavity Method
  - Self Healing Percolation

Power Systems

Electric System



Meshed vs Radial



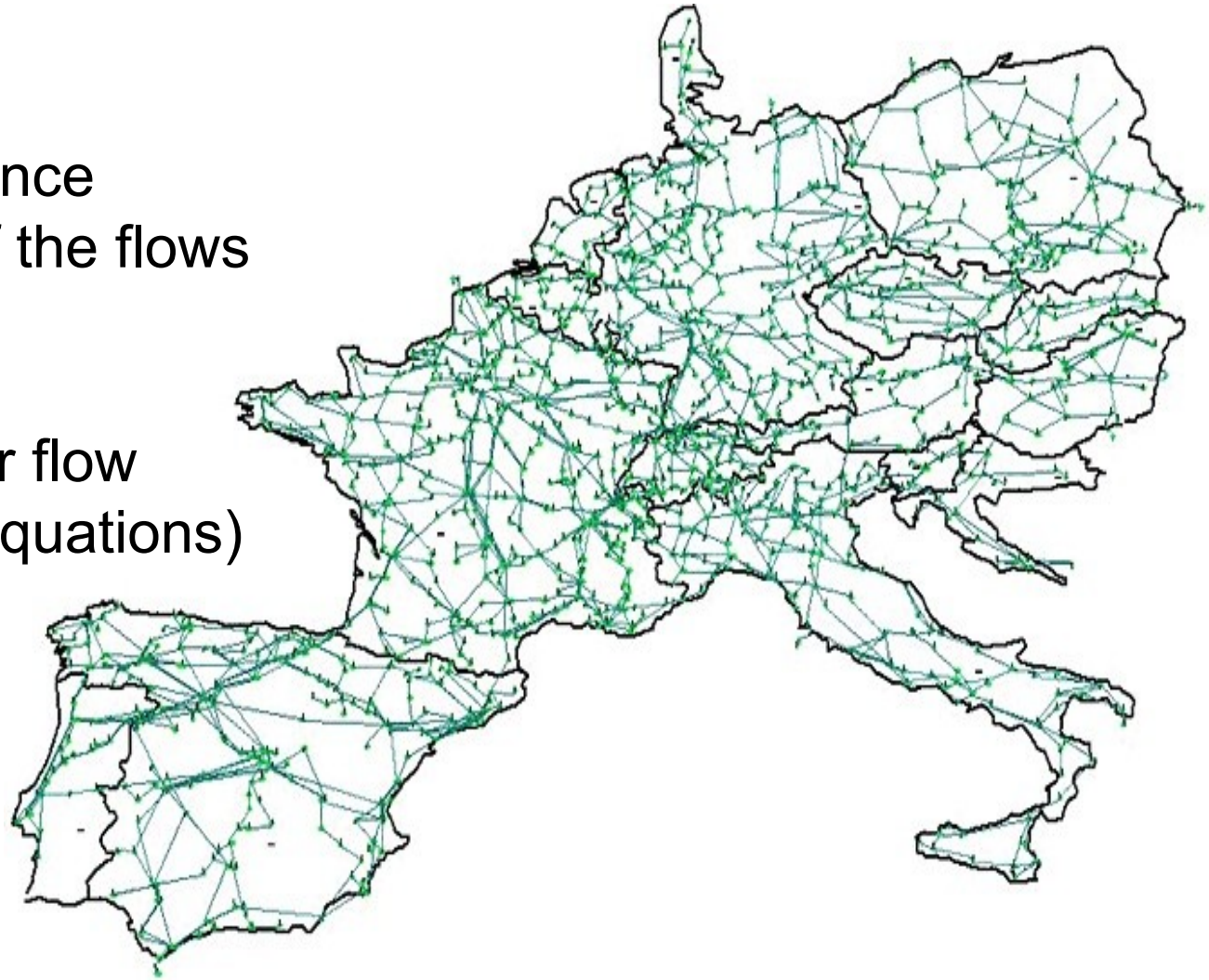
Blackouts

Abruptness of Cascade Failures in Power Grids
Scientific Reports 4 (3694)

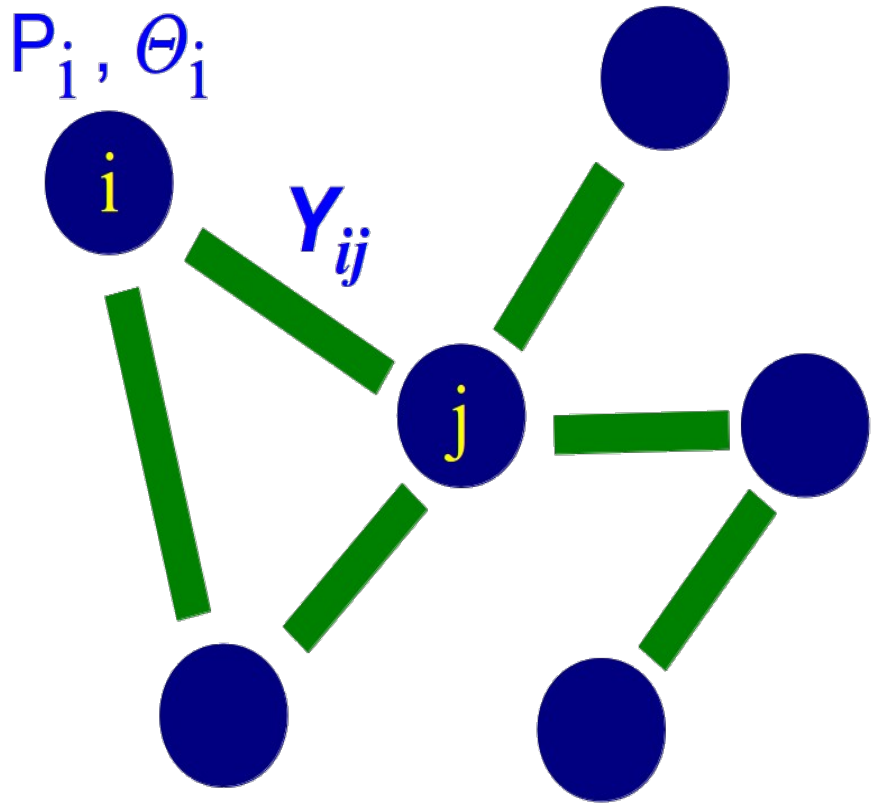
Transmission networks

- Power inbalance
- Magnitude of the flows

AC power flow
(non-linear equations)



DC Power Flow



- Linearized system:

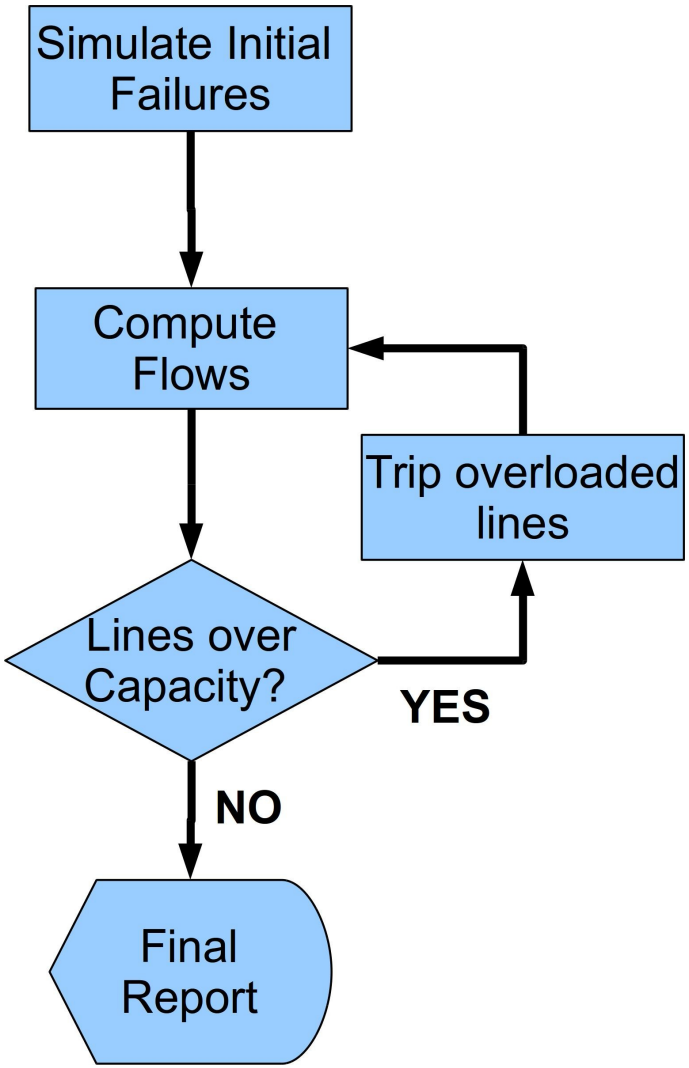
$$\mathfrak{L}\,\Theta = P$$

- $\mathfrak{L}$ depends on
  - the topology
  - line values
- Fluxes proportional to:

$$\Theta_{ij} = \Theta_i - \Theta_j$$

Overload Cascade Model

- Not considering transients
- Not considering voltage instabilities
- Not considering phase sync
- **Just a sequence of line trippings**



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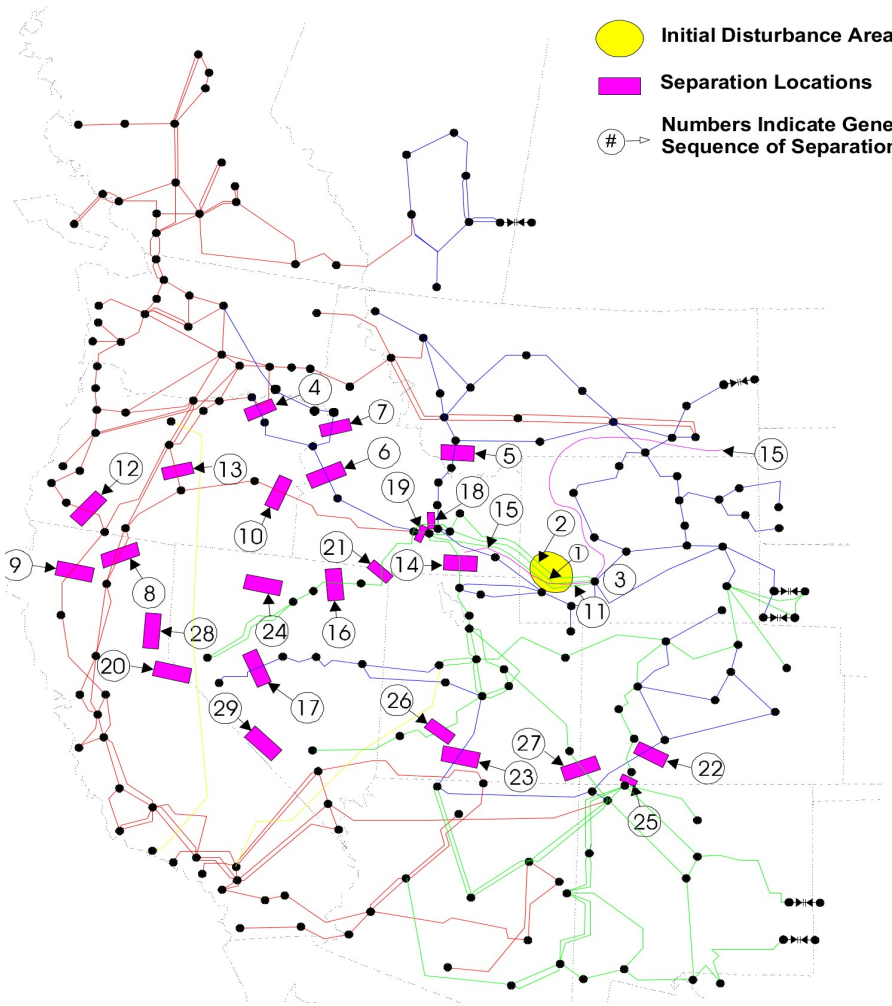
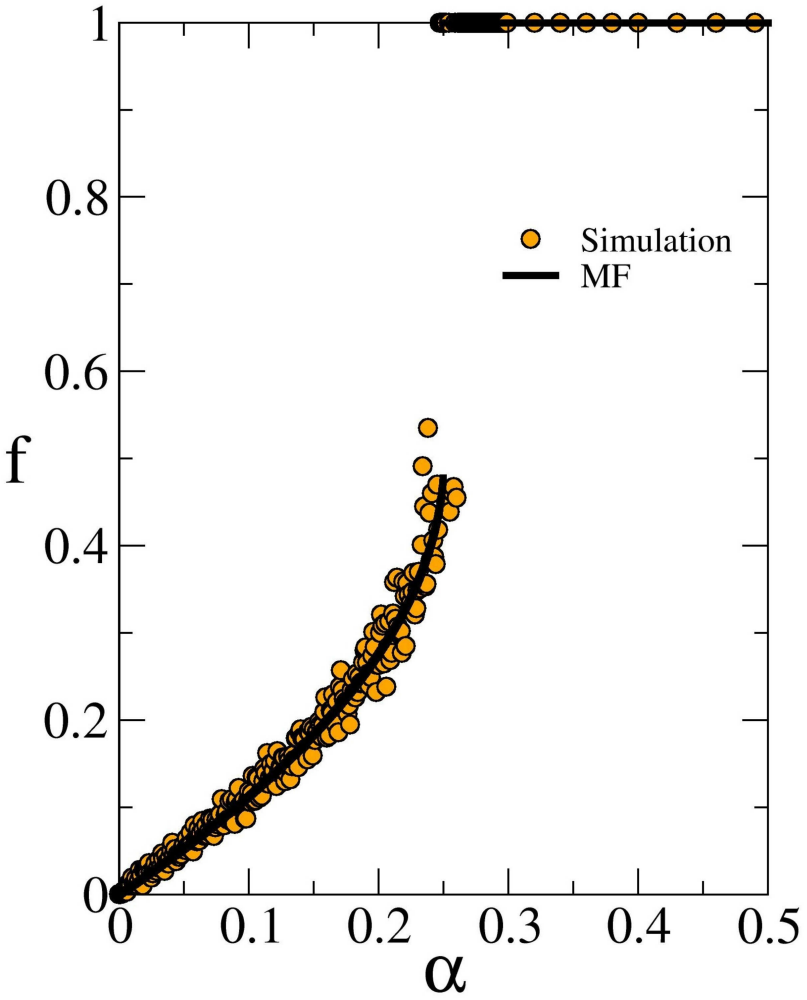
Blackout: “fast” & long-range



- following the fault: 5-15 min window to restore (N-1) condition (adjust generation, network reconfiguration etc)
- If another fault within 15 min window: operator intervention (time wasted!) and defence plans (e.g. load shedding, wide area monitoring and protection)
- Most blackouts happened due to multiple faults -> beyond the (N-1) reliability criterion

Janusz W. Bialek, CWPE 0407
Cambridge Working Papers in Economics

Mean Field model



Load per line l^t
Fraction of failed lines f^t
Number of survived lines M^t
Random thresholds $P(C)$

$$\begin{cases} l^{t+1} &= L/M^t \\ f^{t+1} &= P\left(l^{t+1}\right) \\ M^{t+1} &= \left(1-f^{t+1}\right) M \end{cases}$$

$$f^{t+1} = P\left(\frac{L}{\left(1-f^t\right) M}\right)$$

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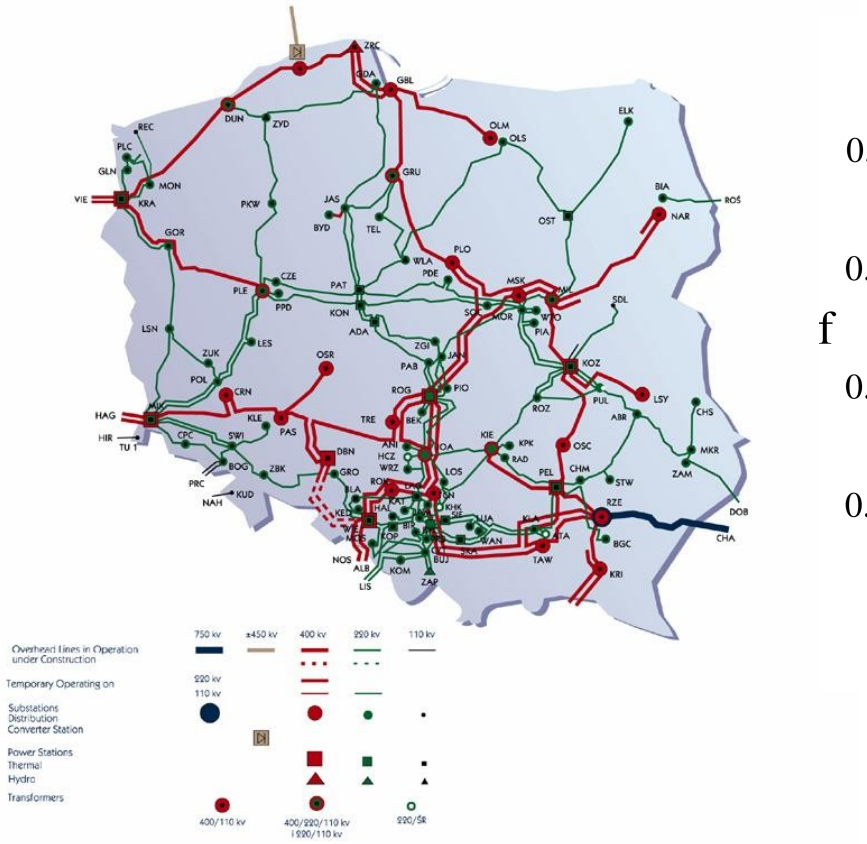
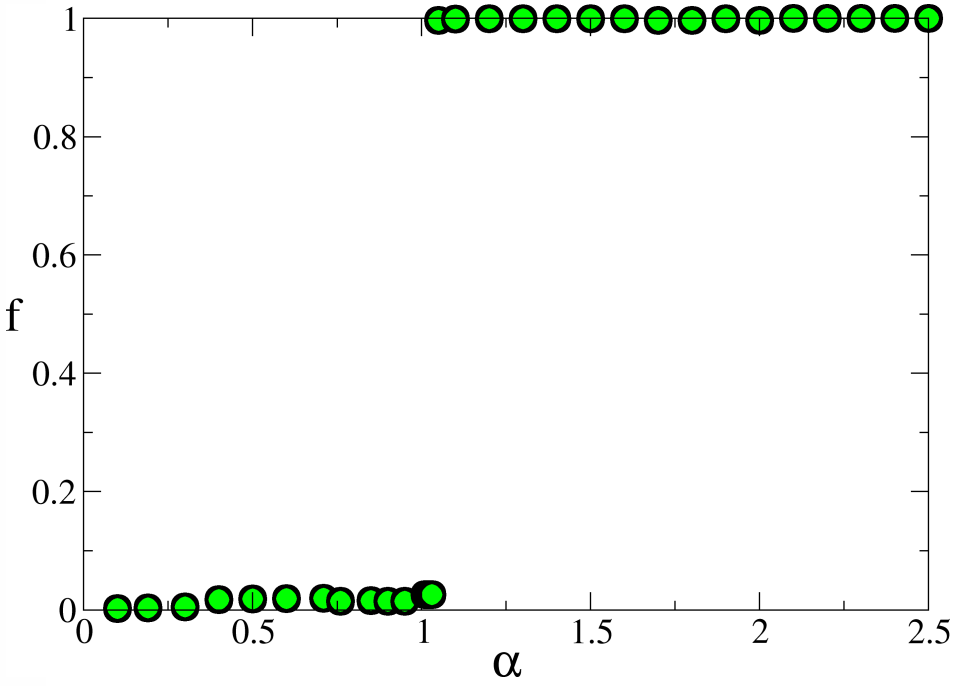
Polish Grid – Increasing Demand





f : fraction of failed links

α: increase of demand

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Renewable Sources

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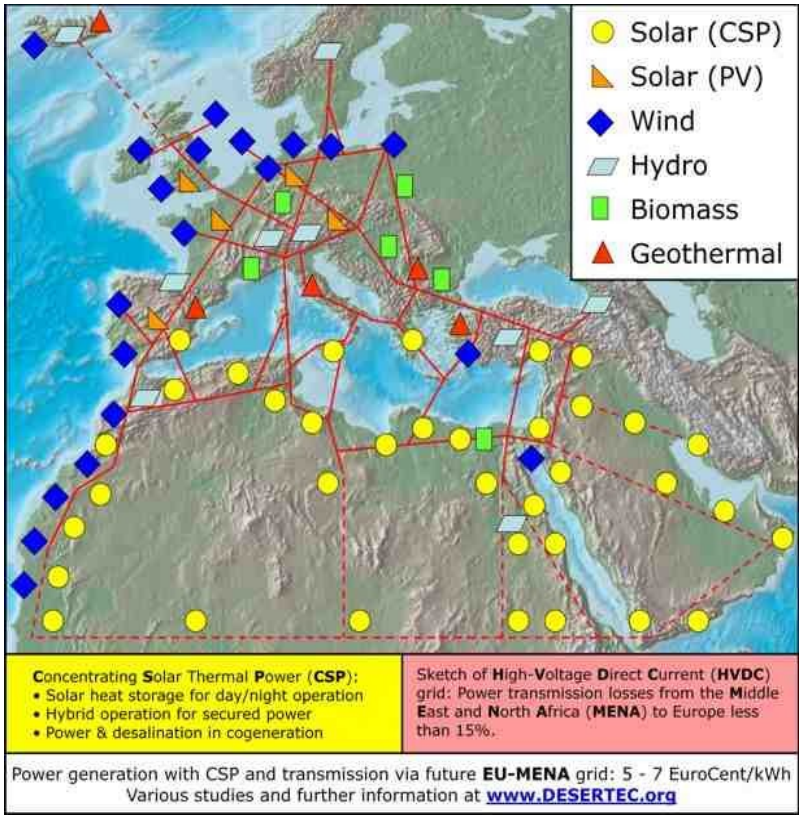
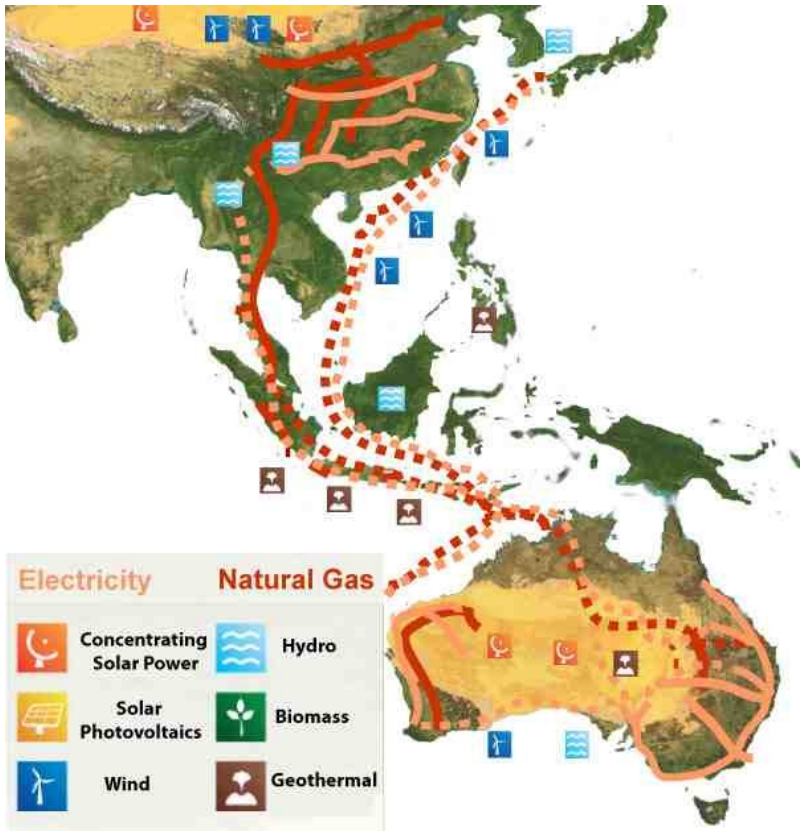
Mega Grids



EU-MENA
(DESERTEC+AIRTRICITY)



PAN ASIA
ENERGY INFRASTRUCTURES

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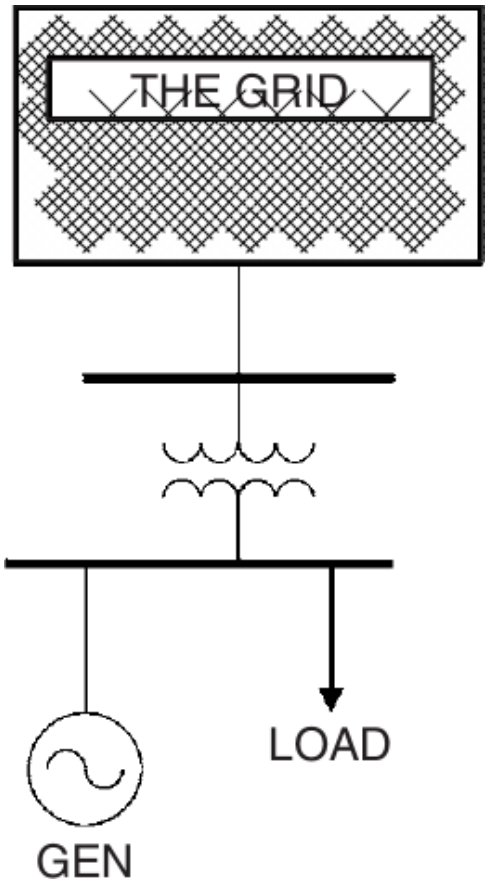
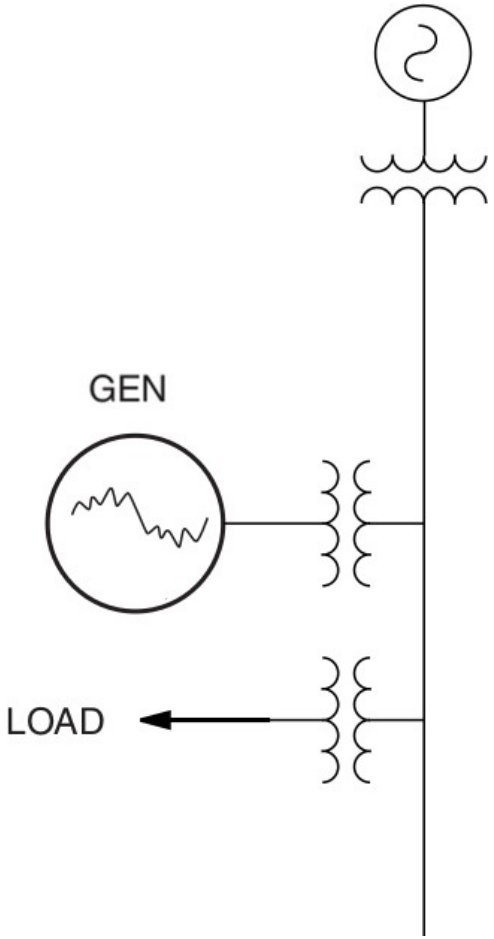
Different perspectives

End User:
grid as an opportunity



Grid owner:
harmful perturbations



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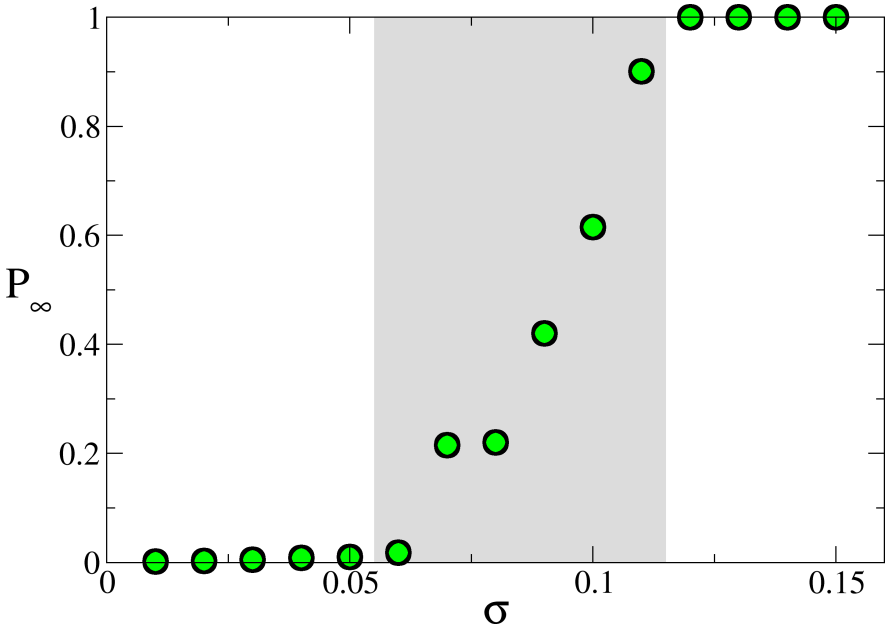
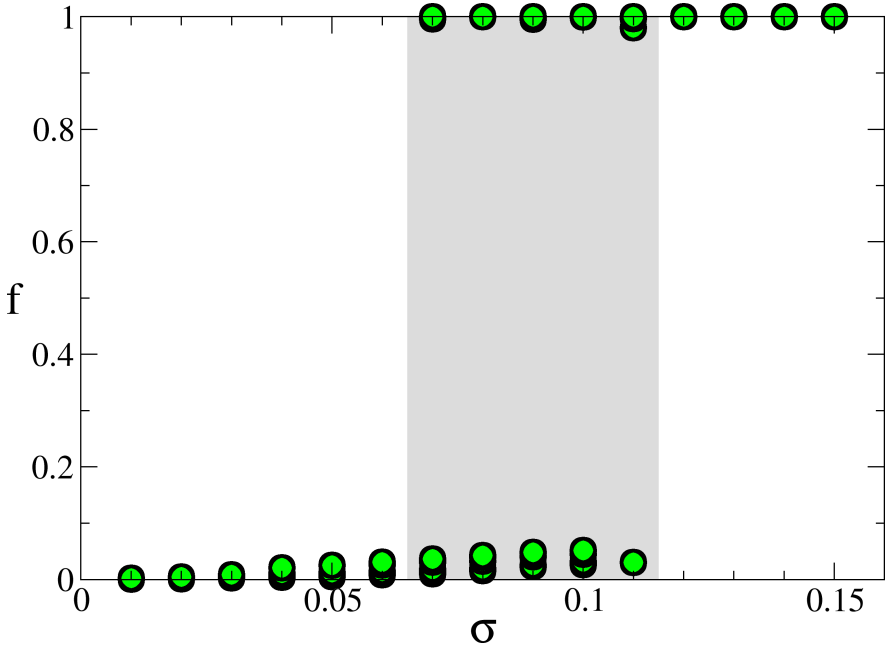
Polish Grid – with Renewables





P : probability of blackout

σ: magnitude of fluctuations

f : fraction of failed links

σ: magnitude of fluctuations

Blackout probability increases, yet single blackouts are abrupt!

Abruptness of Cascade Failures in Power Grids
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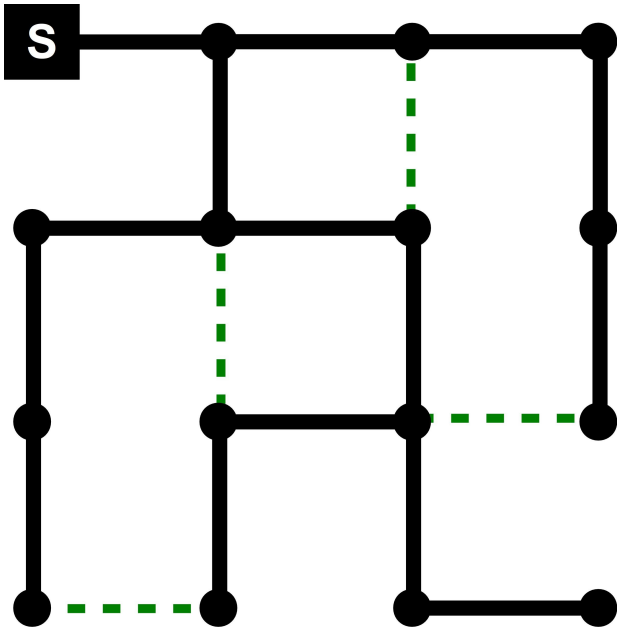
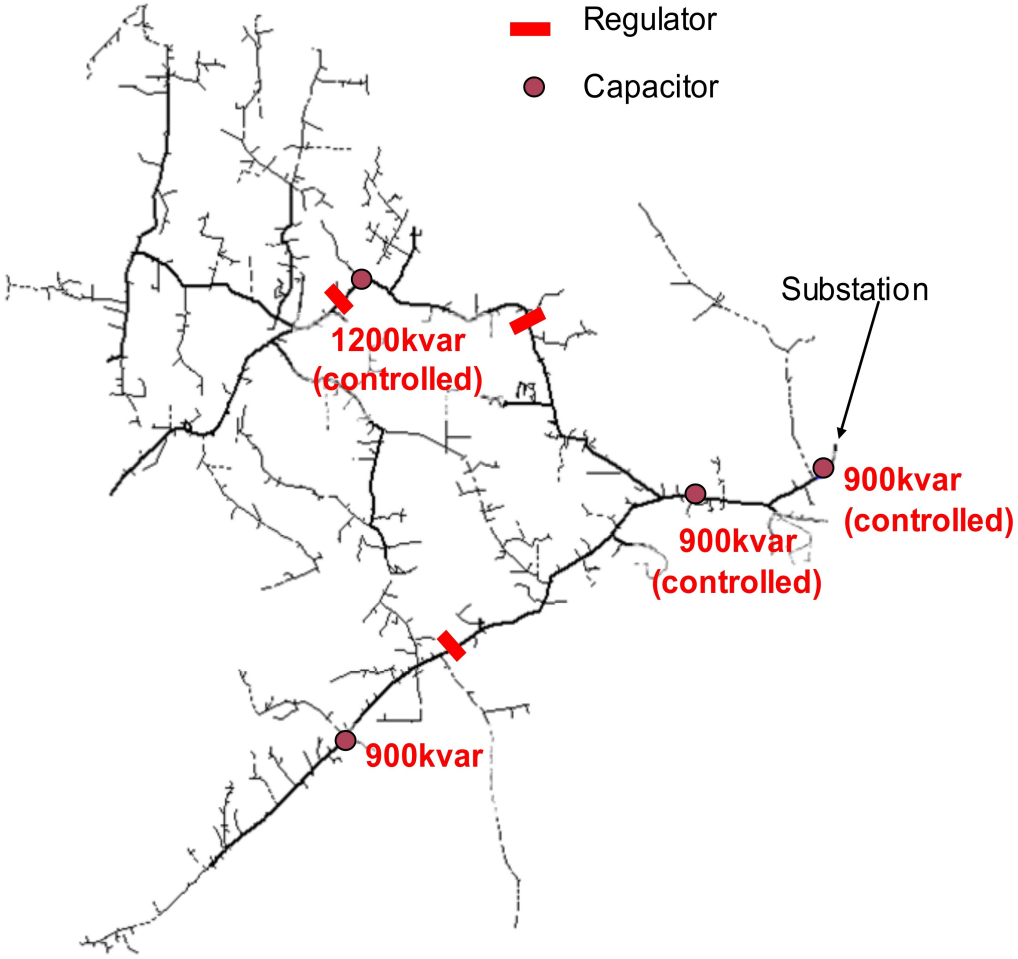
Smart Networks

Self-Healing Networks: Redundancy and Structure
PLoS ONE 9 (2), e87986

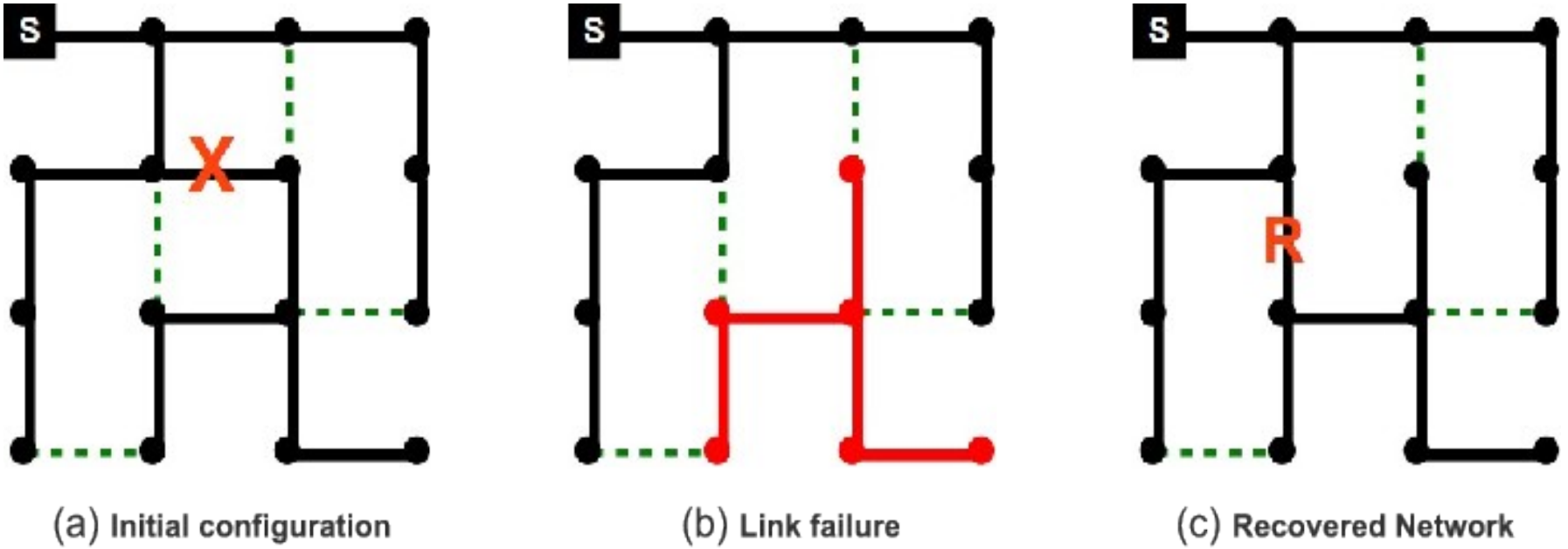
Distribution networks





IEEE 9500 bus test feeder
(US, medium voltage)

Self-healing Networks



(a) Initial configuration (b) Link failure (c) Recovered Network

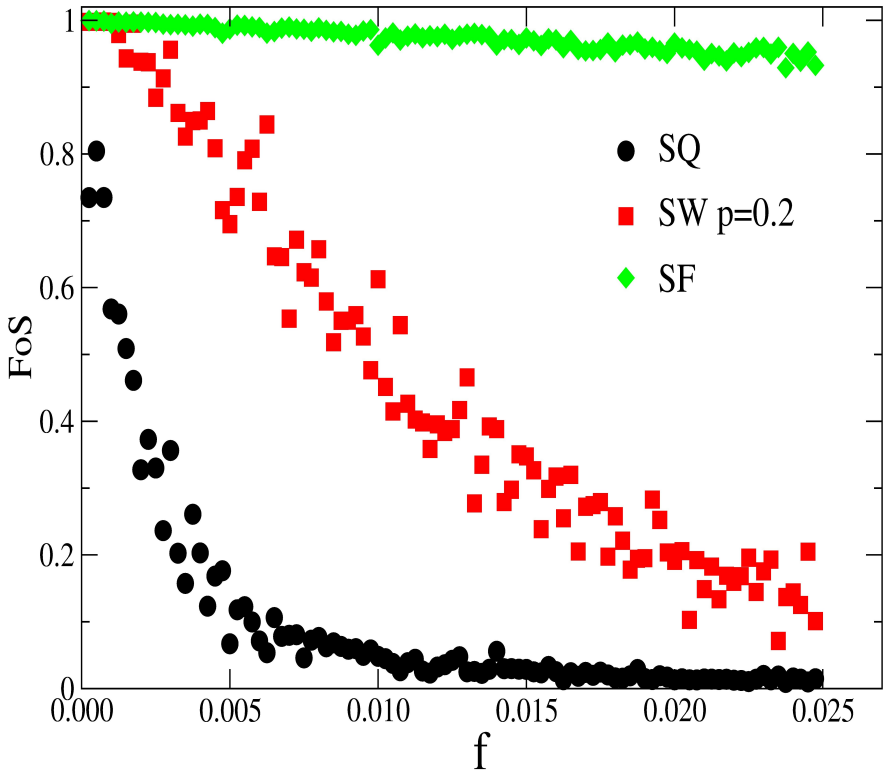
- Inspired by real distribution networks
- Routing Algorithms for Smart Networks

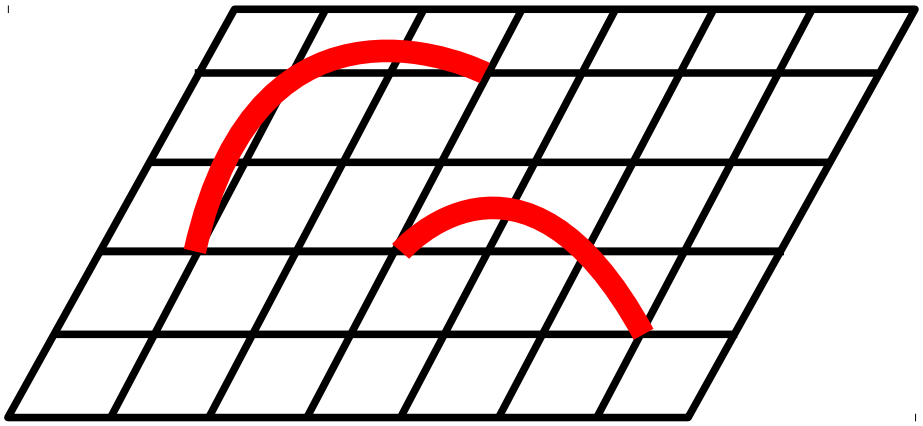
Self-Healing Networks: Redundancy and Structure
PLoS ONE 9 (2), e87986

Simulations

1. Generate a **host network** topology
2. Generate a **tree topology** on such network
3. Add a fraction **r** of recovery links
4. Delete a fraction **f** of active links
5. **Reconnect** the nodes using recovery links
6. Calculate the fraction **FoS** of connected nodes

FoS = Fraction of Served nodes





p = fraction of random (long range) links added to a regular lattice

SQ = Planar square lattice
SW = Small World
SF = Scale free

Self-Healing Networks: Redundancy and Structure
PLoS ONE 9 (2), e87986

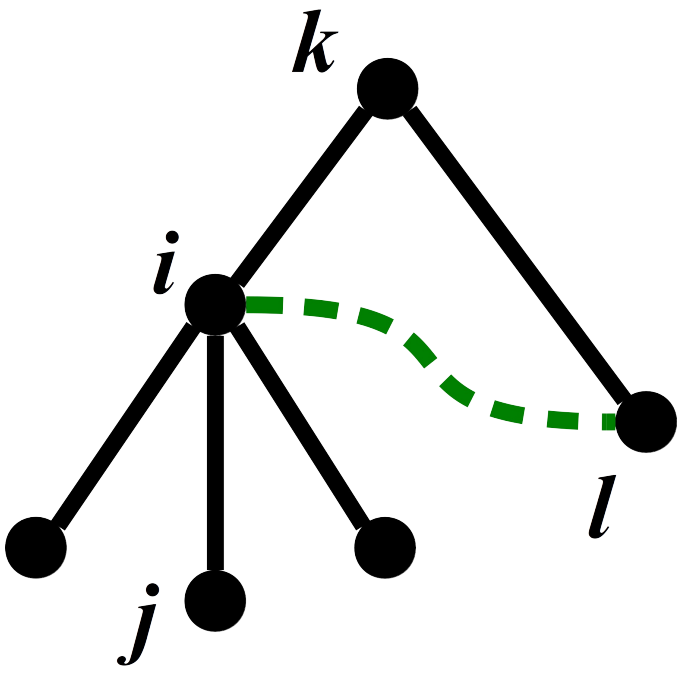
Cavity Method

in preparation – **soon on arXiv**:

Cavity approach to Self-Healing

F Morone, H Makse, G Caldarelli and A Scala

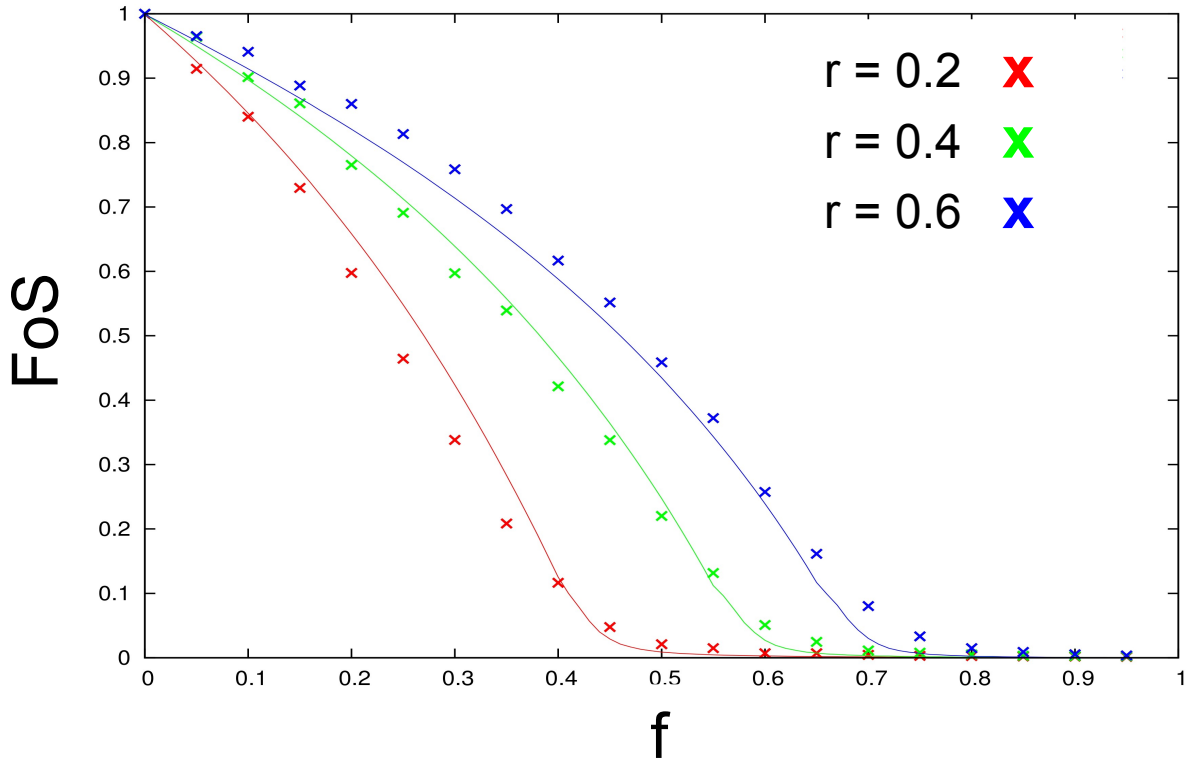
Message Passing & Cavity Equations



Self consistent equation set for:

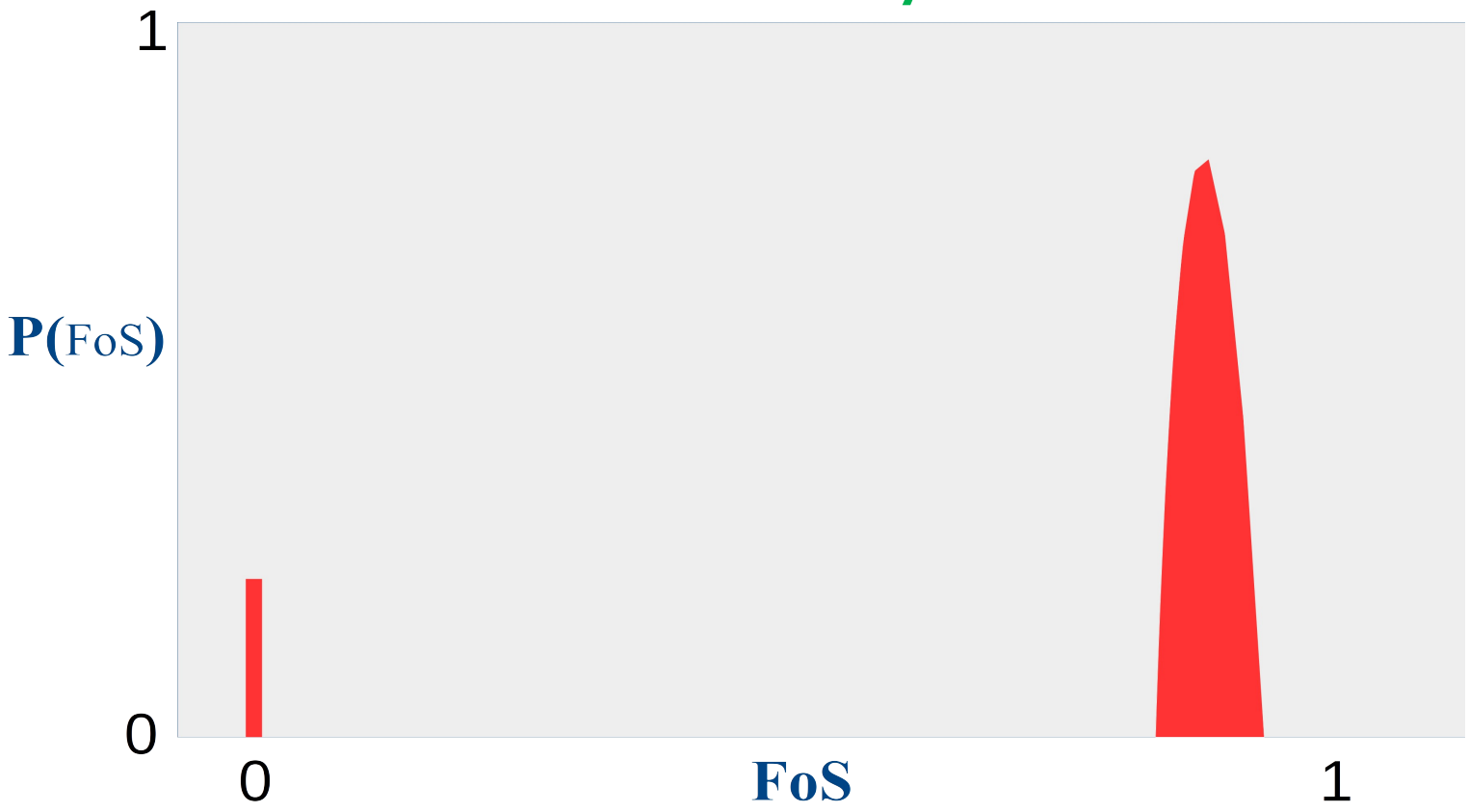
- $down_{ij}$ probability of being connected when son j fails
- up_{ik} probability of being connected when father k fails
- $redund_{il}$ probability of being connected when neighbour l fails

Simulations & theory



Self-consistent equations for messages running on the edges of the tree and on redundant edges

Corrections to the Cavity Method



Two kinds of events:

- Blackouts
- Percolation

Self-Healing Percolation

in preparation – **soon on arXiv**:

Self-Healing percolation

P Ballister, B Bollobas, G Caldarelli, W Quattrociocchi and A Scala

Self-Healing percolation

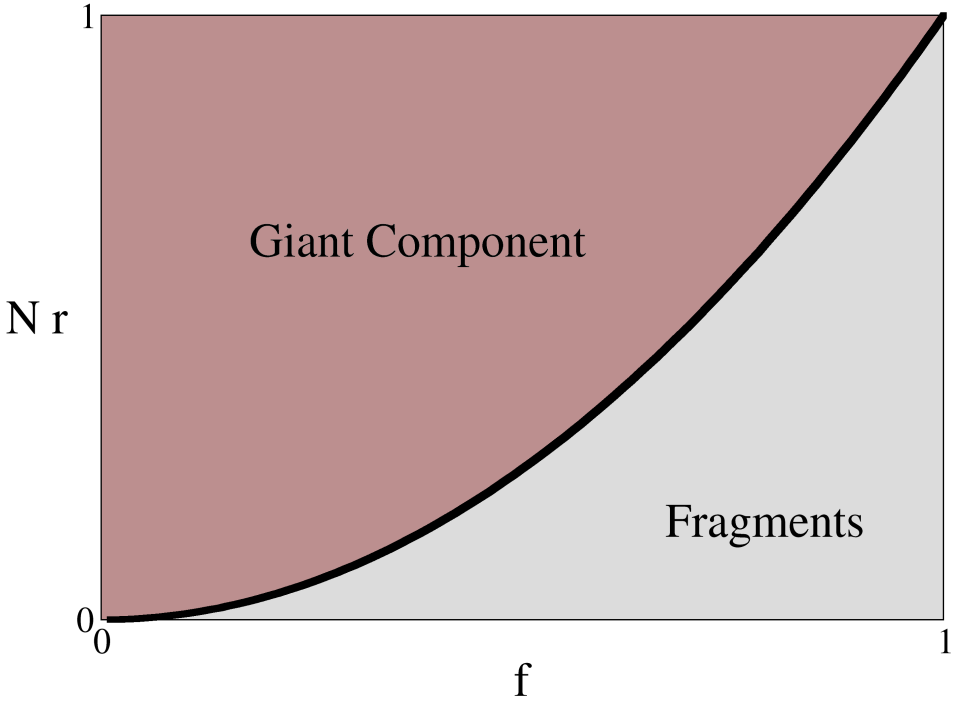
Given a network topology (distribution network)

- Fix a fraction **f** of failures
- Find the fraction **r** of recovery links at which appears a ***giant component***

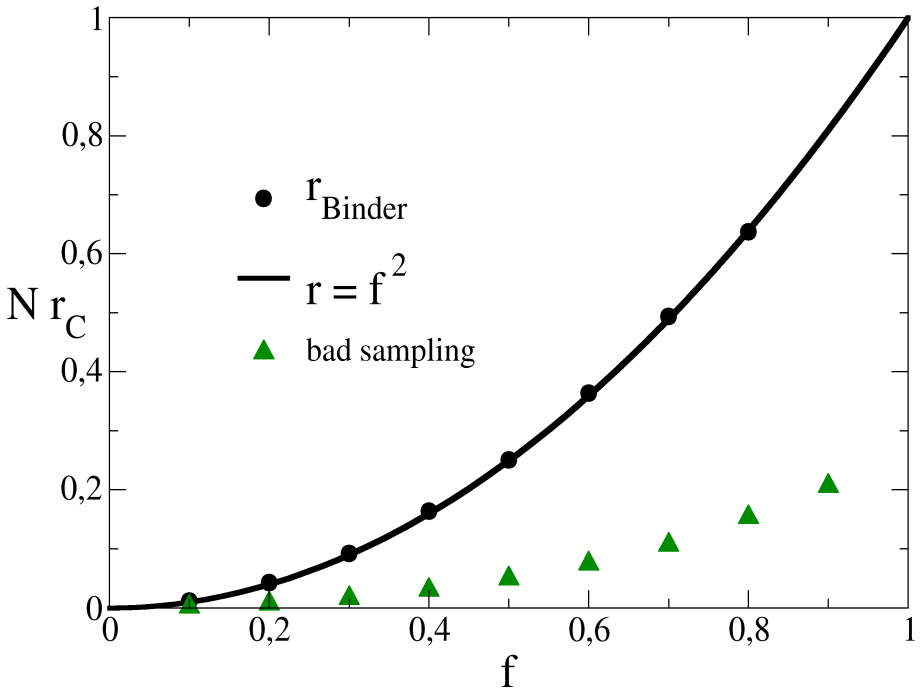
NOTICE: distribution network does not need to be a tree

Random Graph

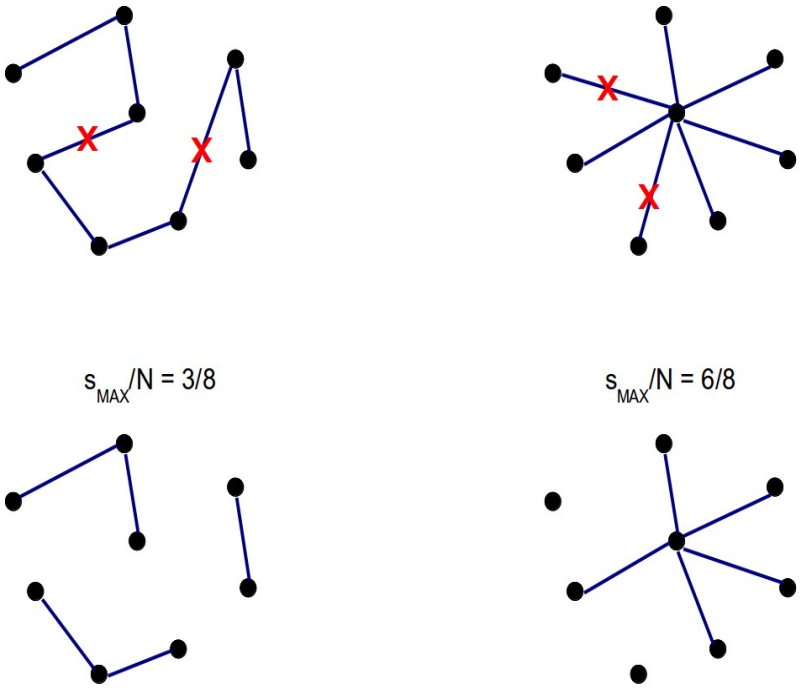
Random Graph (theory)

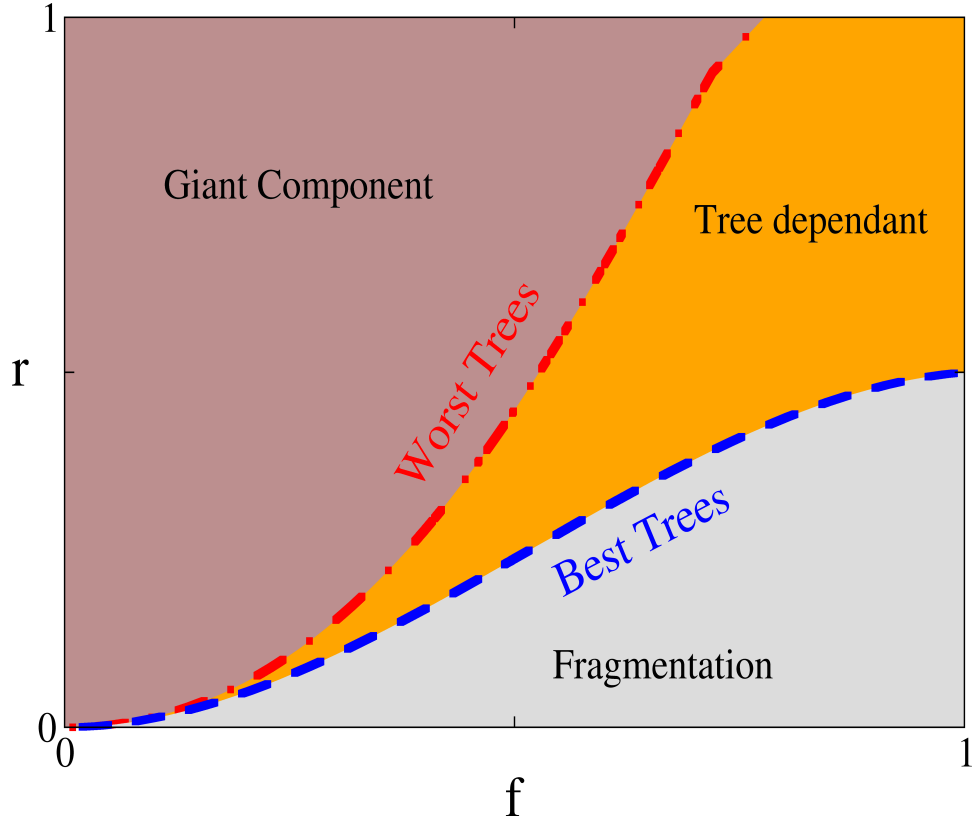


Random Graph (numerical)



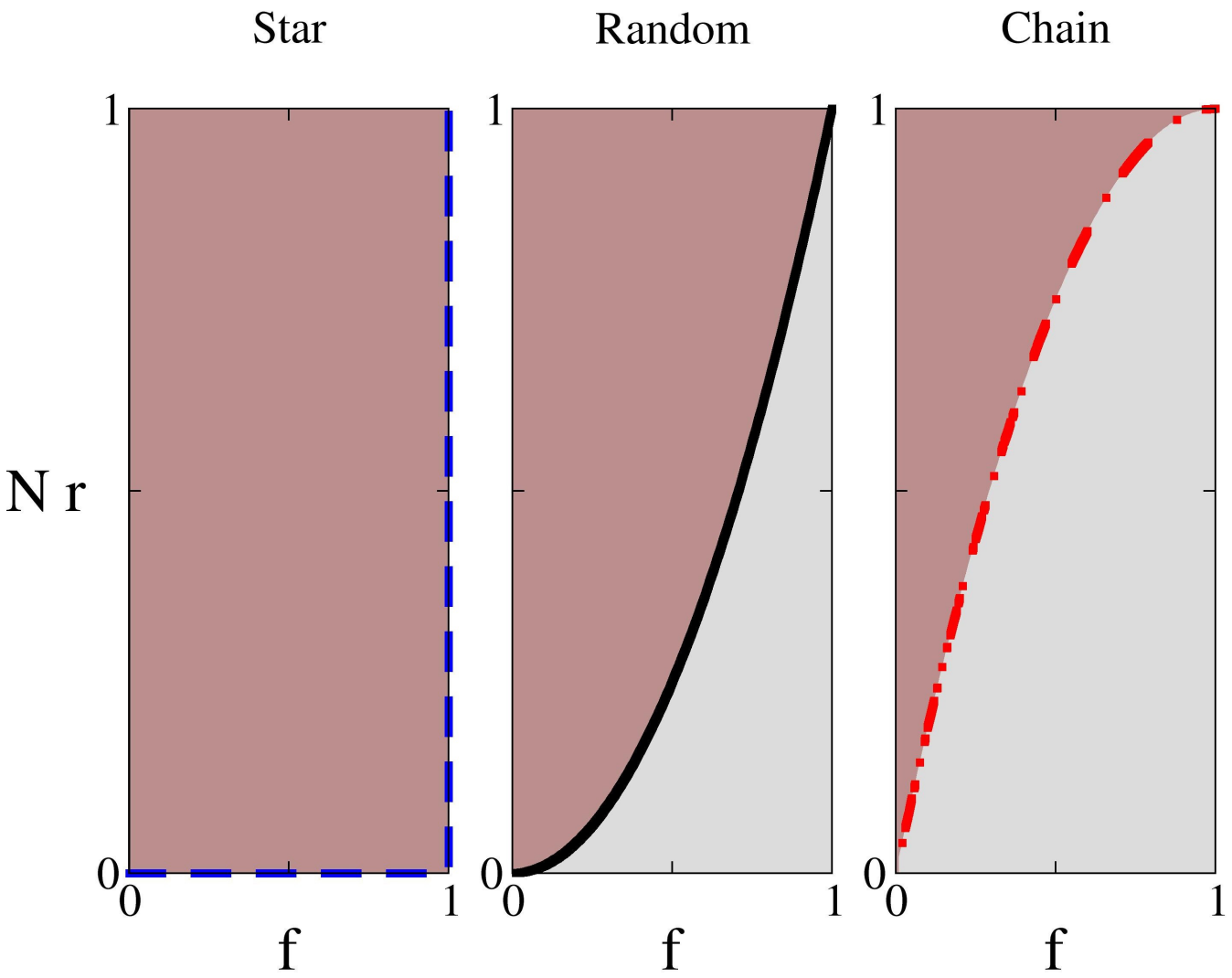
Topology of the distribution tree



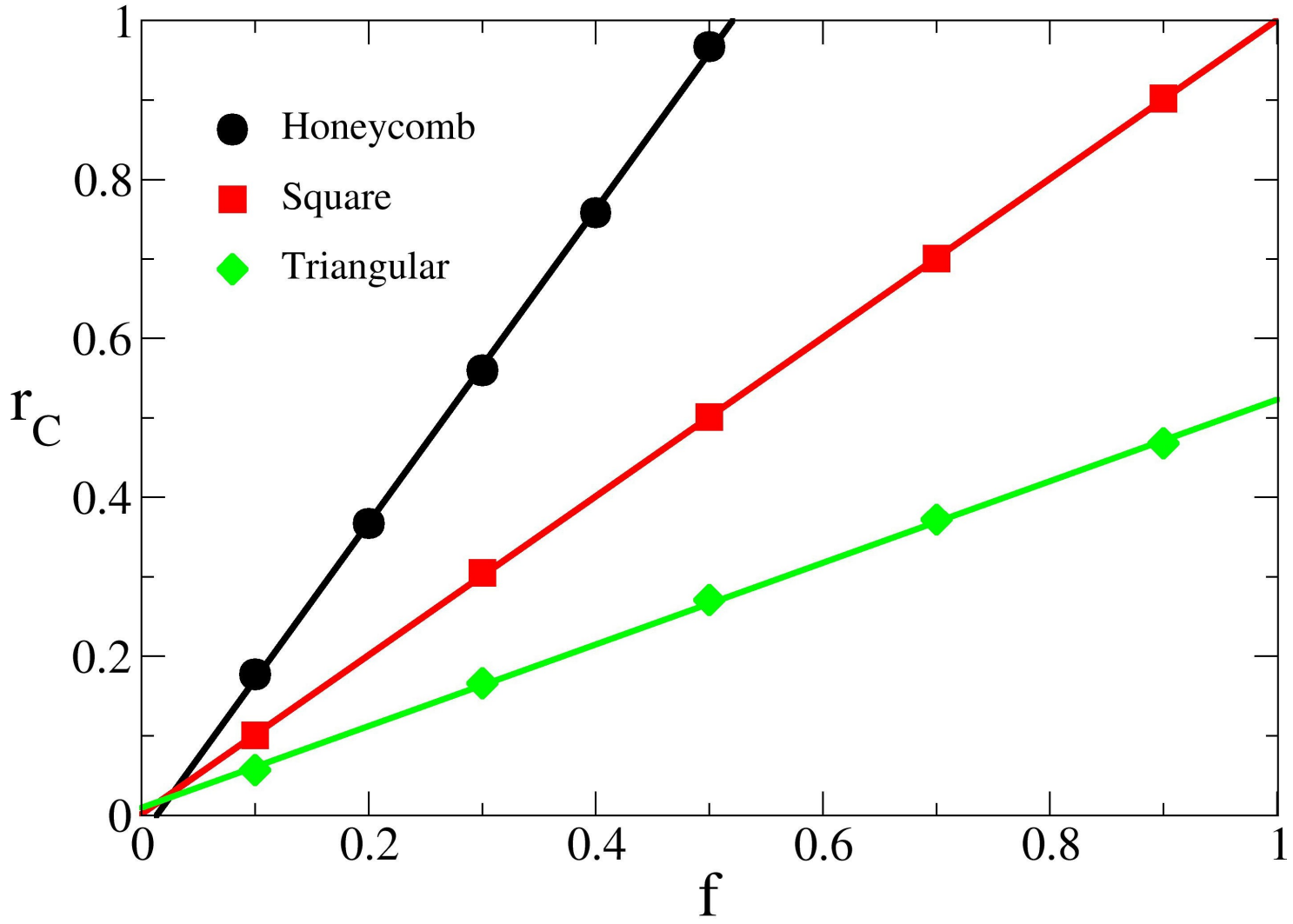


- Chain is the most fragile
- Star is the most robust

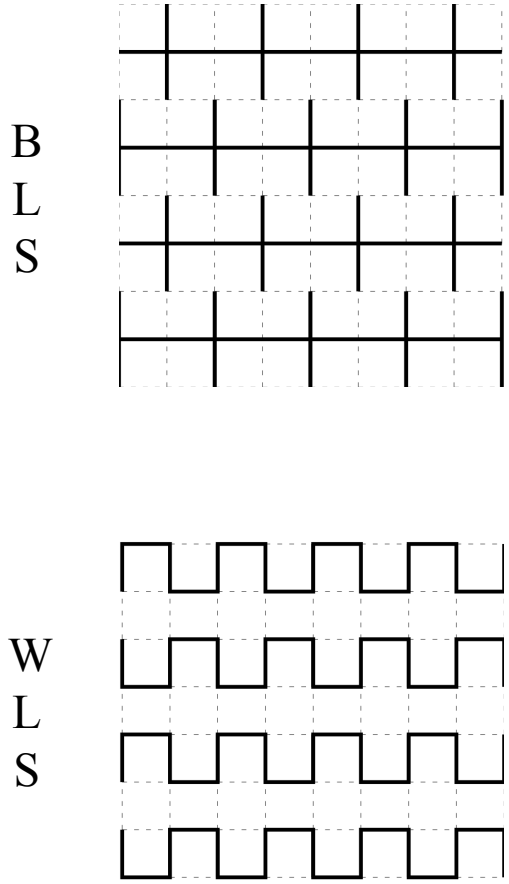
Best/Worst trees for ER graphs

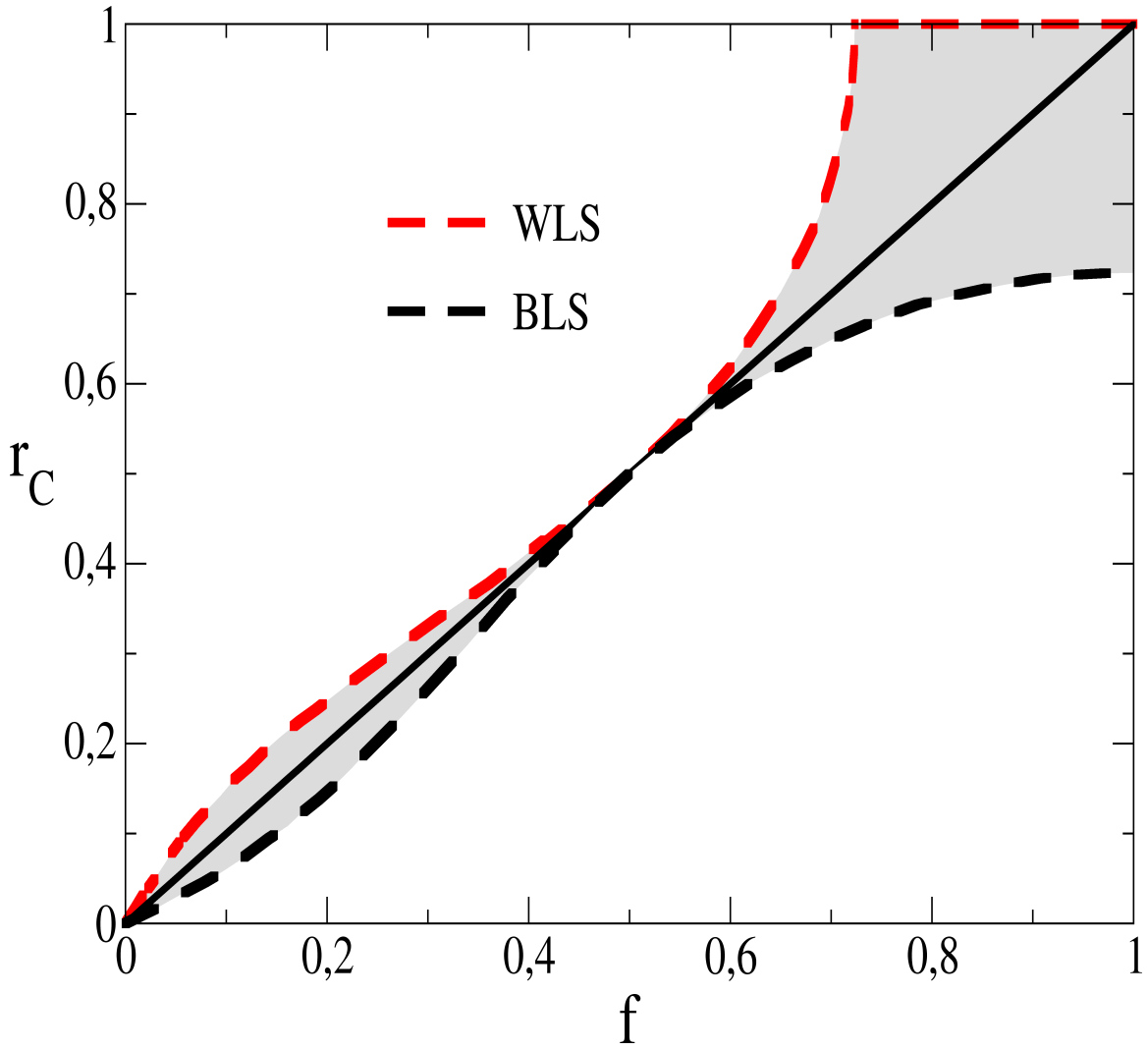


Planar lattices



Optimal trees on SQ lattice





Conclusions

- Statistical Mechanics can spot possible sources of systemic risks in large power grids
- "Smartness" could be accomplished customizing "on the market" routing protocols

THANKS TO:

- CNR-PNR National Project Crisis-Lab
- FP7 project MULTIPLEX - Foundational Research on MULTIlevel comPLEX networks and systems
- H2020 project DOLFINS - Distributed Global Financial Systems for Society
- EU HOME/CIPS project CI2C "Critical Infrastructures and Cloud Computing: understanding cross-sectorial criticalities and security practices"