Power Blackouts and the Domino Effect:
Real-Life examples and Modeling

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Acknowledgments

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- Dirk Helbing, ETH, Zurich
- Rafal Weron, Wroclaw

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- EU project IRRIIS
  - IRRIIS : "Integrated Risk Reduction of Information-based Infrastructure Systems"
- ERC
  - COST P10, "Physics of Risk"

Motivation

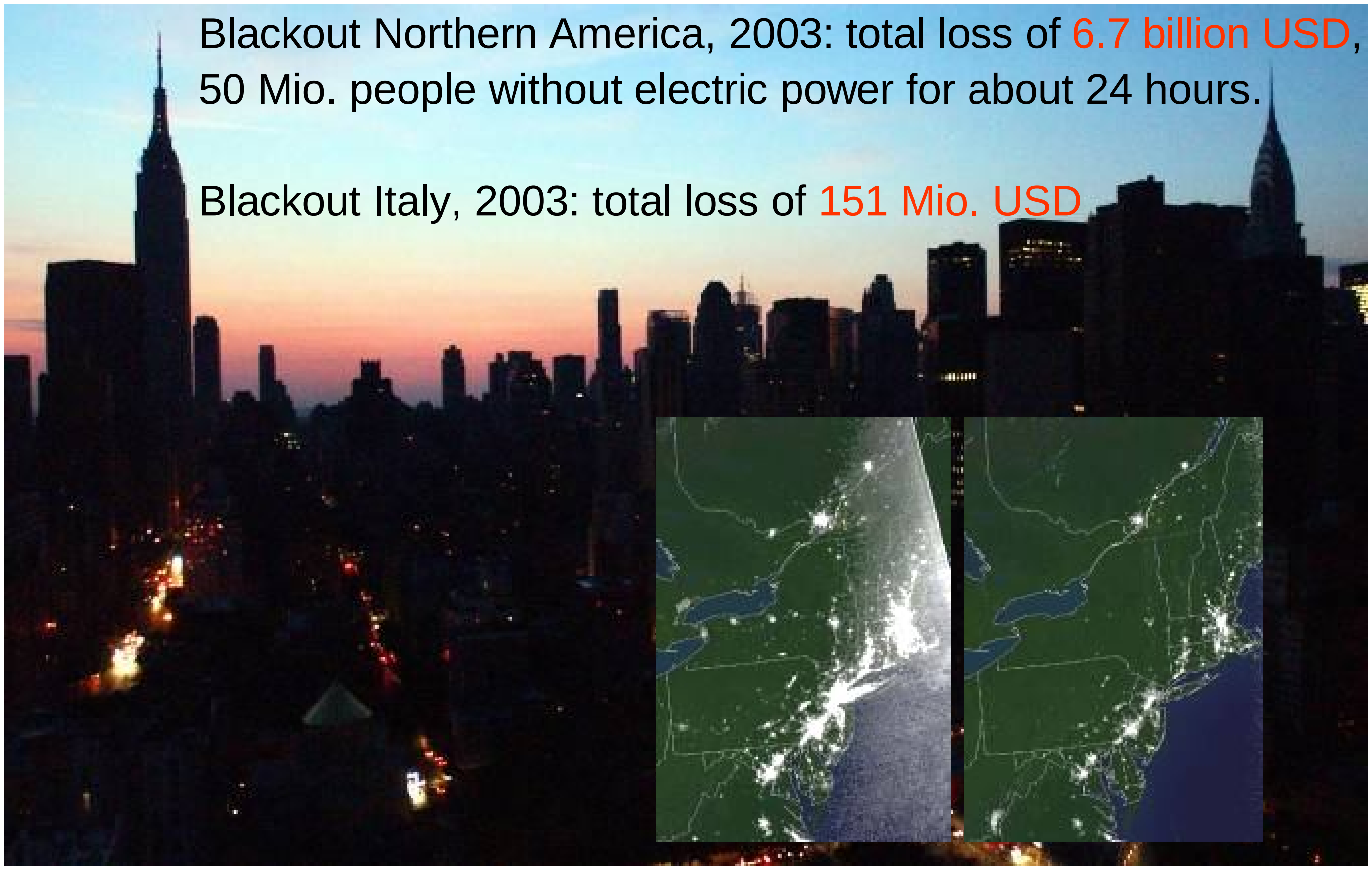
New York, August 14, 2003

Rome, September 28, 2003

Motivation

Blackout Northern America, 2003: total loss of 6.7 billion USD, 50 Mio. people without electric power for about 24 hours.

Blackout Italy, 2003: total loss of 151 Mio. USD

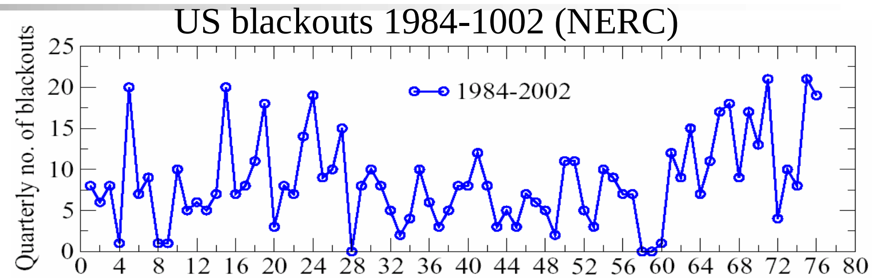


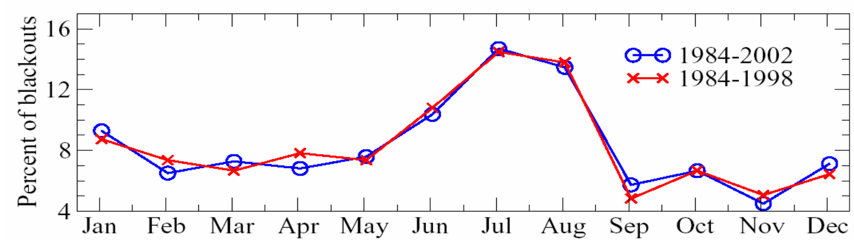
Blackout in parts of the USA and Canada (2003), an impressive example of the long-reaching accompaniments of supply network failures.

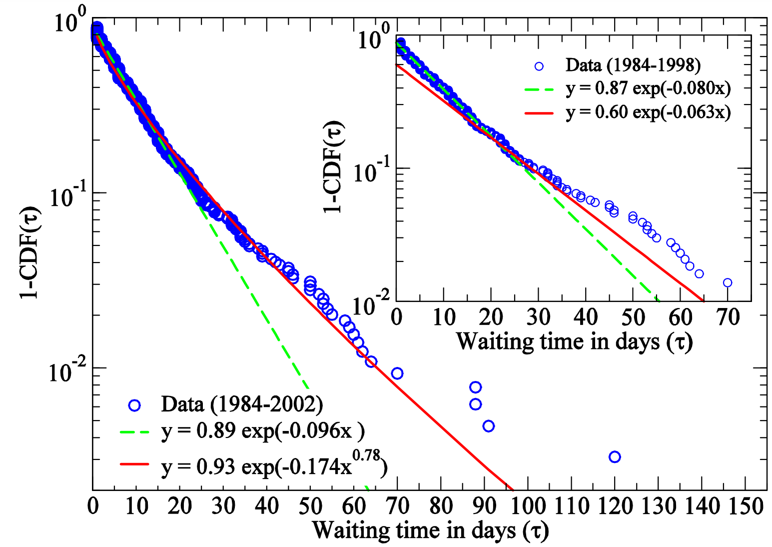
Power Blackouts : How frequent are they?

- North American Electricity Reliability Council (NERC) data
  - Analyzed by Carreras, Dobson, Newman & Poole
  - 15 years of data (1984-1998)
  - 427 blackouts
  - on average **28.5** per year, waiting time of **12** days

- Three measures of blackout size
  - energy unserved (MWh)
  - amount of power lost (MW)
  - number of customers affected





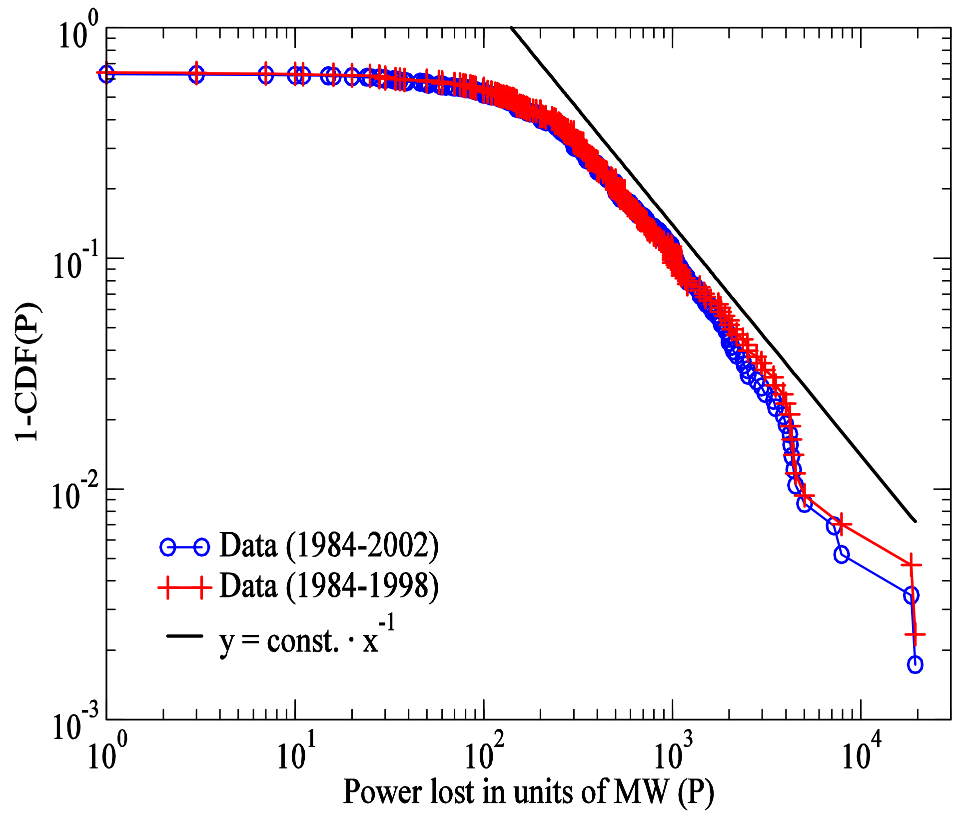


Risk of Power Blackouts

- There are rather few *large* blackouts
  - So why should we care at all?

- Risk = Probability * Cost
- Large Power Blackouts are the most RISKY!

US blackouts 1984-1002 (NERC)



Source : Weron and Simonsen (2005)

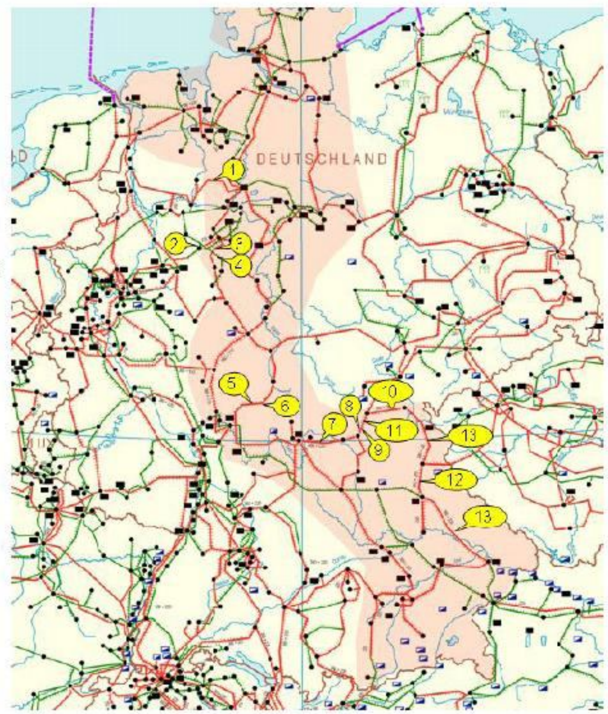
Power Blackouts: Real-Life examples

Europe Nov. 2006: What happened…?

State of the power grid shortly before the incident

Sequence of events on November 4, 2006

Nr.	Zeit	kV	Leitung
1	22:10:13	380	Wehrendorf-Landesbergen
2	22:10:15	220	Bielefeld/Ost-Spexard
3	22:10:19	380	Bechterdissen-Elsen
4	22:10:22	220	Paderborn/Süd-Bechterdissen/Gütersloh
5	22:10:22	380	Dipperz-Großkrotzenburg 1
6	22:10:25	380	Großkrotzenburg-Dipperz 2
7	22:10:27	380	Oberhaid-Grafenrheinfeld
8	22:10:27	380	Redwitz-Raitersaich
9	22:10:27	380	Redwitz-Oberhaid
10	22:10:27	380	Redwitz-Etzenricht
11	22:10:27	220	Würgau-Redwitz
12	22:10:27	380	Etzenricht-Schwandorf
13	22:10:27	220	Mechlenreuth-Schwandorf
14	22:10:27	380	Schwandorf-Pleinting



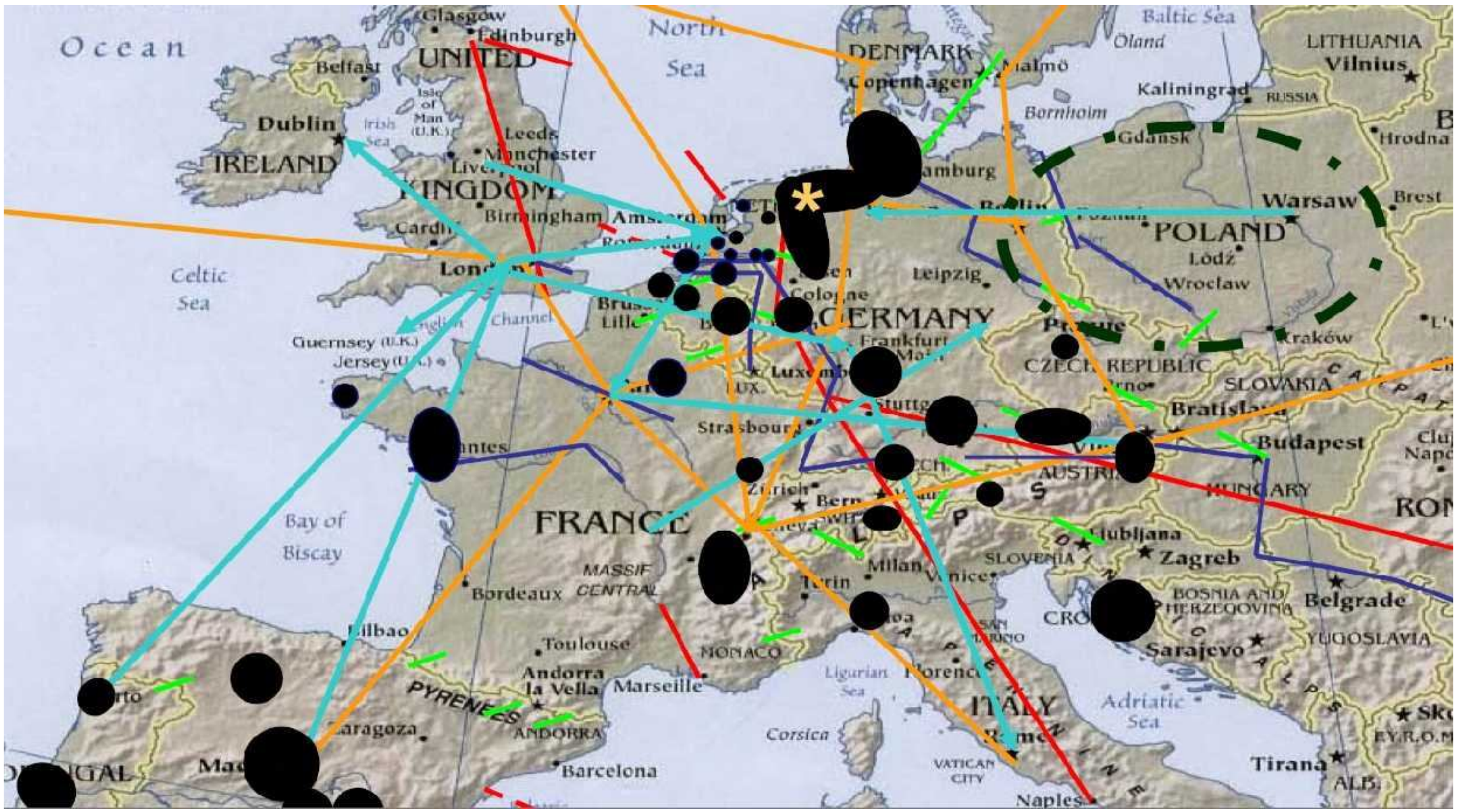
1,3,4,5 – lines switched off for construction work

2 – line switched off for the transfer of a ship by Meyer-Werft

Source : Report on the system incident of November 4, 2006, E.ON Netz GmbH

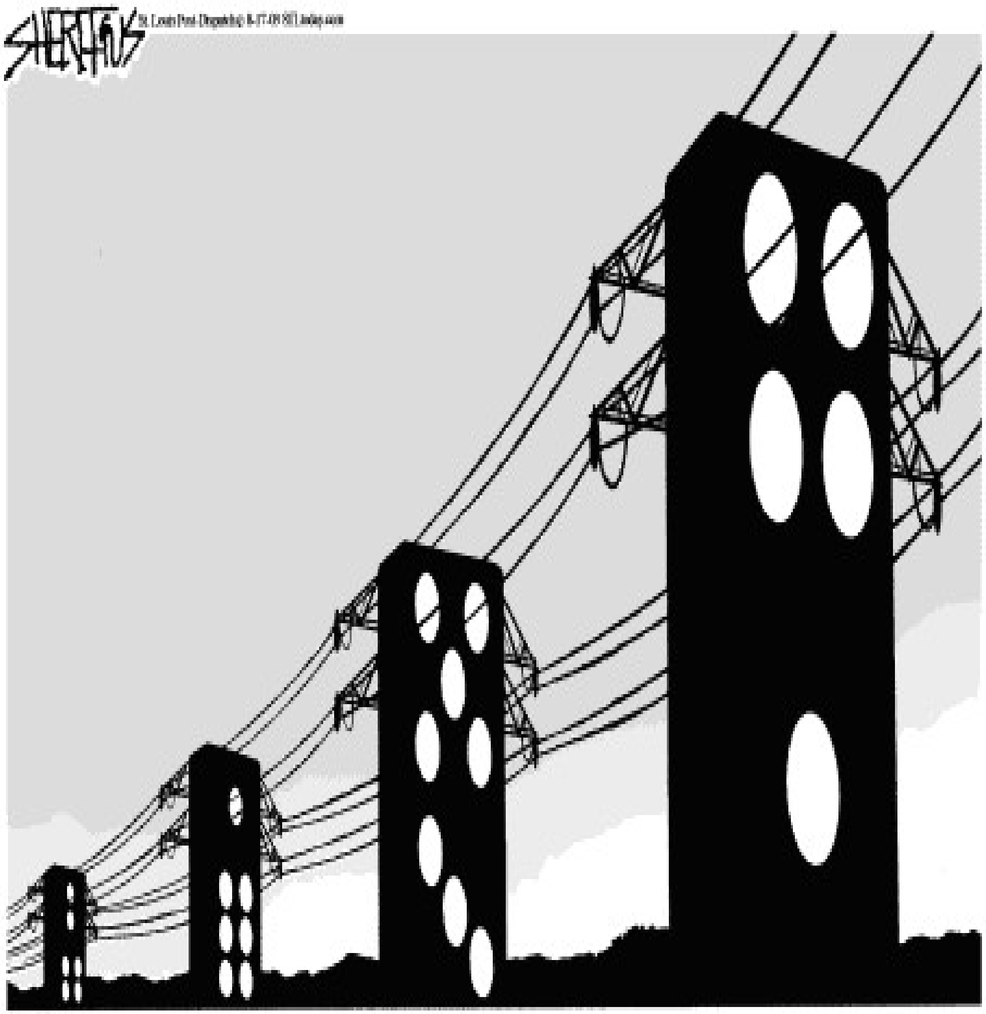
Power Blackouts: Real-Life examples

Failure in the continental European electricity grid on November 4, 2006



EU project IRRIIS: E. Liuf (2007) Critical Infrastructure protection, R&D view

Power Blackouts:
The Domino Effect (Cascading Failure)

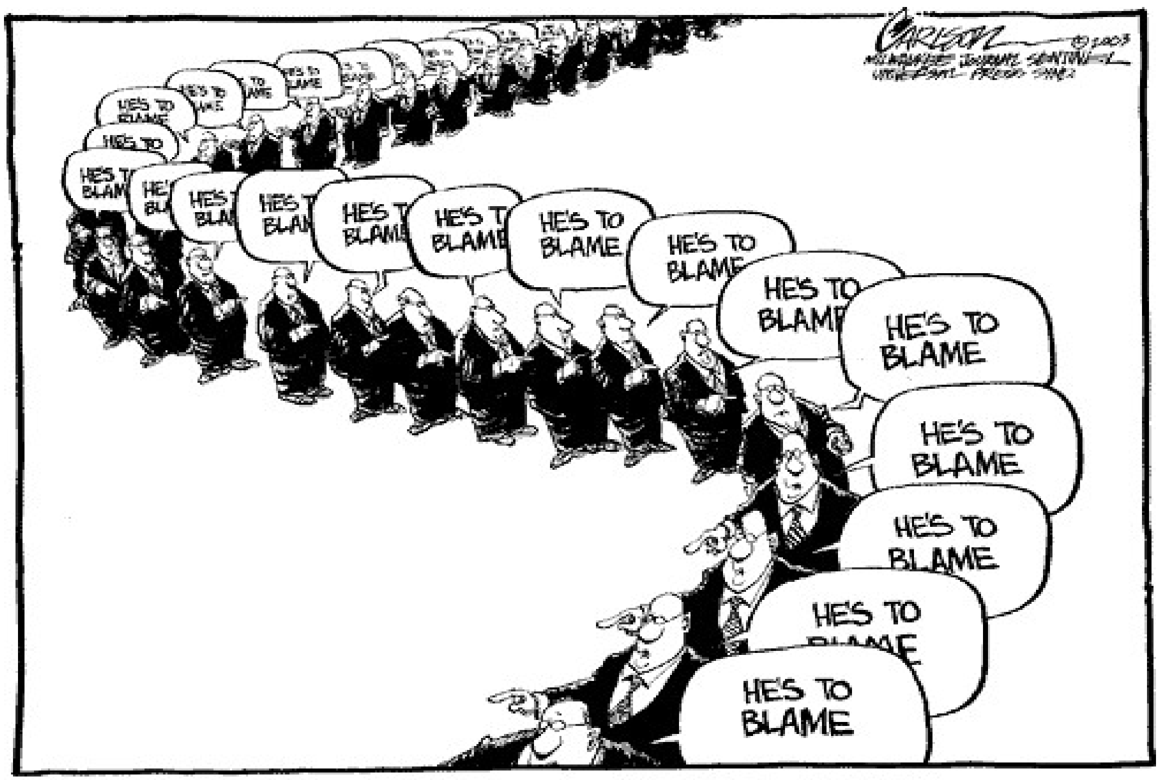


"Under certain conditions, a network component shutting down can cause current fluctuations in neighboring segments of the network, though this is unlikely, leading to a cascading failure of a larger section of the network. This may range from a building, to a block, to an entire city, to the entire electrical grid."

Source :Wikipedia

Power Blackouts: Real-Life examples

US Blackout Nov. 2003: What happened…?



BLACKOUT OF '03 —The "CASCADE EFFECT"

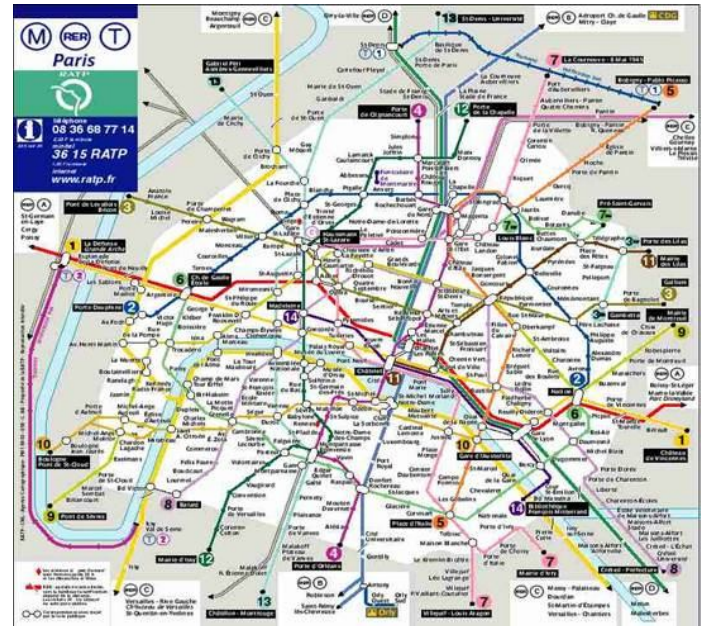
See : Wikipedia for sequence of events

Power Blackouts : Summary

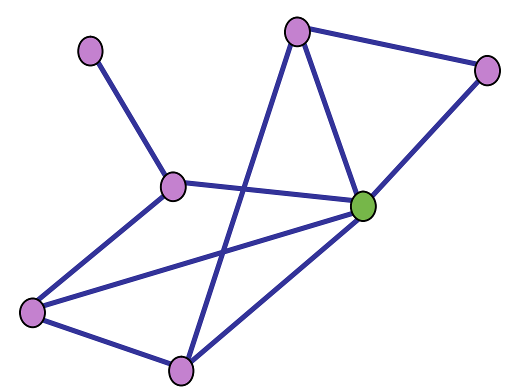
- *Cascading failures* do exist in real life system
  - Examples
    - The power grid
    - Telecommunication networks
    - Transportation systems
    - Computer networks/ the Internet
    - Pipe line systems (water/gas/oil)
- They can be very *costly*
- They typically affect many people

Question : *How* can one protect (supply) network systems against cascading failures?

A Short Primer on Complex Networks



- A network is a collection of
  - Nodes connected by links
- Adjacency matrix W_{ij}
- Degree (#links) distribution
  - Scale-free (e.g the Internet)
  - Exponential (e.g. power networks)
- <u>Betweenness centrality</u> of a node
  - Total # shortest paths passing through *that* node for any pair of nodes



A few words on System Design

- The systems are designed with a *given load* in mind
- To ensure stability, the engineering approach, is to introduce some *overcapacity* into the system (security margins)
- …but overcapacity is *costly*!
- System robustness is often ONLY evaluated locally

- Cascading failure: When an initial perturbation occurs, loads have to redistributes. If the resulting loads exceed the capacities of link/nodes, new failures can result…. "the Domino effect"

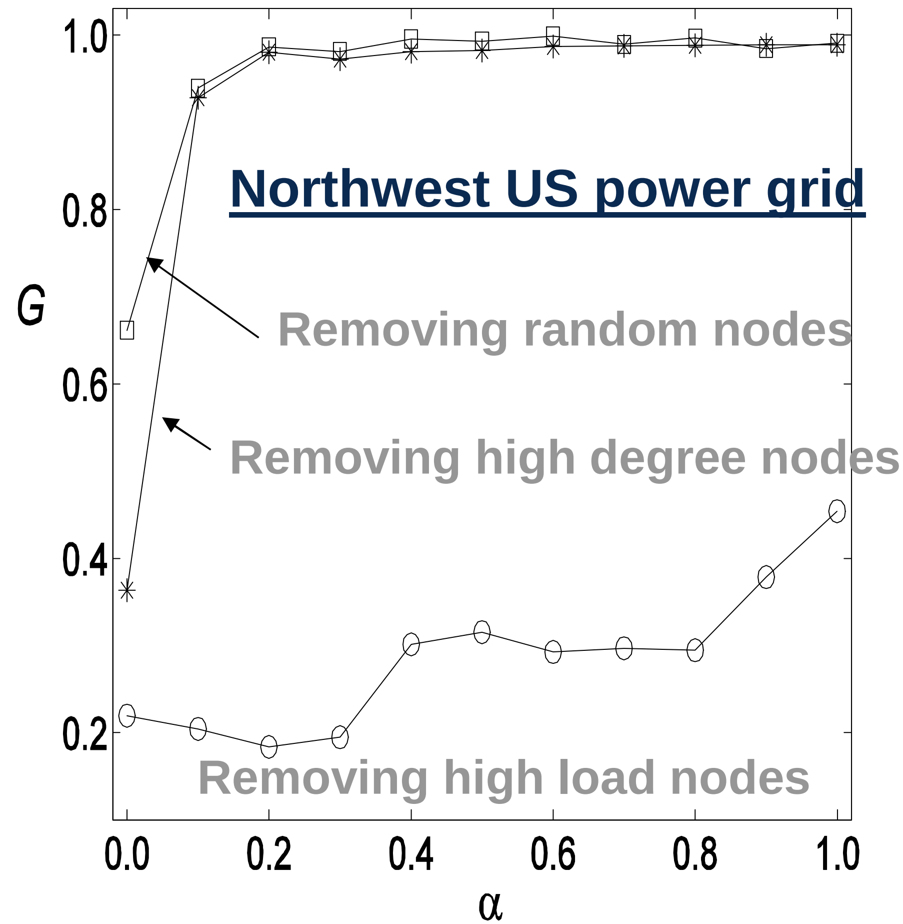
Why do we have blackouts…..?

- System load (throughput)
  - optimized to get the maximum out of the system
  - high load means small operating margins
  - has impact on interactions and component failures
- Tradeoff between load and risk of failure
  - at system level
  - for system components
- What is the role of the deregulation?

Previous physics works : Cascading Failures

Seminal paper by Motter and Lai: PRE **66,** 065102R (2002)

- No sinks/sources
- Initial load of a node, L_i, is its betweenness centrality
- Node Capacity : $C_i = (1+\alpha)L_i$
- One probes only the ***stationary state*** of the system …..
- The system is *perturbed*, and the fraction of nodes remaining in the largest component, G, is recorded after the cascade has stopped.



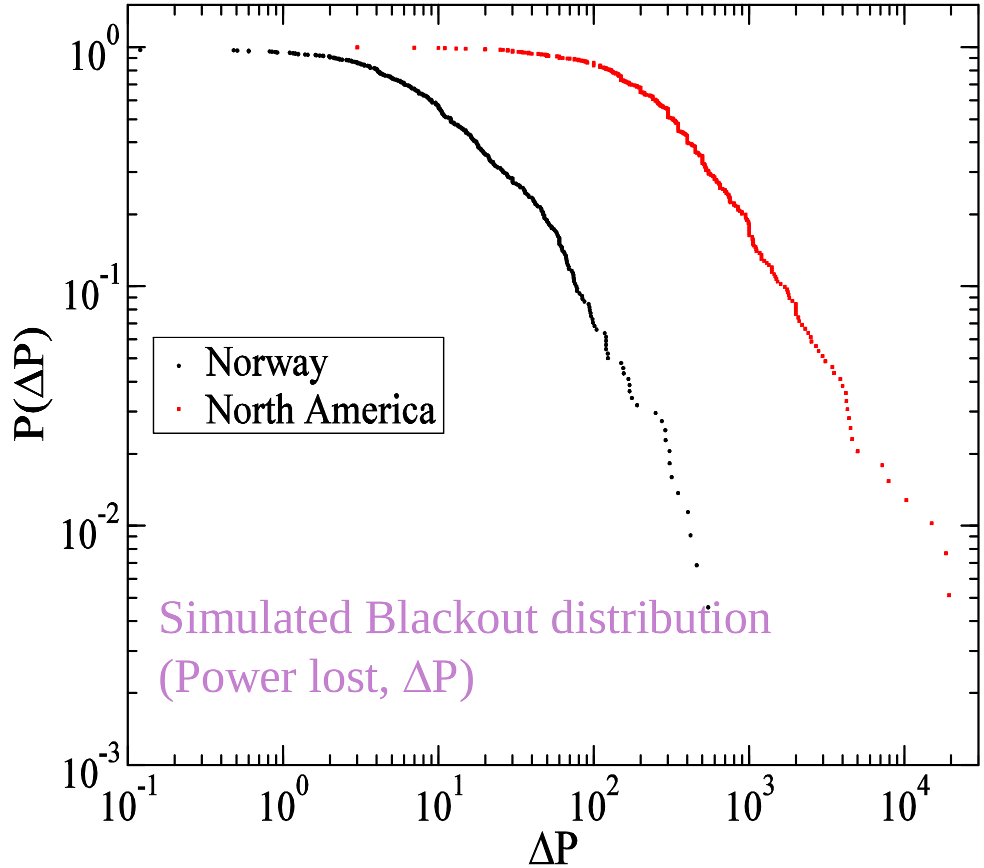
Previous works : Cascading Failures

Bakke *et al*. Europhys. Lett ***76***, *717 (2006)*

- More physically realistic model for the current flow (the Kirchoff laws)
- "*The price to pay*" :

  one has to solve a large system of linear eq.

- NOTE: Also here one probes only the *stationary state* of the system …..

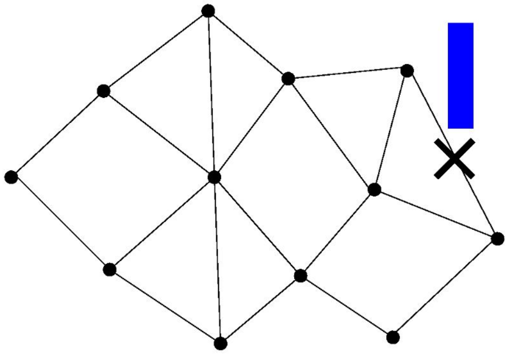


Previous works : Summary/Open Questions

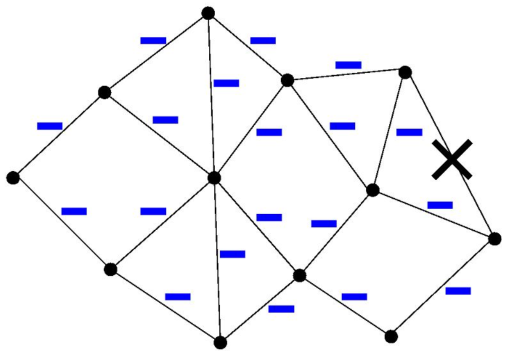
- Previous works of cascading failures exclusively considered the stationary state
- We asked ourselves: Why should the system *not* experience additional failure due to overloading during the transient period?
- Question to address:
  - What is the role played by dynamics in cascading failures in complex networks
- A dynamical model is needed for such a study
  - .... But which one to choose?

Expected differencee between a static and a dynamic model for flow redistribution

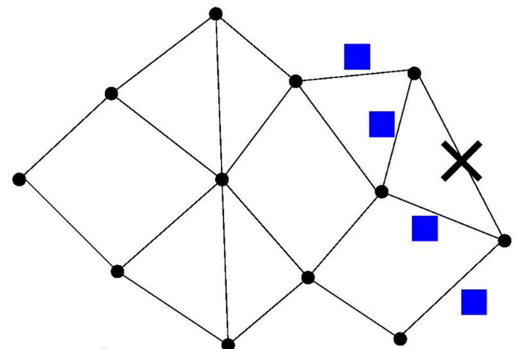
Initial failure



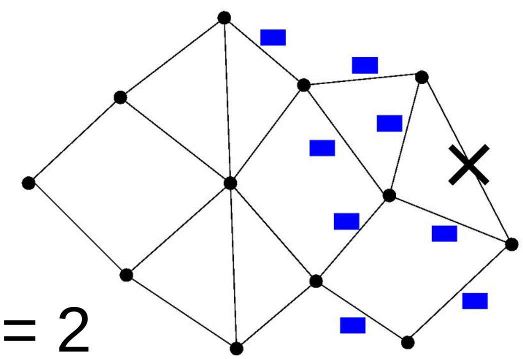
Stationary model



Dynamic model



t = 1



t = 2

Model : Requirements

- It should be:
  - Generic : no particular physical process is addressed
  - As simple as possible, but not simpler…

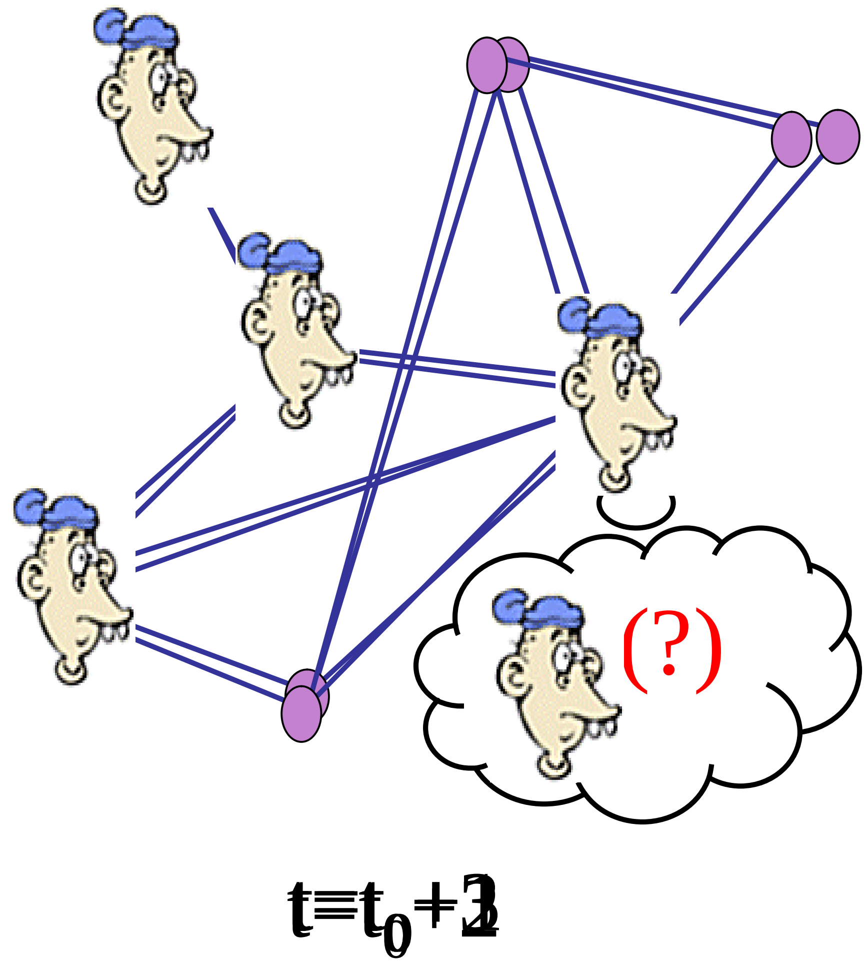
- Important ingredient (in our opinion)
  - The flowing quantity should be *CONSERVED*

Our solution : *A Random Walk (or Diffusion type)* model !

The Dynamical Model:
Basic Principle (Flow/Diffusion Model)

- Random walkers (i.e. particles) “live” on the nodes
- They are moving (flowing) around on the network!
- In each time step, a walker move *one* step forward towards one of the neighboring nodes chosen by random
- This process is repeated over and over again…….

- **Note**: The number of walkers is constant in time



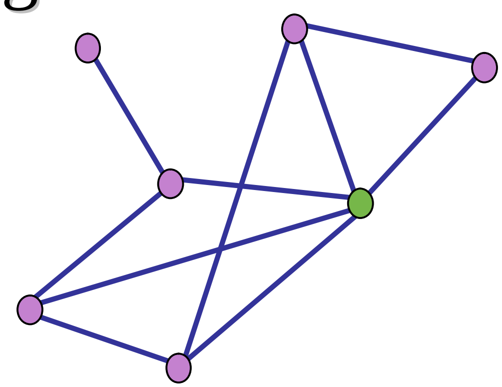
The Dynamical Model: The Master Equation

- Convention : W_{ij} refers to the link from node j to *i;*
- Define the outgoing link weight from node j : $w_j = \sum_i W_{ij}$
- The change in no. of particle at node i from ***t*** to ***t+1***

$$n_i(t+1) - n_i(t) = \sum_j W_{ij} \frac{n_j(t)}{w_j} - \sum_j W_{ji} \frac{n_i(t)}{w_i} + n_i^{\pm}(t),$$

- The "outgoing-term" is simple, and one gets

$$n_i(t+1) = \sum_j W_{ij} \frac{n_j(t)}{w_j} + n_i^{\pm}(t)$$



The Dynamical Model: The Master Equation

- Define the relative fraction of walkers (total N) at node *i*:

$$\rho_i(t) = \frac{n_i(t)}{N}$$

- The outgoing current per weight unit from node *i* is:

$$c_i(t) = \frac{\rho_i(t)}{w_i} = \frac{n_i(t)}{w_i N}$$

- Hence, it follows

$$c(t+1) = Tc(t) + j^{\pm}(t); \qquad T_{ij} = \frac{W_{ij}}{w_i}$$

The Dynamical Model : Summary

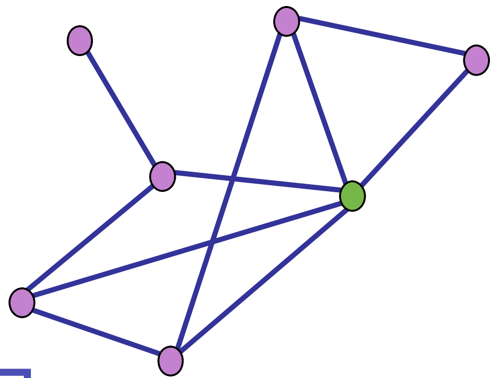
- Our simple dynamical model incorporates:
  - Flow conservation
  - Network topology
  - Load redistribution

$$c(t+1) = Tc(t) + j^{\pm}(t); \qquad T_{ij} = \frac{W_{ij}}{w_i}$$

$c_i(t)$: The outgoing current from node *i* per link weight unit

The Dynamic Model

Network:



$\mathcal{N}$ set of nodes

$\mathcal{L}$ set of links

$\boldsymbol{W}$ adjacency matrix ($W_{ij} \geq 0$, link weight)

Model dynamics:

$$n_i(t+1) = \sum_{j=1}^{\mathcal{N}} T_{ij} n_j(t) + n_i^{\pm}$$

(Master equation)

$n_i(t)$ number of particles hosted by node *i* at the time *t*

$T_{ij} = W_{ij}/w_j, \qquad w_j = \sum_{\ell=1}^{\mathcal{N}} W_{\ell j}$

$n_i^{\pm} > 0$ node is source, $\qquad n_i^{\pm} < 0$ node is sink

Ref : I. Simonsen, L. Buzna, K. Peters, S. Bornholdt, D. Helbing, Phys. Rev. Lett. **100**, 218701 (2008)

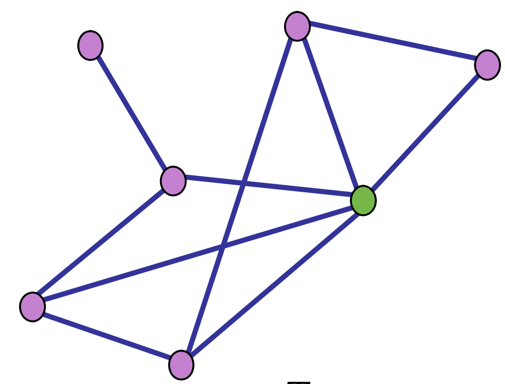
Stationary and Dynamic Models of Cascading Failures

Model normalization:

$\rho_i(t) = n_i(t)/N$ nodal particle density

$c_i(t) = \rho_i(t)/w_i$ utilization of outflow current

$j_i^\pm = n_i^\pm/(N w_i)$ sinks and sources terms



Dynamic model → $$\boldsymbol{c}(t+1) = \boldsymbol{\mathcal{T}}\boldsymbol{c}(t) + \boldsymbol{j}^\pm,$$ $(\tau = T^T)$

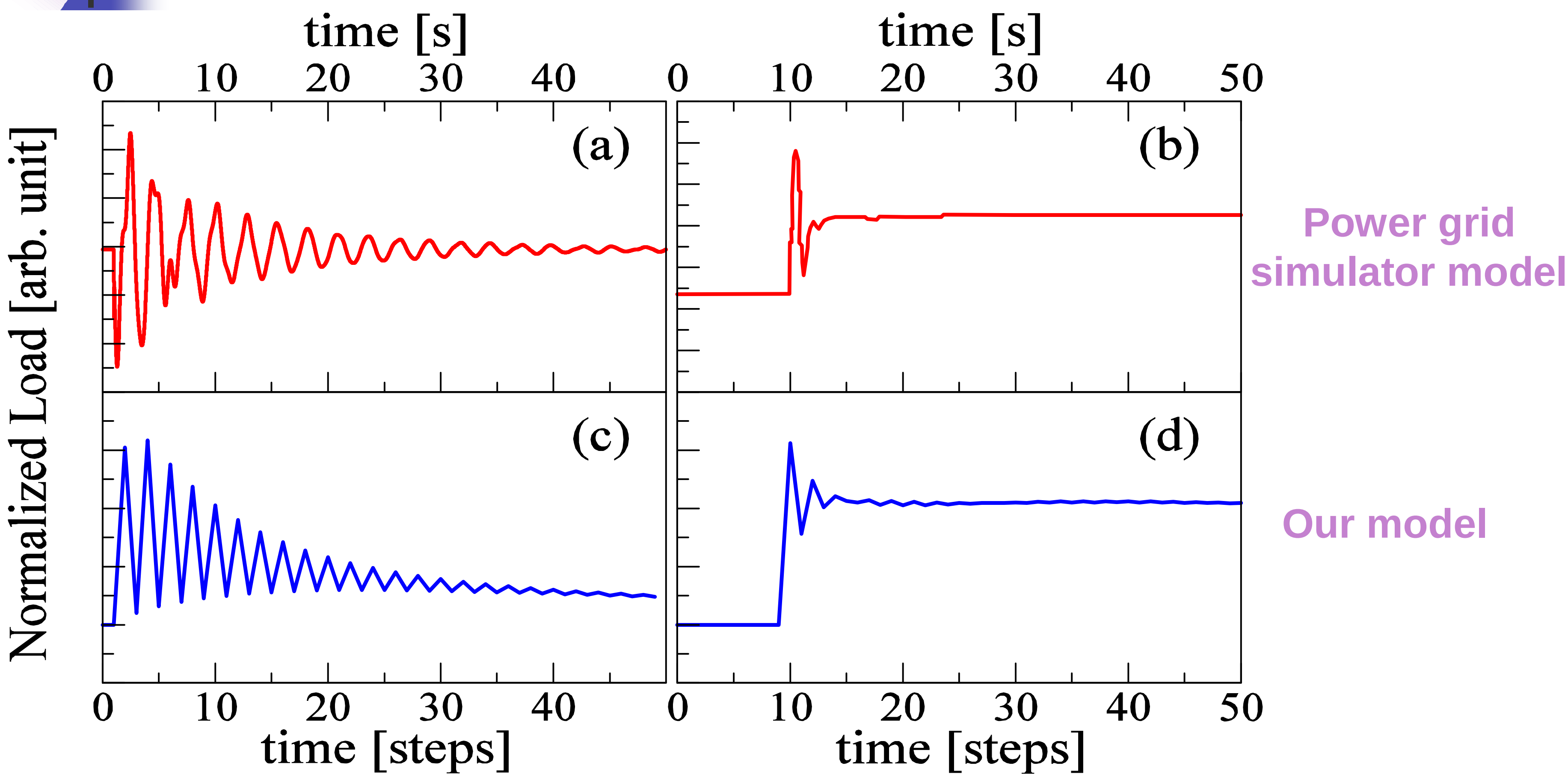
$c_i^{(0)}(\infty) = 1/(N w_i)$ stationary solution for $\boldsymbol{j}^\pm = 0$, otherwise

Stationary model → $$\boldsymbol{c}(\infty) = \boldsymbol{c}^{(0)}(\infty) + (\boldsymbol{1} - \boldsymbol{\mathcal{T}})^+ \boldsymbol{j}^\pm$$

$(\boldsymbol{1} - \boldsymbol{\mathcal{T}})^+$ generalized inverse of matrix $\boldsymbol{1} - \boldsymbol{\mathcal{T}}$ Link flow:

$C_{ij}(t) = W_{ij} c_j(t)$ current on link from *j* to *i* $L_{ij}(t) = C_{ij}(t) + C_{ji}(t)$

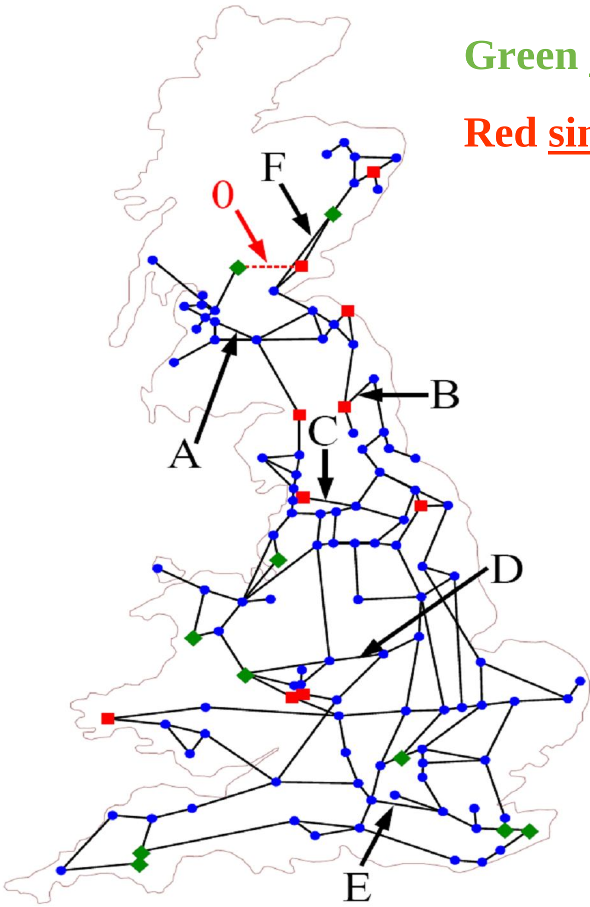
Model Dynamics: Is it realistic?



Source : R. Sadikovic, Power flow control with UPFC, (internal report)

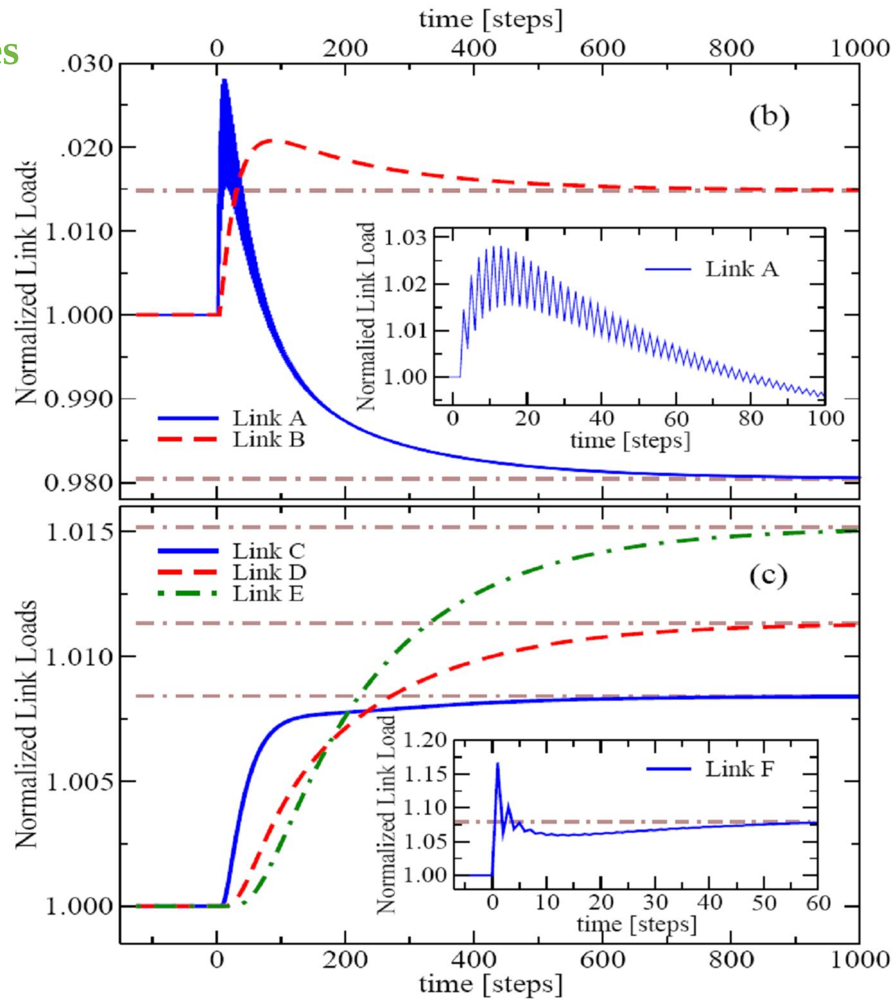
EUROSTAG power simulator : wwwaurostag.epfl.ch

Model Dynamics: UK high voltage power grid (300-400kV)



Green source nodes

Red sink nodes



At t=0, link 0 is broken!

When does a link/node fail?

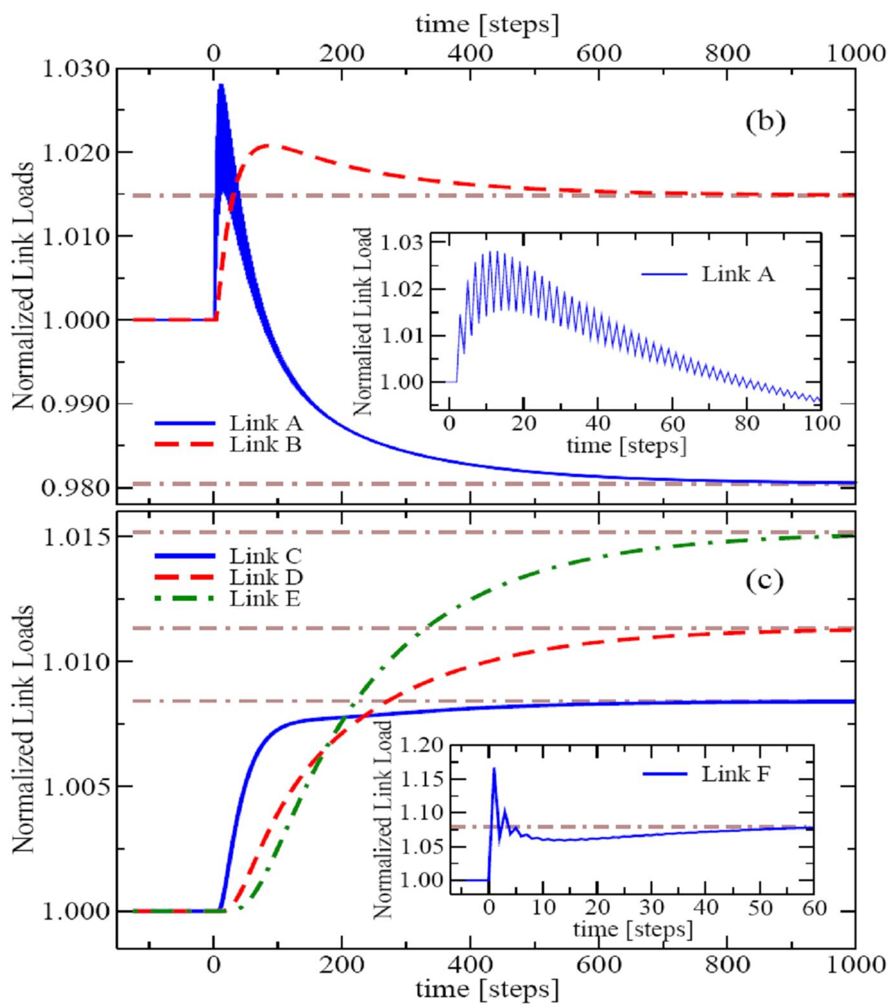
- Link/node capacities relative to the undisturbed state (L_{ij}) via a *tolerance parameter α*

$$\mathcal{C}_{ij} = (1+\alpha)\, L_{ij},$$

- A link/node fails whenever its *current* load, $C_{ij}(t)$ exceeds the capacity of *that* link/node

Failure if :

$$C_{ij}(t) > (1+\alpha)L_{ij}$$



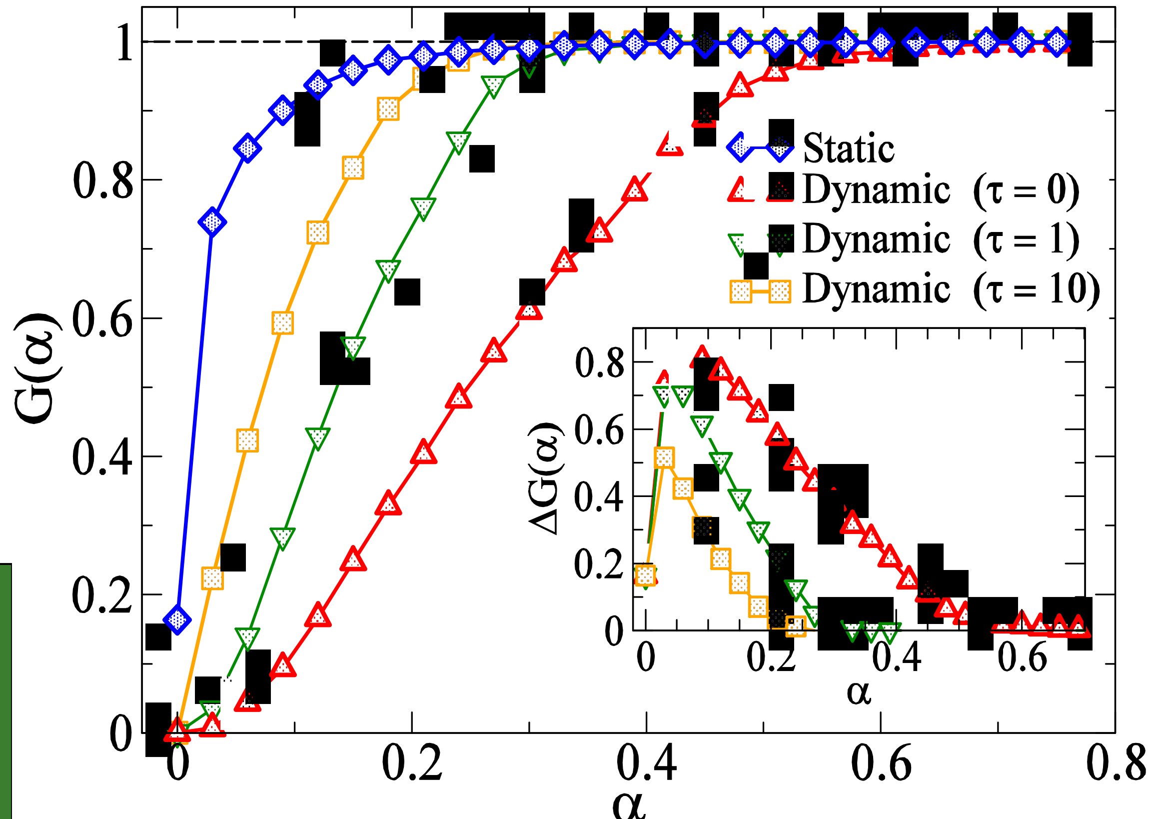
Main steps of the simulations

The simulations consist of the following steps:

1. A *triggering event* (t=0) [remove a random link]
2. Calculate the [new] link loads $C_{ij}(t)$
3. Check if any links are *overloaded* via $C_{ij}(t) > (1+\alpha)L_{ij}$
    1. If so remove such overloaded links
4. Repeat step 2 and 3 till no more links are overloaded
5. Average the results over the triggering event of pnt. 1 (and source and slinks locations)

Stationary Model vs. Dynamic Model :
The northwestern US power transmission grid

$\lvert\mathcal{N}\rvert$	number of nodes (5000)
$\lvert\mathcal{L}\rvert$	number of links
$\lvert\mathcal{N}_R\rvert$	number of remaining nodes
$\lvert\mathcal{L}_R\rvert$	number of remaining links



$$G_{\mathcal{L}}(\alpha) = \frac{\lvert\mathcal{L}_R\rvert}{\lvert\mathcal{L}\rvert} \approx G_{\mathcal{N}}(\alpha) = \frac{\lvert\mathcal{N}_R\rvert}{\lvert\mathcal{N}\rvert} = G(\alpha)$$

The stationary model can <u>*overestimates robustness*</u> by more than 80% (in this case)

Overload exposure times may be relevant and will increase the robustness……

Stationary Model vs. Dynamic Model : The role of the two time-scales

- There are two characteristic time-scales in the problem:
  - Overload exposure time (protection system response time): τ
  - Typical transient time for the dynamics: τ_0
- Control parameter : $$\chi = \frac{\tau}{\tau_0}$$
  - Static cascading failure model: $\chi >> 1$
  - Dynamical ($\tau=0$) cascading failure model : $\chi=0$

- The real situation is probably somewhere in between….

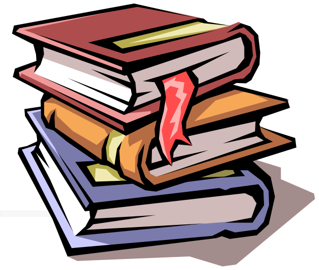
Conclusions

- *The dynamical* process on the network *is* important to consider when evaluating network robustness (cascading)
  - Using a stationary model may dramatically overestimate (by 80-95%) the robustness of the underlying network
  - The actual overestimation do depend on the actual overload exposure time

- In a dynamical model:
  - links may fail that otherwise would not have done so (overshooting)
  - The proximity to a disturbance is more important in a dynamical model

Thank you for your attention!

References



- Dynamical model :
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  - See also :
    - Phys. Rev. Lett. **90**, 14870 (2003).
    - Physica A **357**, 317 (2005).
    - Physica A **336**, 163 (2004).
- Stationary models:
  - Motter and Lai, Phys. Rev. E **66,** 065102R (2002).
  - Bakke *et al*. Europhys. Lett. ***76,*** *717 (2006)*.