A heterogenitások hatásának vizsgálata energia hálózatokban

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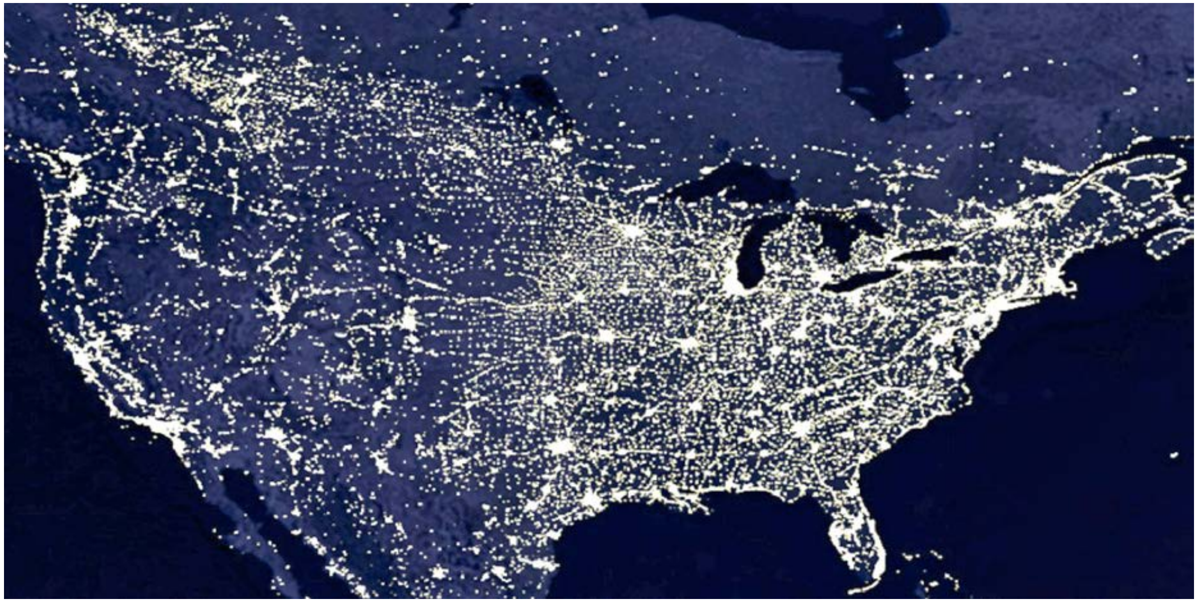
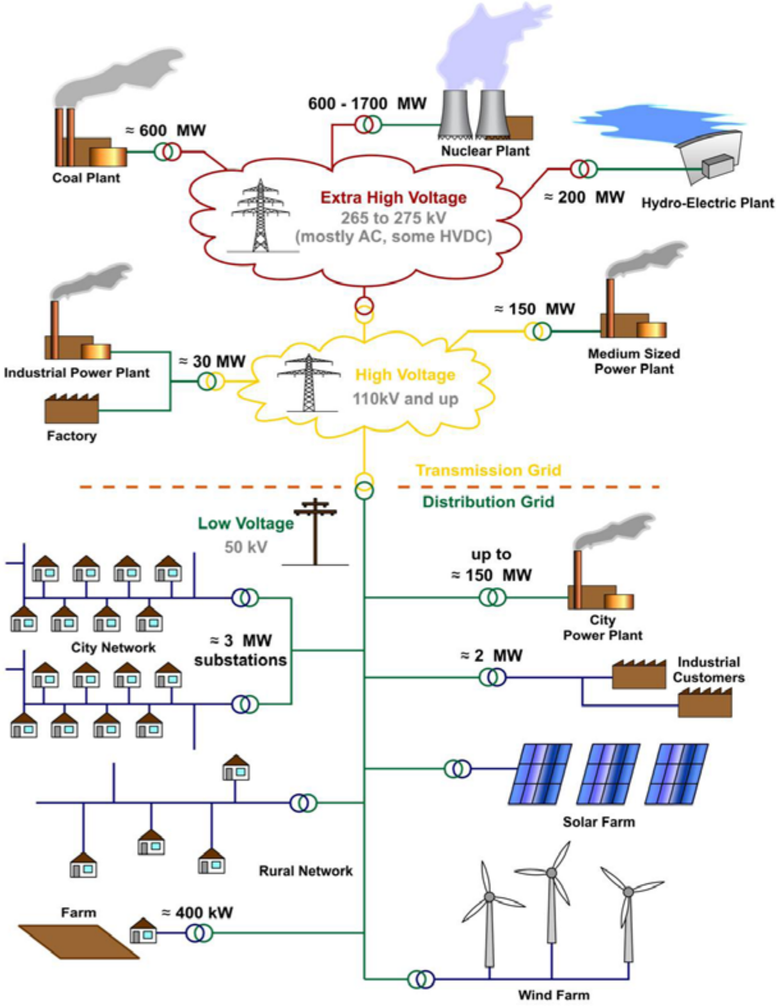
Electric Energy & Power Network





- Electric energy is critical for our technological civilization
- Purpose of electric power grid: generate/transmit/distribute
- Challenges: multiple scales, nonlinear, & complex system, growing number of renewables & deregulation

Challenge: Scale-free blackout size distributions

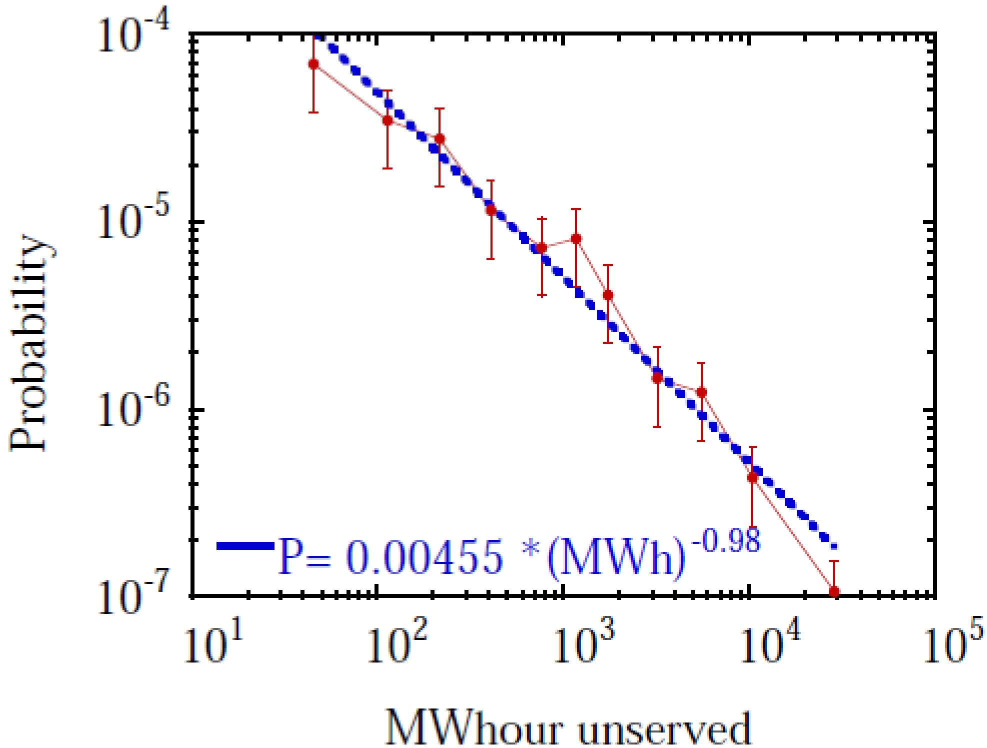


Figure 4. Probability distribution function of energy unserved for North American blackouts 1993-1998.

B. Carreras et al, Proceedings of Hawaii International Conference on System Sciences, Jan. 4-7, 2000, Maui, Hawaii. 2000 IEEE

Extreme events occur more frequently than by Gaussian model prediction

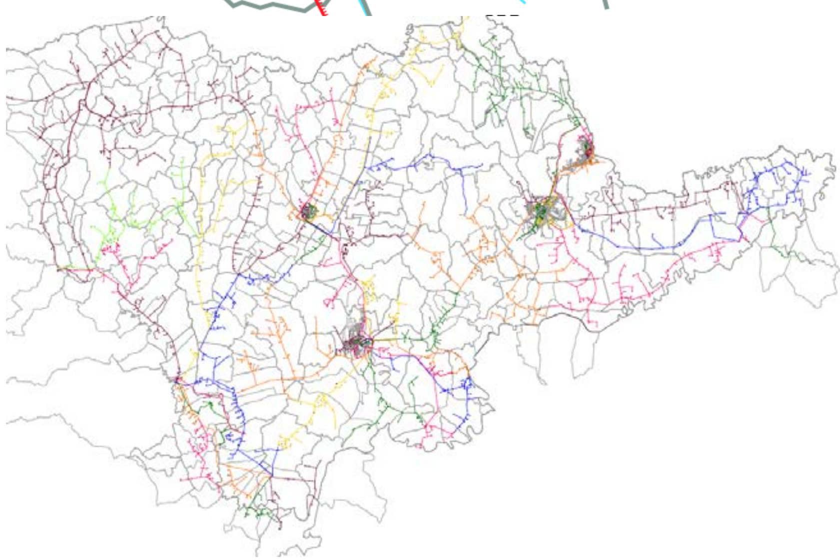
US HV *4941* nodes

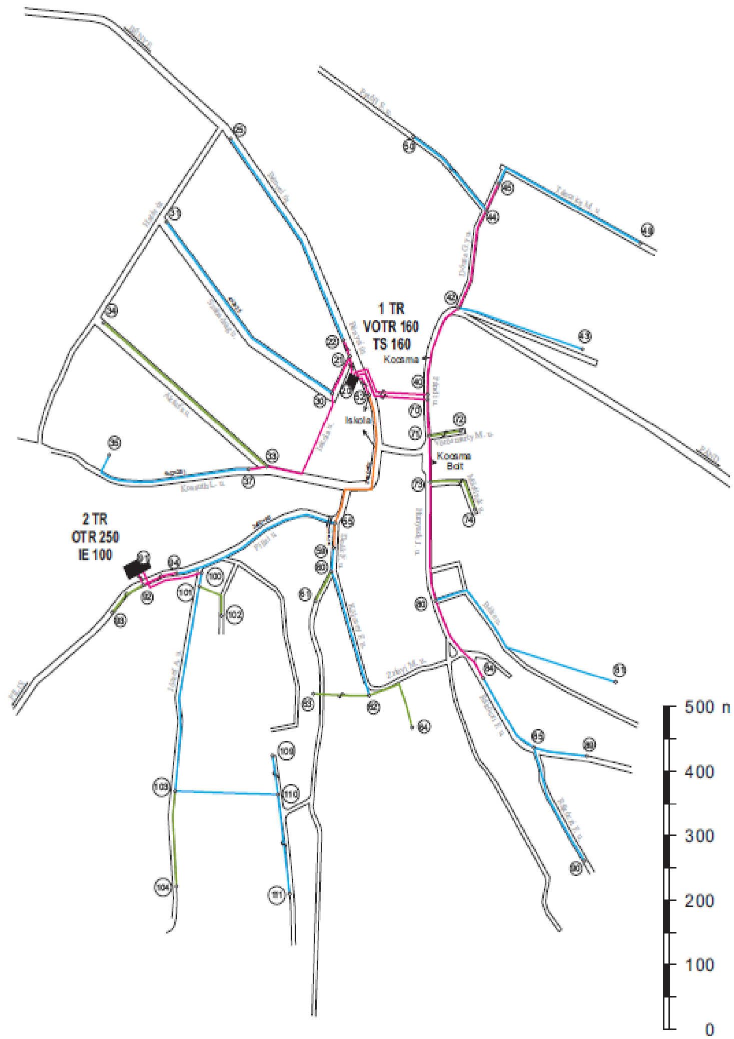
Self-Organized Criticality (SOC) is assumed for modeling this:

Competition of supply and demand

Power-grids form heterogeneous, hierarchical modular networks

- Multi-level : high – medium - low voltages





Synthetic Power grid generation

We created large: HV (transmission) - MV (sub-transmission) - LV(distribution) level graphs with weights

For HV : from utilities and system operators

For MV, LV: representative or reference network models (RNM) : NEW algoritm using iterative random MATLAB processes, using empirical electrical distributions

Admittance matrix:

for HV: Hungarian example

for MV,LV: synthetic grid modeling

HV: undirected loop top $L = \frac{1}{N(N-1)} \sum_{j \neq i} d(i,j)$

L $C^W = \frac{1}{N} \sum_i 2n_i / k_i(k_i - 1)$ d t $C^\Delta = \frac{\text{number of closed triplets}}{\text{number of connected triplets}}$.

of nodes

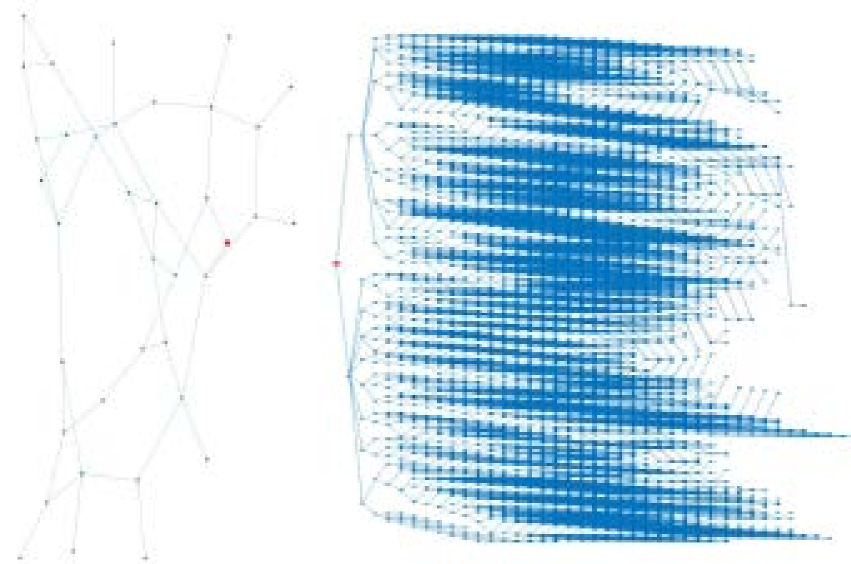


FIG. 1: Structural repreentation of the synthetic networks. Left side: HV, right side: a radial subnetwork. The highlighted red node connects the two layers. The network on the picture has 68850 nodes and 68849 edges.

TABLE I: Power-grids generated and studied.

Network	N	Edge no.	L	C^Δ	C^W
1M	1098583	1098601	1.7440×10^6	0	0
1.5M	1455343	1455367	1.0457×10^6	0.0594	0.0486
2.5M	2356331	2356360	1.6162×10^6	0.0851	0.0586
23M	23551140	23551254	2.1129×10^6	0.0626	0.0741

Network graph analysis

- Basic network distributions:

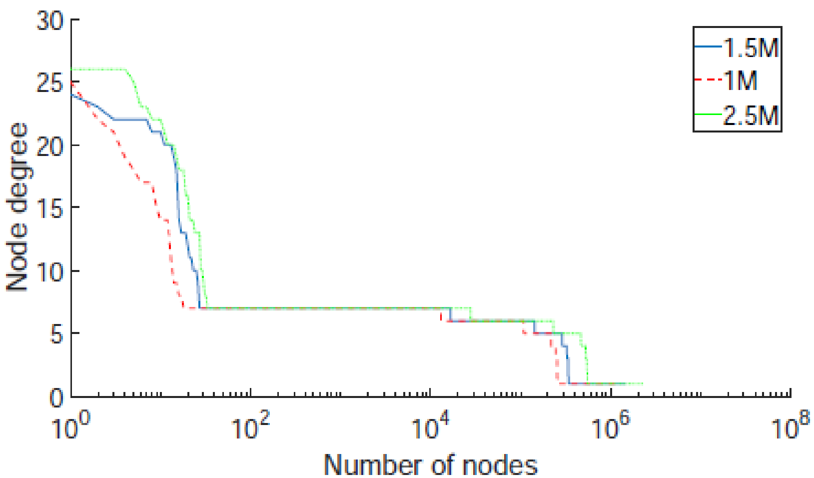


Figure 2. Node degree distribution of the synthetic power-grids generated.

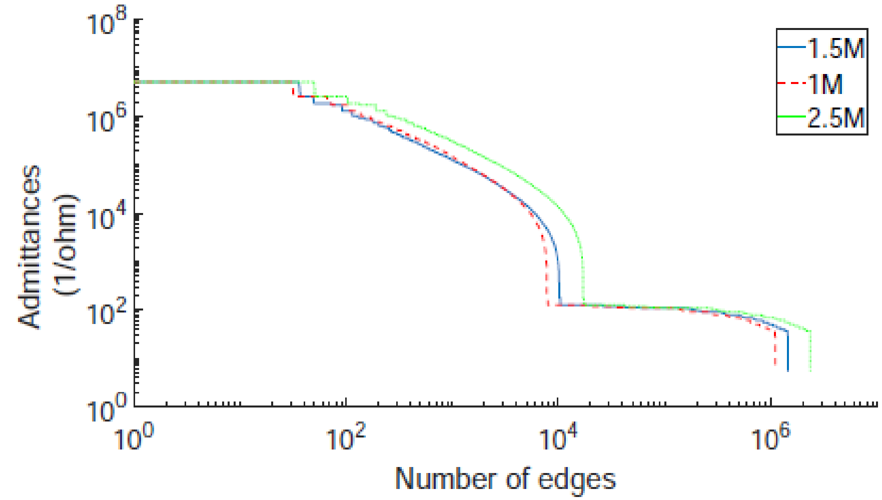


Figure 3. Admittance distribution of the power-grids generated.

- Topological dimension: *<N(R)> ~ R^D* by Breadth first search from each node

$$D_{\text{eff}}(D+1/2) = \frac{\ln\langle N_R\rangle - \ln\langle N_{R+1}\rangle}{\ln(R) - \ln(R+1)}$$

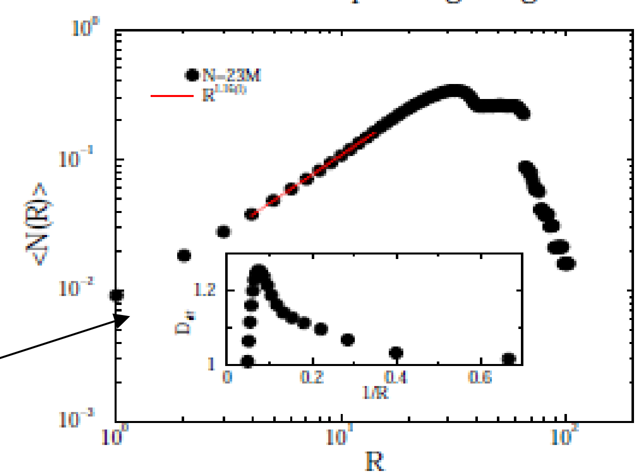


FIG. 4: Average number of nodes within chemical distanc R in the 23 graph. Dashed line shows a power-law fit fo $4 < R < 20$. Inset: local slopes defined in Eq. 6.

The synchronization model

- Network failures, blackouts can be described by de-synchronization of AC power

Simplest model : second order Kuramoto equations for phases θ_i of oscillato

$$
\begin{aligned}
\dot{\theta}_i(t) &= \omega_i(t) \\
\dot{\omega}_i(t) &= \omega_{i,0} - \alpha\dot{\theta}_i(t) + \frac{K}{N_i}\sum_j A_{ij}\sin[\theta_i(t) - \theta_j(t)]
\end{aligned}
$$

coupled by control parameter: K , admittance matrix: A_{ij} and α: dissipation

Quenched disorder in the topology, admittances and in the intrinsic frequencies: $\omega_{i,0}$ of the nodes:

The synchronization transition

- Synchronization is measured by the order parameter

$$z(t_k) = r(t_k)\exp i\theta(t_k) = 1/N\sum_j \exp\left[i\theta_j(t_k)\right]\,, \qquad R(t_k) = \langle r(t_k)\rangle$$

- Numerical integration results in a first order phase transition for a fully coupled (mean-field) network

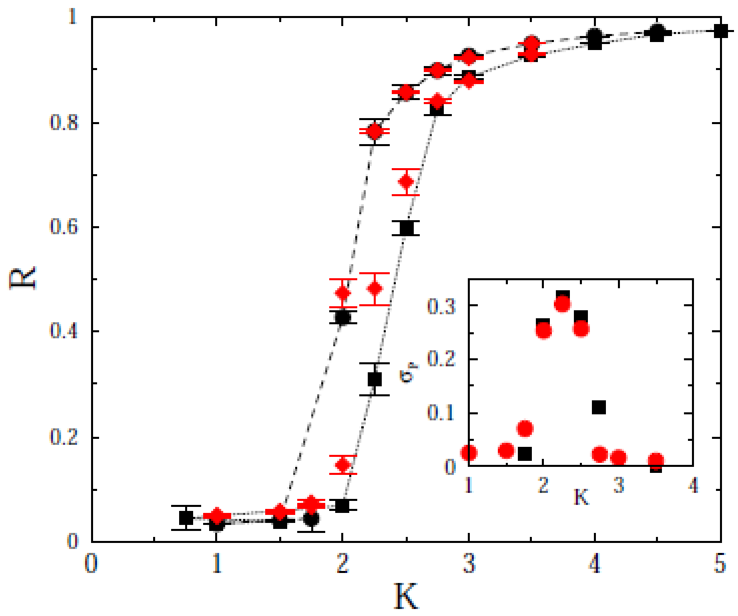


FIG. 2: Hysteresis in the steady state order parameter in fully coupled networks of sizes $N = 1000$ (boxes) and $N = 500$ (diamonds). Inset: $\sigma_R(K)$ peaks for the two different network sizes investigated.

Two-dimensional lattice grid

- Synchronization transition on homogeneous, 2D lattices:
- Numerical integration results in a **crossover** t synchronization at large *K* values
- "Fast" relaxation to the steady state (no power-law)
- Hysteresis
- What is the consequenc of heterogeneities ?

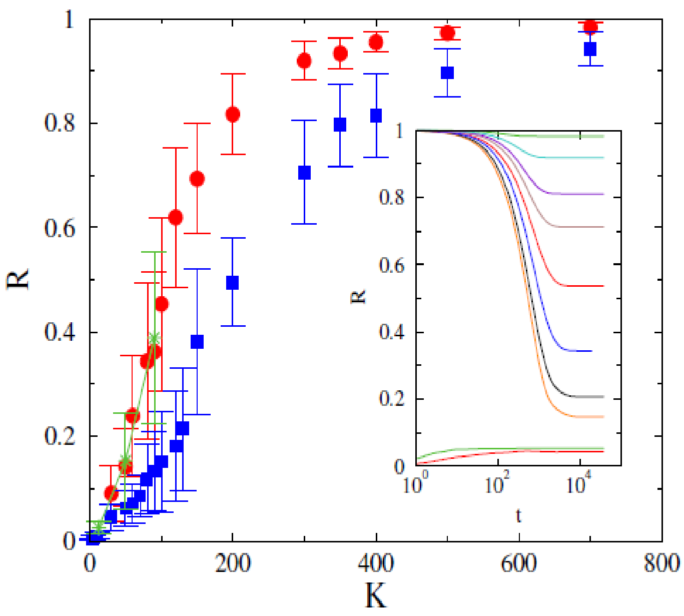
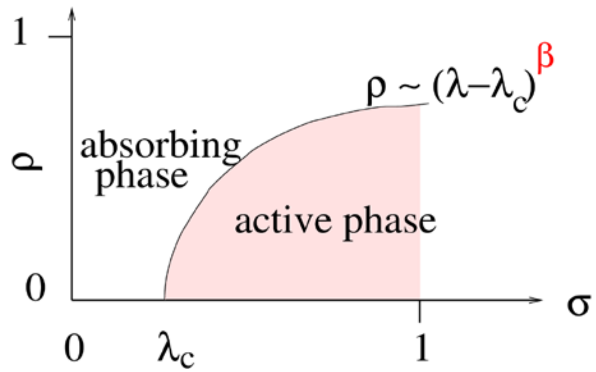
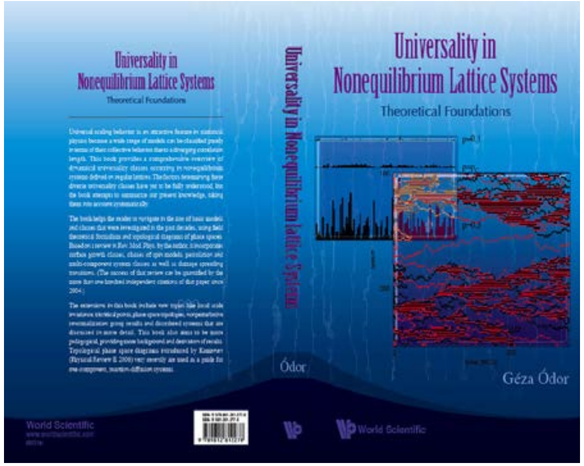


Figure 6. Phase synchronization transition in the steady state in 2D networks of sizes $N = 500 \times 500$ (red bullets), $N = 1000 \times 1000$ (blue boxes) using $a = 3$ and $N = 500 \times 500$ (green stars) using $a = 1$. Inset: time dependence or $R(t)$, in case of the $N = 500 \times 500$ lattice, for control parameters: $K = 700, 350, 200, 150, 100, 80, 60, 50$ in case of synchronized initial condtion (top to bottom curves) and $K = 700, 100$ de-synchronized initial condition (top to bottom curves).

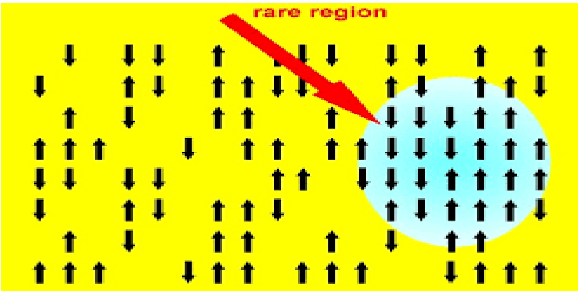
Heterogeneities in other network models

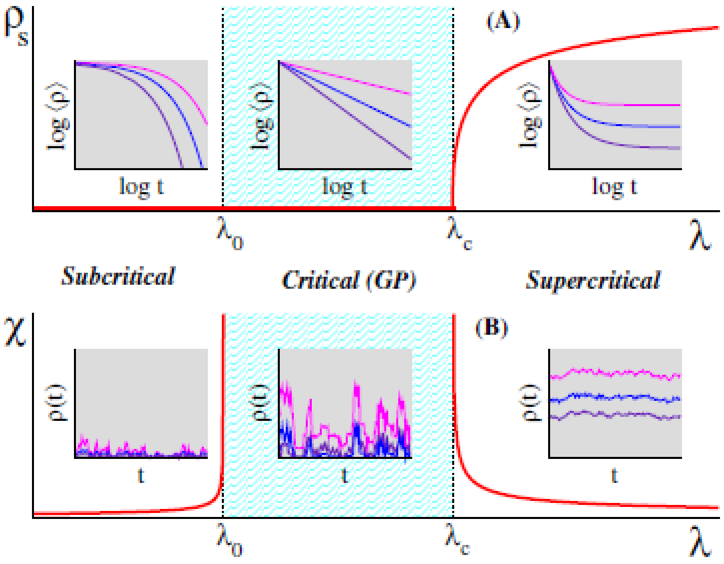
On lower dimensional regular, Euclidean lattices: critical point between ordered and disordered phases *due to the fluctuations*





Quenched disorder : Slowly decaying rare regions





Rounds phase transition, *Griffiths phase:*

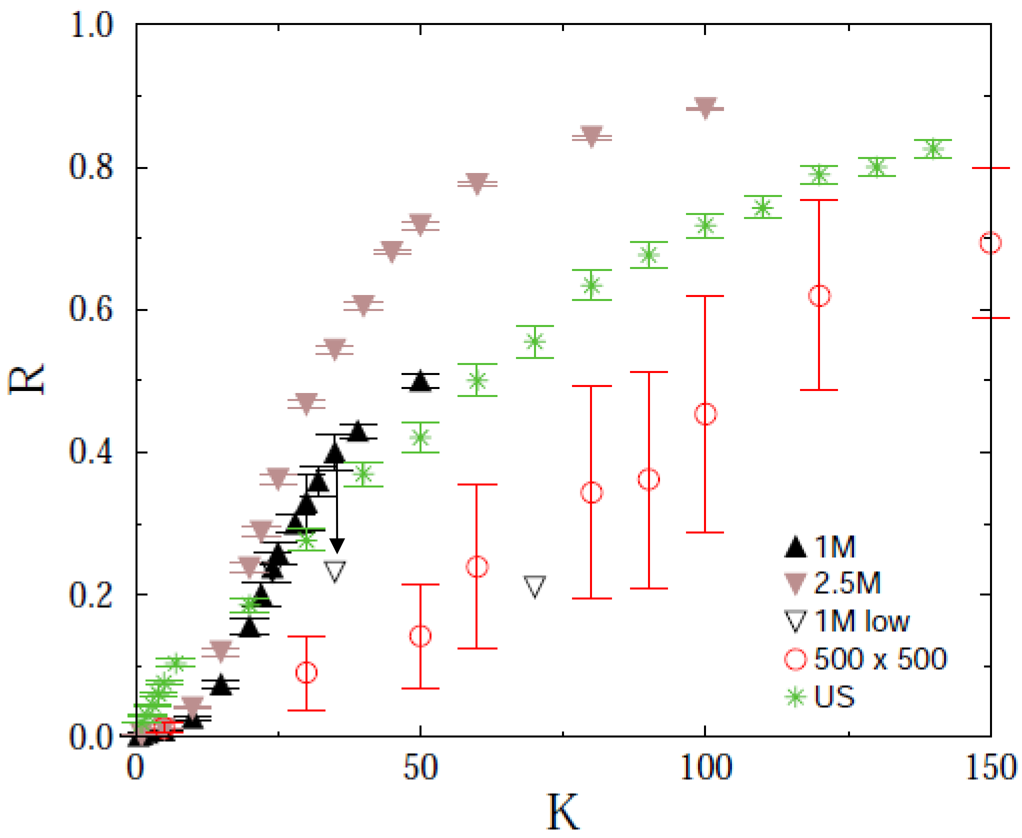
Synchronization in power-grids

Synthetic and real power grids considered without noise

Bigger synchronization *R* values than in *2D* at a given *K* but the stability is weak

Exponential relaxation remains

Adding noisy oscillators: small effects. Even for a Gaussian with $\sigma = 3$: few percent drop, Maximum -20% of *R* at the transition



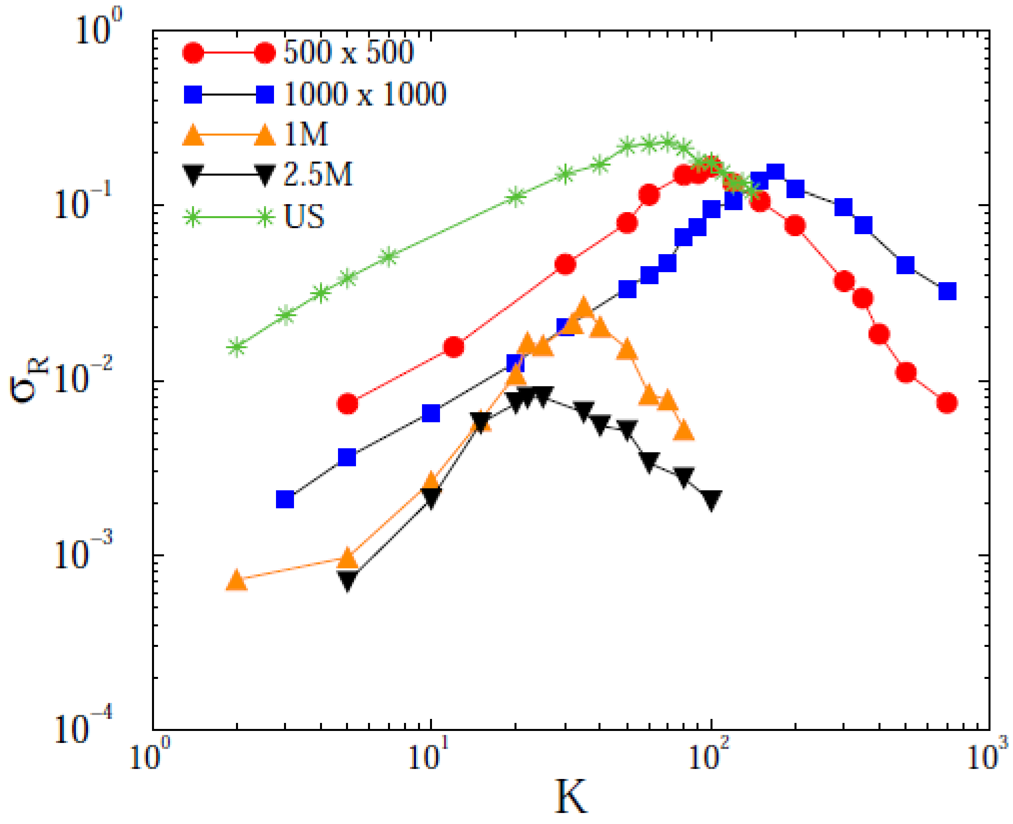
Synchronization in power-grids

Standard deviation σ_R over
50 samples and fixed time
windows in the steady state

Fluctuations peaks disappear
as $N \to \infty$

No real phase transition,
but a crossover,
like in the Kuramoto model

Crossover peaks are at
lower *K-s (~30)*
than in *2D (~100-200)*



De-synchronization avalanches in power grids

The duration distribution of de-synchronization events:

$R = 1 \rightarrow R = 1/N^{0.5}$

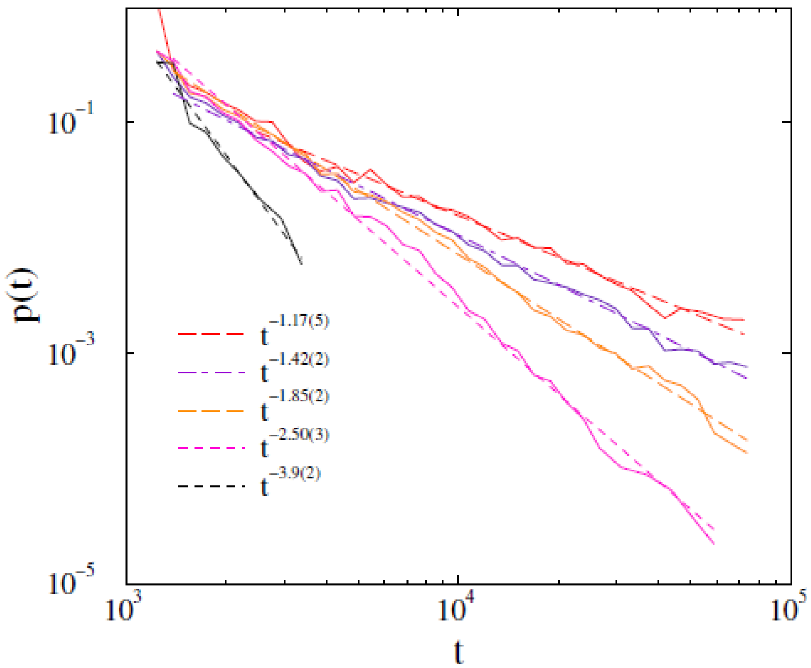


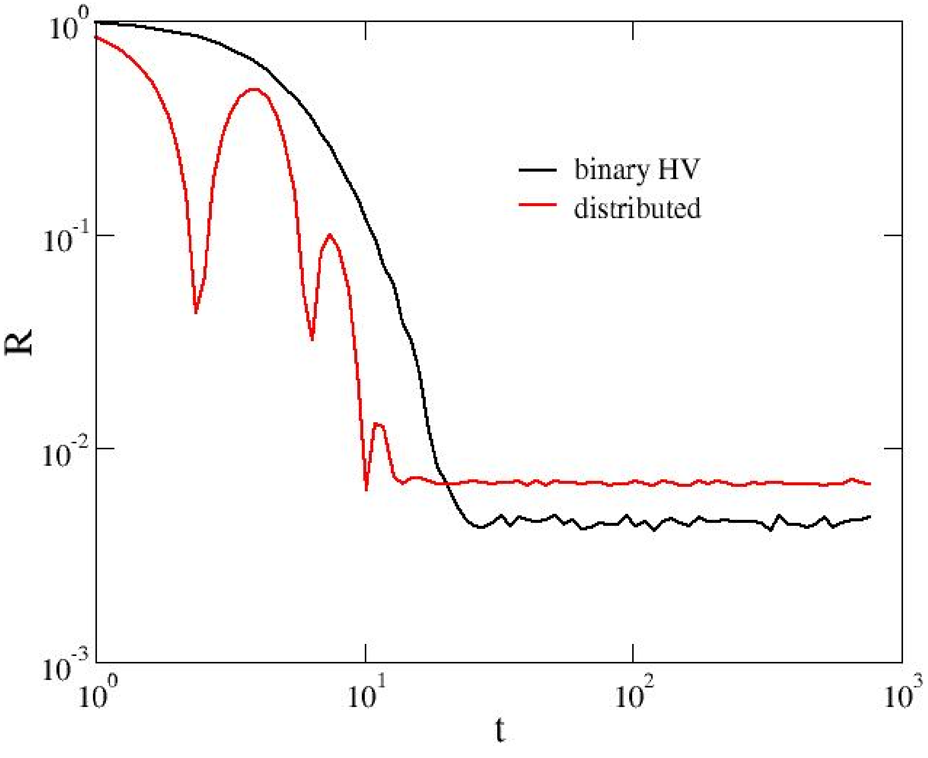
Figure 10. Avalanche duration distribution in the 1M power grid for $a = 3$ and different coupling values $K = 0.7, 0.6, 0.5, 0.4, 0.2$ (top to bottom solid curves). Dashed lines: PL fits for the tails.

K-dependent power-law tails: scale-free distributions like in GP

Centralized vs distributed sources

Renewable energy sources → distributed across the whole network → Instability ?

We compared HV sources ↔ distributed



Conclusions

The topological heterogeneity smears the transition that remains for large couplings only : no real phase transition but a crossover

With respect to 2D topological+weight disorder enhances the synchronization but decreases the fluctuations

Scale-free desynchronization duration avalanches → Rare large events occur more frequently than in case of a Gaussian mathematical model

Frustrated synchronization ?

K-dependent power-law tails : heterogeneity effects (no SOC assumption)

Fault tolerance study : many stochastic elements have low influence

Distributed energy sources: After initial instability higher synchronization than in HV

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