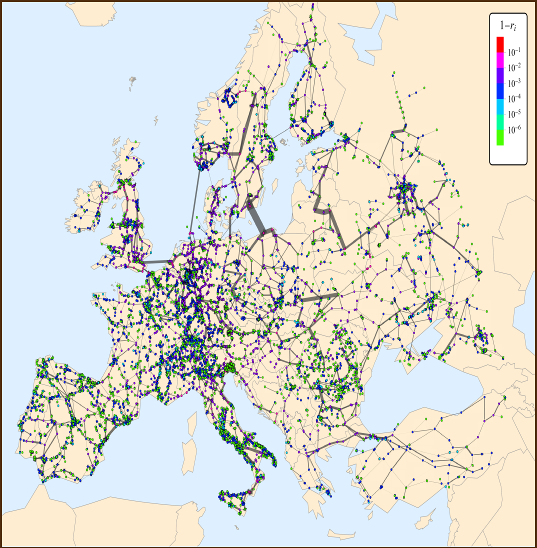

Heterogeneity of the European grids

Edge weight, community structure, structural improvements

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Géza Ódor
Shengfeng Deng
Bálint Hartmann
István Papp
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GPU Day, May 16, 2023

MŰEGYETEM 1782

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Outline

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Motivation: Stabilizing against cascade failures, blackouts and increasing efficiency

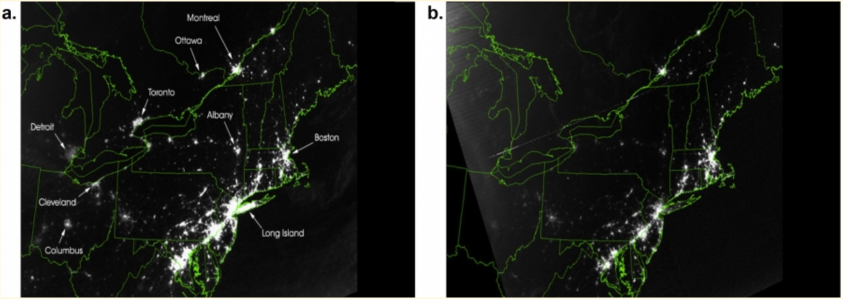

Figure: 2003 North American Blackout *(a)* Satellite image on Northeast United States on August 13th, 2003,at 9:29pm (EDT), 20 hours before the 2003 blackout. *(b)* The same as above, but 5 hours after the blackout [Barabási and Pósfai, *Network science*].

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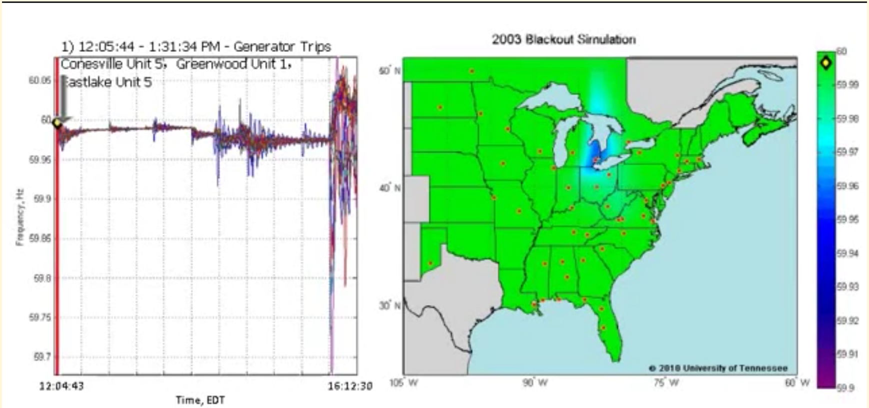
Motivation: Stabilizing against cascade failures, blackouts and increasing efficiency



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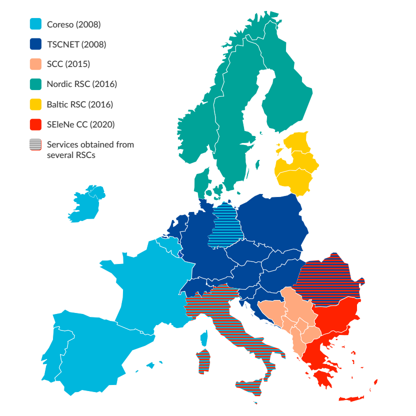
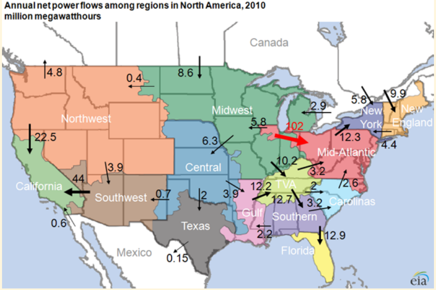
Interconnections and Transmission System Operators



(a) European (electric) power regions *ENTSO-E.*



(b) US (electric) power regions and flows *U. S. Energy Information Administration.*

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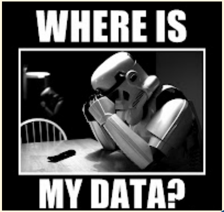
Constructing the network, outlining the task

To be done...

- **real** network
- valid physical parameters
- weighting the links
- identify weak points wrt. synchronization
- Find possible way(s) to improve the network.
- Graph theory + engineering
- Crosscheck the results

Problems

- Detailed data is not open source
- Open source data is incomplete
- Correct assumptions to complete the data set



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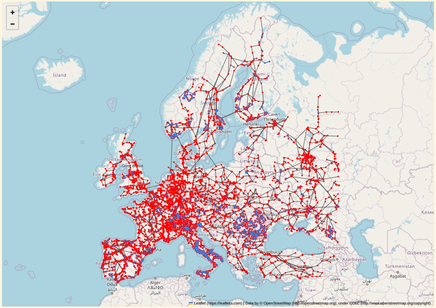
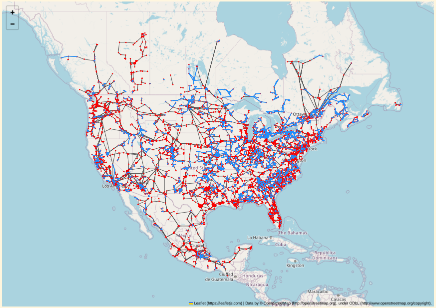
The grids, 2016 data



(a) EU high voltage power grids [Ódor, Benedek, Deng, *et al.*, "Heterogeneity of the European grids: nodal behaviour, edge weight, frequency analysis"].



(b) US high voltage power grid [Ódor, Benedek, Deng, *et al.*, "Heterogeneity of the European grids: nodal behaviour, edge weight, frequency analysis"].

- EU-HV: 13478 nodes with 18004 links
- US-HV: 14990 nodes with 18804 links
- Clustering, Watts-Strogatz: $C = \frac{1}{N}\sum_i 2 \cdot \frac{n_i}{k_i}(k_i - 1)$

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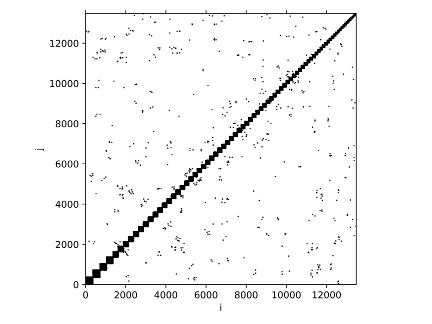
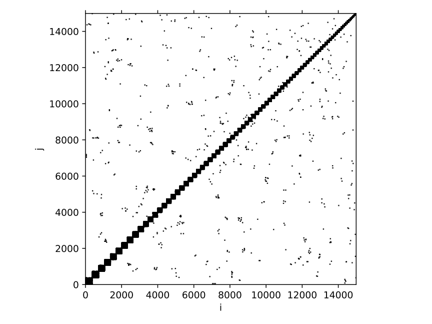
The grids, 2016 data

- $C_{US} = 0.084$ and $C_{EU} = 0.089$. Both networks: much higher clustering coefficient than that of a random graph with the same N and E $C_r = \langle k \rangle / N = 0.000186229$.



(a) EU-HV power grid adjacency matrix [Ódor, Deng, Hartmann, *et al.*, “Synchronization dynamics on power grids in Europe and the United States”].



(b) US-HV power grid adjacency matrix.

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First results: Considering topology accuracy only in network

The underlying model: **Kuramoto oscillators** (swing equation)

$$\dot{\theta}_i(t) = \omega_i(t)$$

$$\dot{\omega}_i(t) = \omega_i(0) - \alpha\dot{\theta}_i(t) + K\sum_{j=1}^{N} A_{ij}\sin(\theta_j(t) - \theta_i(t))$$

Synchronization measures:

- Global order parameter $R(t_k)$:

$$z(t_k) = r(t_k)\exp(i\theta(t_k)) = \sum_{j=1}^{N}\exp(i\theta_j(t_k))$$

$$R(t_k) = \langle r(t_k)\rangle$$

- Frequency spread (variance):

$$\Omega(t, N) = \left\langle \frac{1}{N}\sum_{j=1}^{N}(\overline{\omega} - \omega_j)^2 \right\rangle$$

- Line-cut threshold:

$$F_{ij} = |\sin(\theta_j - \theta_i)| > T$$

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Using GPUs

- Simulation on K40 Tesla GPU cards
- Leo and Komondor Supercomputers
- Large interacting system: massively parallelized
- Written in CUDA

- boost::numeric::odeint from odeint.com
  - supports various vector backends for accelerators
- VexCL/OpenCL libraries
- Integration method: Bulirsch-Stoer

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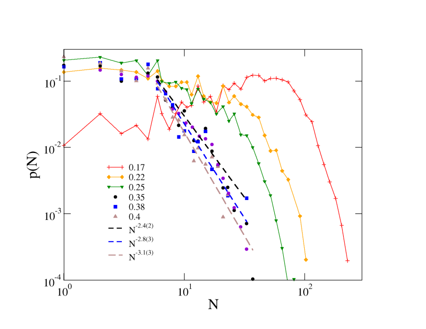
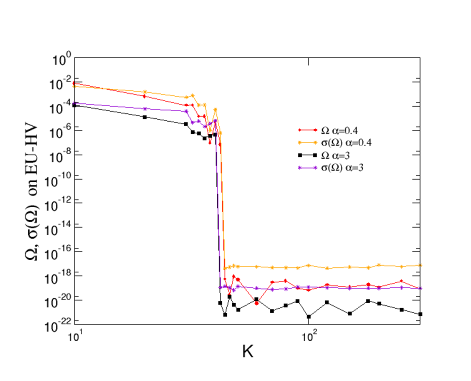
Hybrid synchronization transition an PL of cascade sizes

- investigations done by GPU optimized simulations
- Cascade failures follow power law distributions



- Dragon-King (DK) cascades
- Phase transition in Ω



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Making the grid more physical. Weights.

- Missing over 5000 links' parameter
- Consider characteristic values of relevant physical quantities (engineer involved)
- Process the data and fill the gaps: classify the links in voltage levels
- Work on common voltage level
- Weight as:

$$W_{ij} = \frac{\frac{P_{ij}}{X_{ij}}}{\left\langle \frac{P}{X} \right\rangle}$$

- Cross check with known data (Hungarian power grid)
- Run simulations, identify synchronization levels, weak nodes, essential links
- Future: Come up with more elaborated data acquiring process (open question: How?)

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Next: checking PLs, DKs, distributions and phase transitions

- Checking power-law distributions
- Presence of DK failures, size of islanding effects
- Other bypass patterns
- Considering "interacting" networks, ie. multiple phases are taken account; the coupling will look like:

$$K \cdot \sin\left(\Delta\theta_{\text{n.n.}}\right)$$

  (creating simplexes between the neighbors)
- Using the node properties as well
- Understand whether the frequency spread or the global order parameter is of more importance
- Analysis for the US grid
- Analysis and comparison with 2022 data (currently facing problems)

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Summary

- Real world network
- Topology is not enough
- Data analysis and estimations for physical parameters
- Weighting the network
- Improving the grid with graph theory: bypasses and community detection
- Stability, synchronization improved

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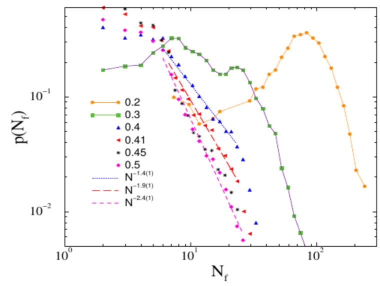

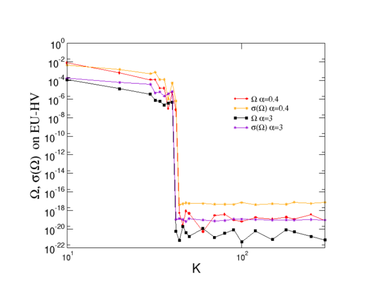

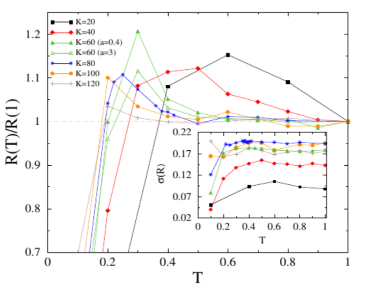

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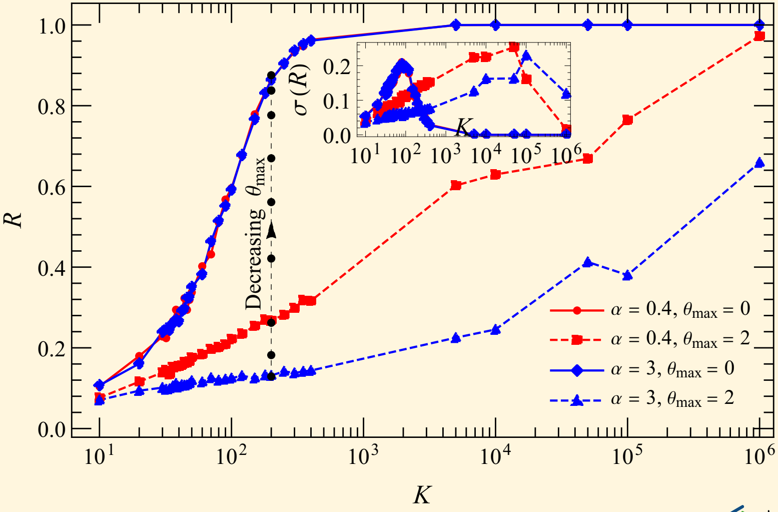
Hysteresis of R



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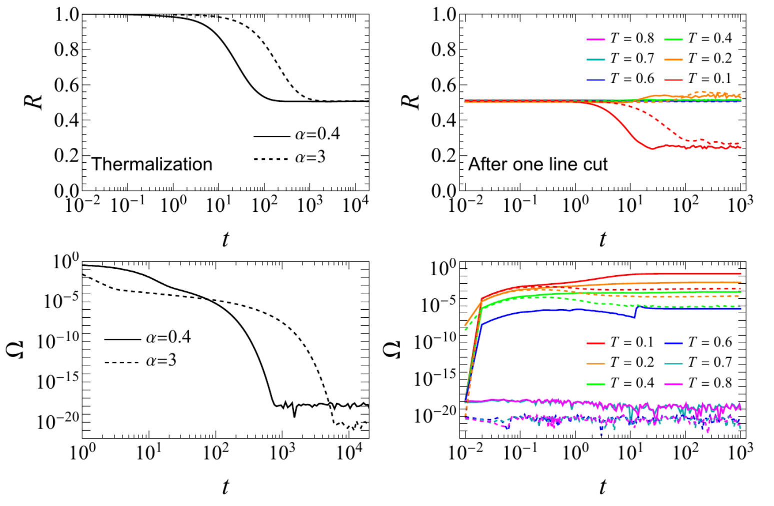
R, Ω evolution



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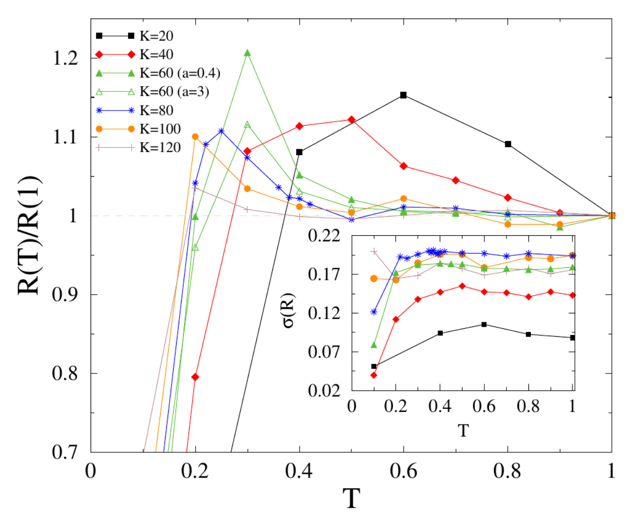
R evolution



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