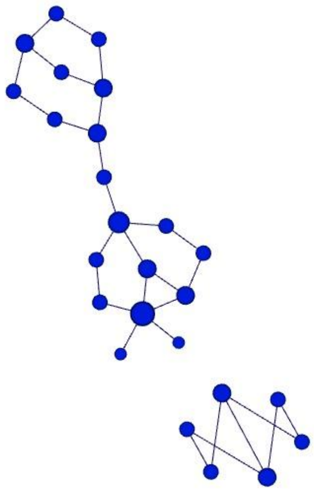
No More Cascading Failure!

Team 8: Xuening Tang, Shuangtong Li, Lucas Keijzer, Ayman Stitou , Kushnava Singha

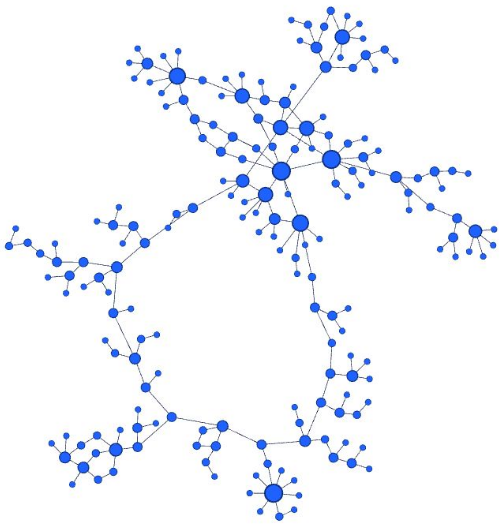
Introduction

- Power Grids as a Network
- Components of a Power Grid and their network analogies :
  - Buses (Nodes)
  - Transmission Lines (Edges)
- Common Failure modes in a Power Grid:
  - Excess Load
  - Excess Voltage
- Ways of analyzing a Power Grid:
  - Topological Approach
  - Powerflow Approach

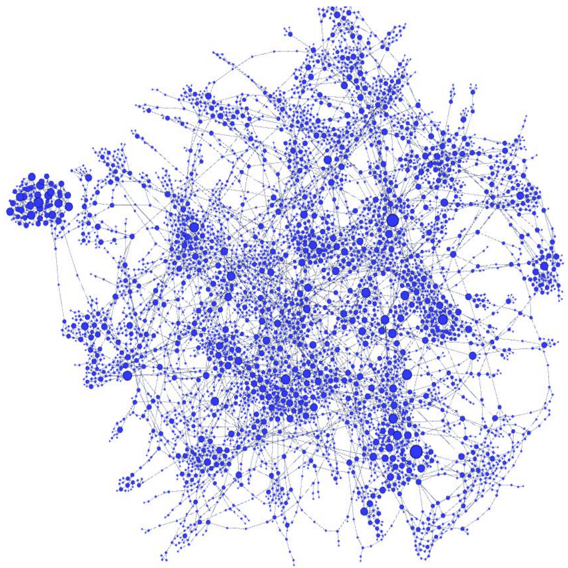
Networks we tested



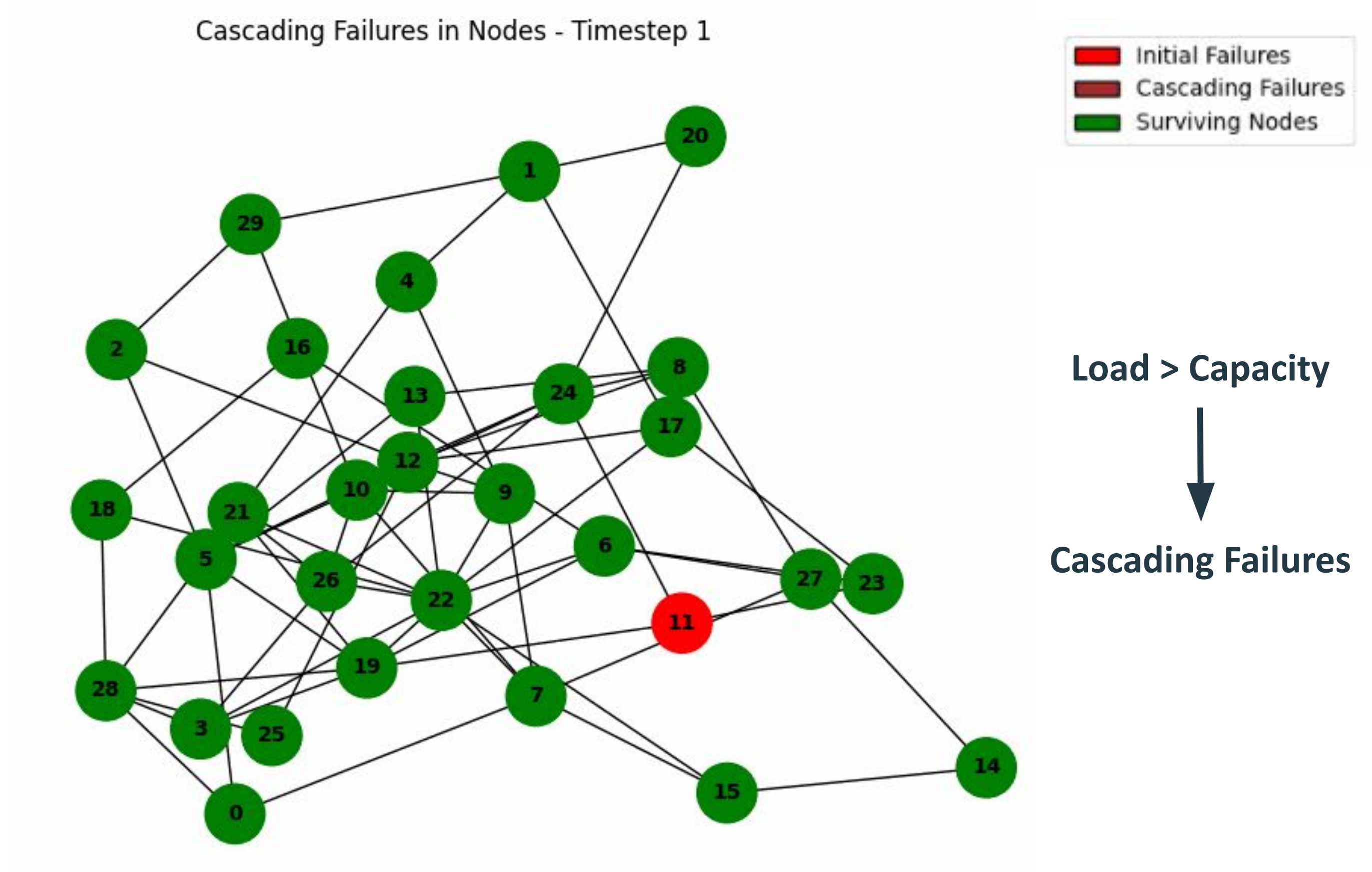
Toy network



Iceland electrical grid



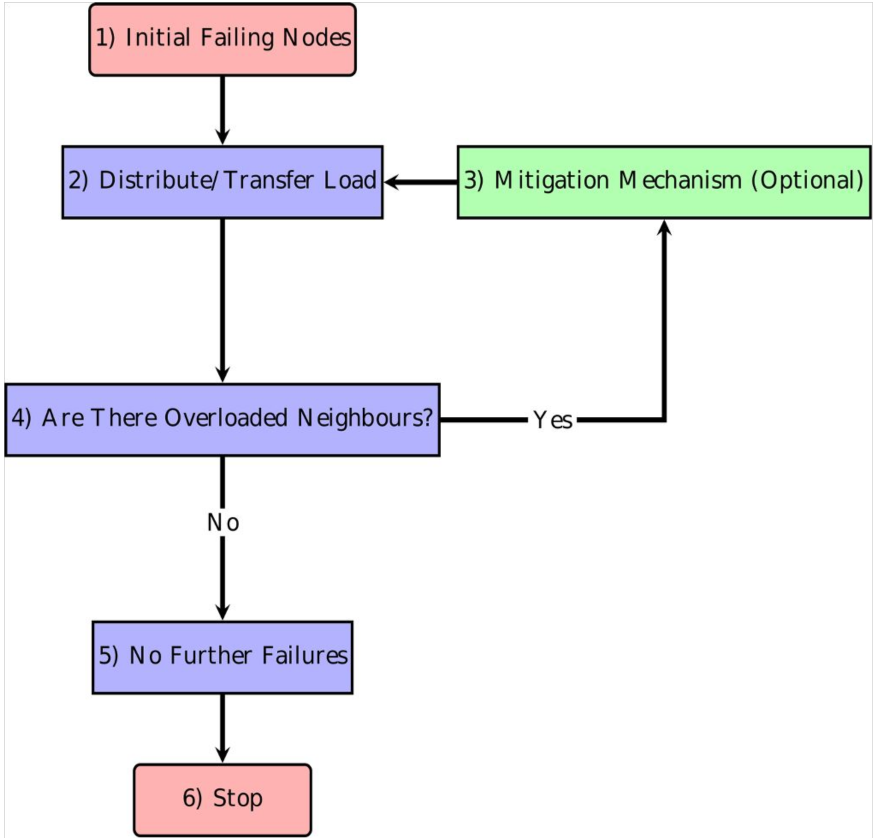
US electrical grid

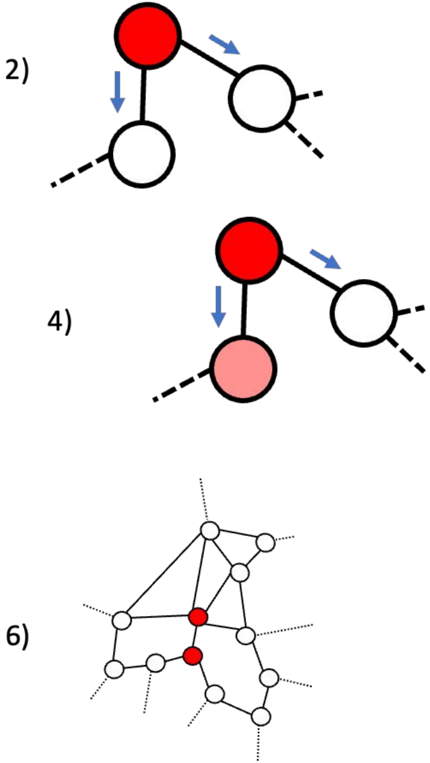


Load > Capacity

Cascading Failures

Load Capacity Model





Parameters

- Initial load L: determined by different degree distributions
- Capacity C: a non-linear relationship with initial load

$$C = (1 + \alpha) \cdot L^{ß}$$

- tolerance parameter: α
- nonlinear parameter: ß
    - If ß = 1, this model represents the Motter-Lay model
- Initial failure: 0.01 (or 1%) of total number of nodes
- Load proportionally distributed by:

$$\Delta_{ij} = L_j \cdot \frac{C_i}{\sum_{m \in \Gamma_j} C_m} \text{ with } \Gamma_j \text{ as the set of neighbours of node } j$$

- Fraction of Failed Nodes I: the proportion of failed nodes in a network

I = Number of Failed Nodes/Total Number of Nodes

Initial load distribution

Dependent on node centrality measure:

- Degree Centrality (DC)
  - Number of connections
- Betweenness Centrality (BC)
  - How often a node is on the shortest path between other nodes
- Closeness Centrality (CC)
  - Average shortest path to all other nodes

$$\mathrm{DC}_i = \frac{k_i}{N-1}, \quad i = 1, 2, \ldots, N$$

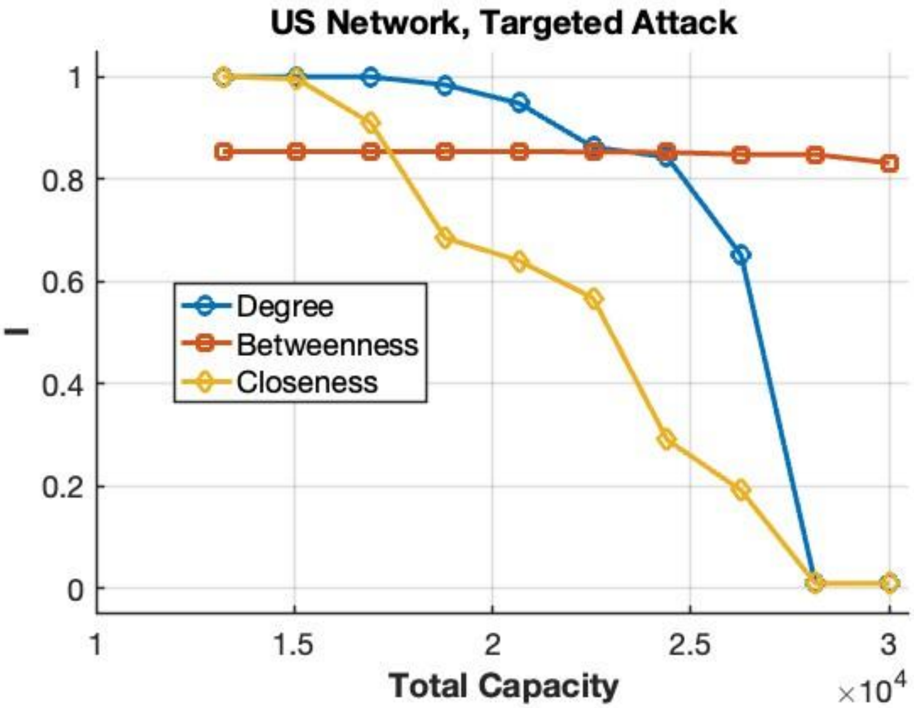
$$\mathrm{BC}_i = \frac{1}{(N-1)(N-2)/2} \sum_{s \neq i \neq t} \frac{n_{st}^i}{g_{st}}, \quad i = 1, 2, \ldots, N$$

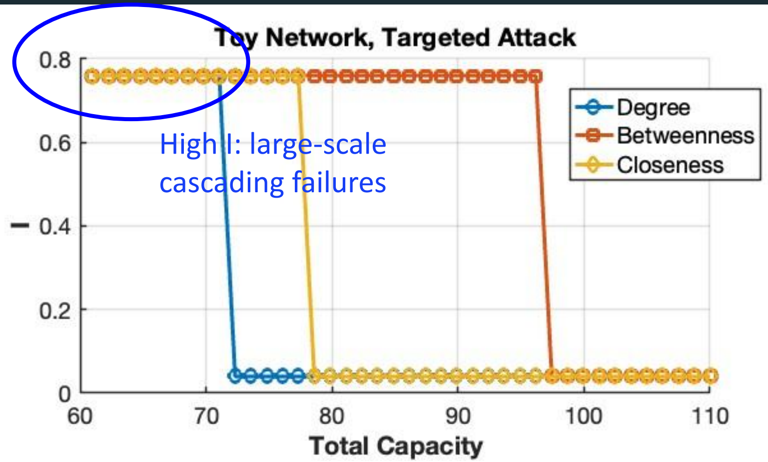
$$\mathrm{CC}_i = \left(\frac{1}{N-1} \sum_{j=1}^{N} d_{ij} \right)^{-1}, \quad i = 1, 2, \ldots, N$$

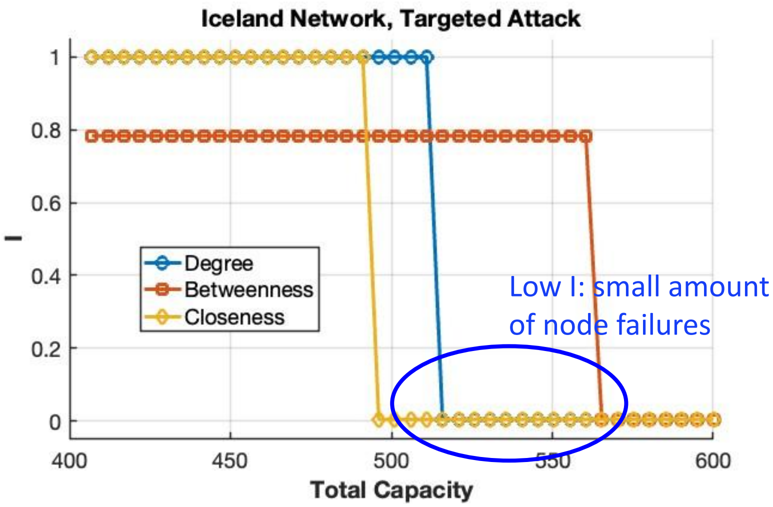
Research Questions

1. How does the network robustness varies with different tolerance (α) and nonlinear (ß) parameters? (Note: $C = (1 + \alpha) \cdot L^{\beta}$, C = node capacity, L = node initial load)
    - H1: The robustness of network improves as parameter (α or ß) increases.
2. How does target attacks and random attacks affect the fraction of node failures in the network?
    - H2: The network is more vulnerable to the target attack.
3. To what extent can prevention mechanisms prevent cascading failures across the network?
    - H3: The network is more robust under prevention mechanism.

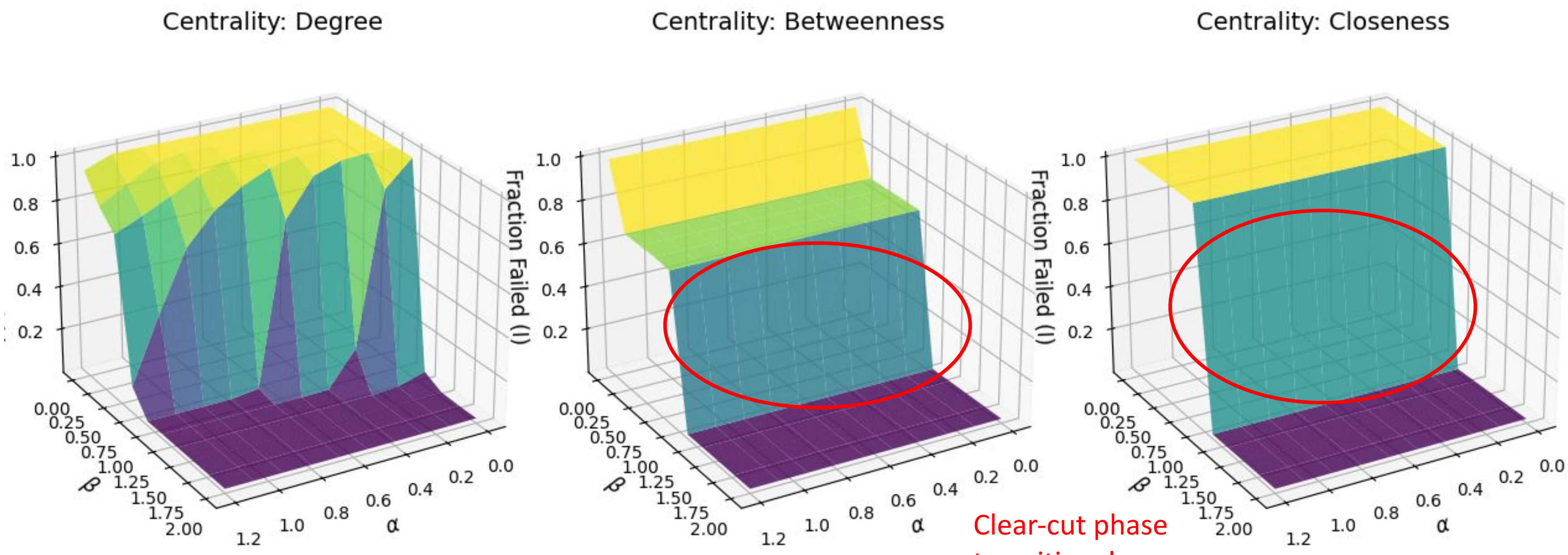
Check for phase transition, with 1% target attacks.







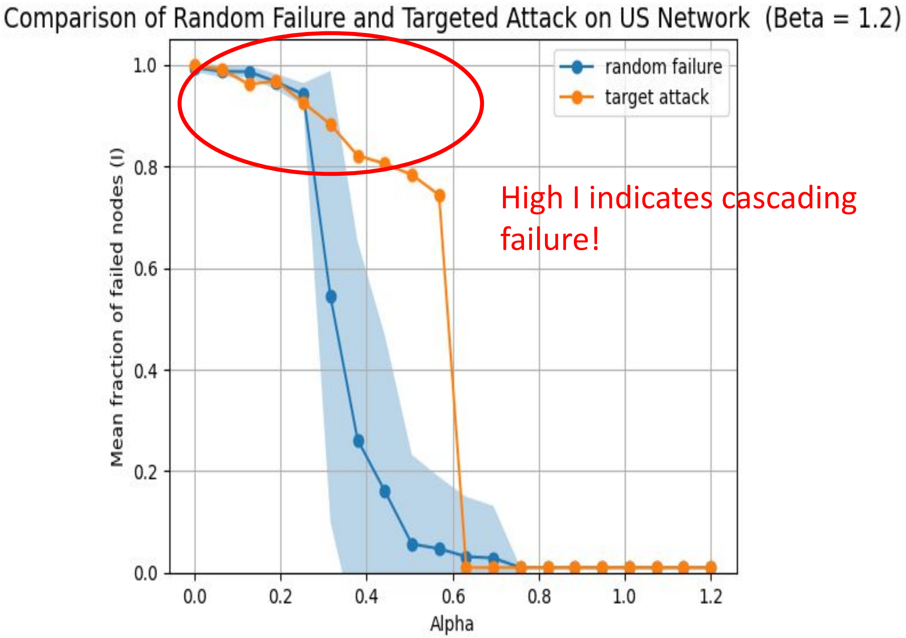
Influence of Alpha and Beta on the Fraction of Failed Nodes



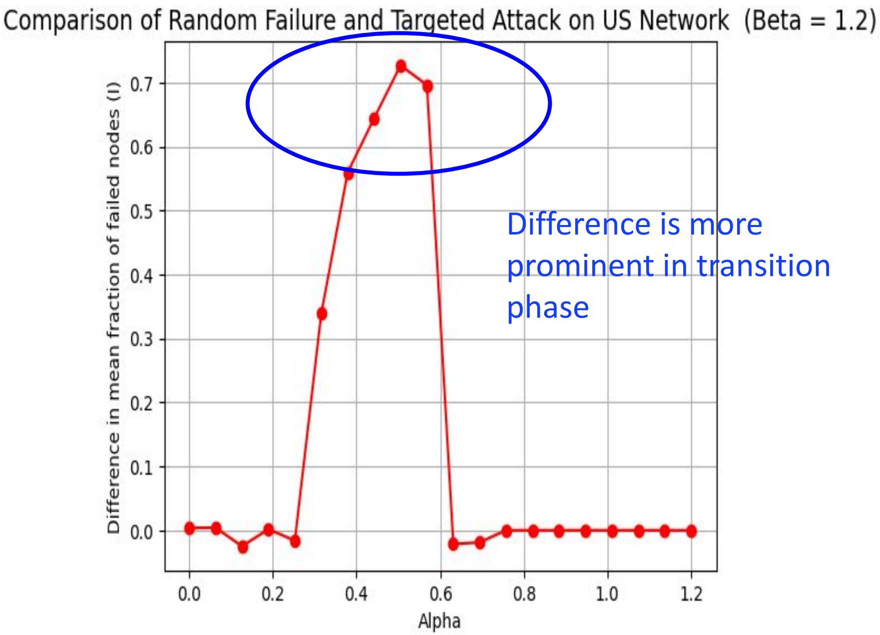
Clear-cut phase transitions!

US Network

Random Failure vs. Target Attack

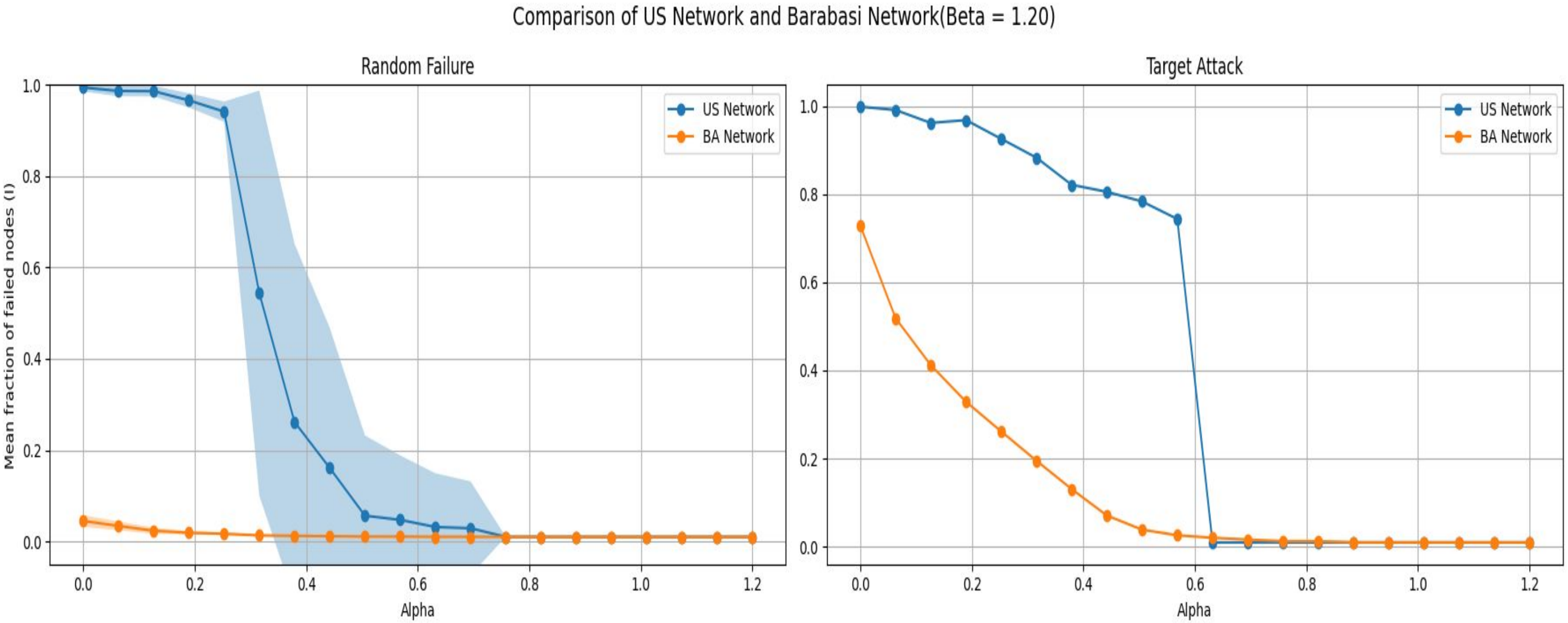


High I indicates cascading failure!



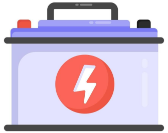
Difference is more prominent in transition phase

Is US Network a BA Network?



Prevention of cascading failures

Mechanisms:

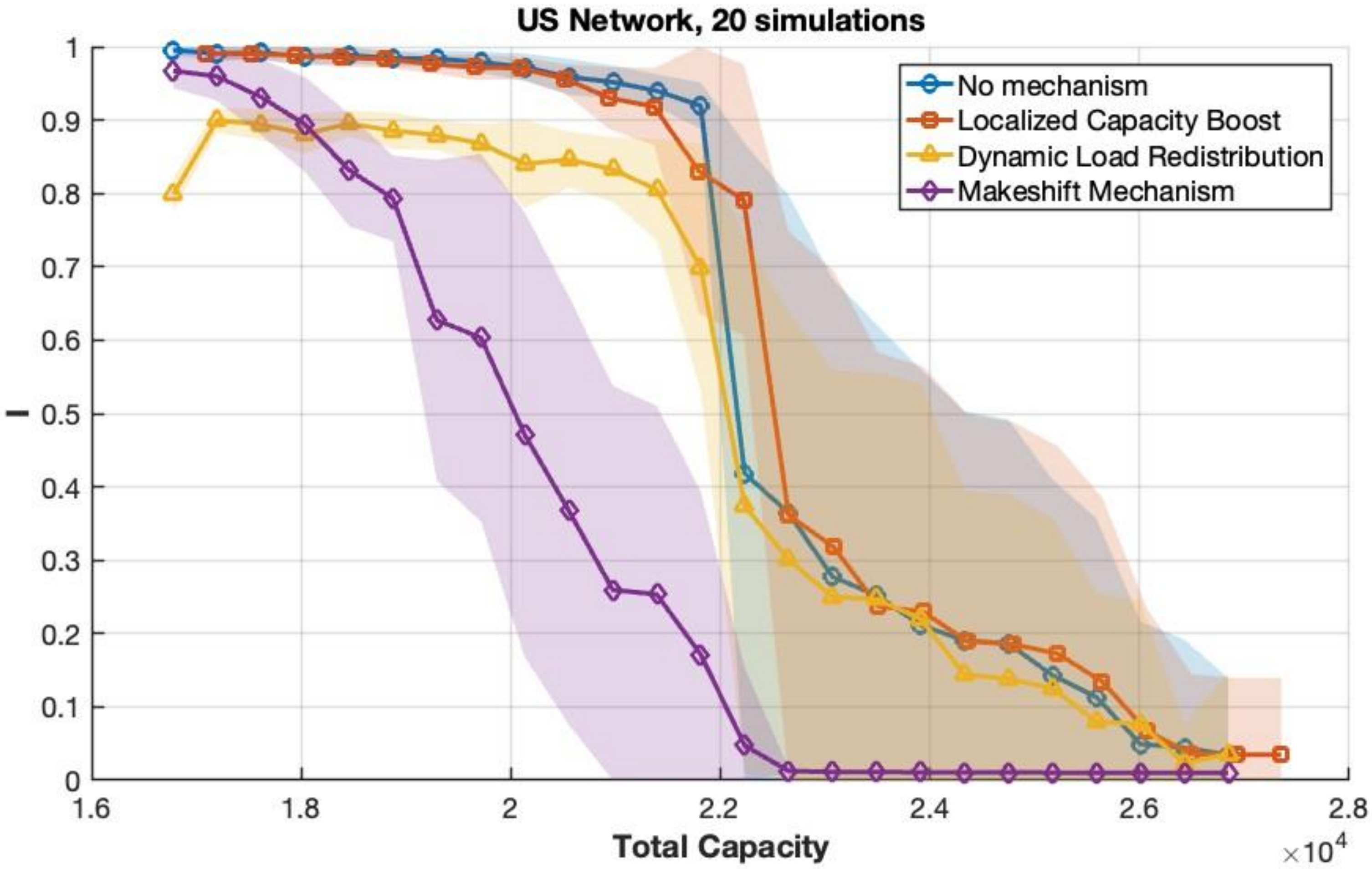


- Localized capacity boost
- Dynamic load distribution

$$\Delta_{ij} = L_j \cdot \frac{C_i - L_i}{\sum_{m \in \Gamma_j} C_m - L_m} \text{ with } \Gamma_j \text{ as the set of neighbours of node } j$$

- Makeshift mechanism

  Neighbouring nodes distribute load pre-emptively away from failing node



US Network, 20 simulations
No mechanism
Localized Capacity Boost
Dynamic Load Redistribution
Makeshift Mechanism
I
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.6
1.8
2
2.2
2.4
2.6
2.8
Total Capacity
$\times 10^4$

Conclusion

To answer our research questions:

1. The nonlinear parameter, ß, has a more pronounced influence on the robustness of the network than the tolerance parameter α
2. Both random failure and targeted attack result in phase transition in the fraction of failed nodes. The US power-grid network is more sensitive to targeted attacks than to the random failure.
3. Not all prevention mechanisms are effective (i.e. localized capacity boost), but cascading failures are clearly mitigated for the other mechanisms (i.e. the makeshift mechanism and dynamic load distribution)

Thank you for Listening!

Any Questions?

Reference

C. Chen, Y. Hu, X. Meng and J. Yu, ***"Cascading Failures in Power Grids: A Load Capacity Model with Node Centrality,"*** in Complex System Modeling and Simulation, vol. 4, no. 1, pp. 1-14, March 2024, doi: 10.23919/CSMS.2023.0020. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10525231

Crucitti, Paolo, Vito Latora, and Massimo Marchiori. ***"Model for cascading failures in complex networks."*** Physical Review E69.4 (2004): 045104. Available at: https://journals.aps.org/pre/abstract/10.1103/PhysRevE.69.045104

Yang, Y., & Motter, A. E. (2017). ***Cascading failures as continuous Phase-Space transitions.*** Physical Review Letters, 119(24).

Dataset:W. A. Bukhsh, Ken McKinnon, ***Network data of real transmission networks,*** April 2013. Available at: https://www.maths.ed.ac.uk/OptEnergy/NetworkData/howtouse.html