SAND2015-2008PE

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Measuring & Influencing Resilience of Adapting Flow Networks

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Sandia National Laboratories

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Presentation to Sandia National Laboratories' Complex Systems Advisory Panel

- This presentation describes a model designed to study the effects of adaptive network growth on the network's resilience, summarizing:
  - Research questions
  - Model formulation
  - Initial results

Understanding Connections between Network Structure and Performance

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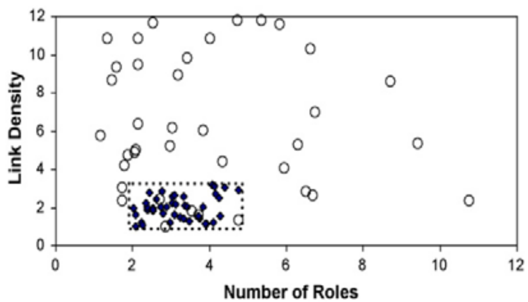
that c ≥ 1 says simply that the networks being considered are all fully connected. Any value c < 1 would imply that the graph



From Ulanowicz et al., Eco. Compl. 6 pp 27-36

- Trophic (and other) networks are topologically intermediate between minimally and richly connected
- Maybe this reflects a compromise between being efficient as a system and needing to survive local disruptions
- Maybe structure is an indicator of resilience

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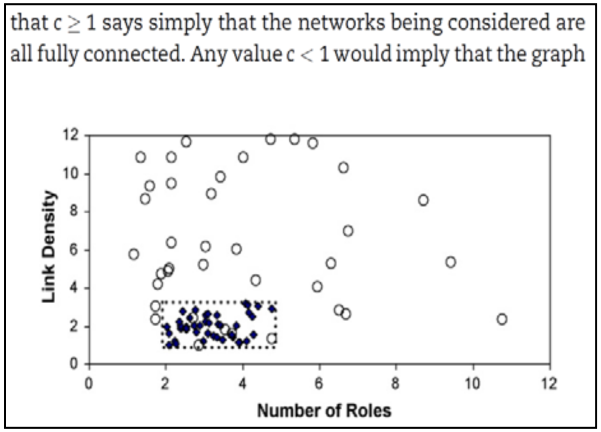

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- Can local adaptation accomplish this tradeoff?
- Does it leave a signature in the topology?
- Is it a (systemically) good tradeoff?
  ... can it be made so?
- Can structural measures predict performance resilience?
  - Against historical shocks?
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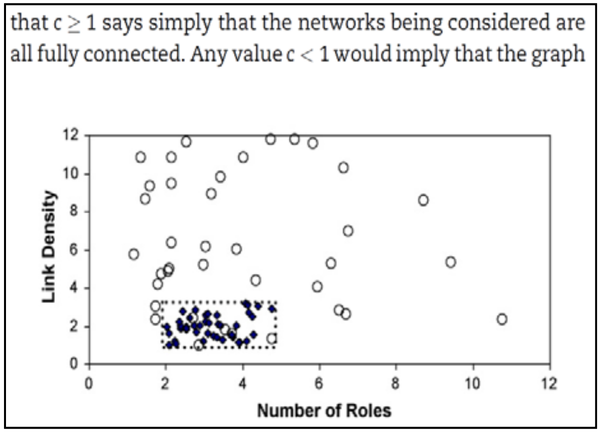

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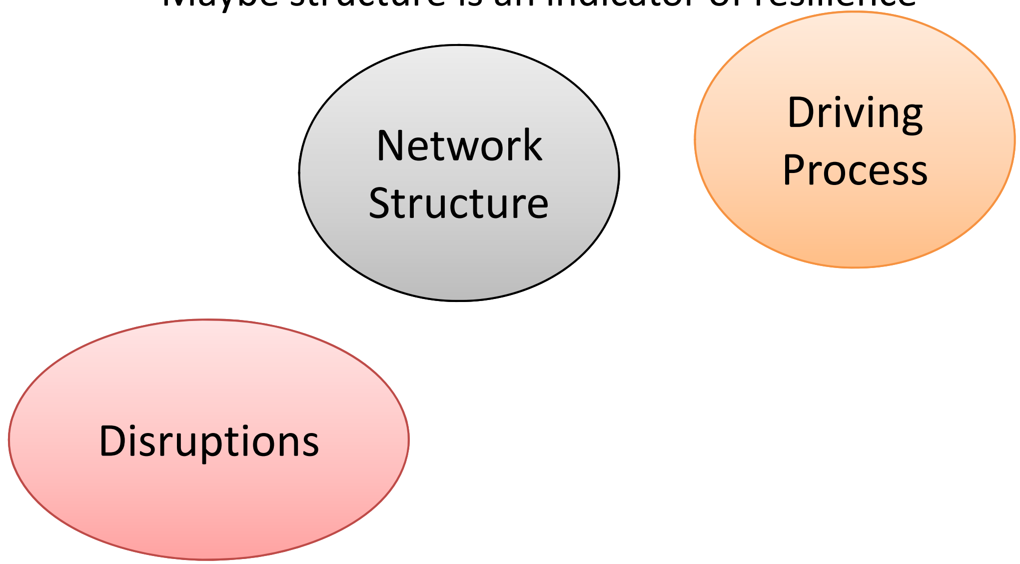

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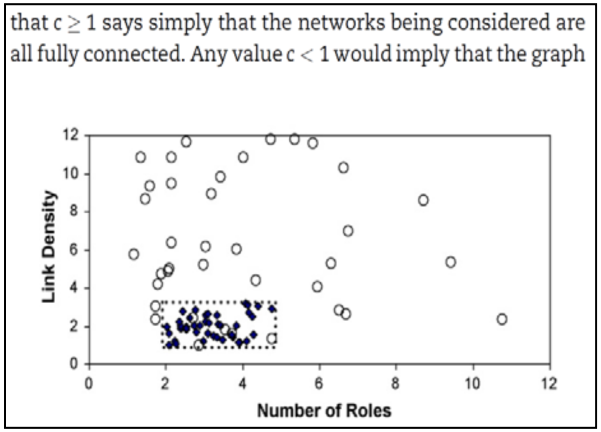

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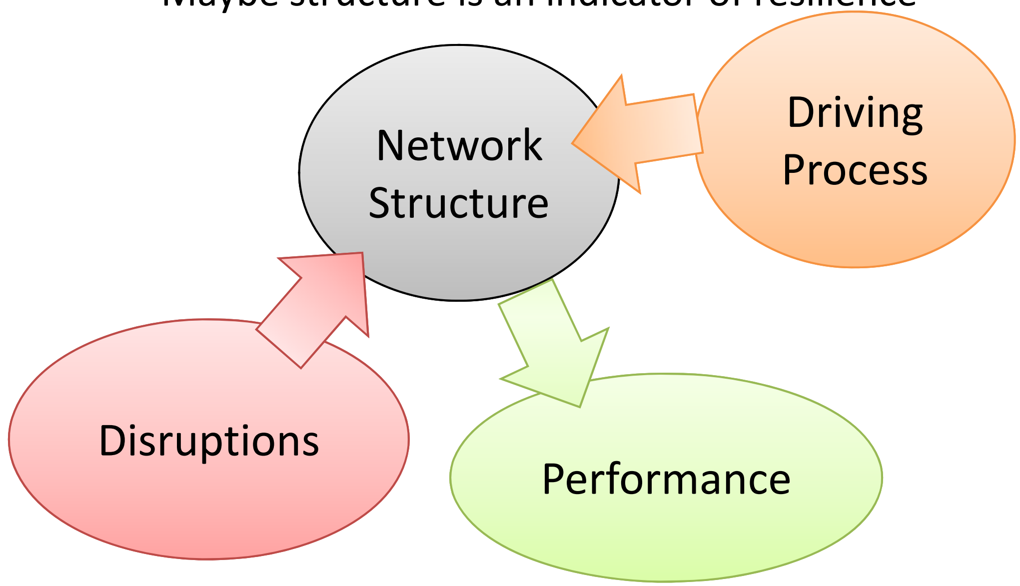

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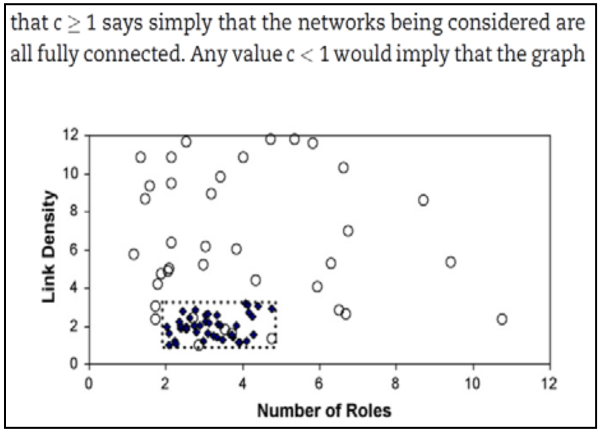

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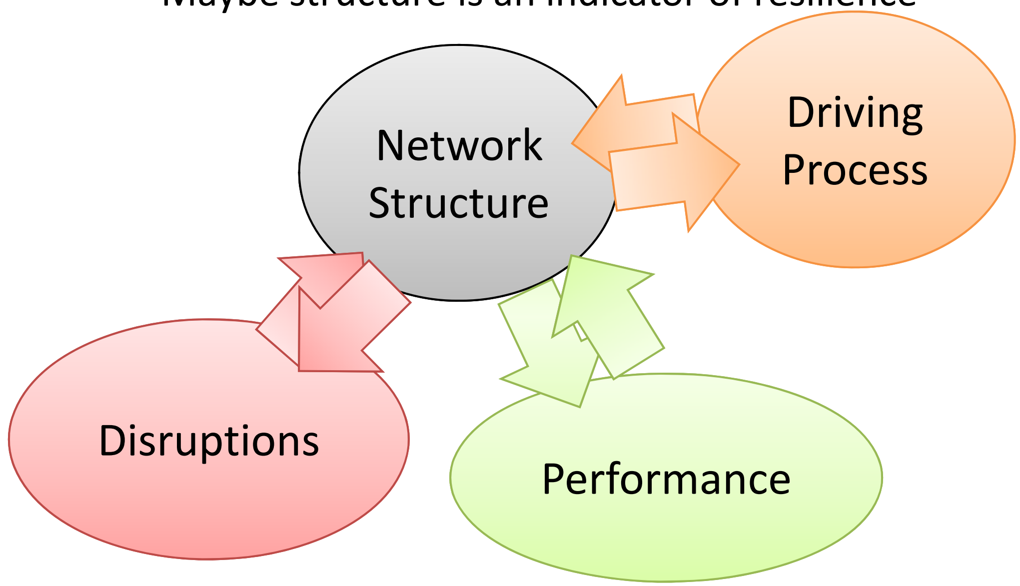

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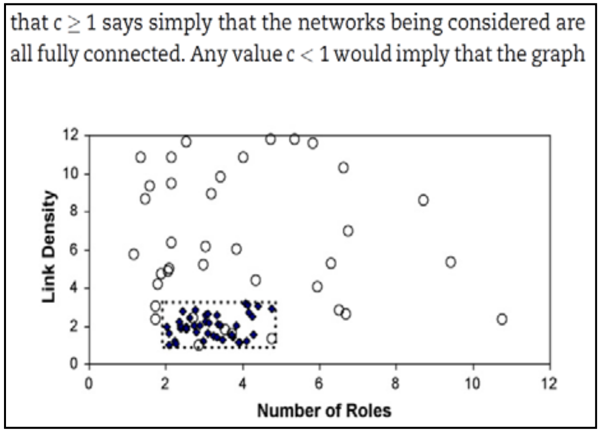

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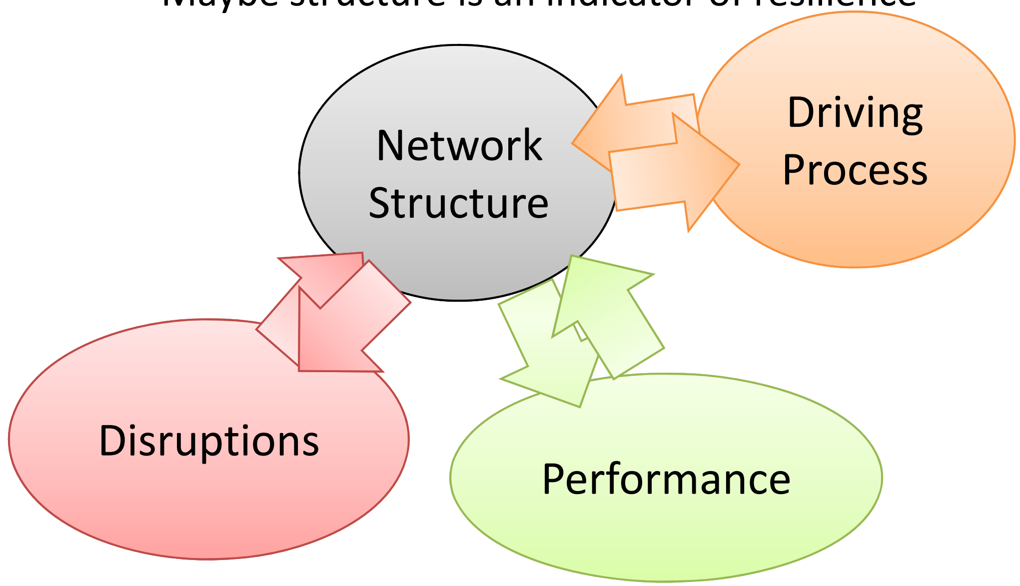

Answers depend on specifics.
We start with a simple flow model…

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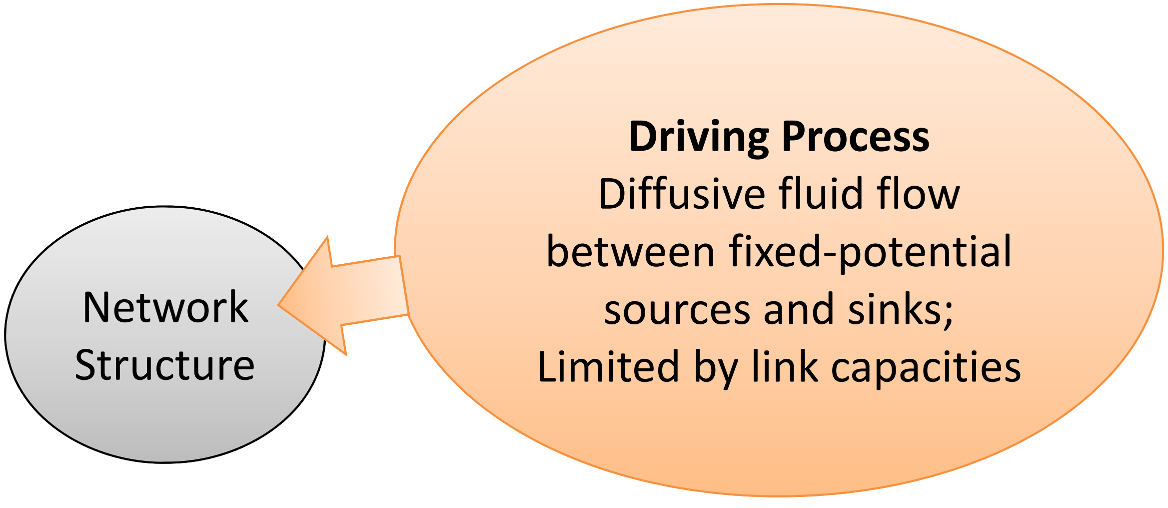
Model Features



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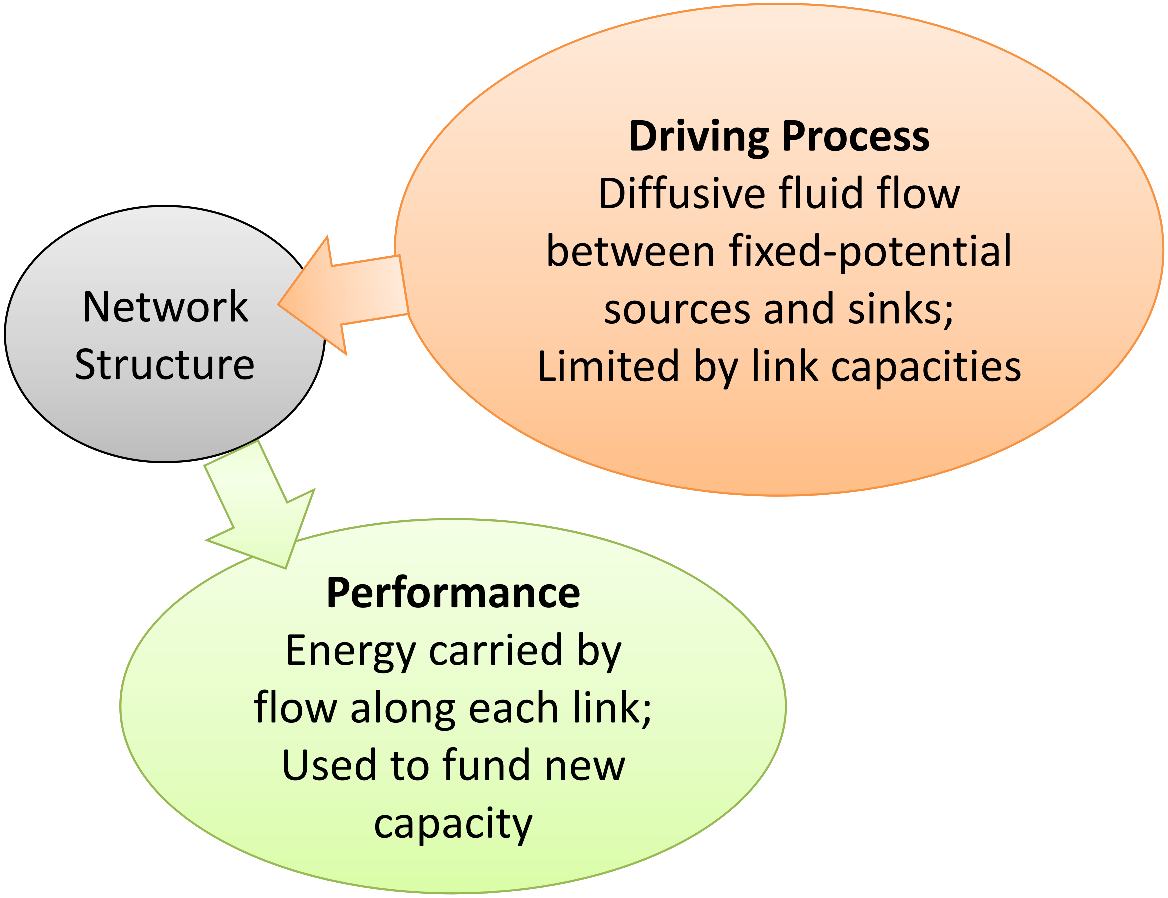

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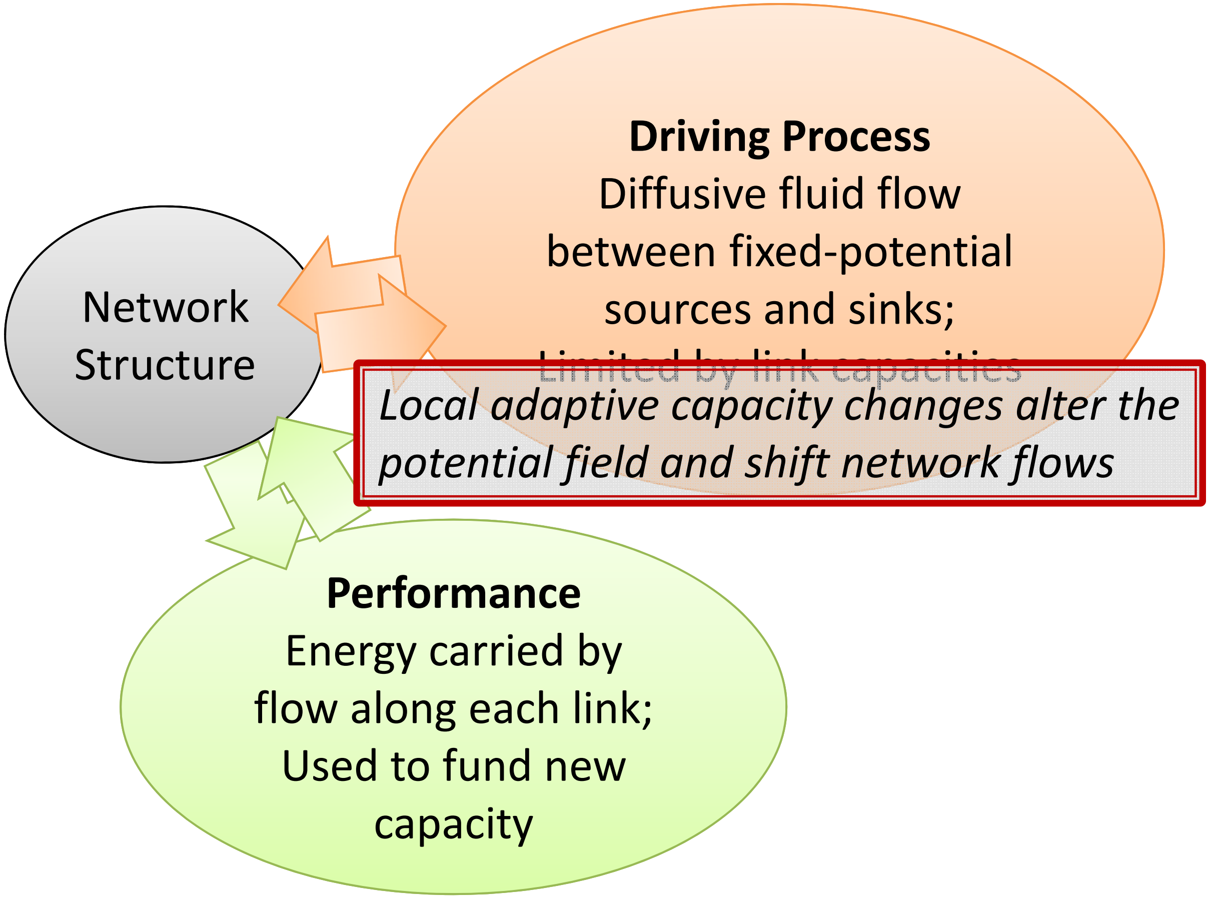

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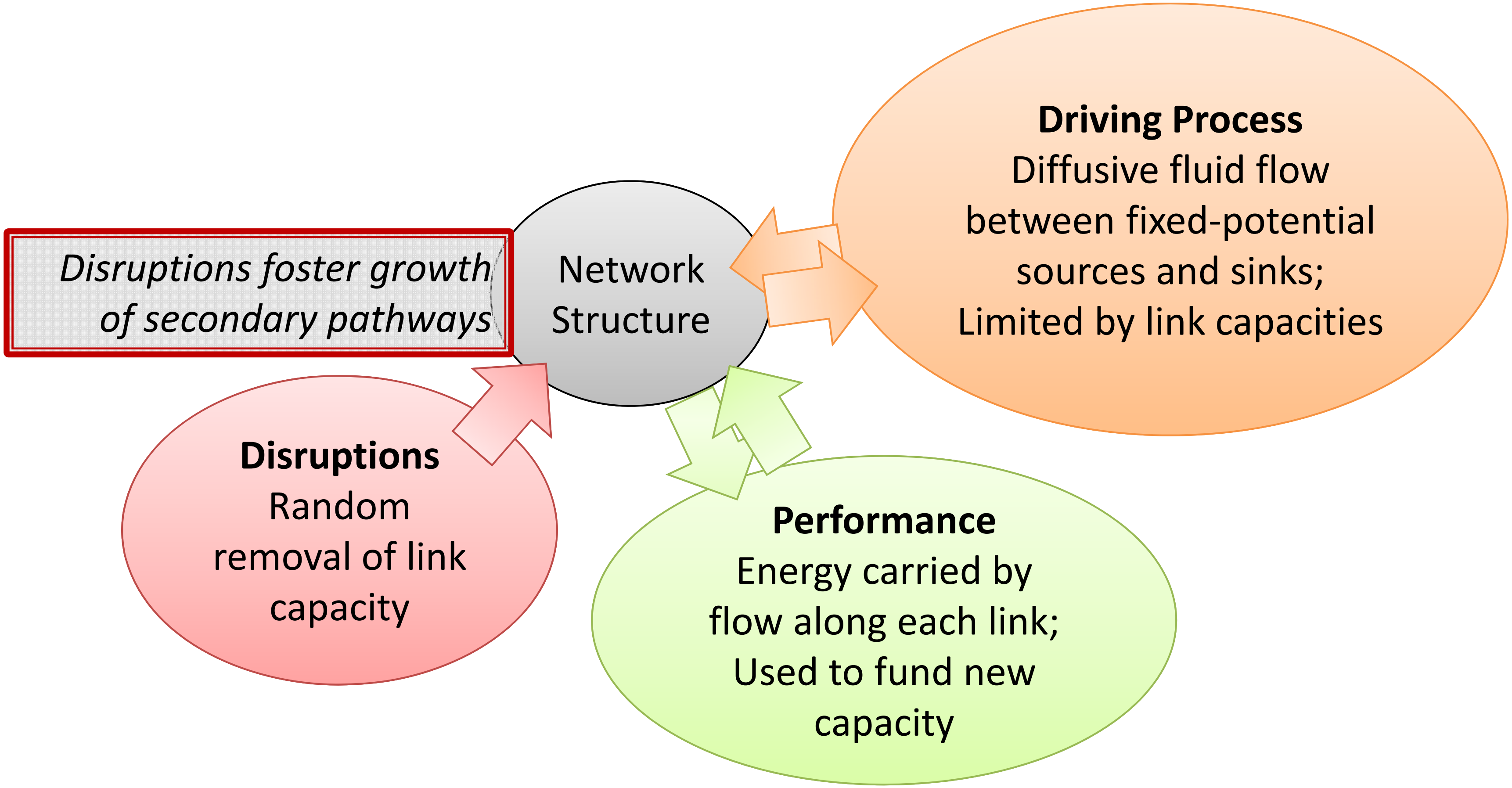

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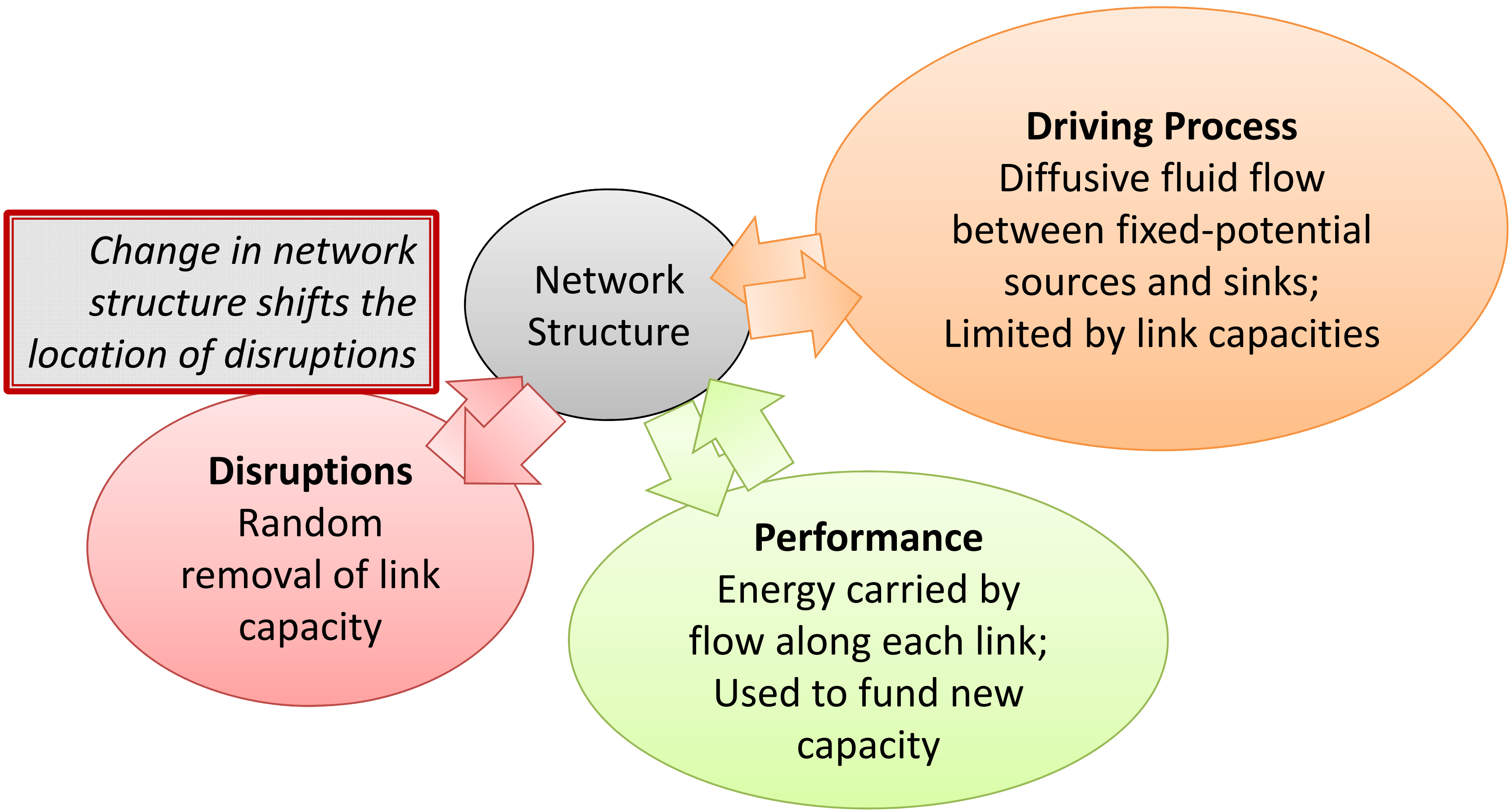

Flow and Growth Process Models

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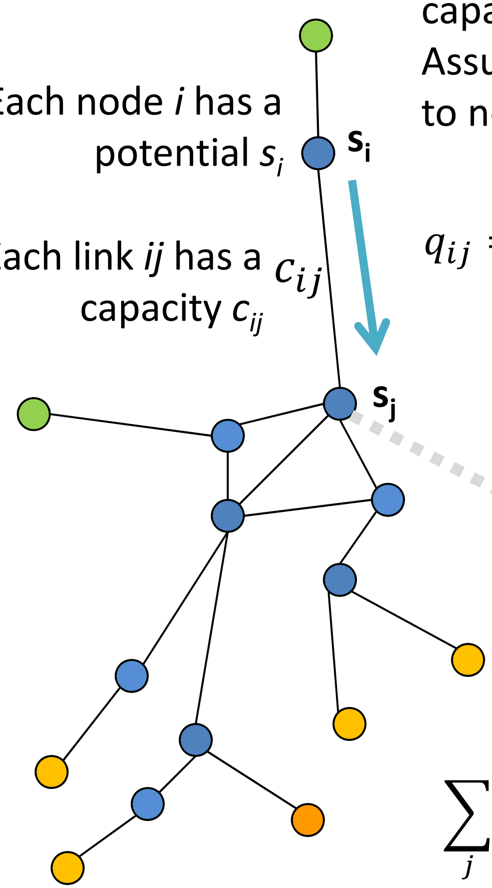
Each node i has a potential s_i

Each link ij has a capacity c_{ij}



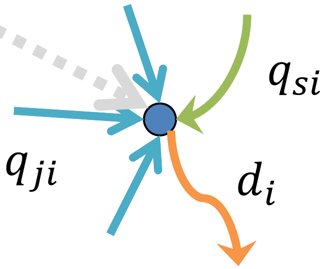
Flow rates are limited by a (directed) capacity associated with each link, c_{ij}. Assuming $s_i > s_j$, the flow from node i to node j is given by:

$$q_{ij} = c_{ij}\, f\big((s_i - s_j)k_{ij}\big) \quad (1)$$

where k_{ij} is a conductance parameter and the function f(x) models linear resistance as x->0 and enforces the capacity limit for large x:

$$f(x) \equiv 1 - e^{-x} \quad (2)$$

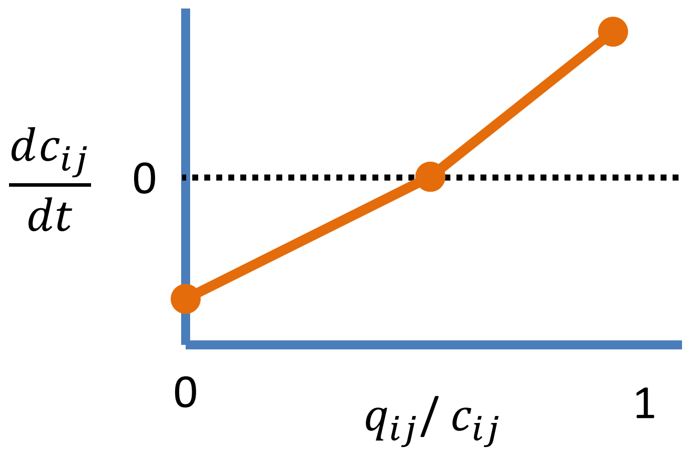
In equilibrium, the net flow at each node i is 0, including any internal sources (q_{si}) or sinks(d_i):



$$\sum_j q_{ji} + q_{si} - d_i = 0 \qquad \forall i \quad (3)$$

The equilibrium solution $\{\hat{s}_i\}$ is obtained by solving equations (1-3).

Network adapts by changing link capacities in response to utilization:



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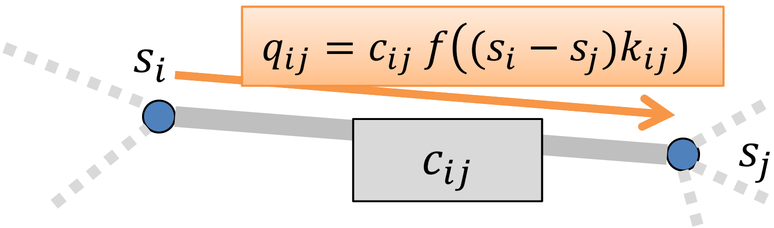
Link Capacity Dynamics



Link Capacity Dynamics

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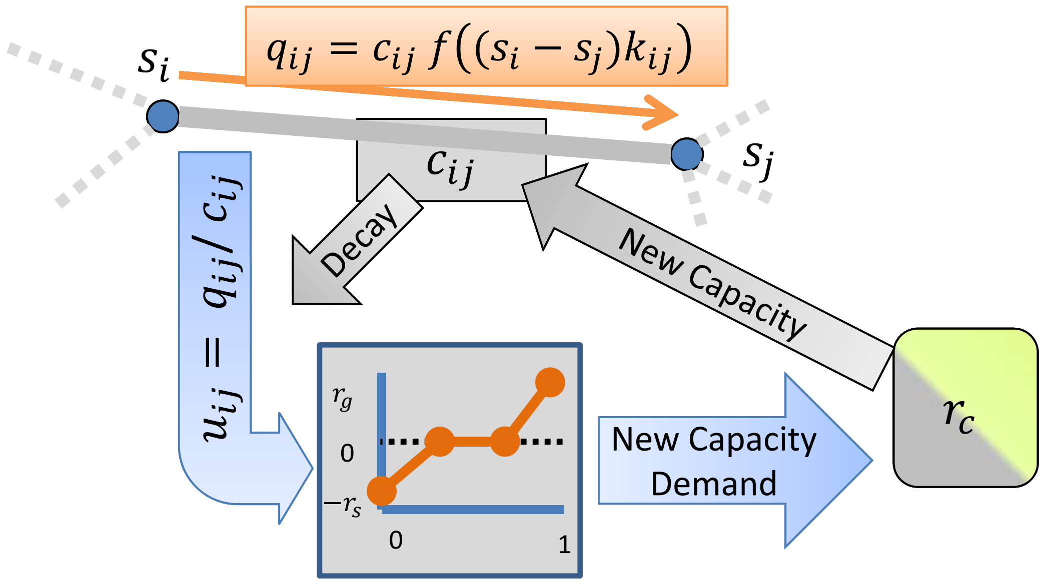

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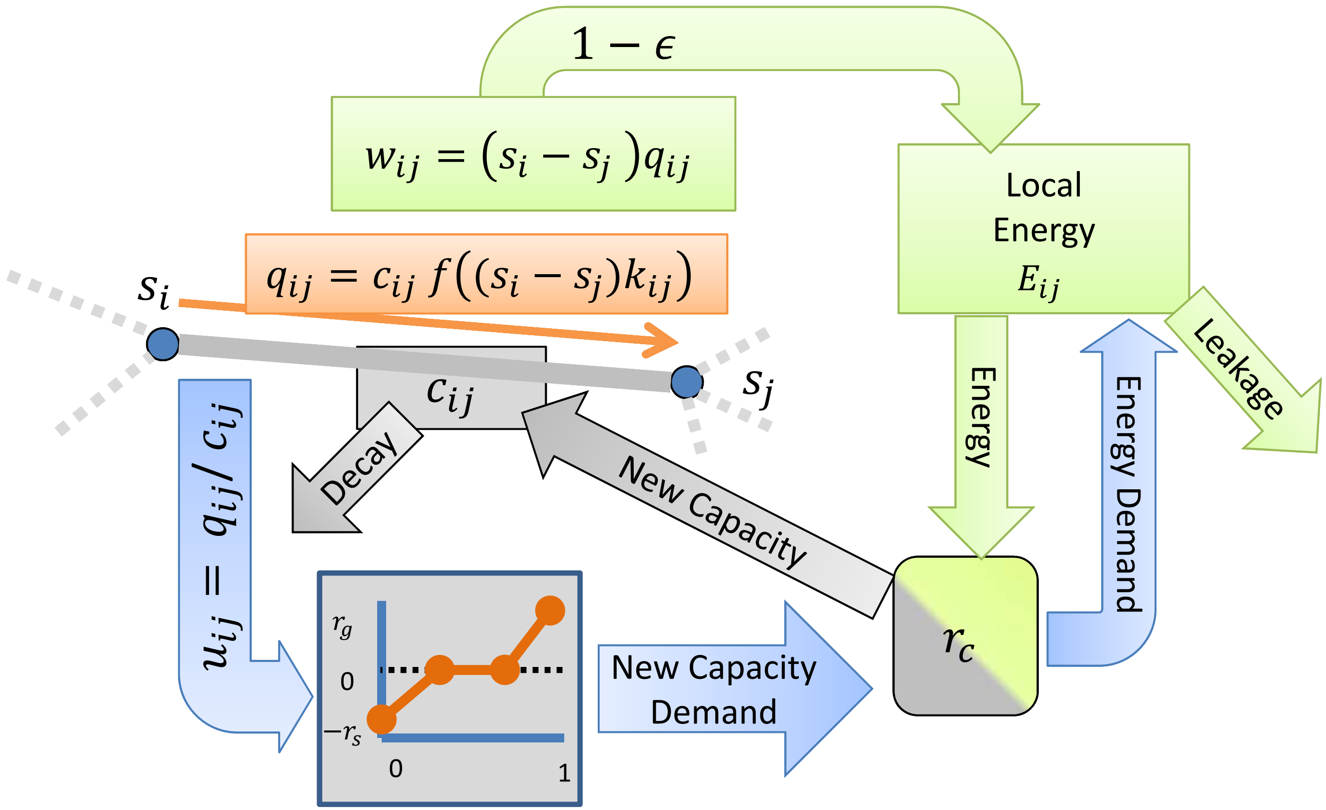

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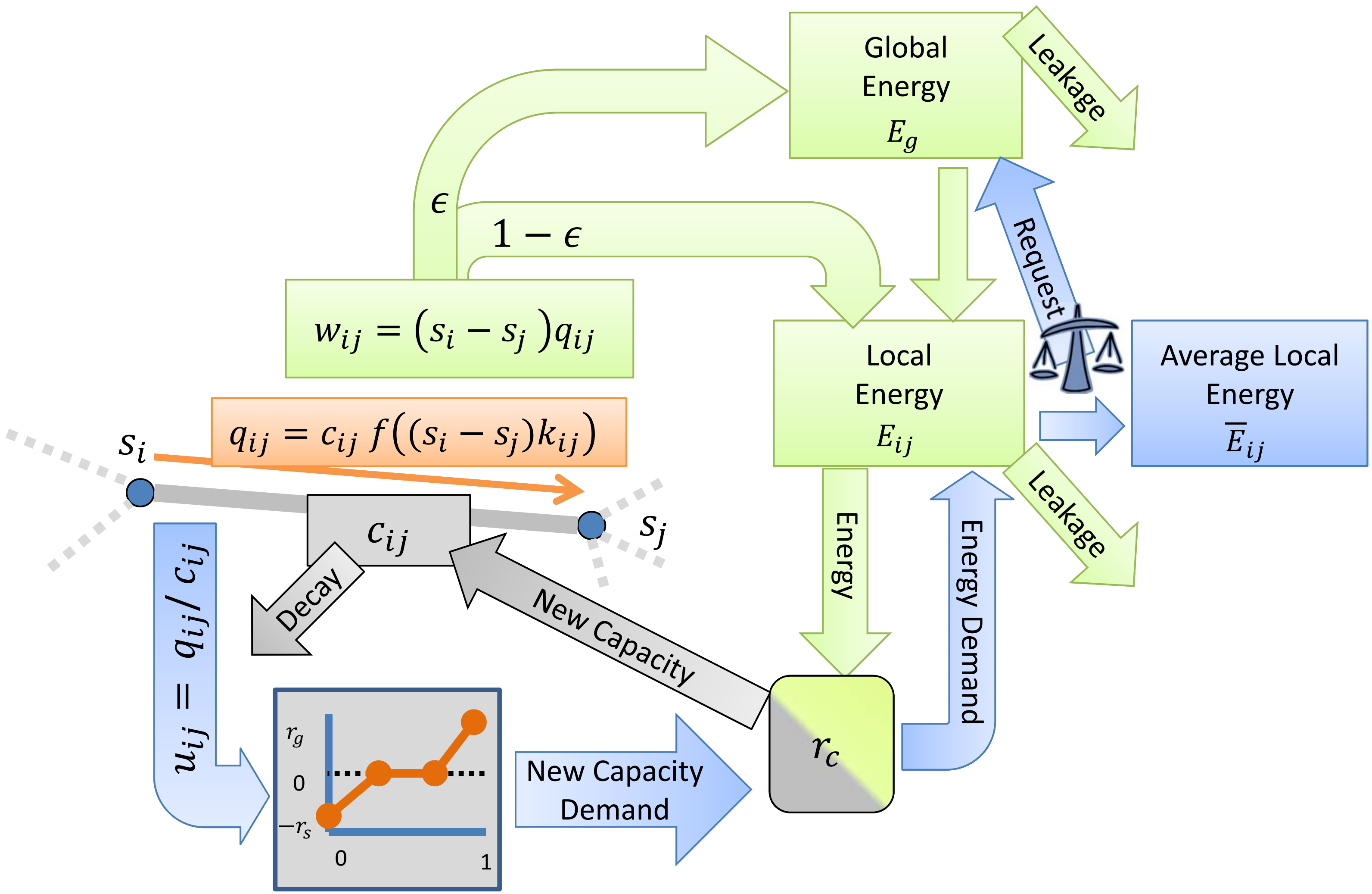
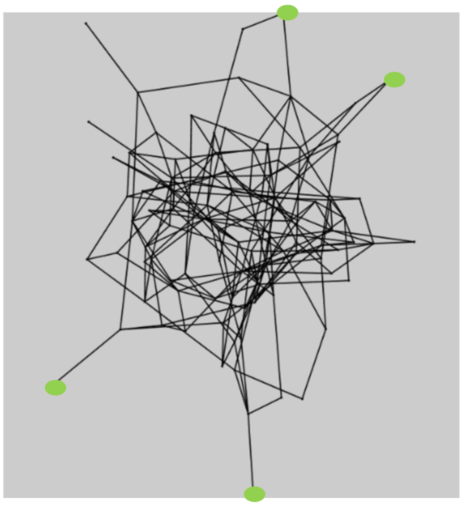


Adaptation without Disruption



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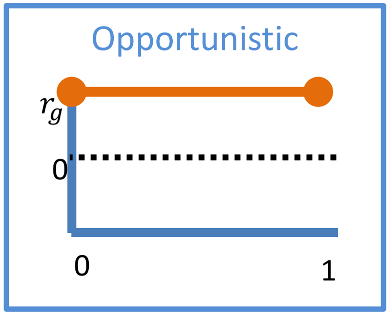

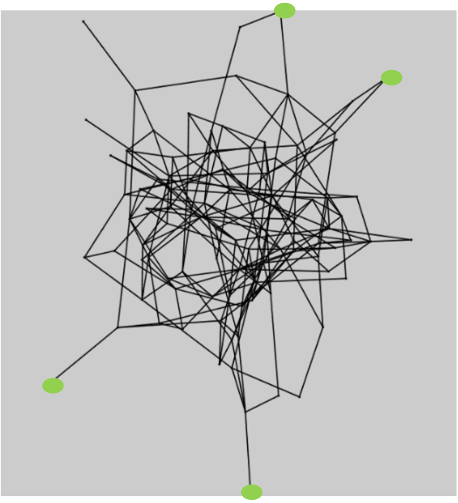

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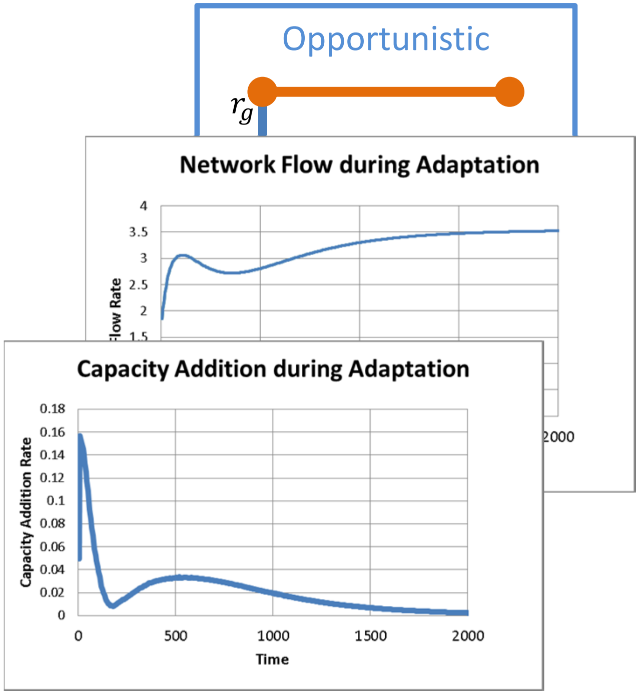

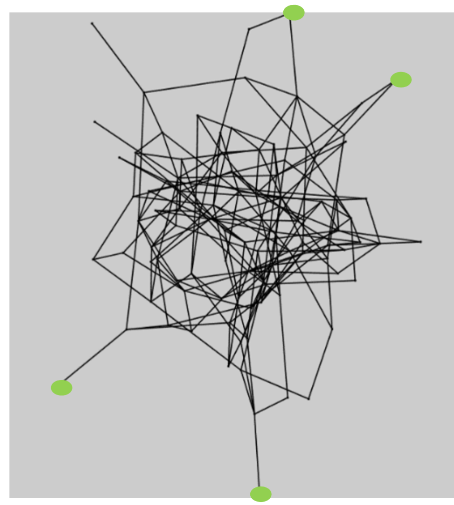

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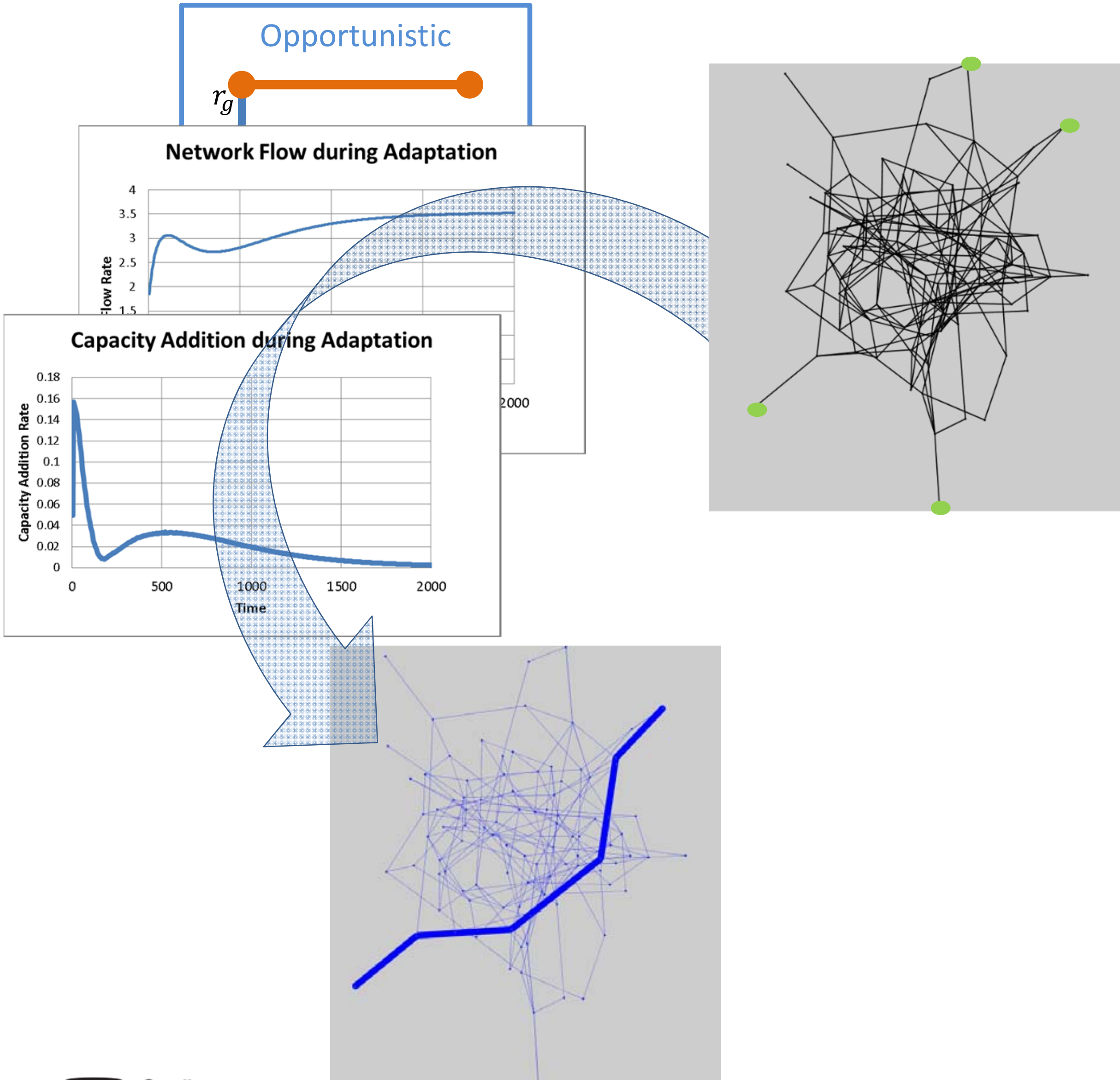

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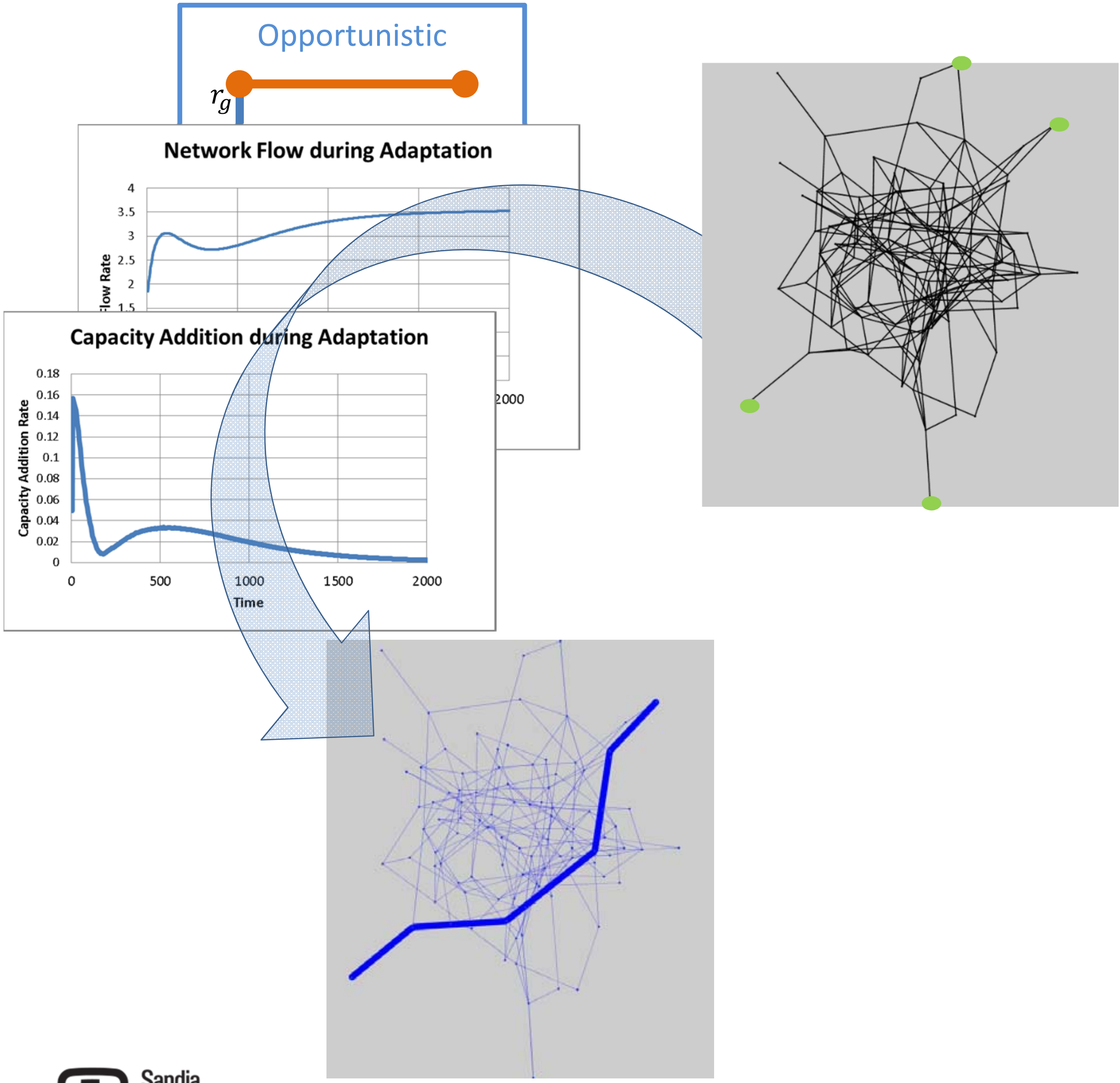

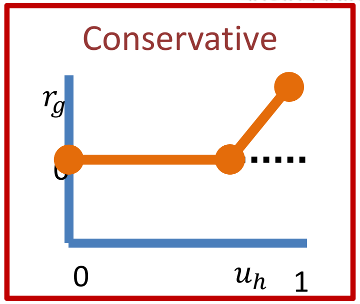

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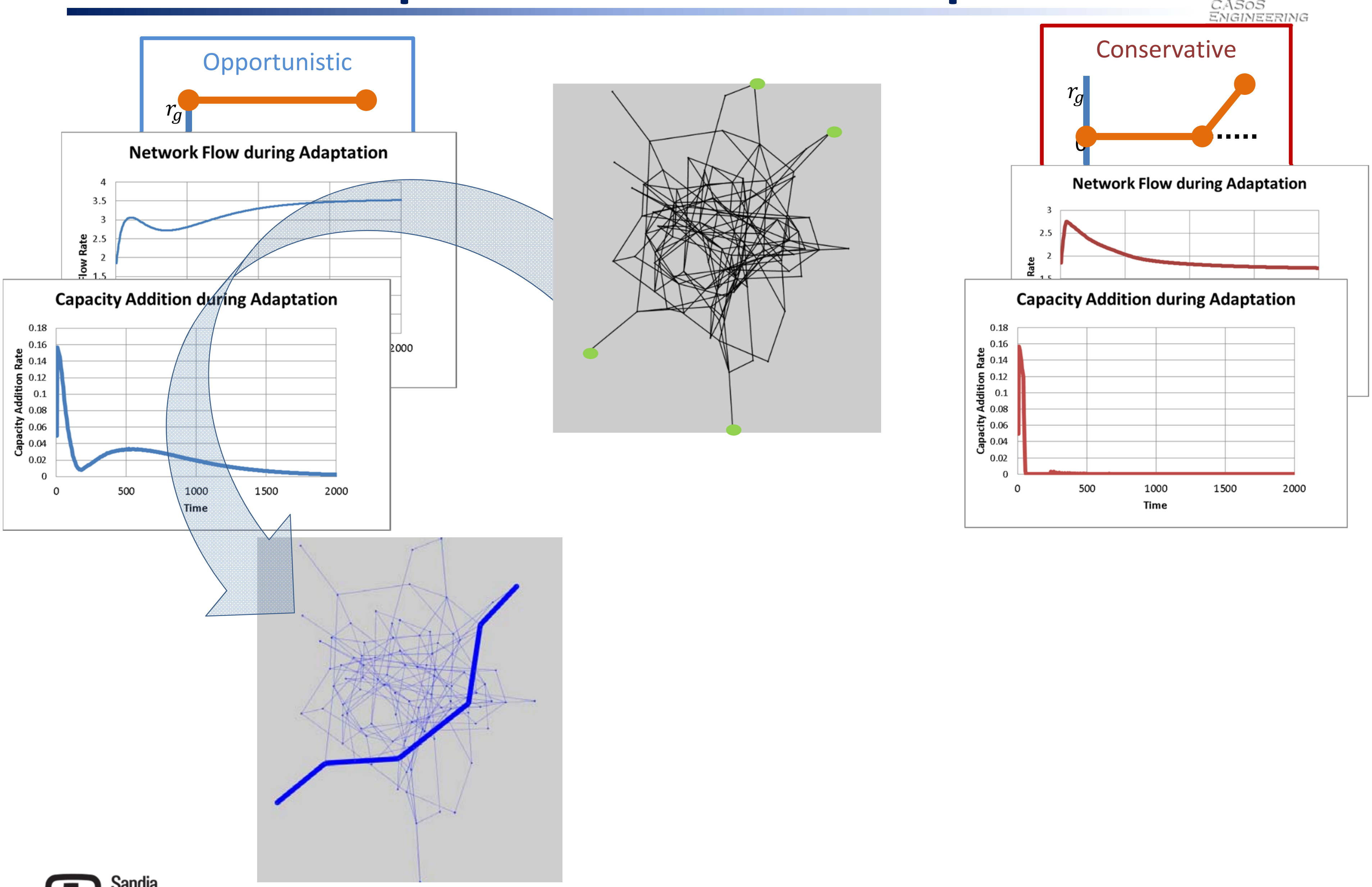

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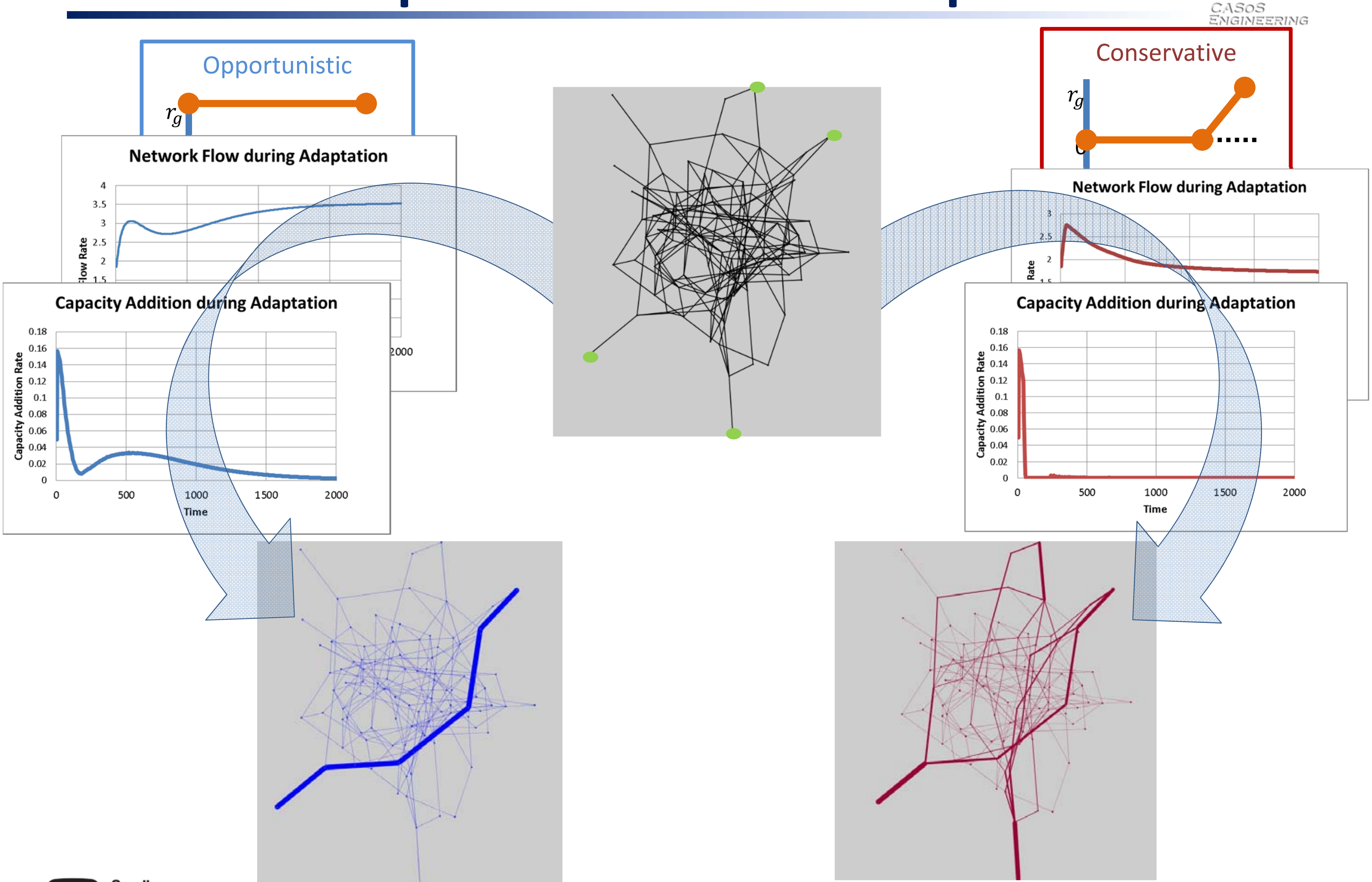

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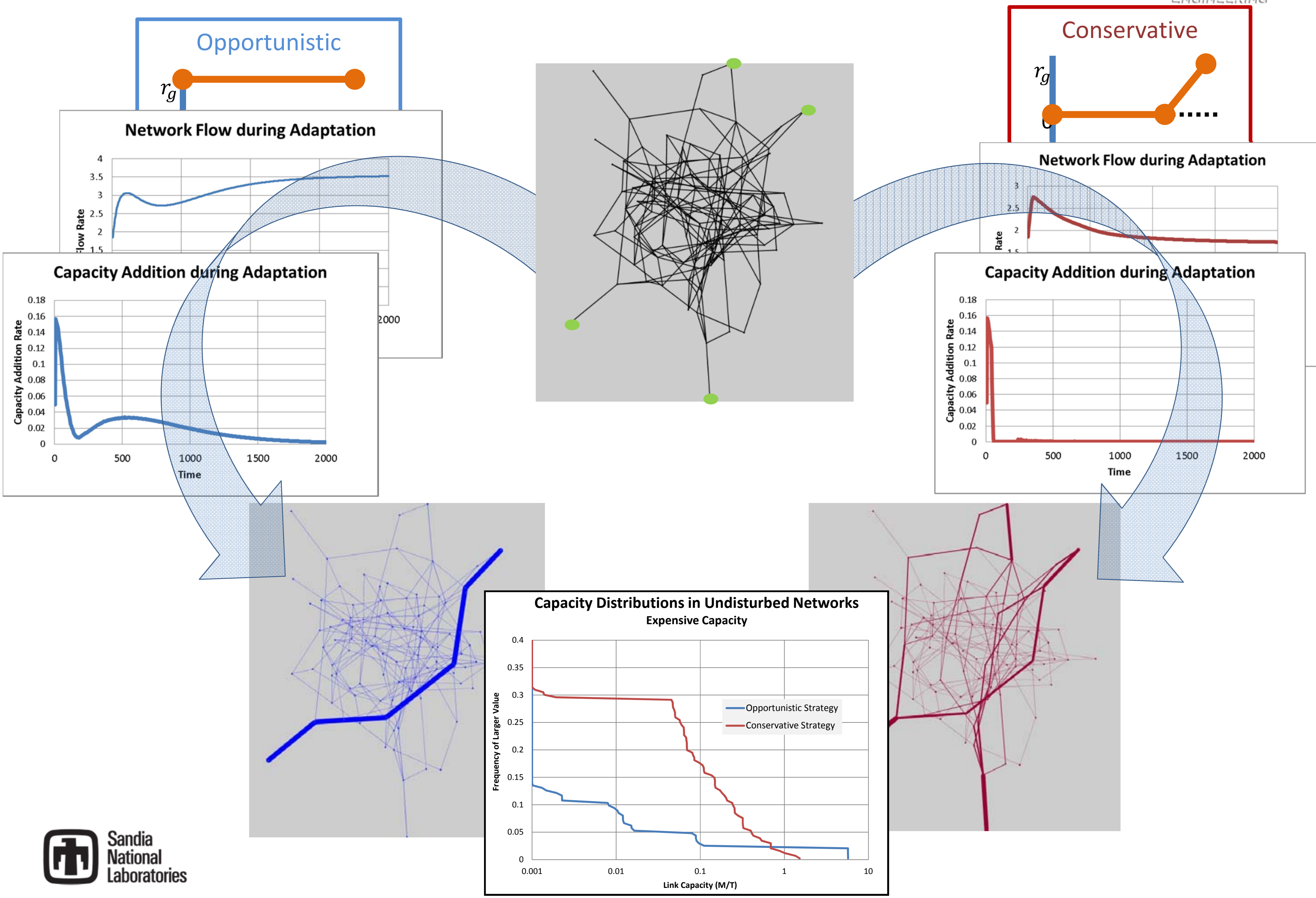

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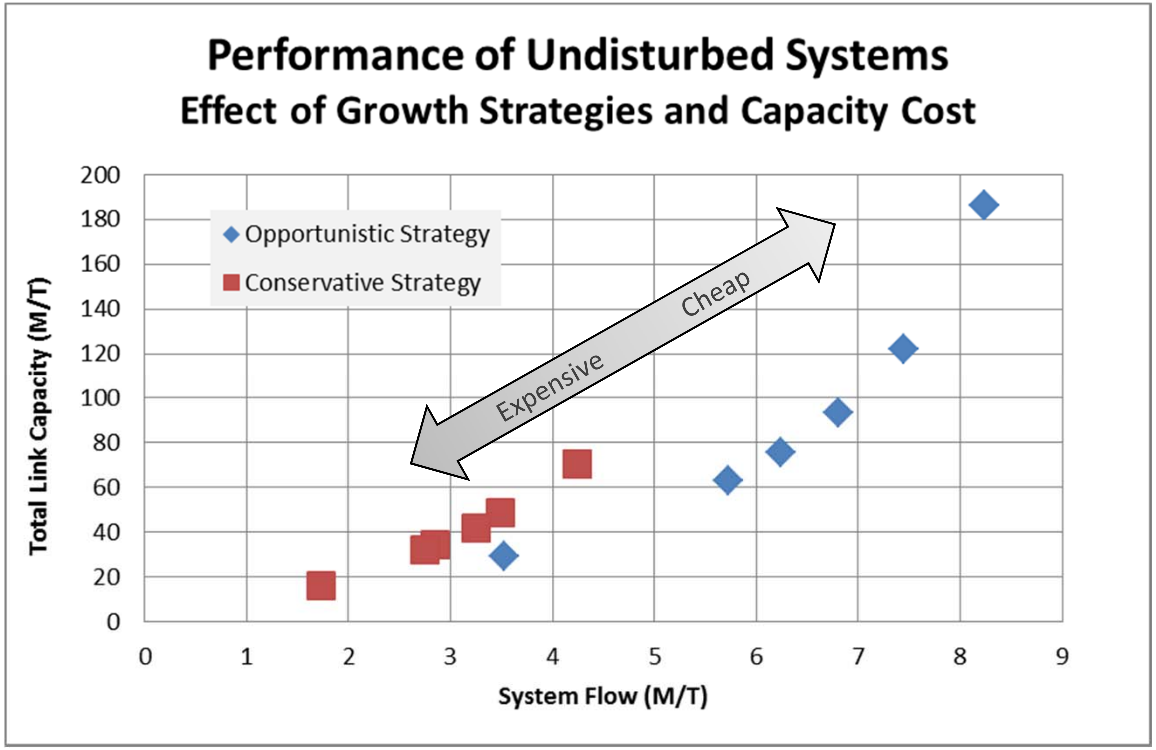
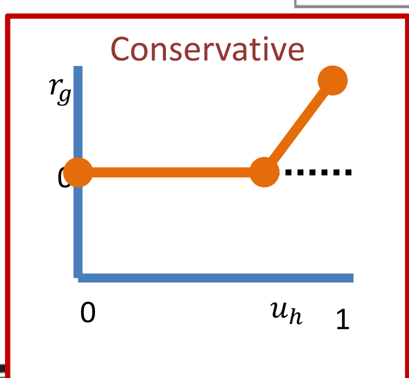
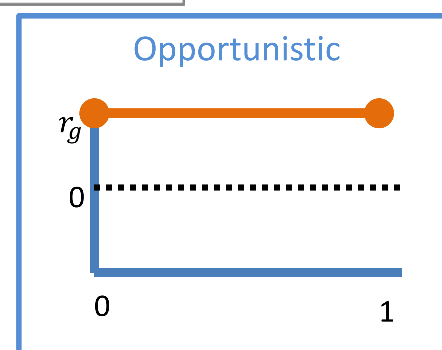
Local Strategies Shape Configuration and Performance

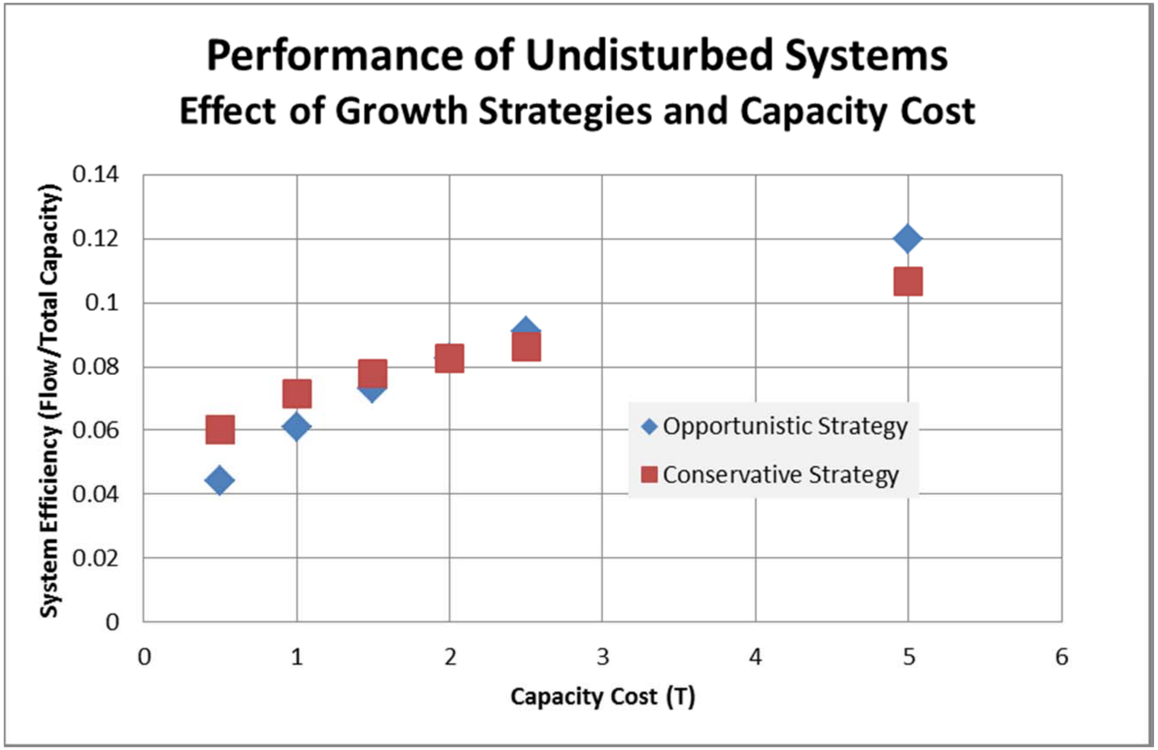


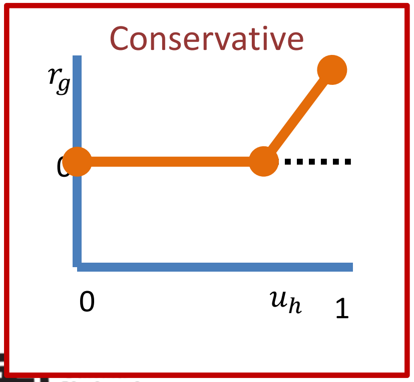


Higher capacity costs induce efficiency



Capacity Costs Encourage Efficiency





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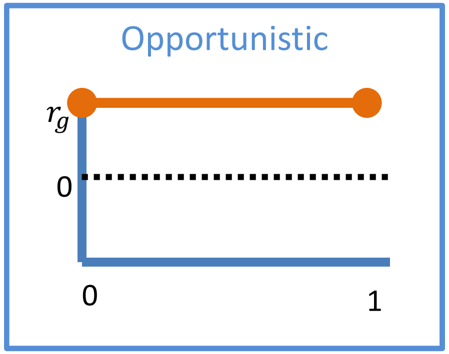

Influence of Disruption on System Performance

Opportunistic Strategy with Expensive Capacity

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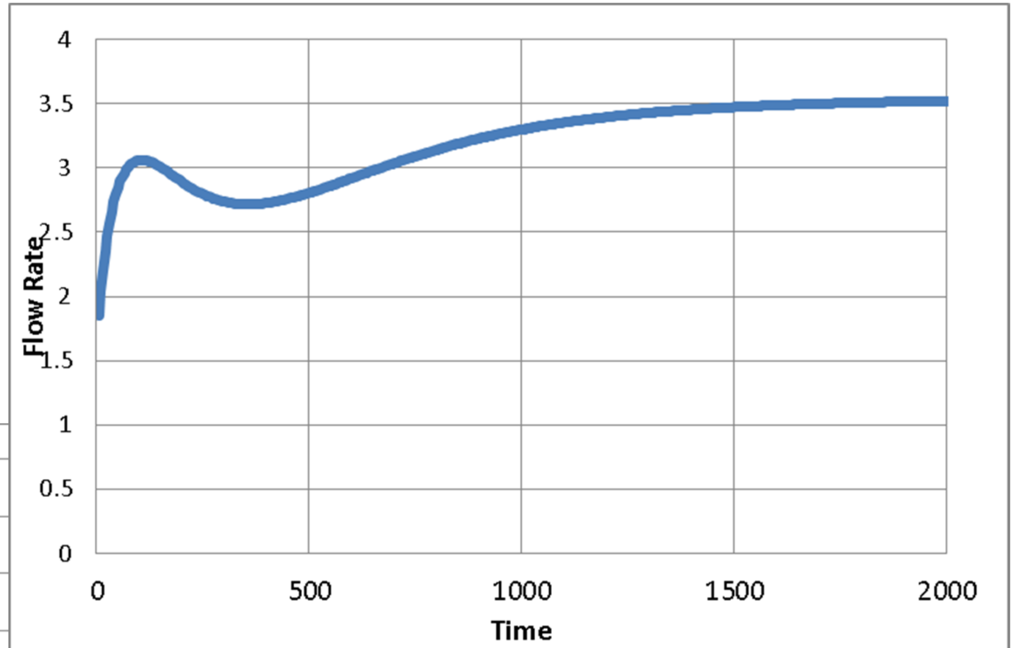
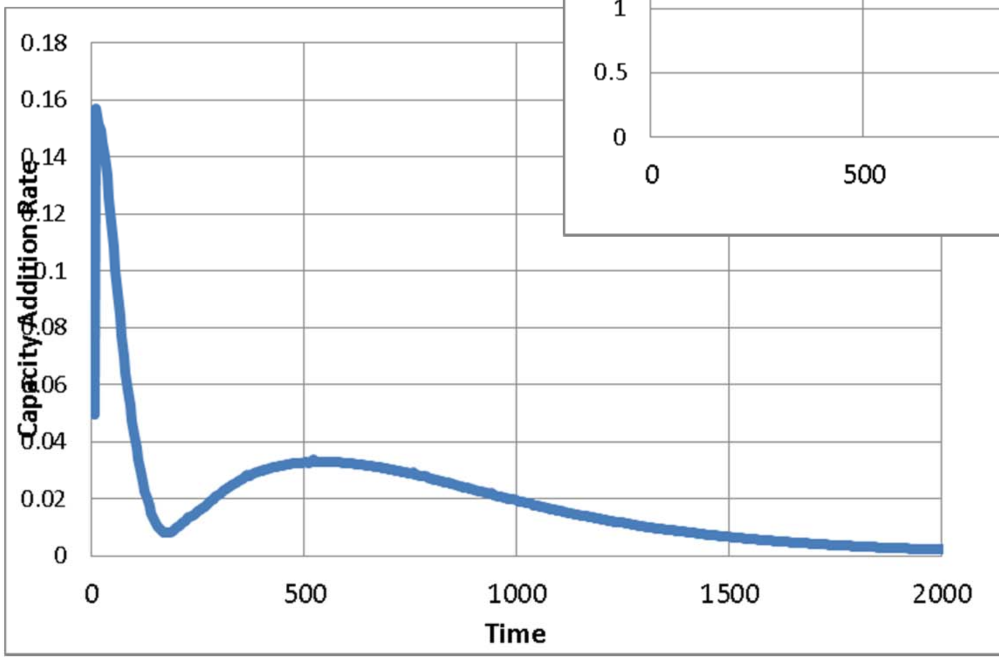
No Disruption





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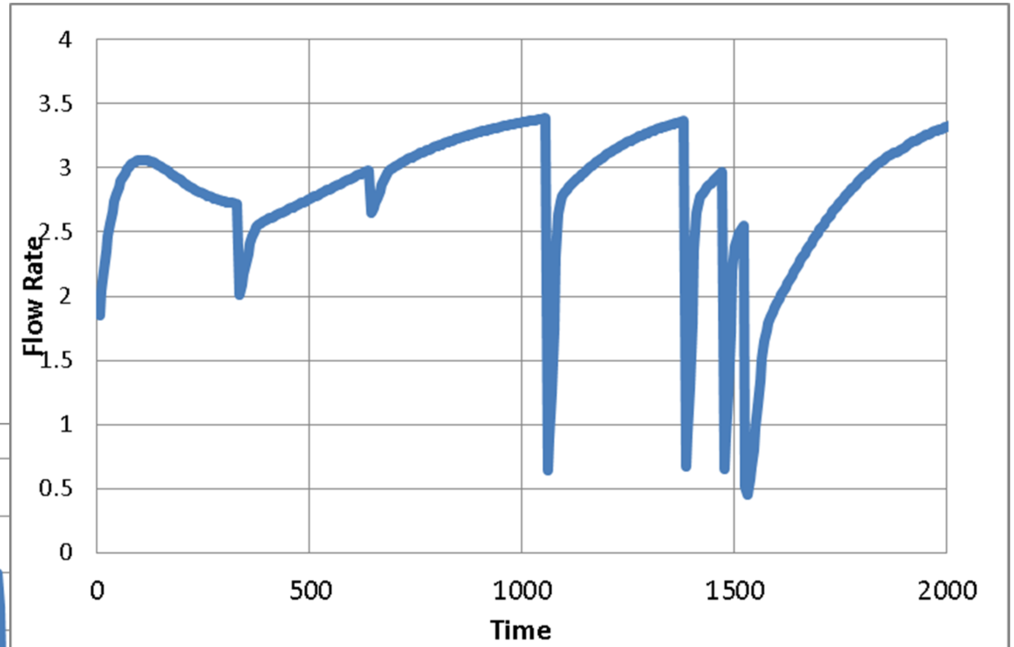

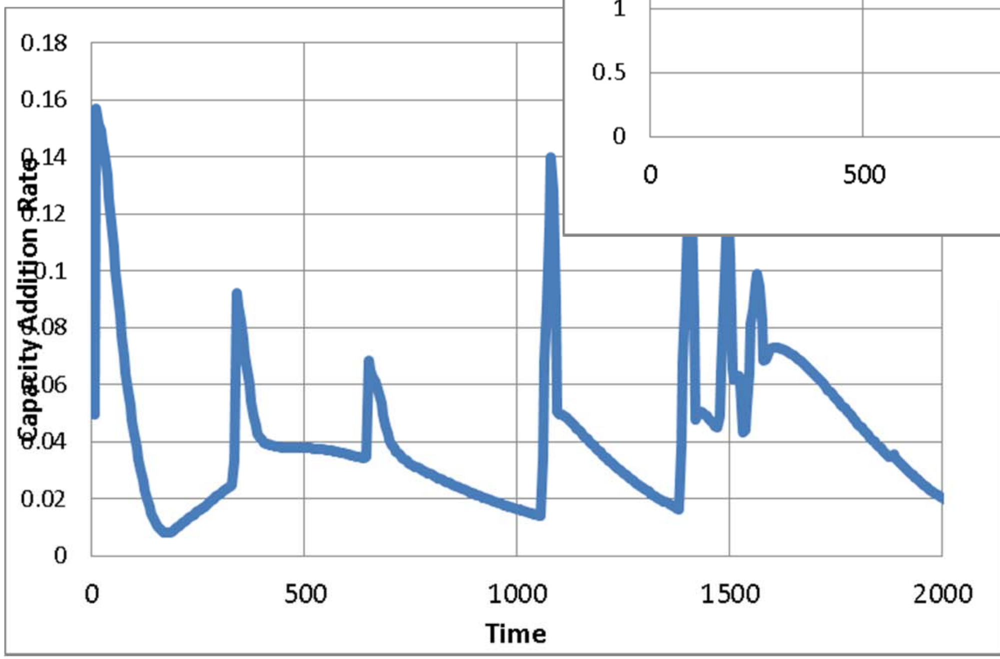

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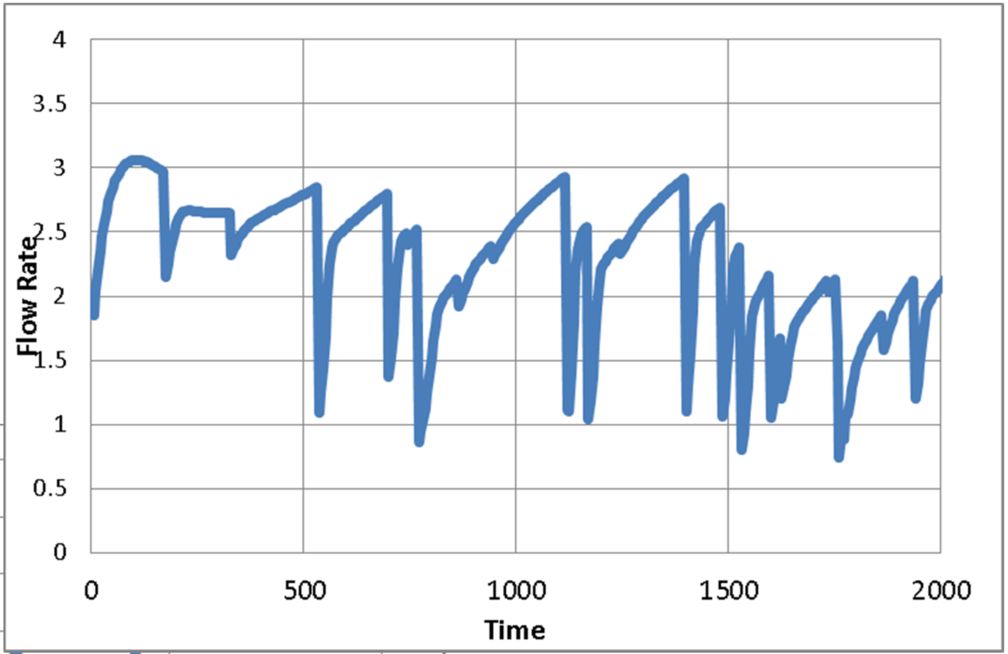

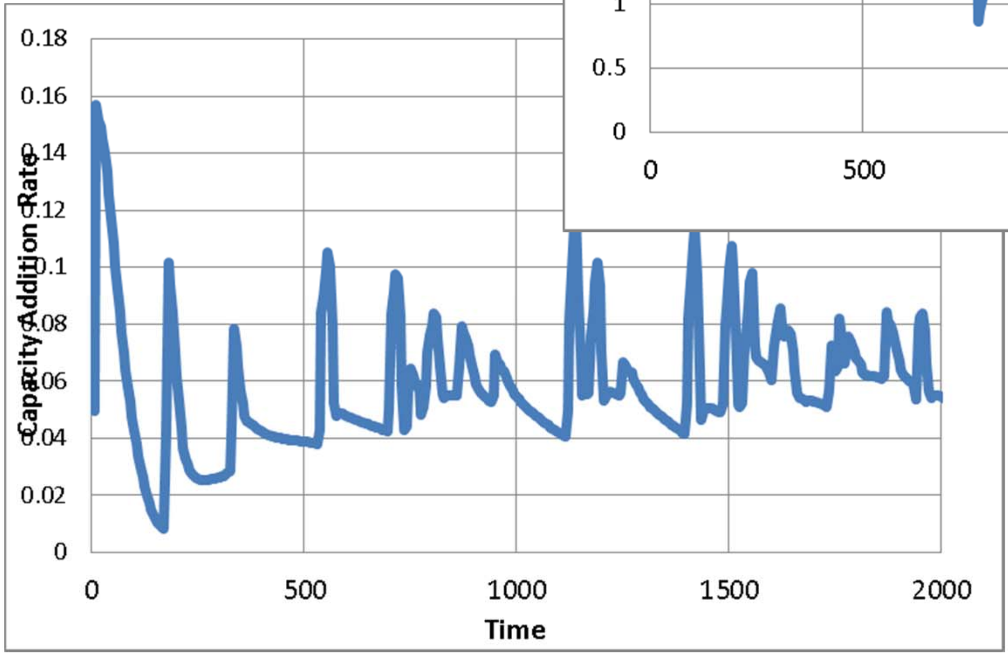

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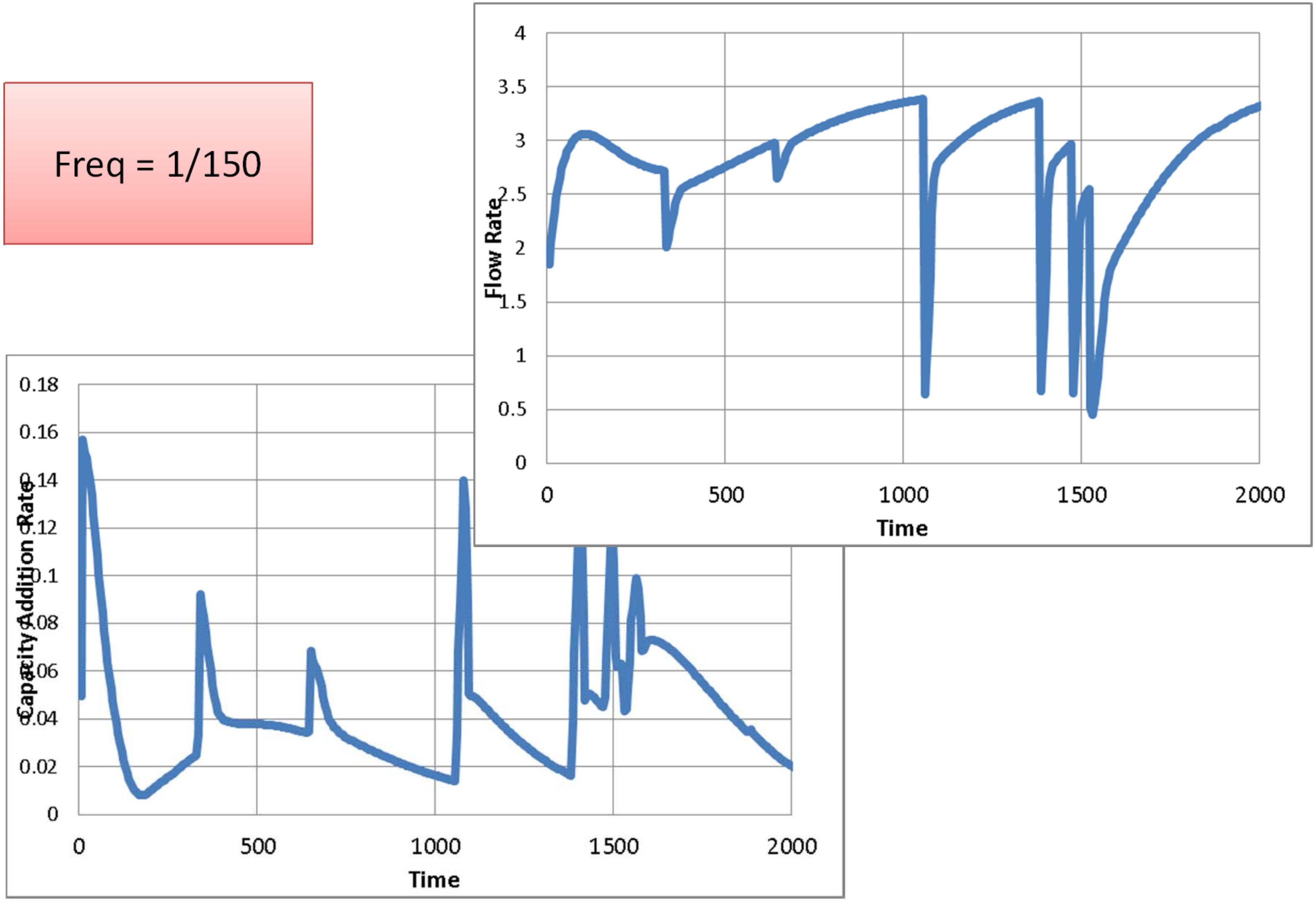

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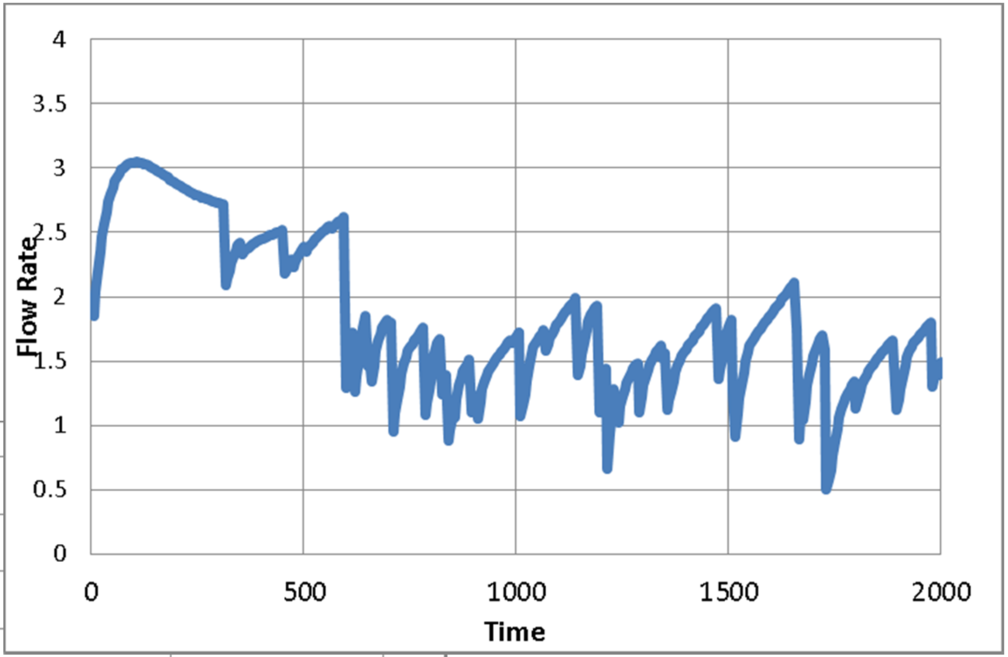

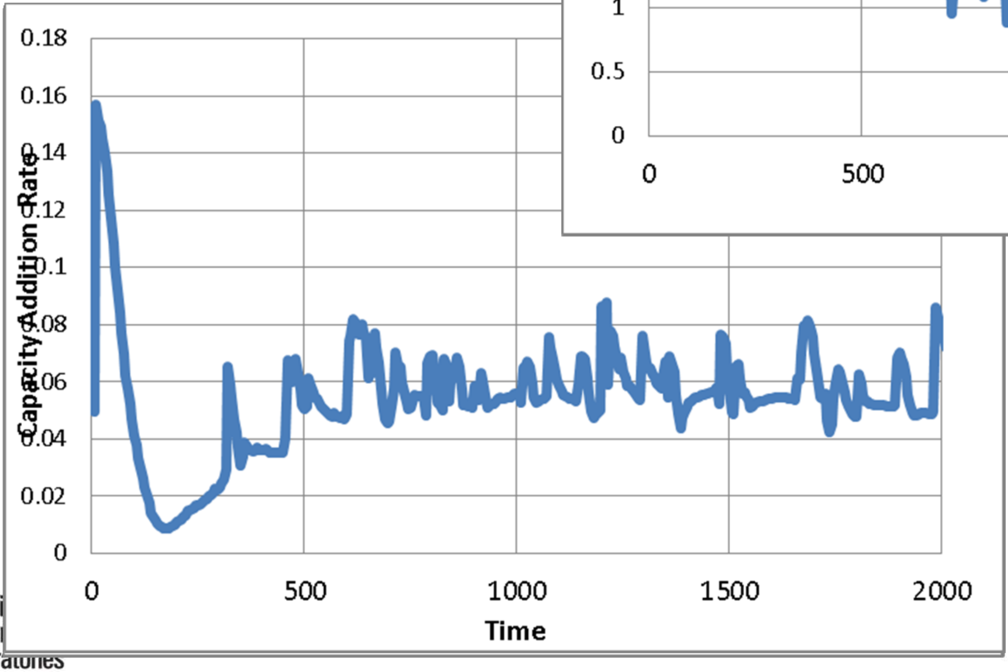

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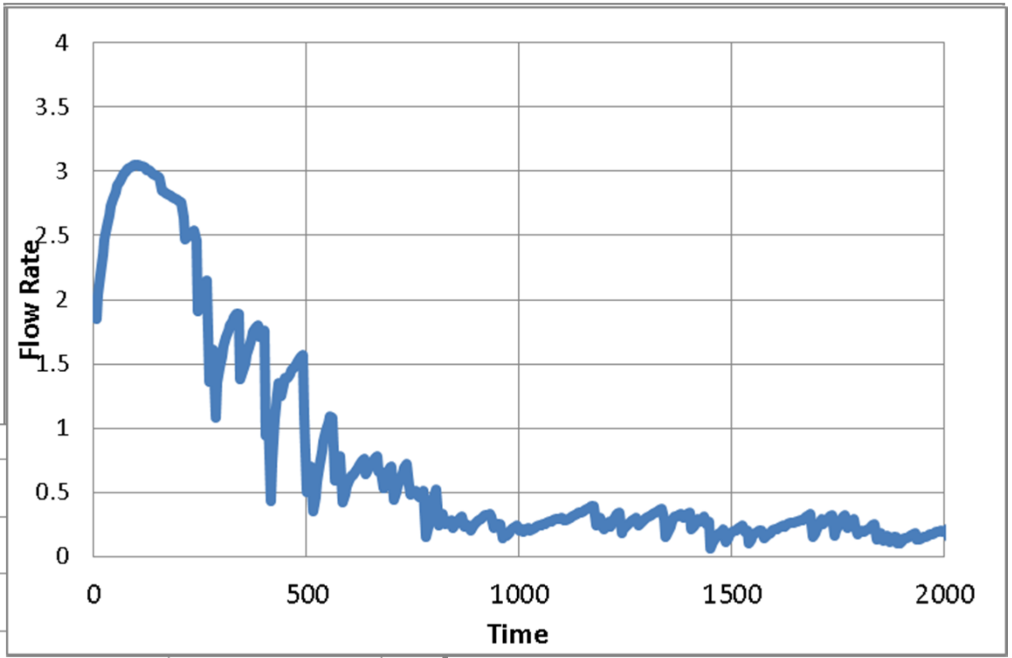

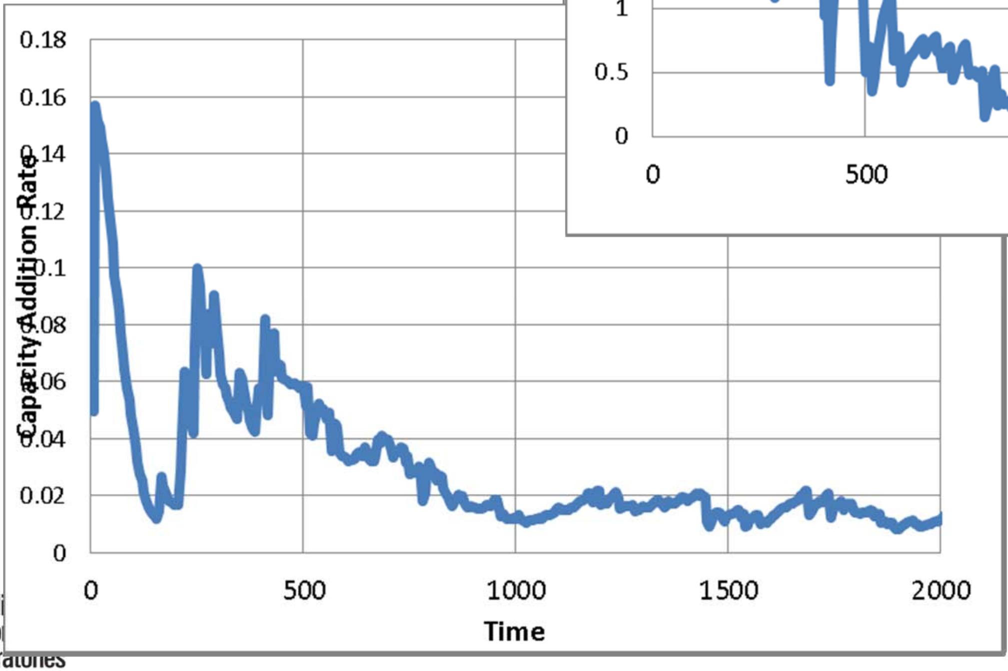

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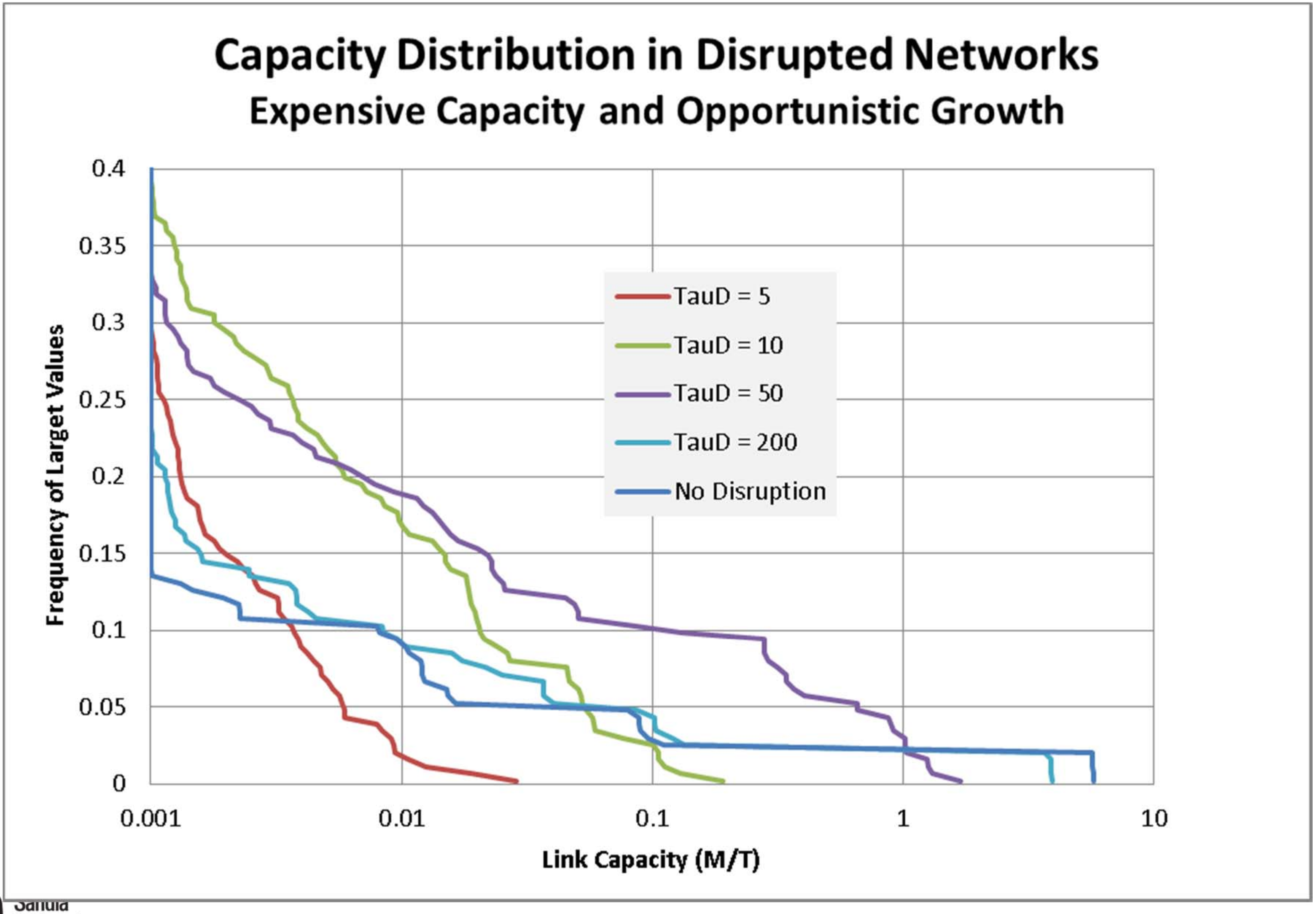
Influence of Disruption on System Structure
Opportunistic Strategy with Expensive Capacity



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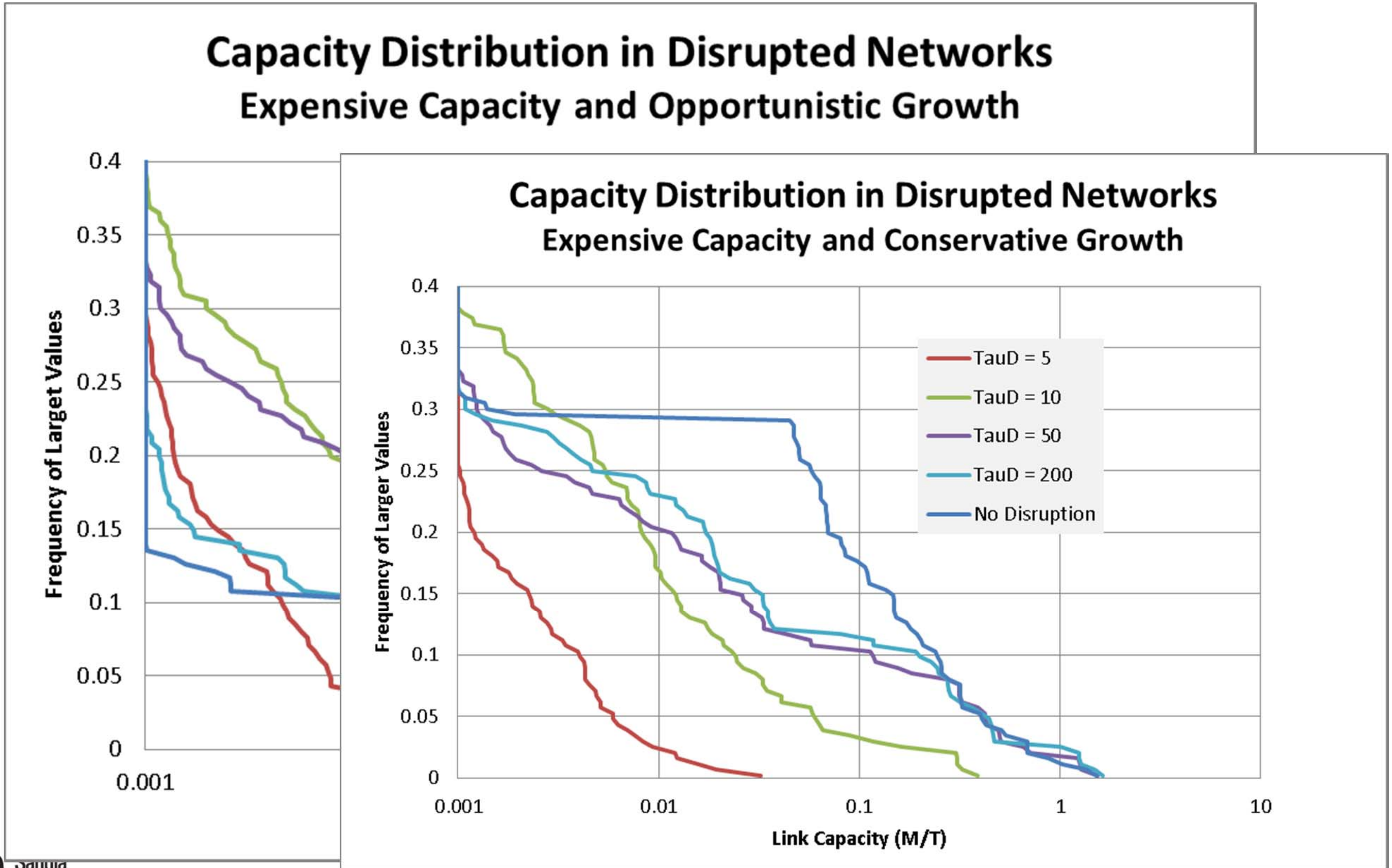

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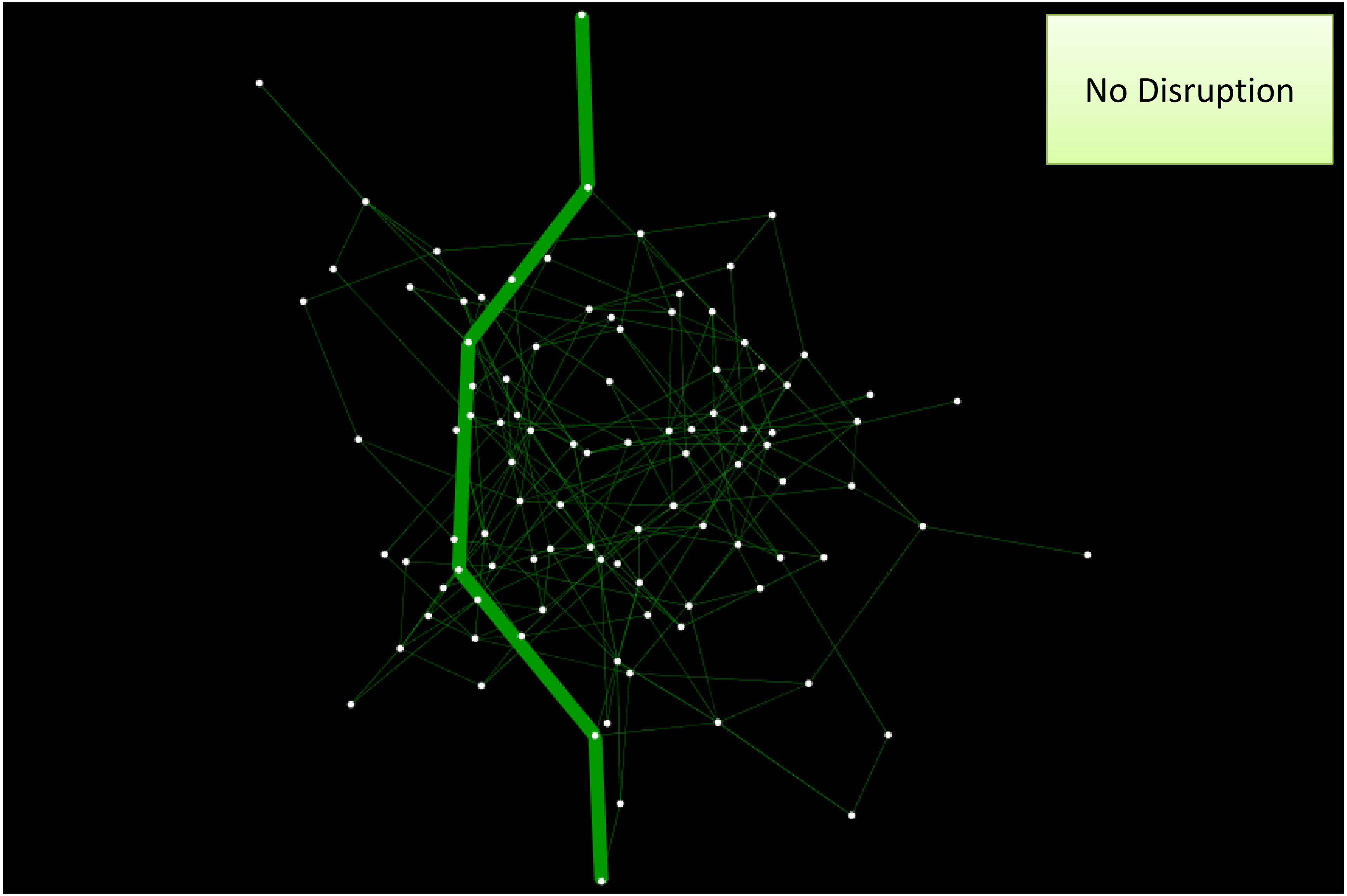

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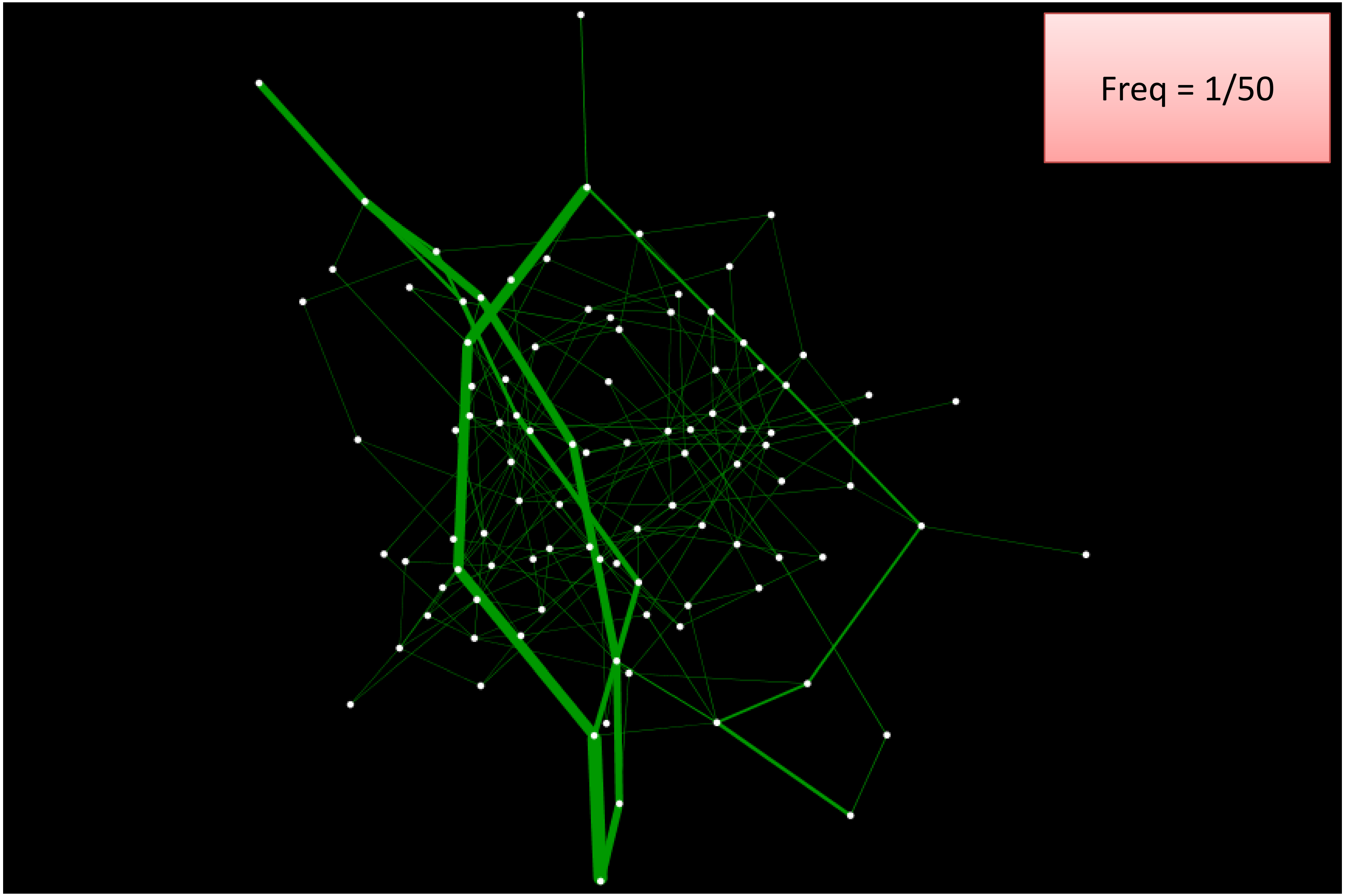

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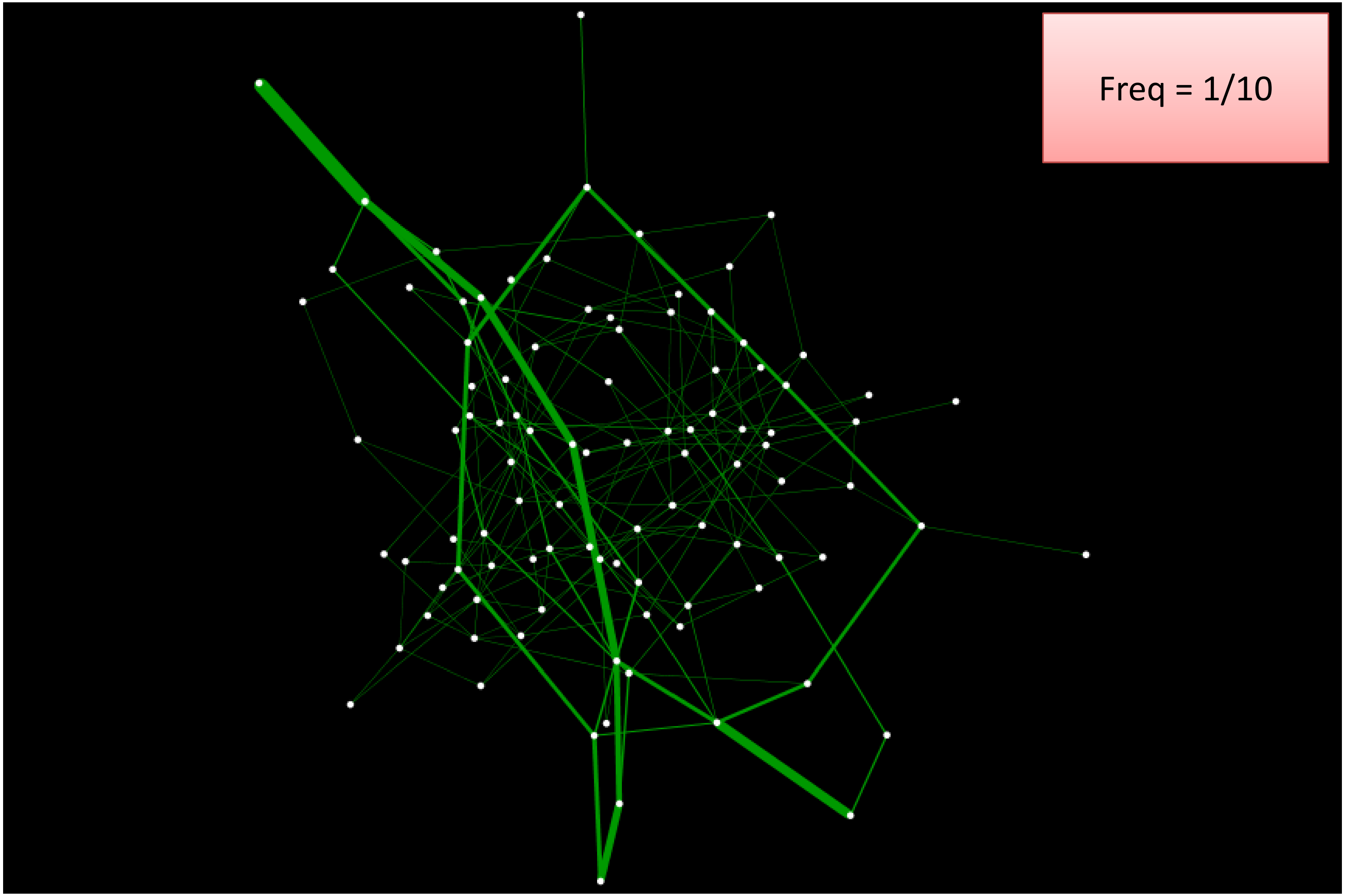

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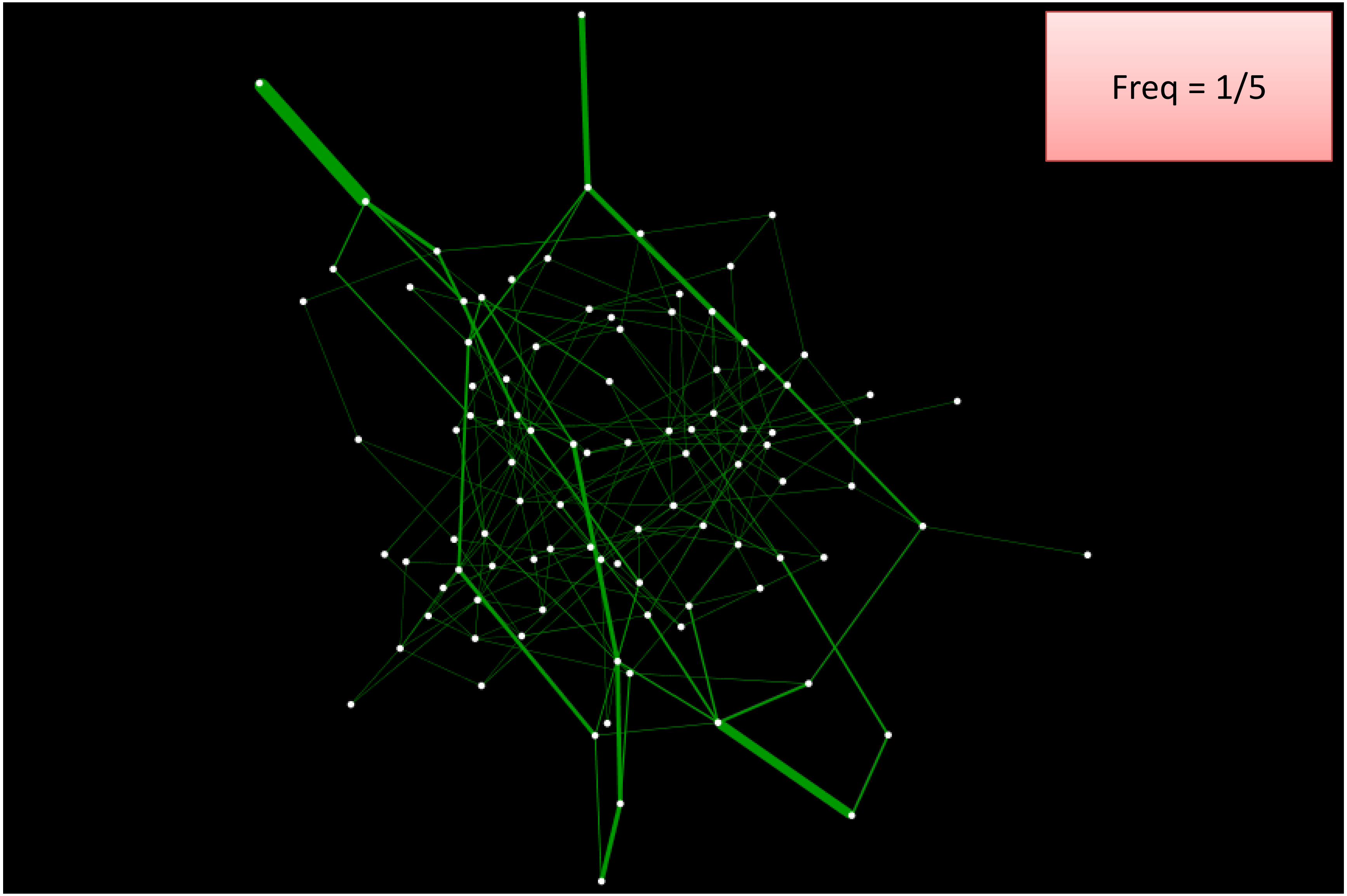

Assessing Resilience to Extraordinary Disruptions

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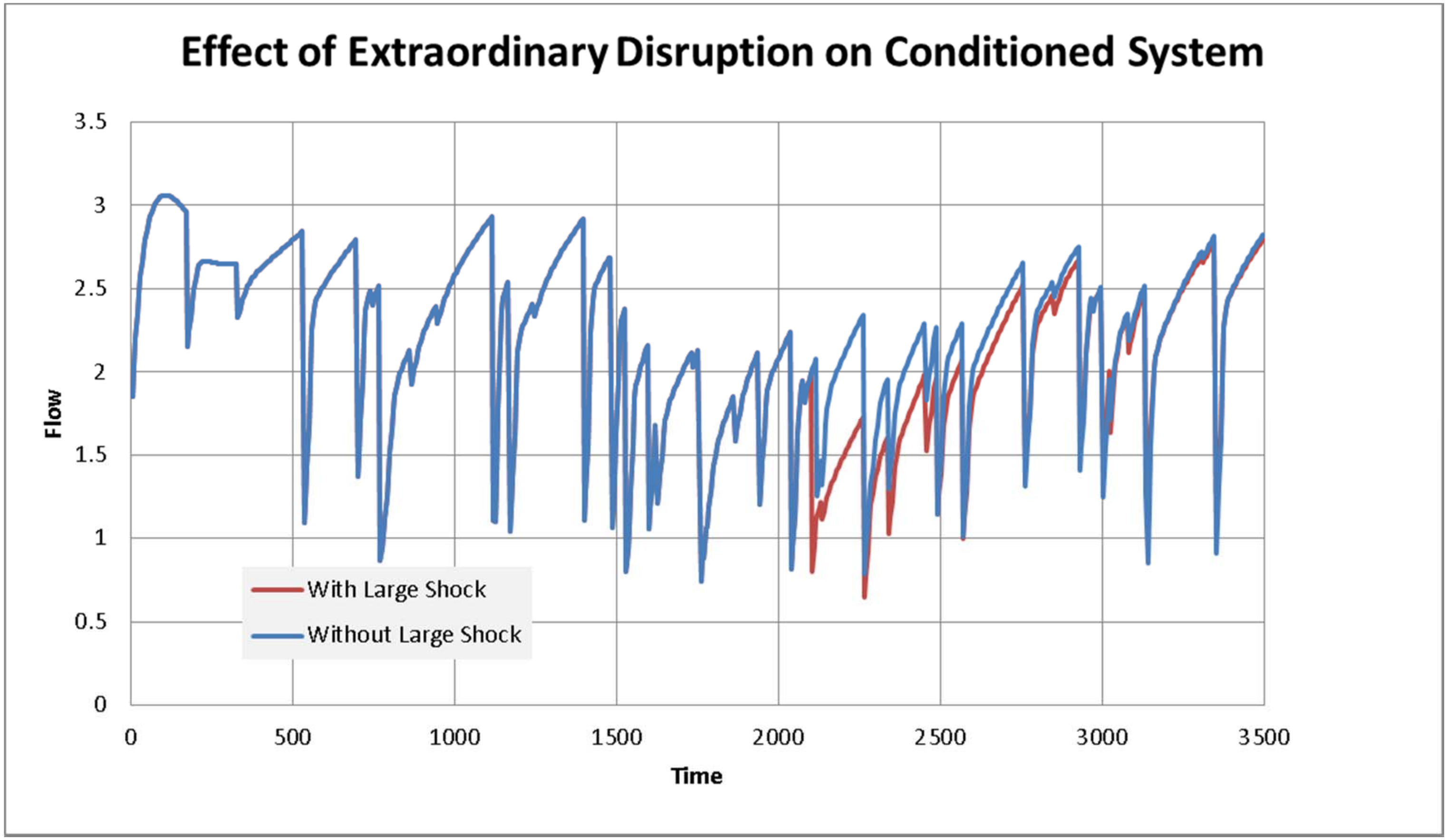

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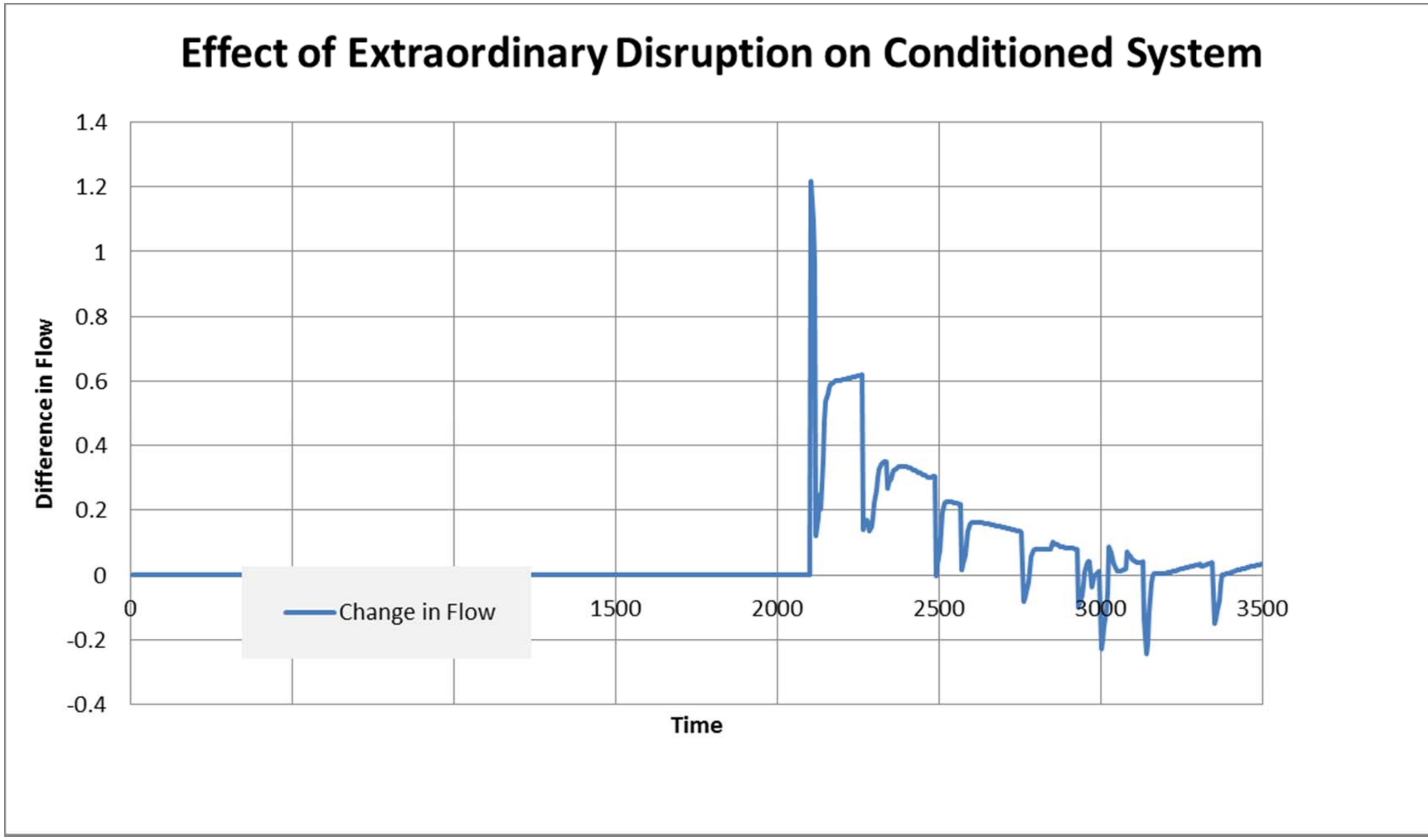

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Assessing Resilience to Extraordinary Disruptions

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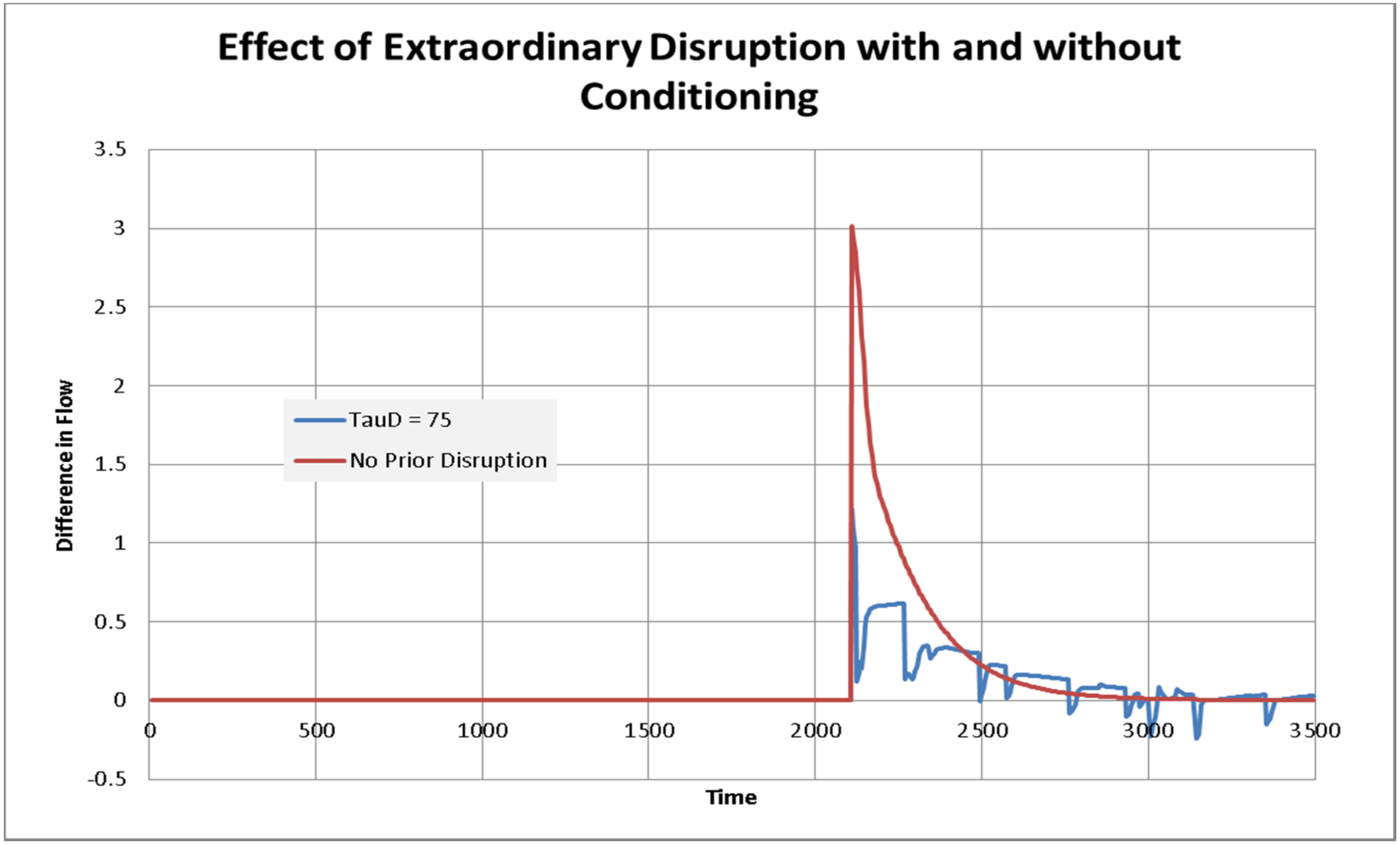

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Summary

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- Network structure can reflect an adaptive response, balancing requirements for good nominal performance and resistance to disruption
- Whether this adaptation leads to a resilient system depends on …
- We are using a simple model of a class of infrastructure systems to understand whether (or under what conditions) adaptation to small disruptions can confer resilience to big ones
- Initial results suggest that
  - The undisturbed system tends toward efficiency
  - Adaptation under disruption can improve performance compared to naïve systems
- Next:
  - Complete and publish an exploration of parameter space for this model
  - Explore application of the approach to other systems of interest having different driving processes and adaptive responses (human networks, communications systems, biological systems)