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Measuring & Influencing Resilience of Adapting Flow Networks

Walt Beyeler, Eric Vugrin, Steve Verzi,
Geoff Forden, Munaf Aamir,
Chris Lamb, Sasha Outkin

Sandia National Laboratories

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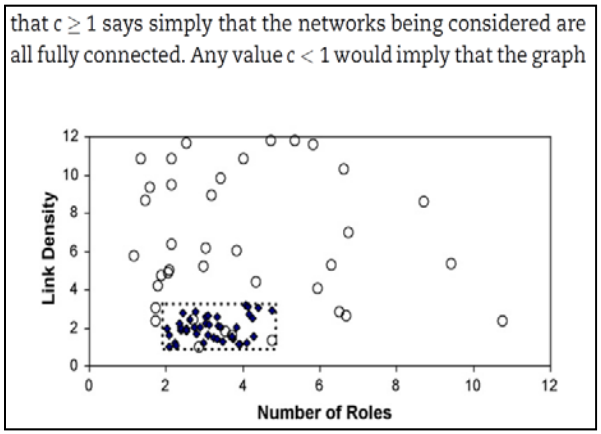
Presentation to Sandia National Laboratories' Complex Systems Advisory Panel

- 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



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

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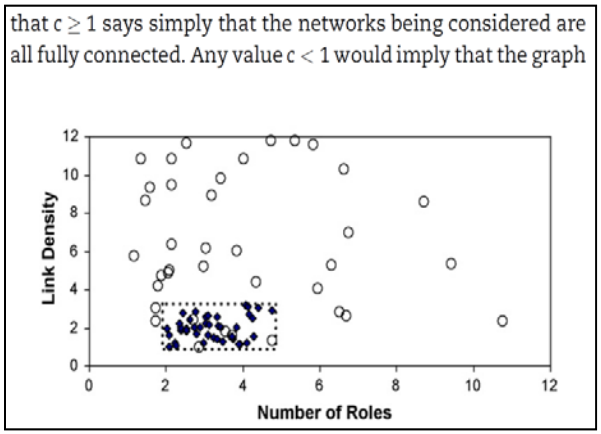

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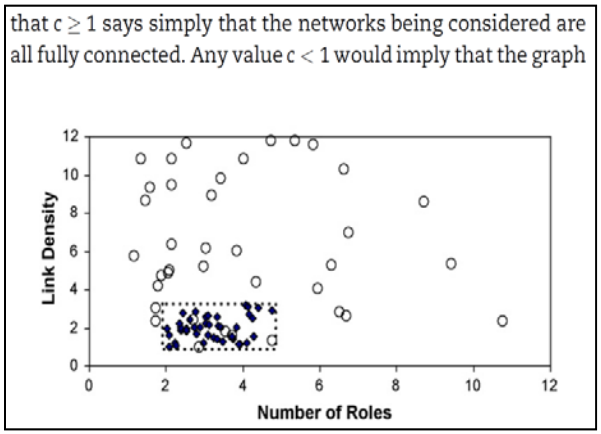

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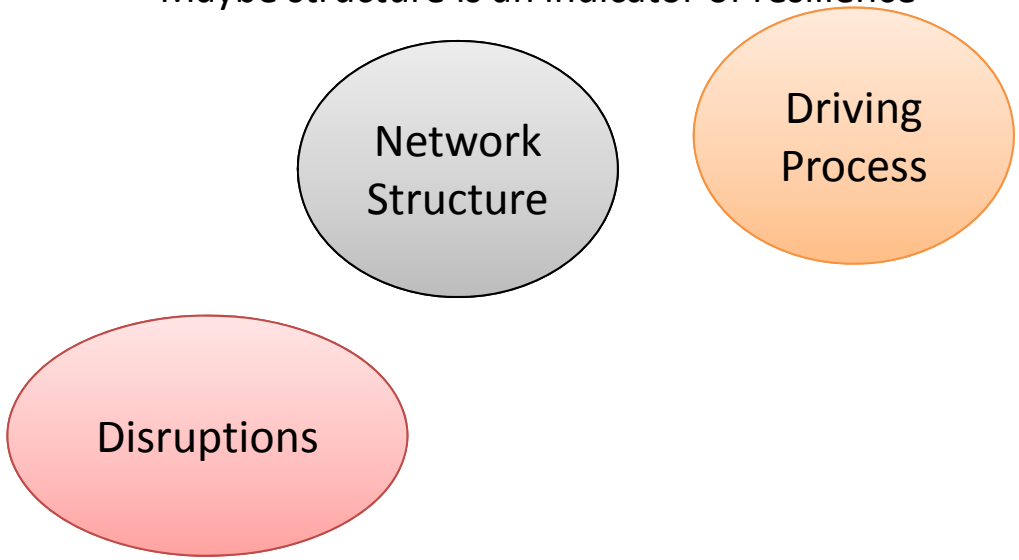

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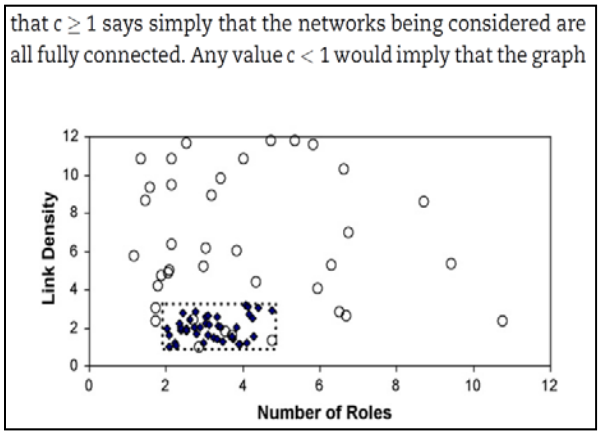

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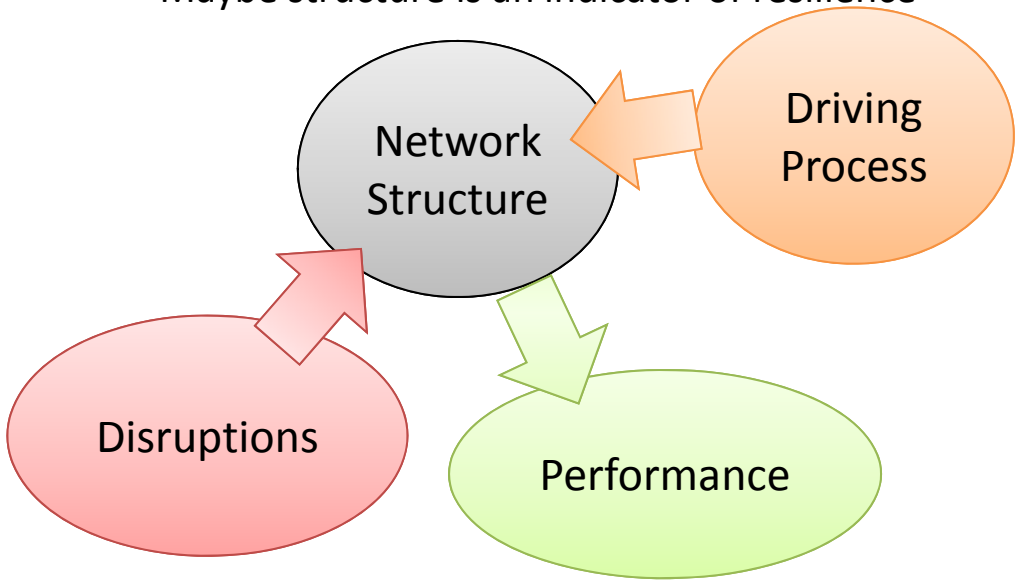

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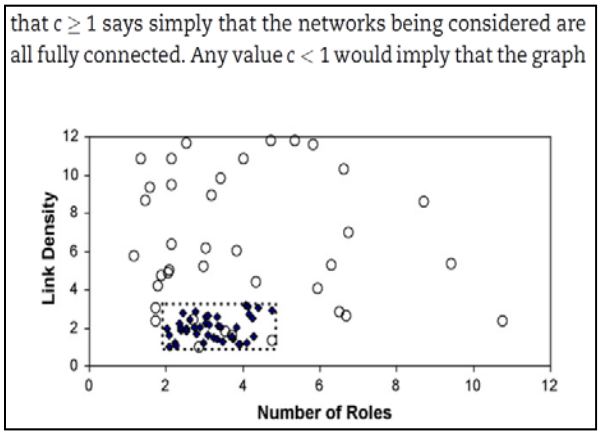

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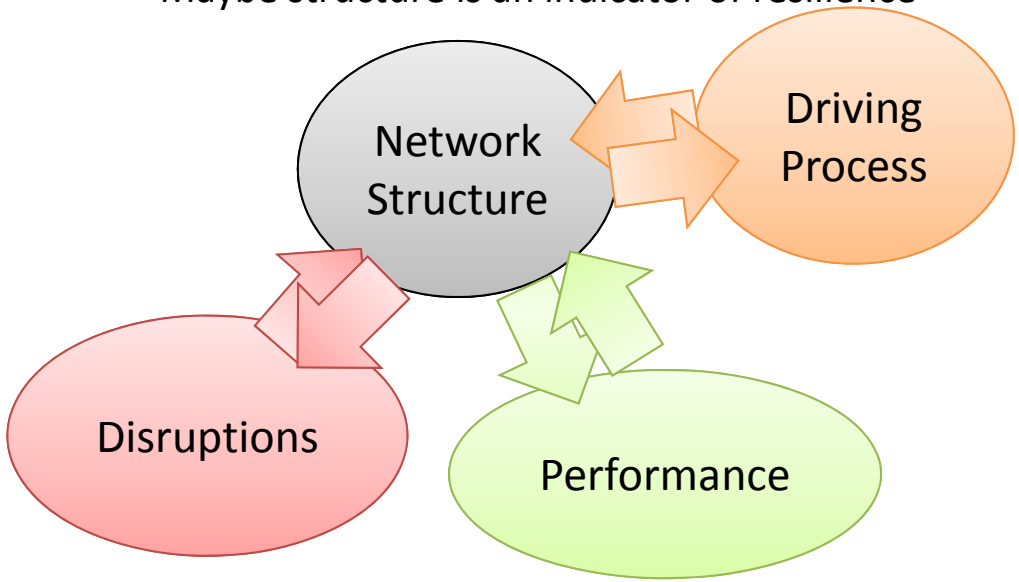

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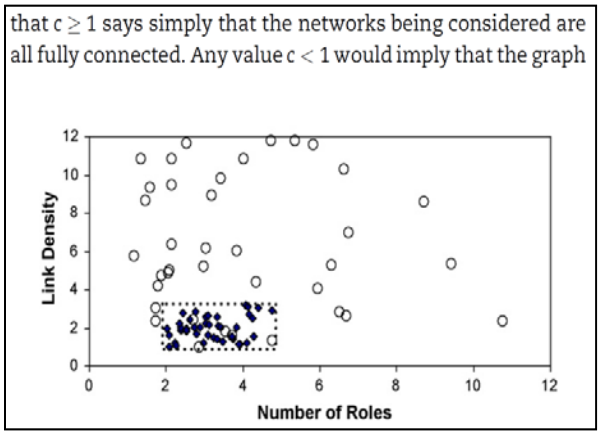

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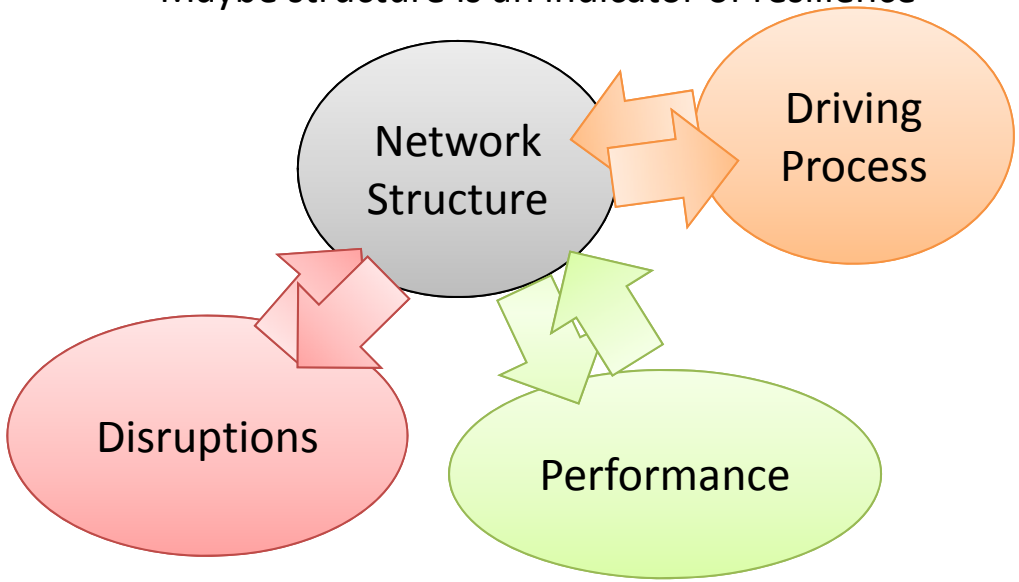
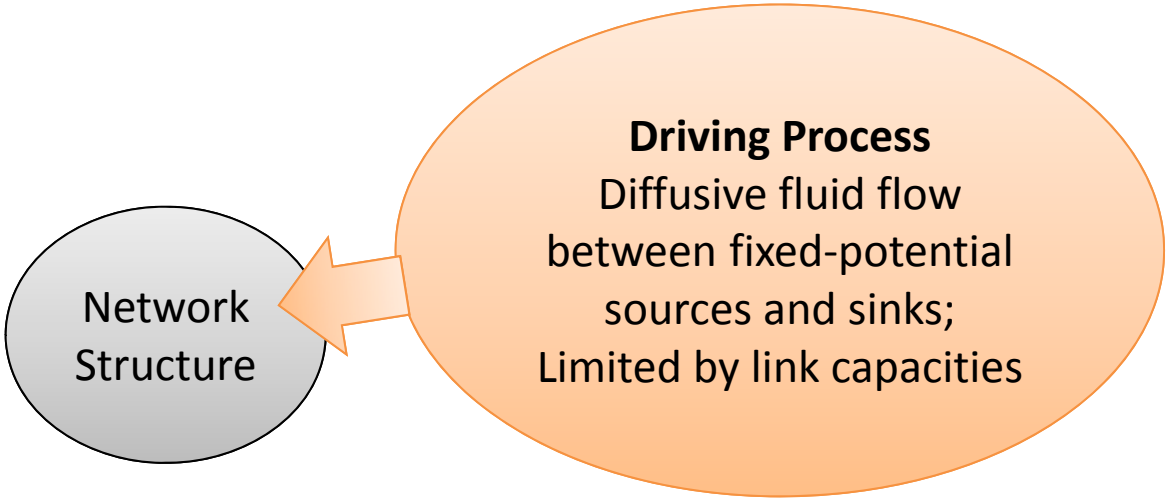


Answers depend on specifics.
We start with a simple flow model…

Model Features



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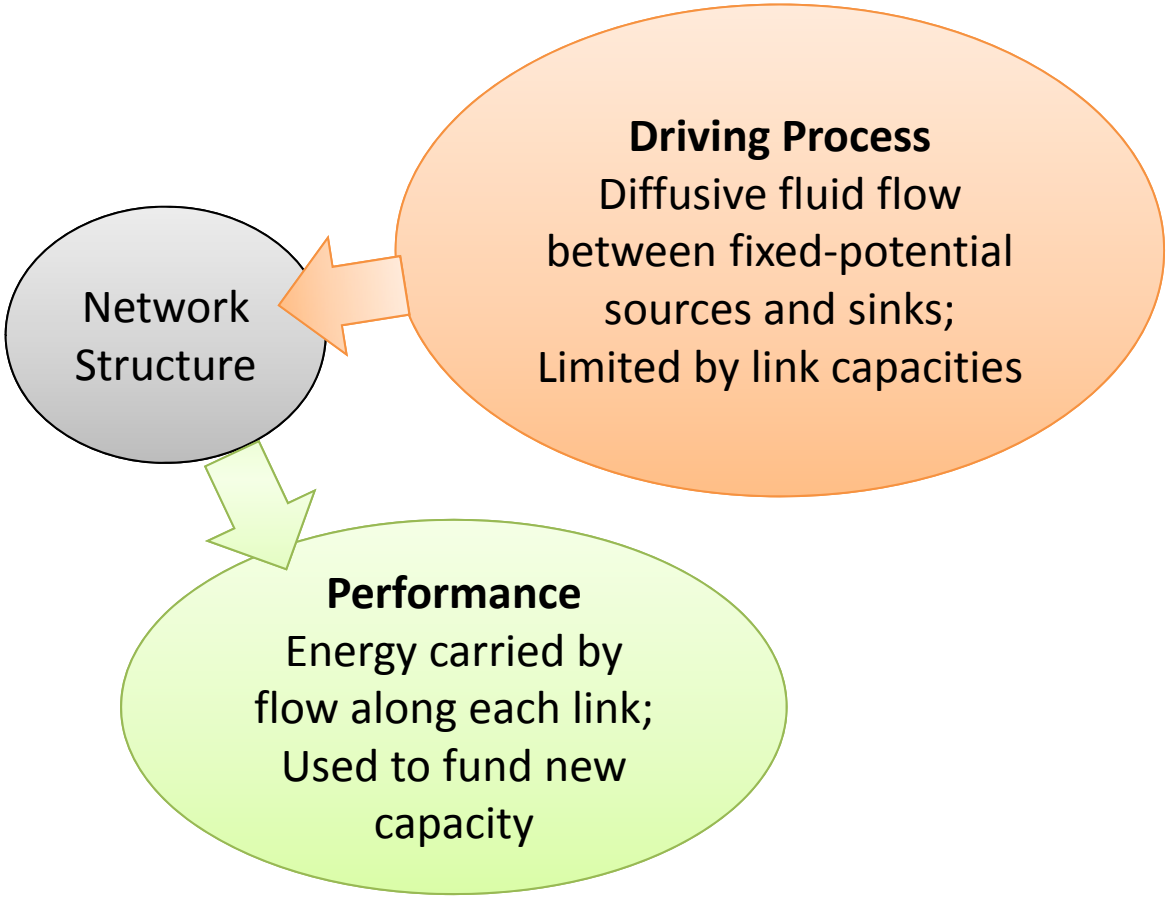

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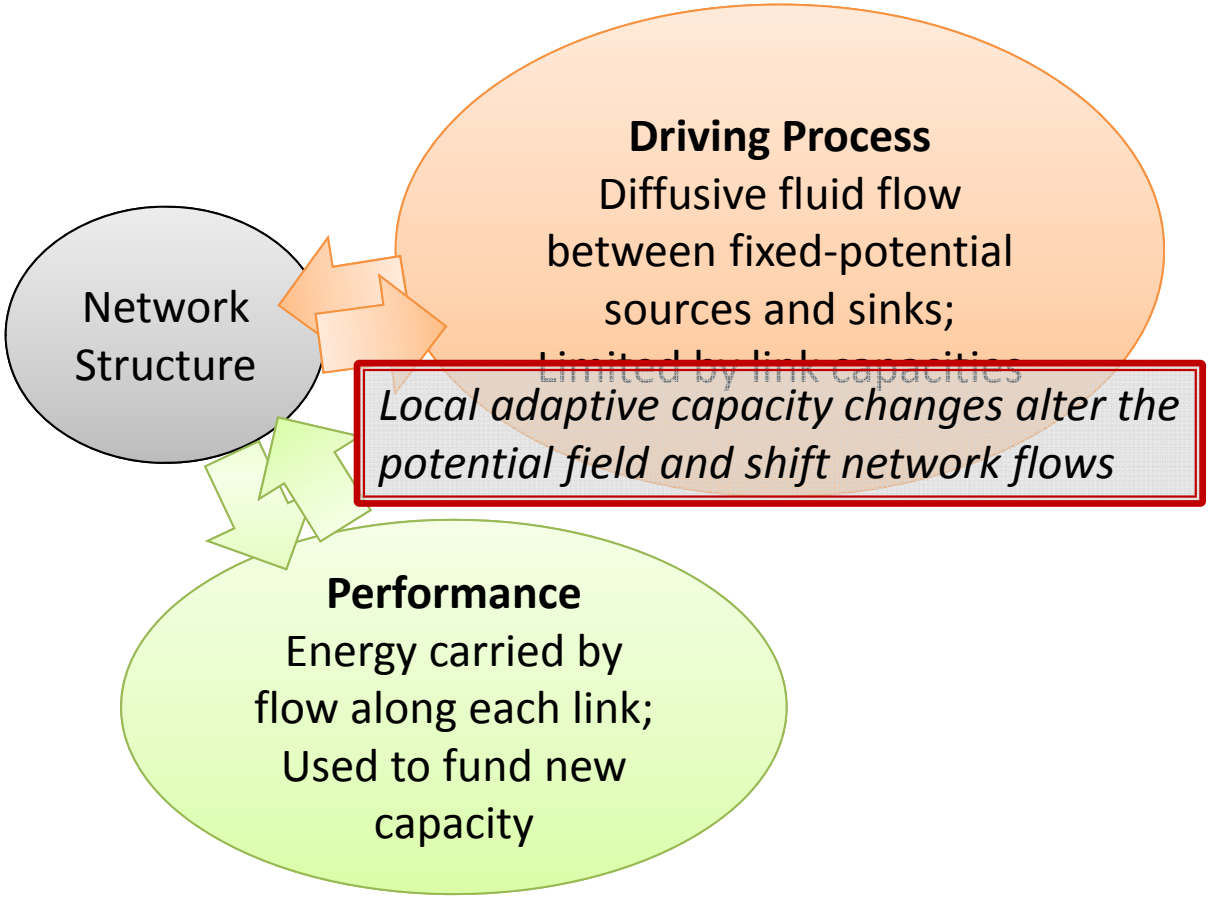

Model Features

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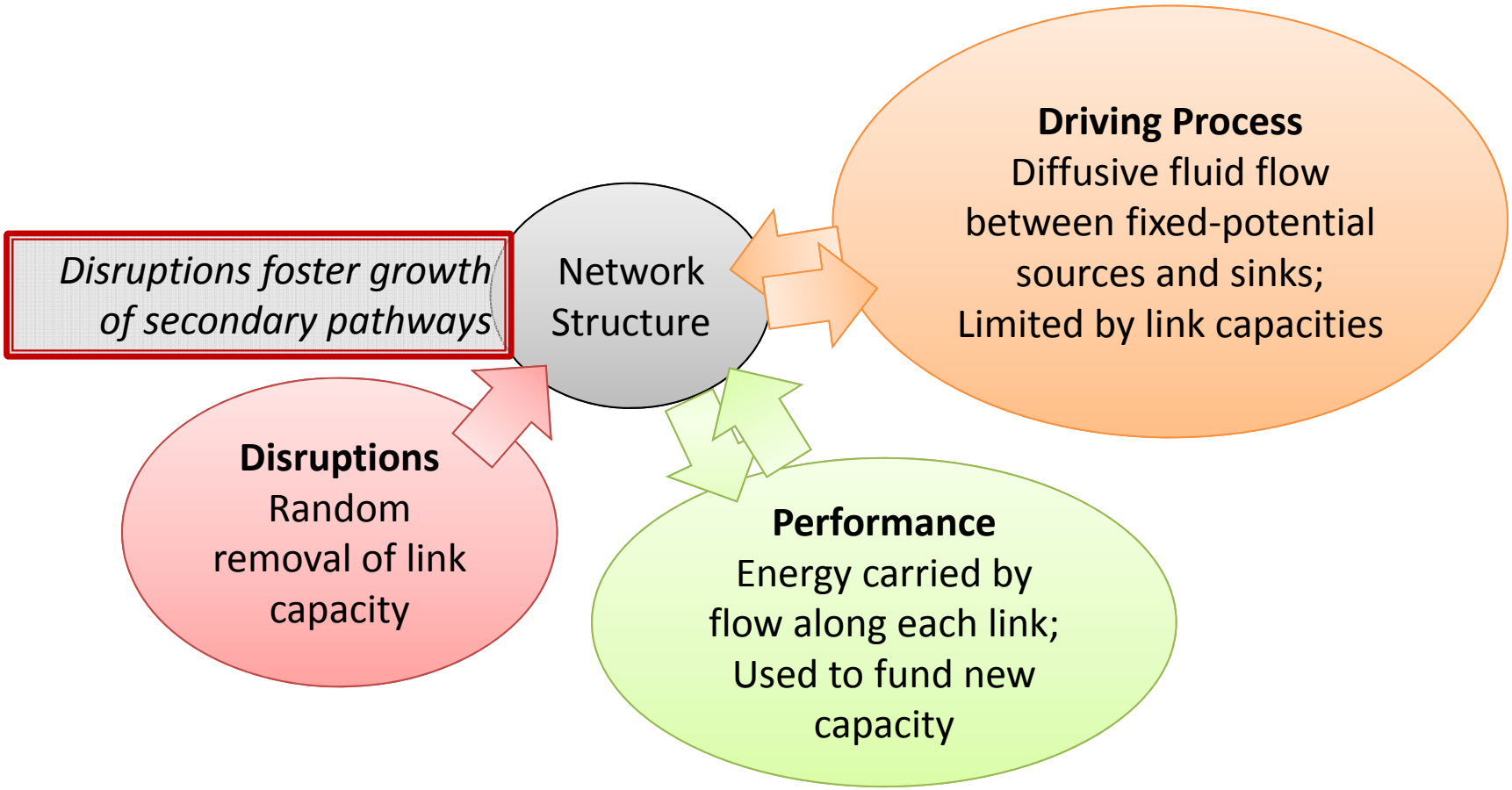

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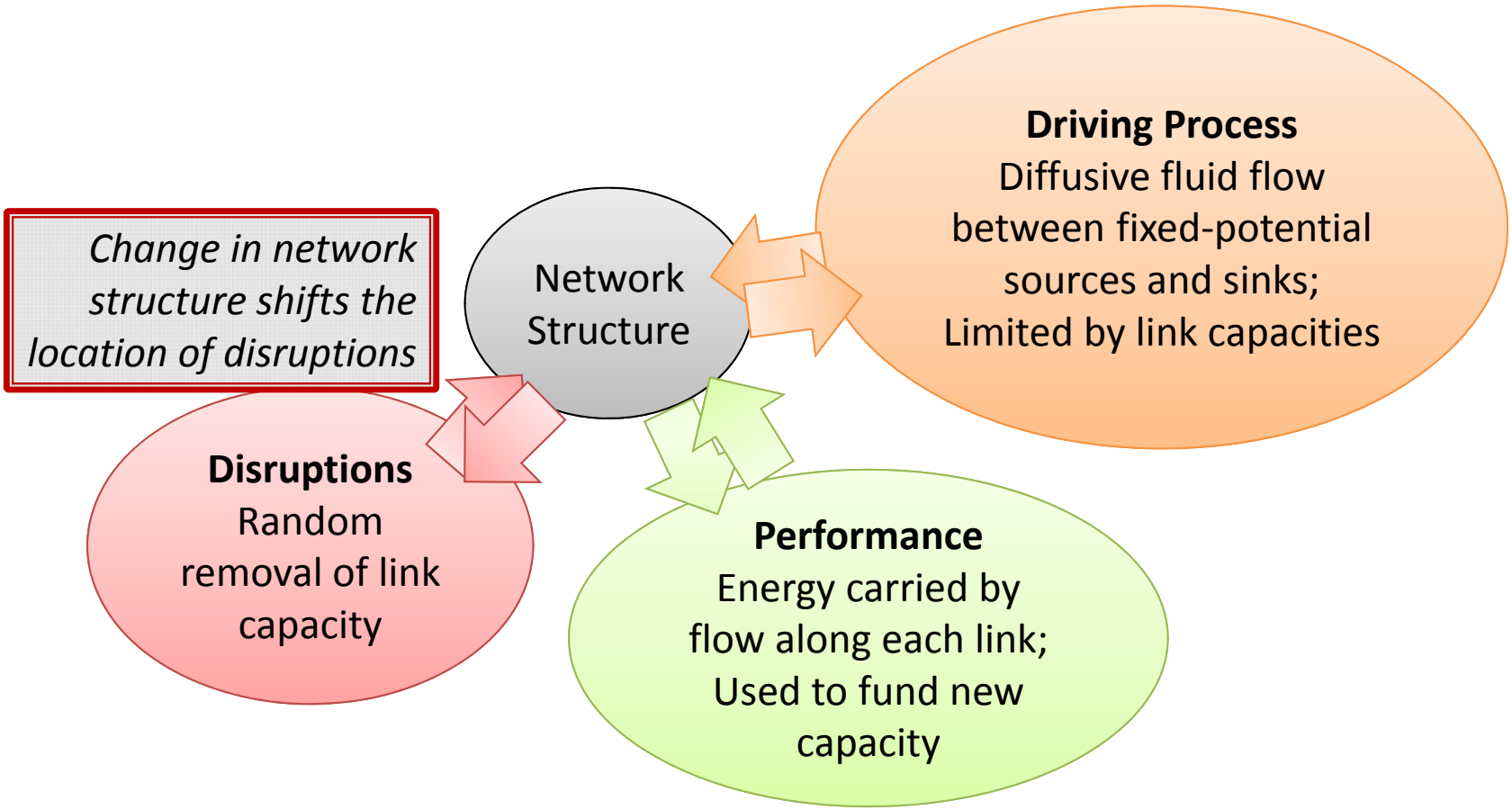

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Flow and Growth Process Models

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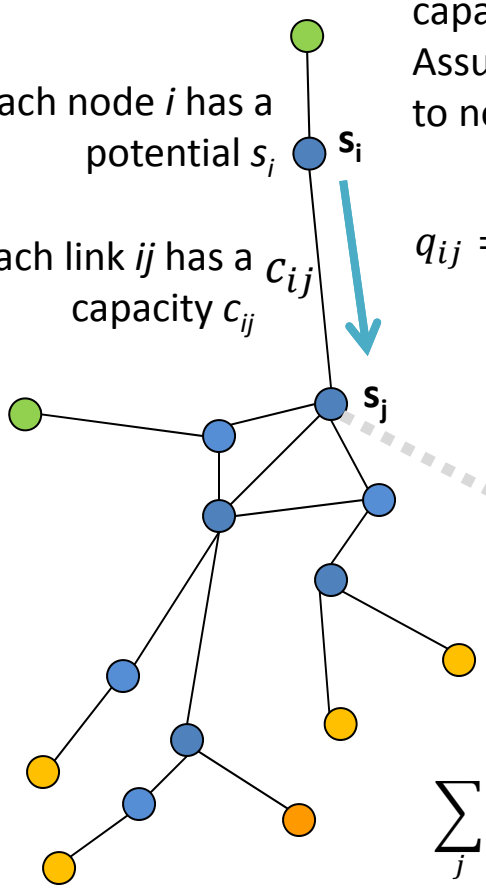
Each node *i* has a potential s_i

Each link *ij* has a capacity c_{ij}



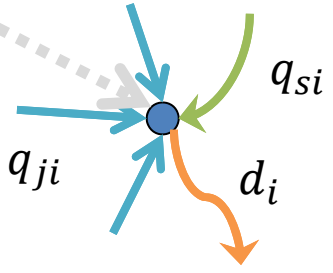
Flow rates are limited by a (directed) capacity associated with each link, c_{ij}. Assuming $s_i > s_j$, the flow from node *i* to node *j* is given by:

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

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:

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

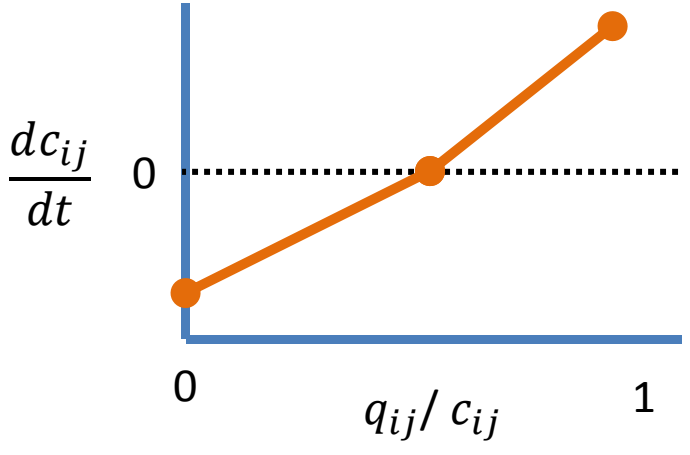
In equilibrium, the net flow at each node *i* is 0, including any internal sources (q_{si}) or sinks(d_i):



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

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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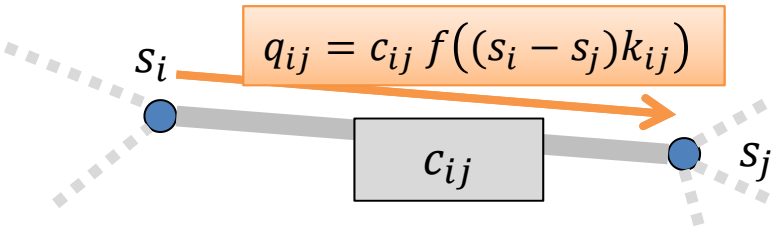
Link Capacity Dynamics



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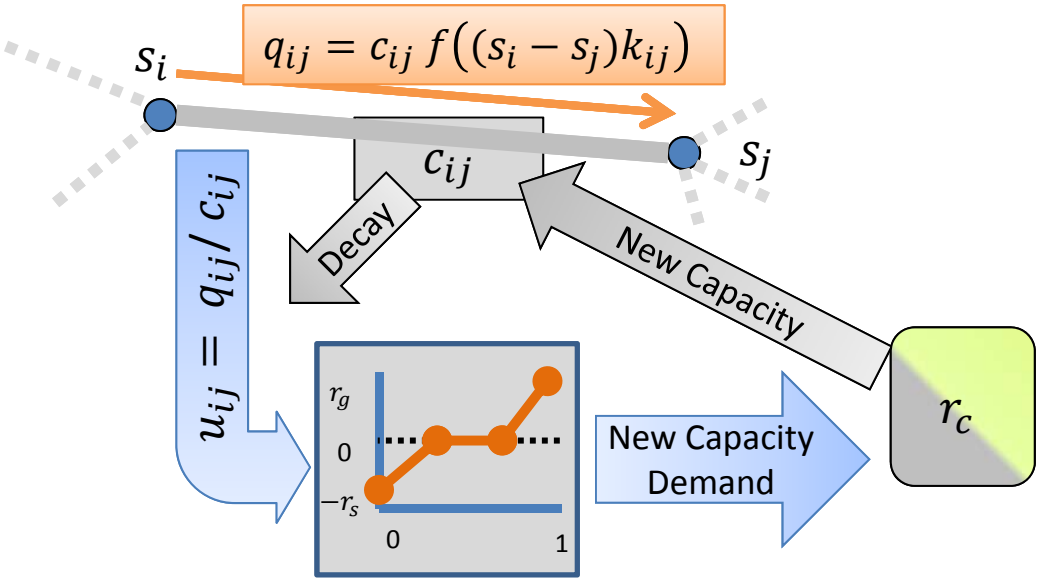

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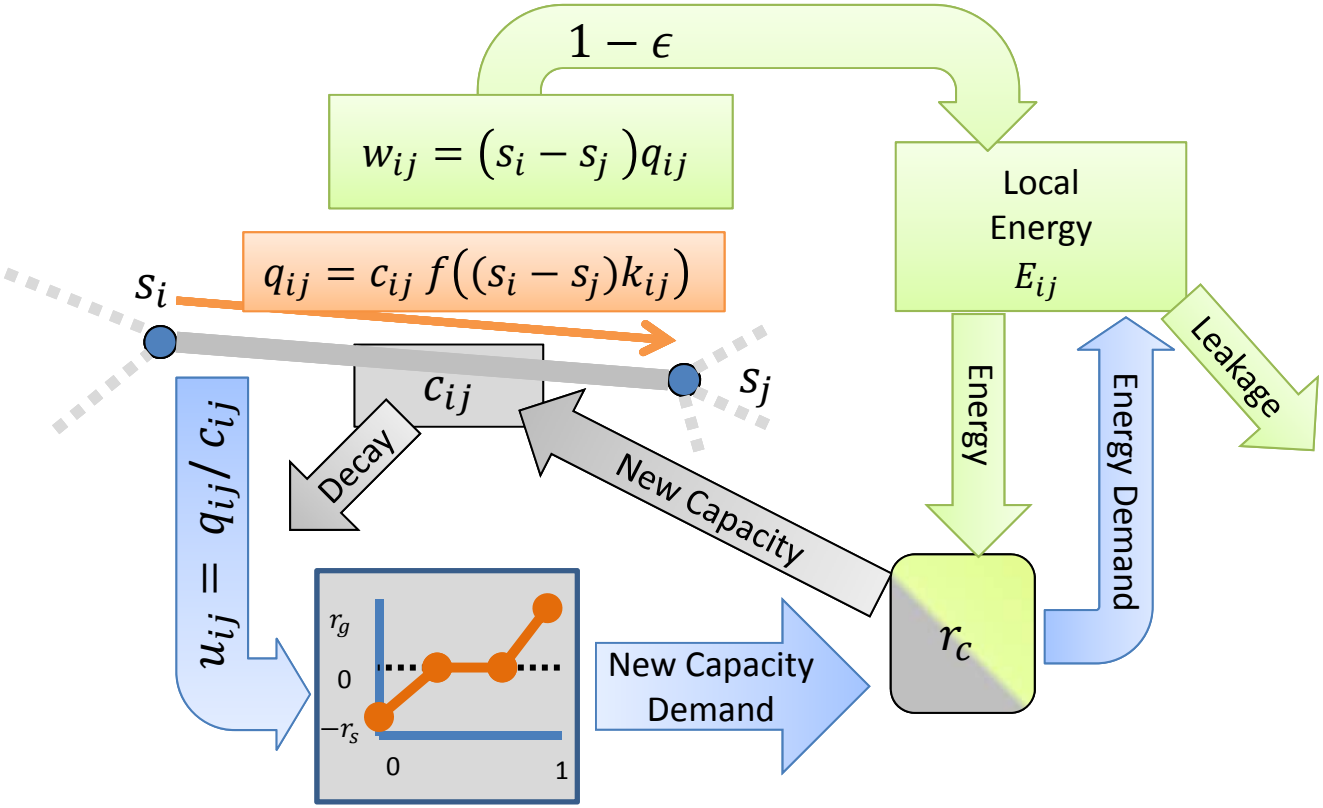

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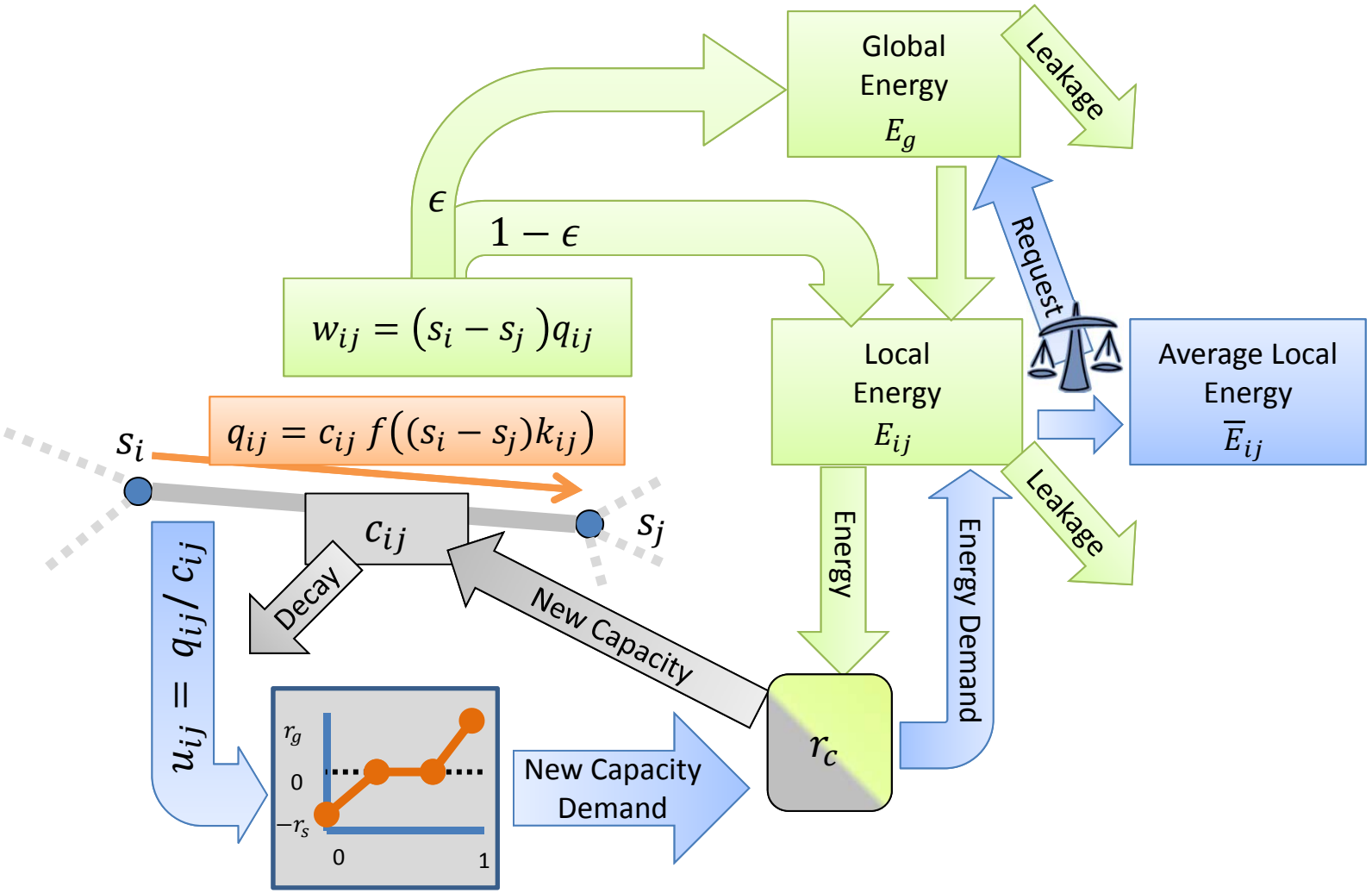
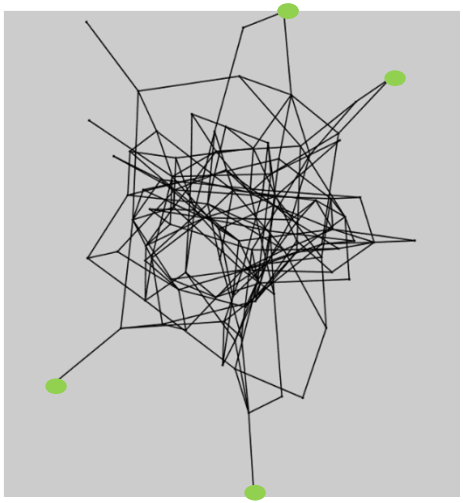


Adaptation without Disruption



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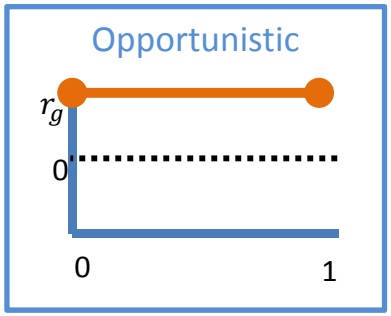

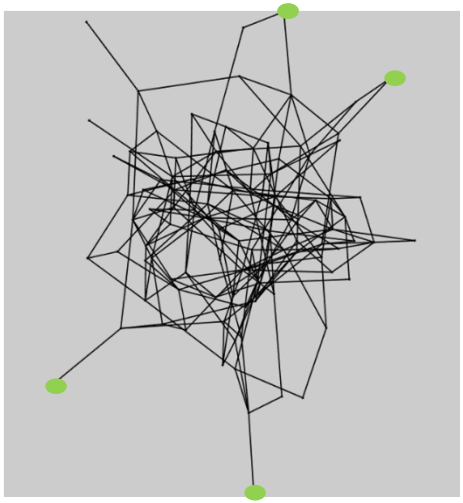

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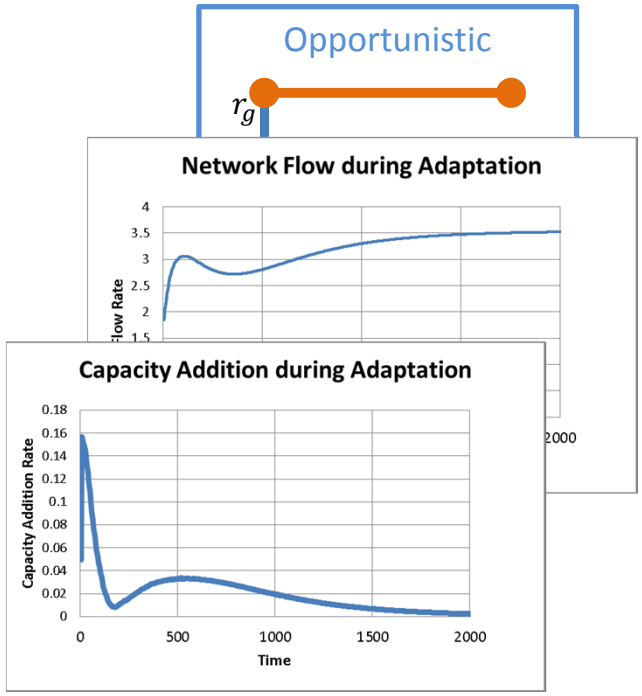

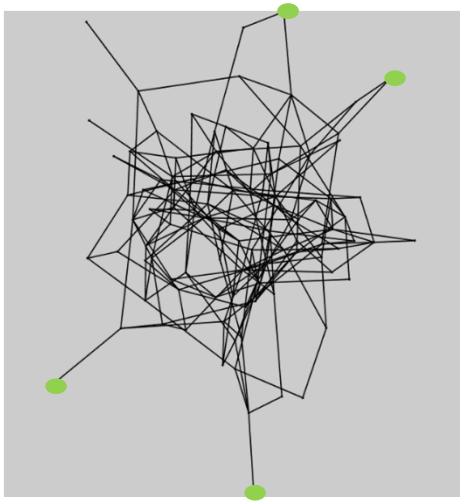

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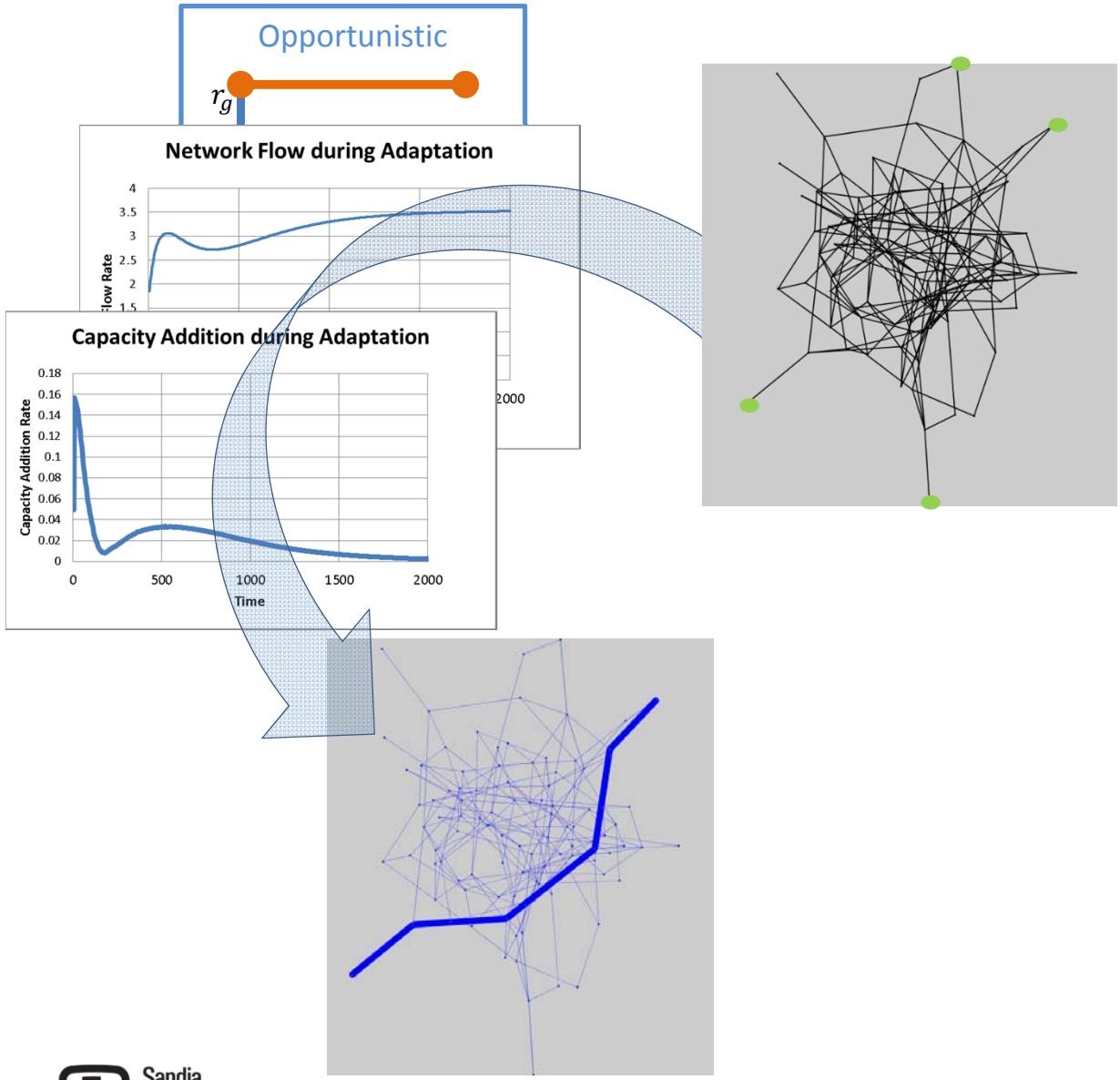

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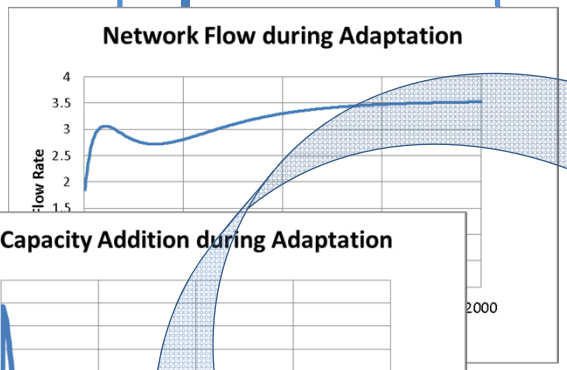

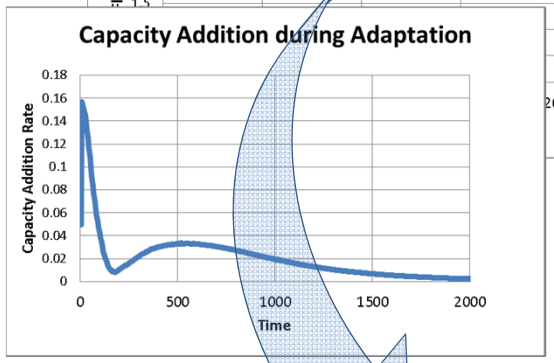

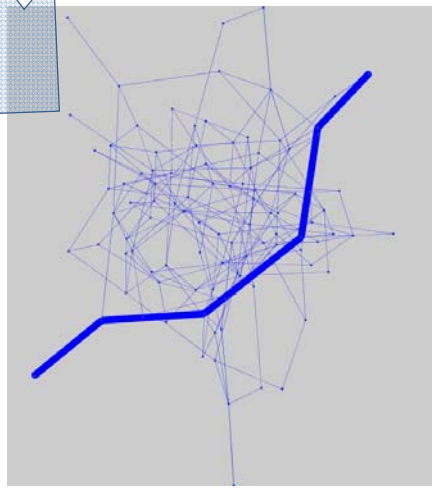

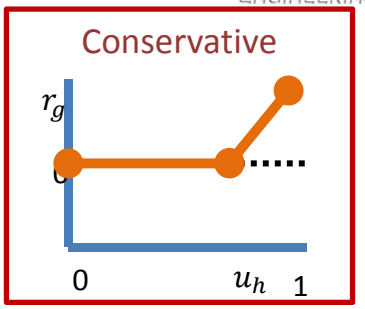

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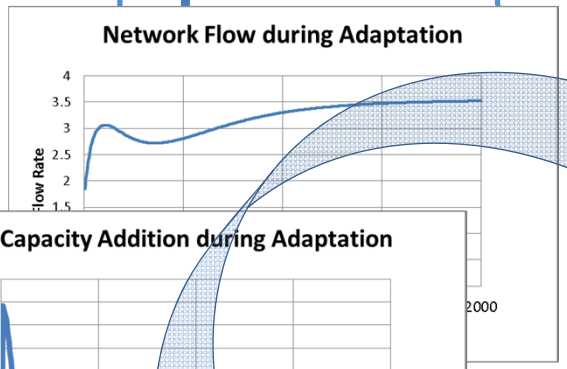
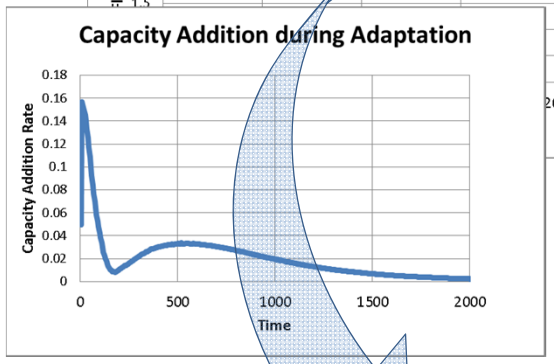
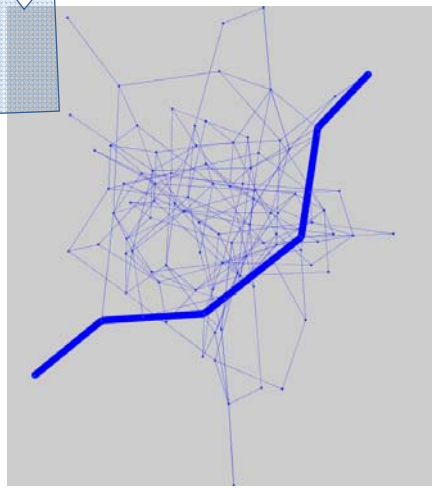
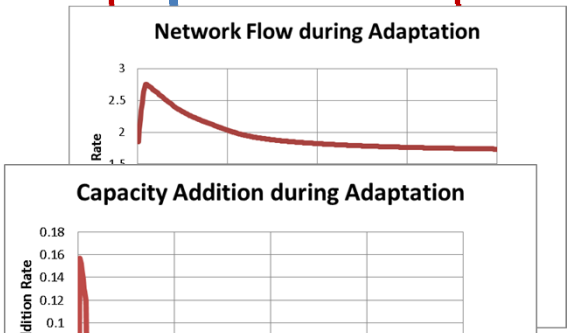
Opportunistic

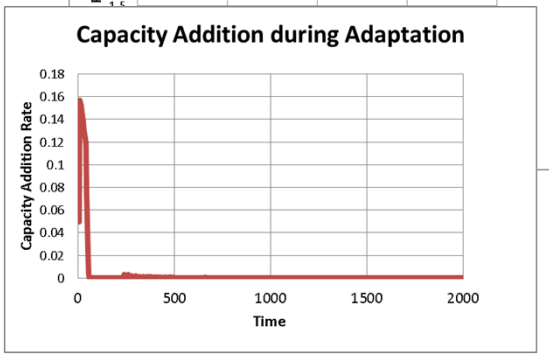






Conservative





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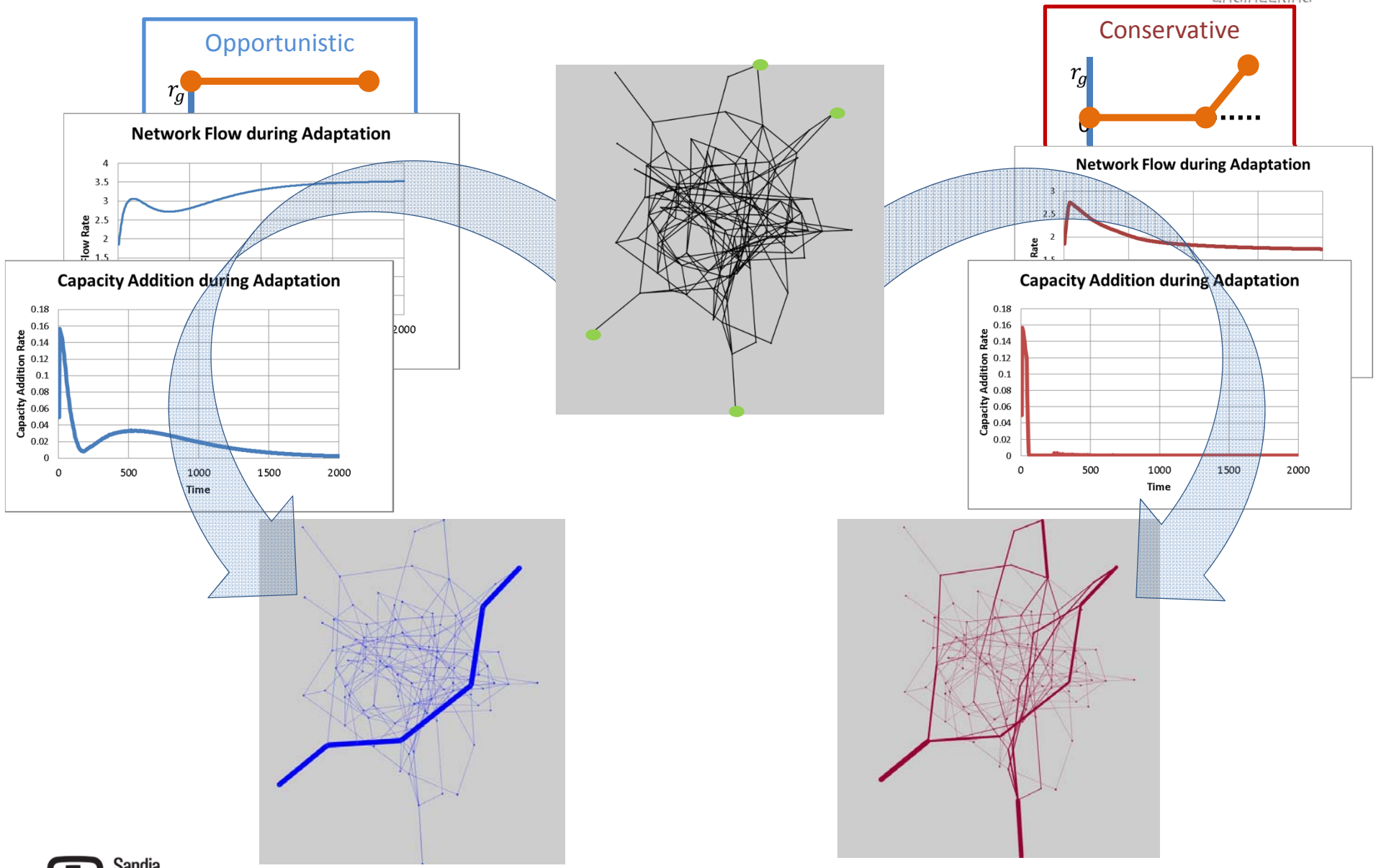

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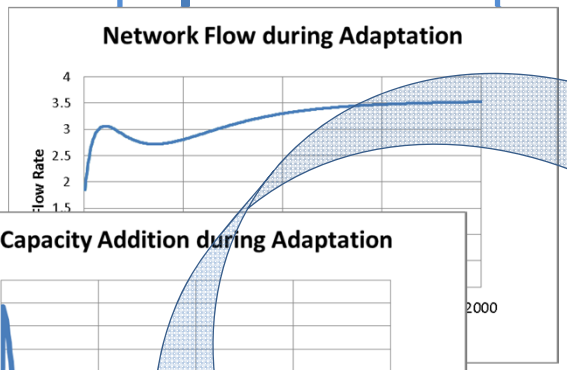

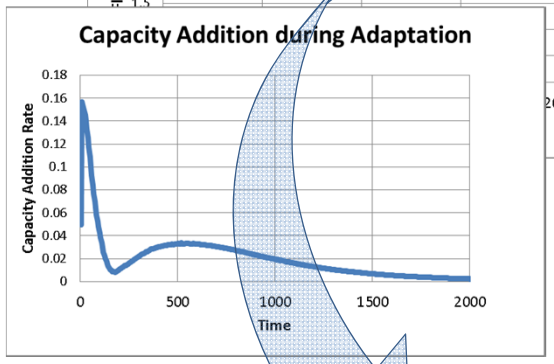

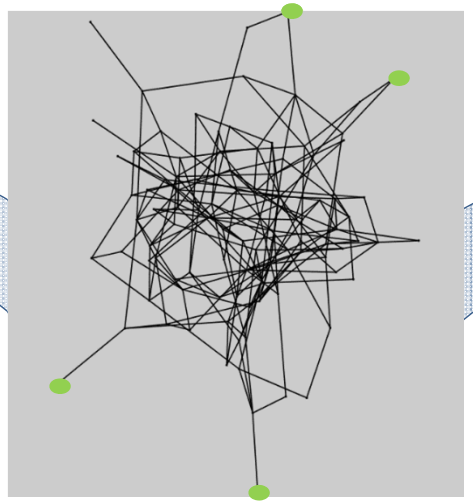

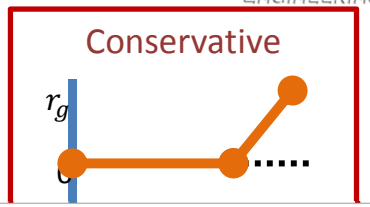

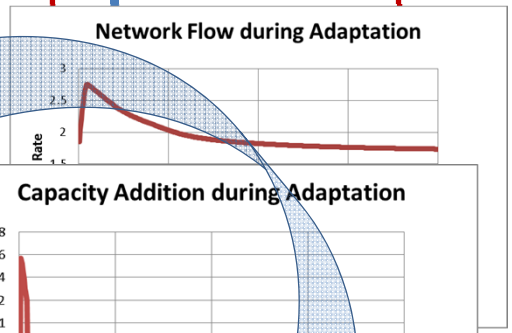

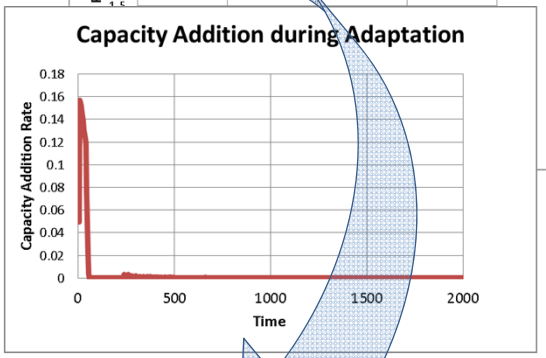

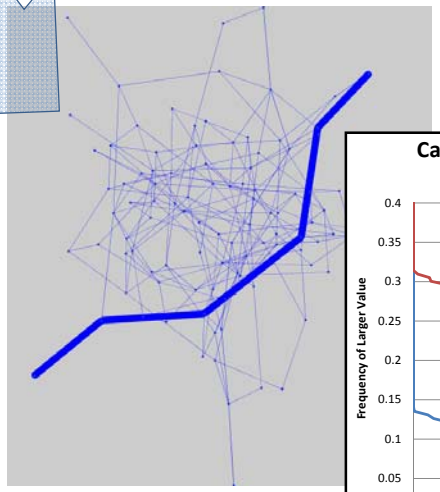

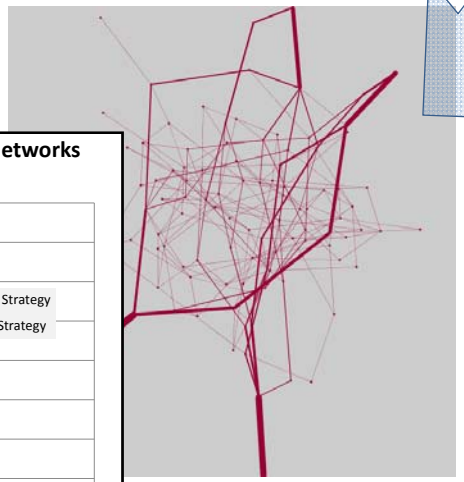

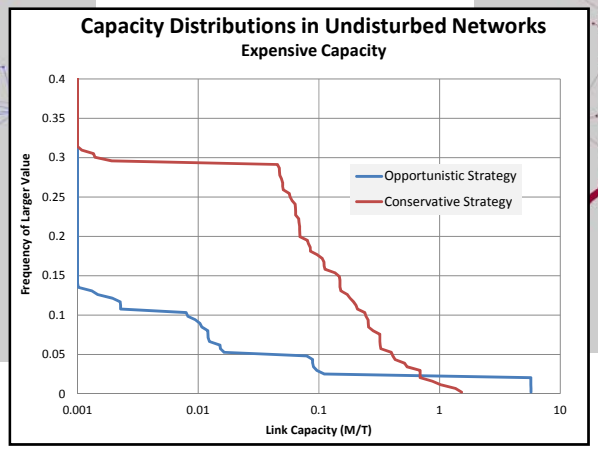

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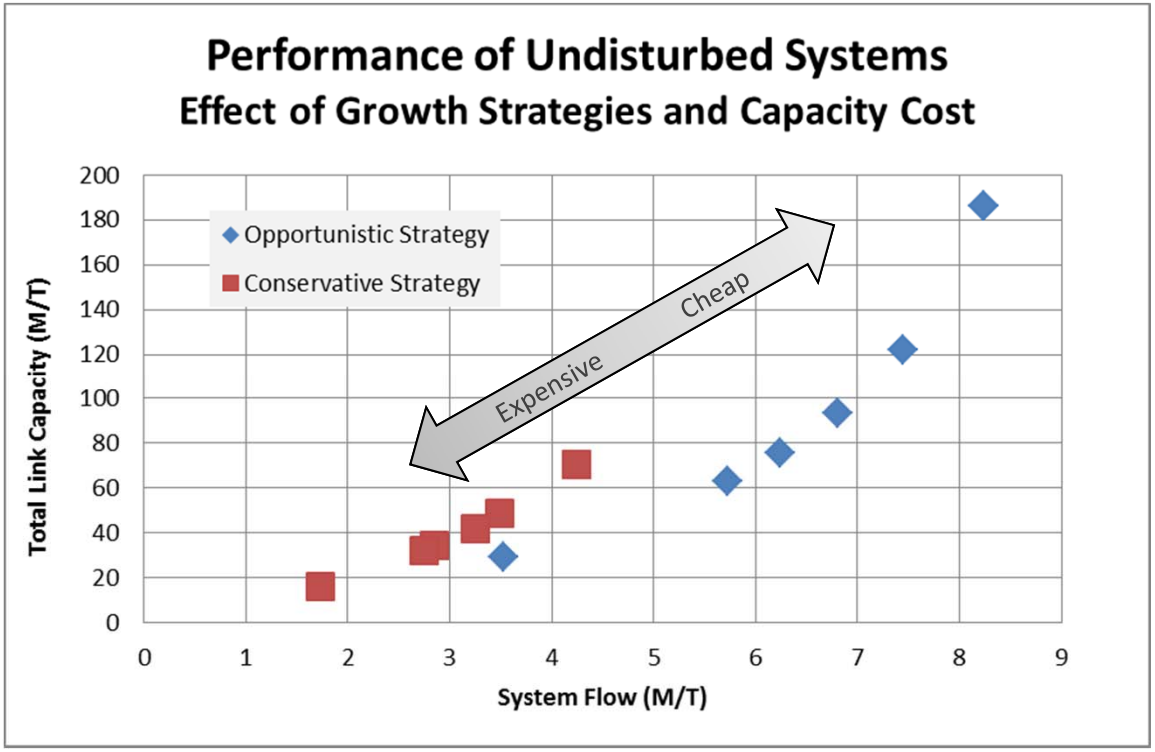
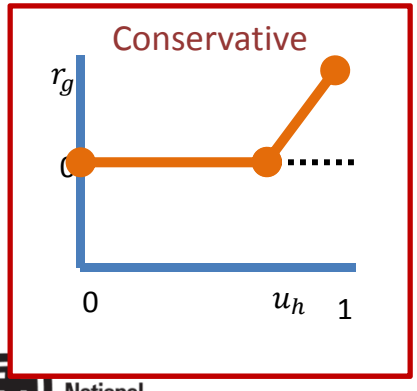
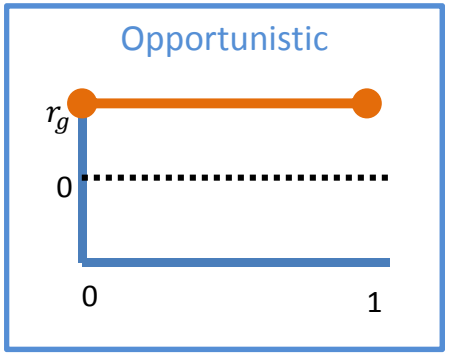
Local Strategies Shape Configuration and Performance

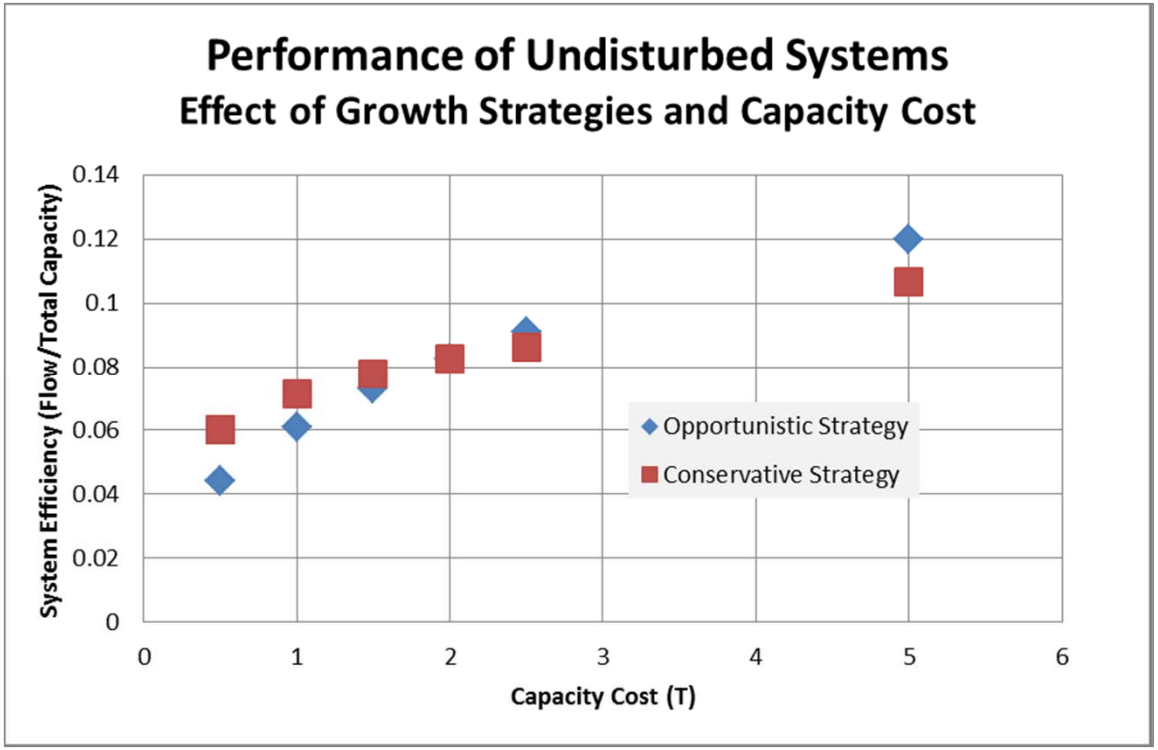


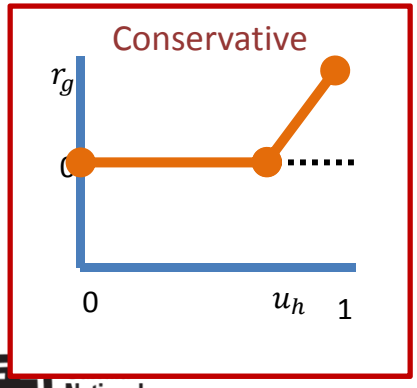


Higher capacity costs induce efficiency

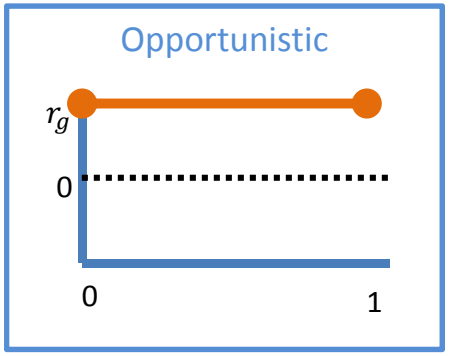


Capacity Costs Encourage Efficiency



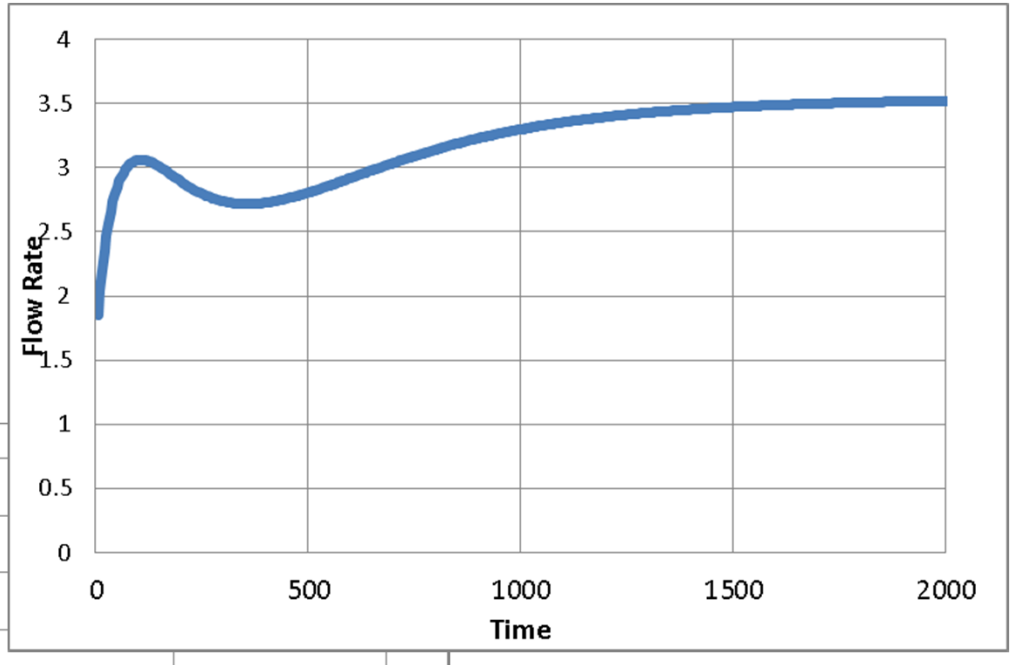


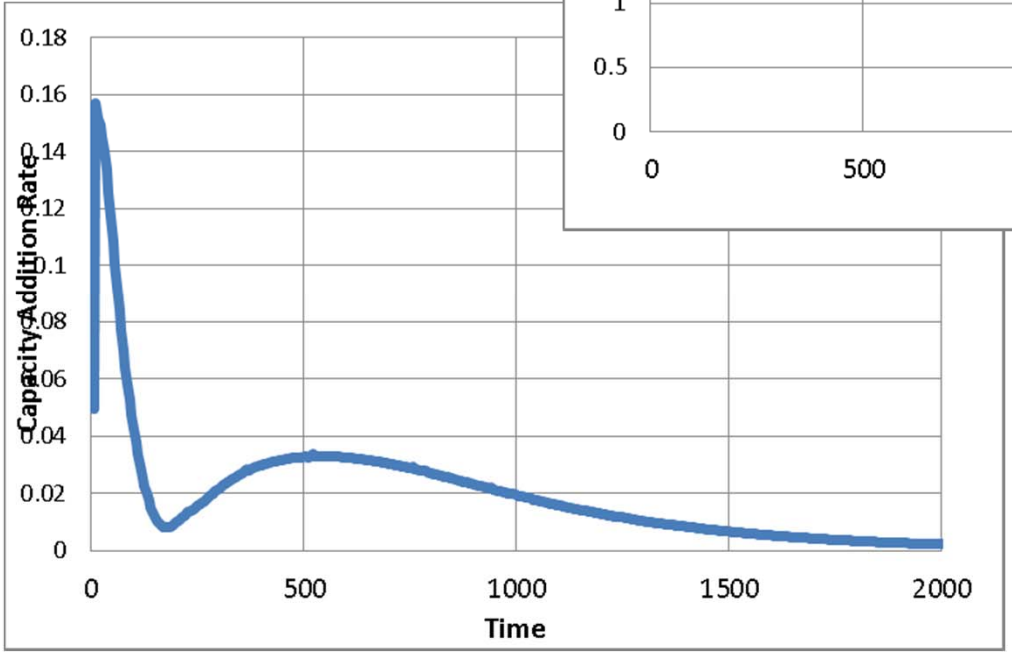
Higher capacity costs induce efficiency



Influence of Disruption on System Performance
Opportunistic Strategy with Expensive Capacity

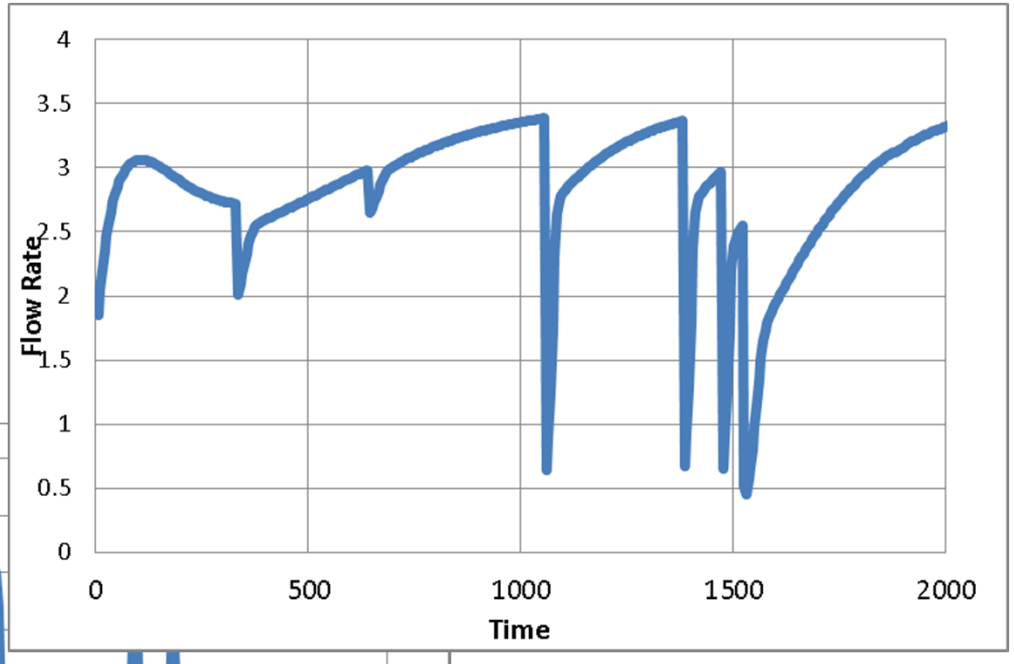
No Disruption

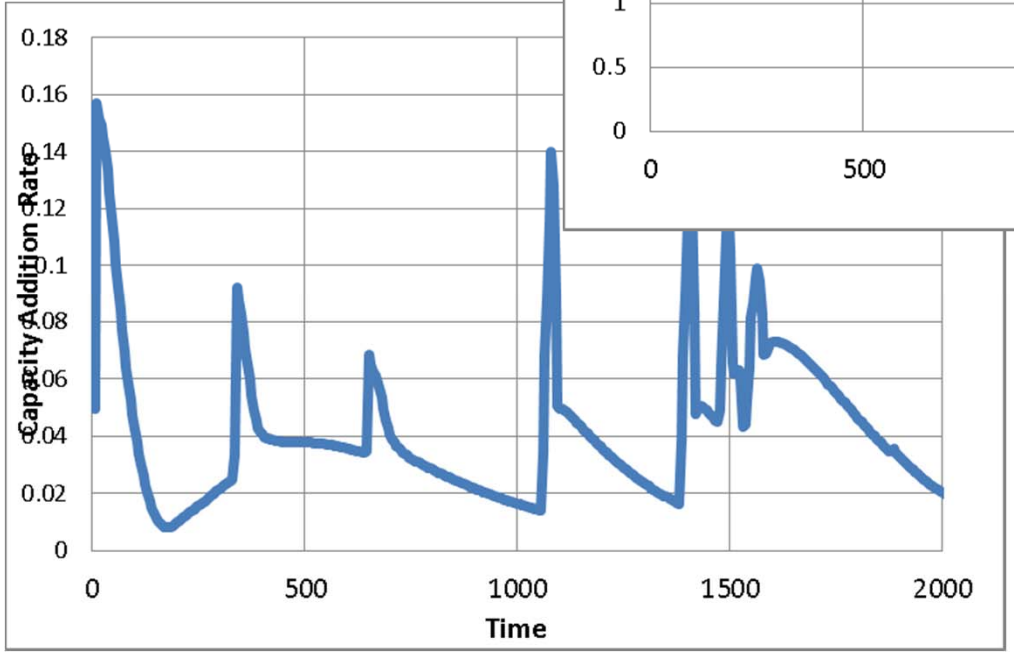




Influence of Disruption on System Performance
Opportunistic Strategy with Expensive Capacity

Freq = 1/150





Influence of Disruption on System Performance
Opportunistic Strategy with Expensive Capacity

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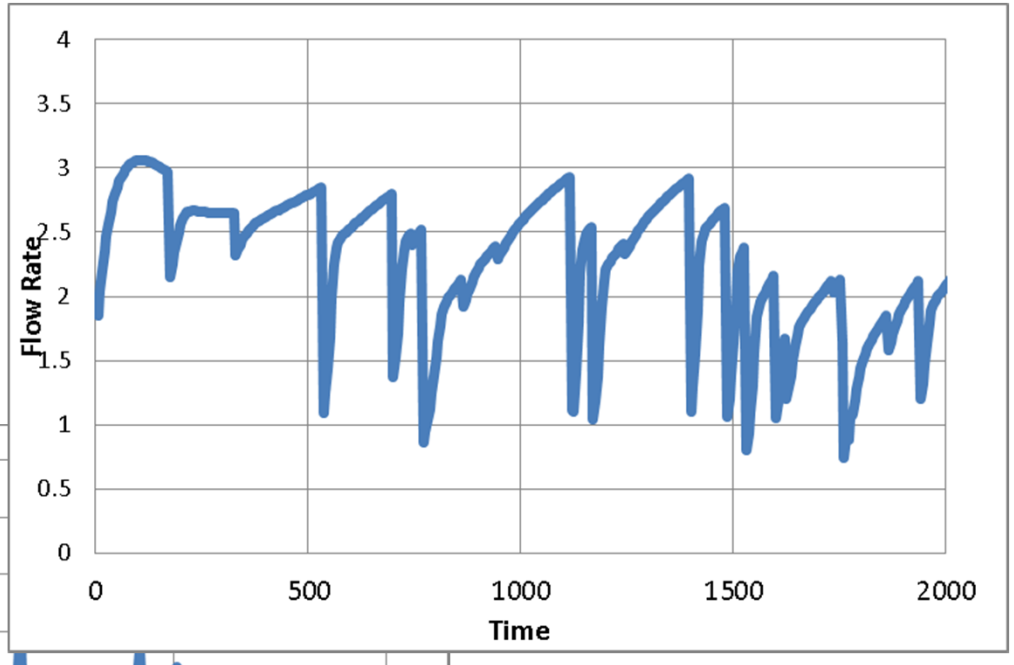

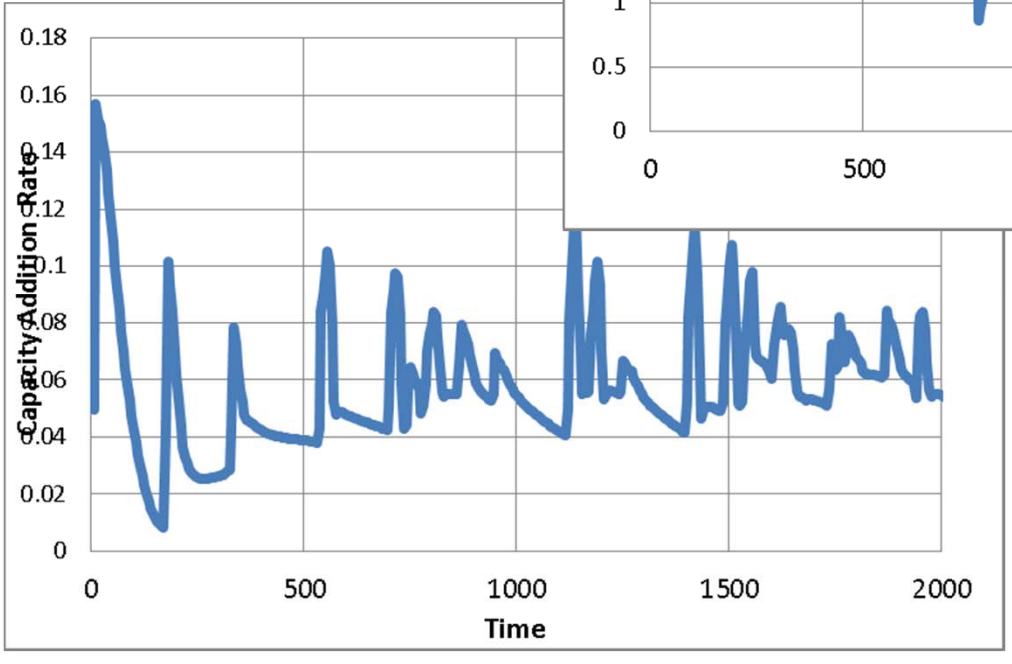

Influence of Disruption on System Performance
Opportunistic Strategy with Expensive Capacity

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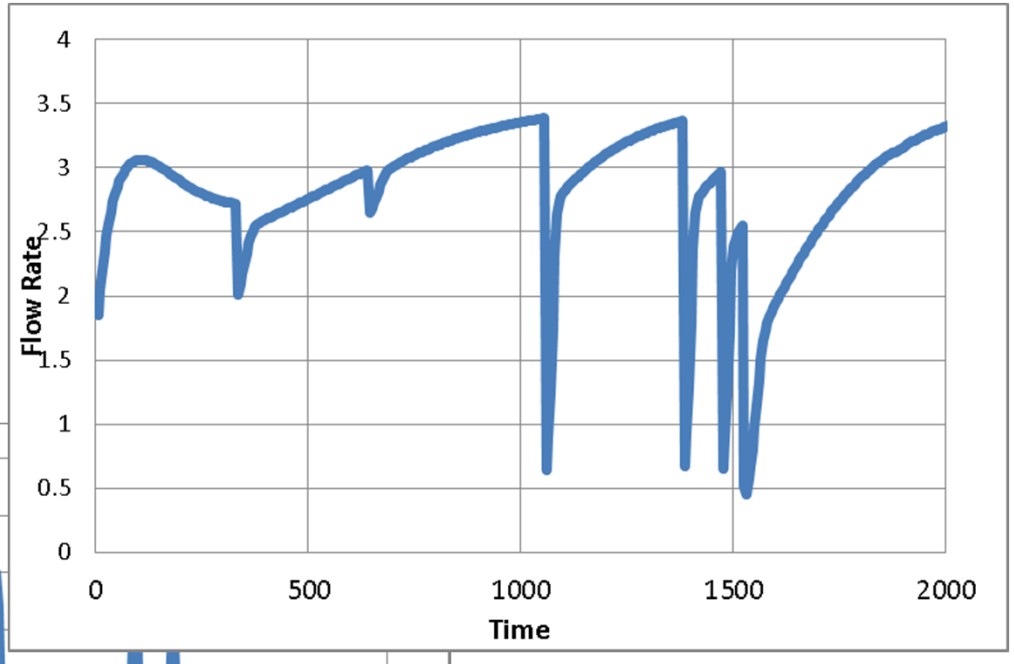

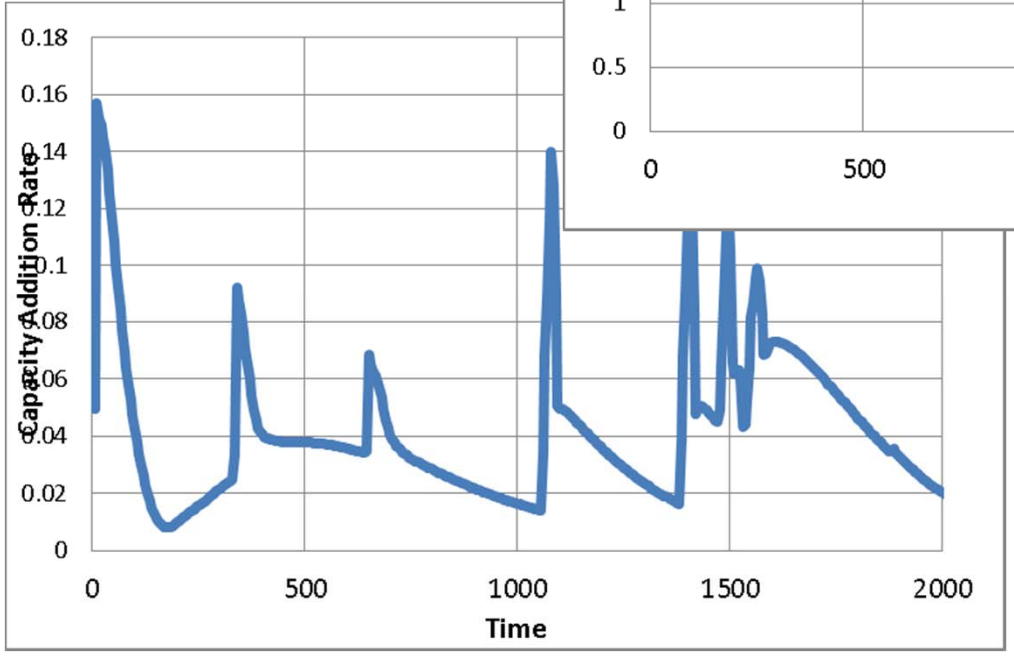

Influence of Disruption on System Performance
Opportunistic Strategy with Expensive Capacity

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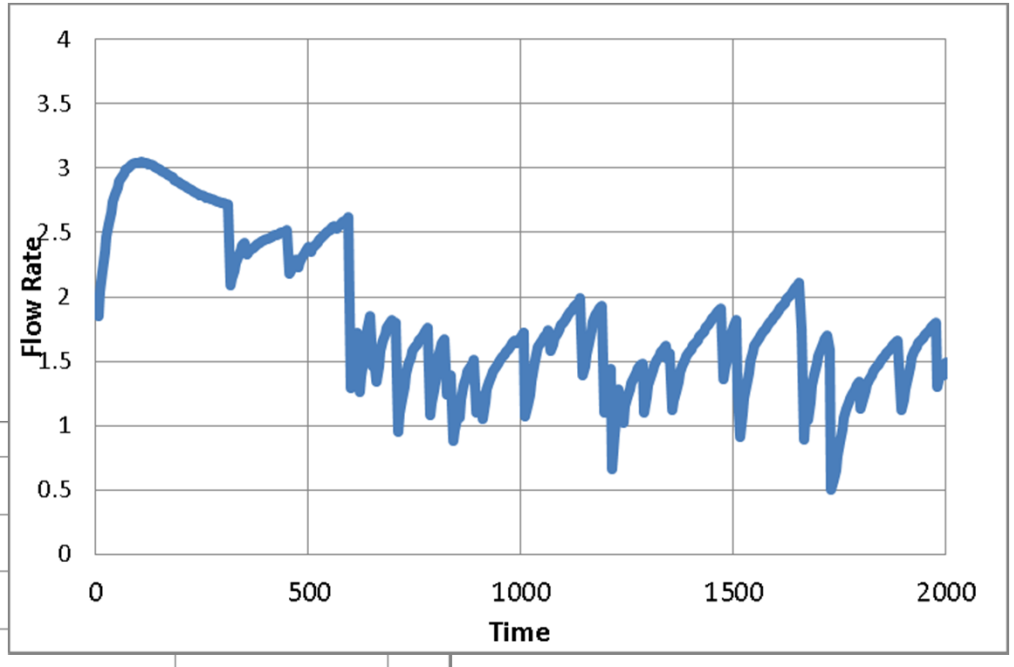

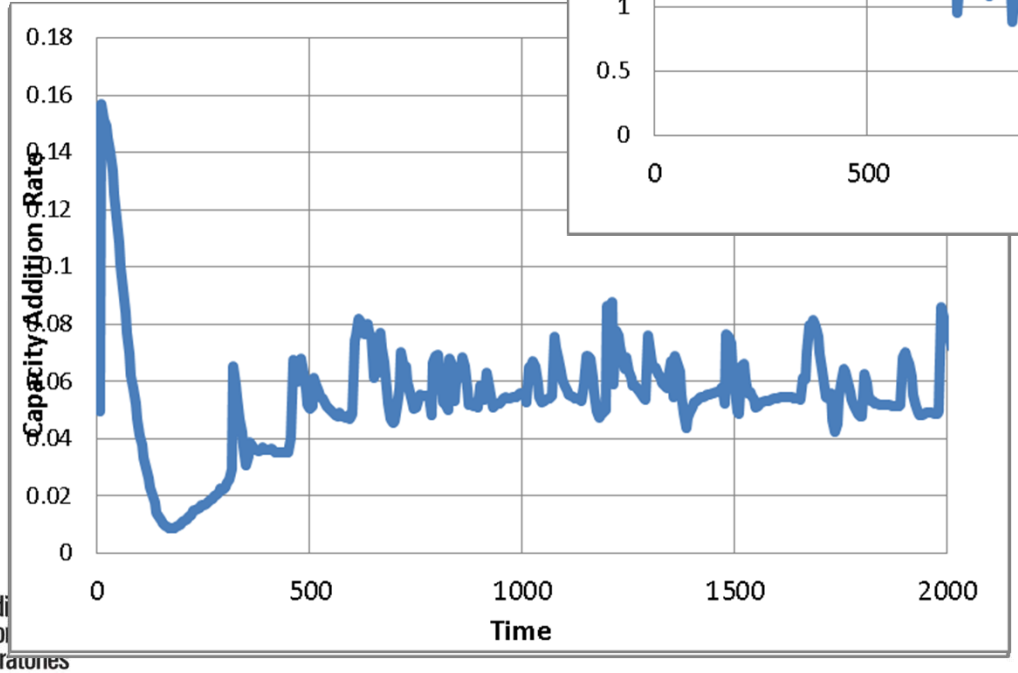

Influence of Disruption on System Performance
Opportunistic Strategy with Expensive Capacity

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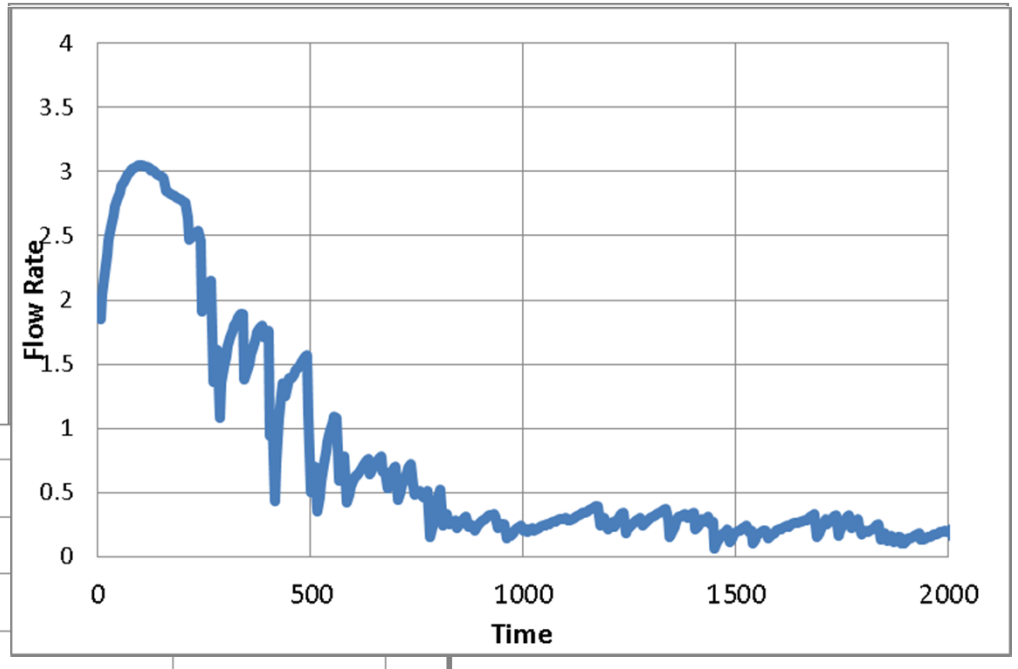
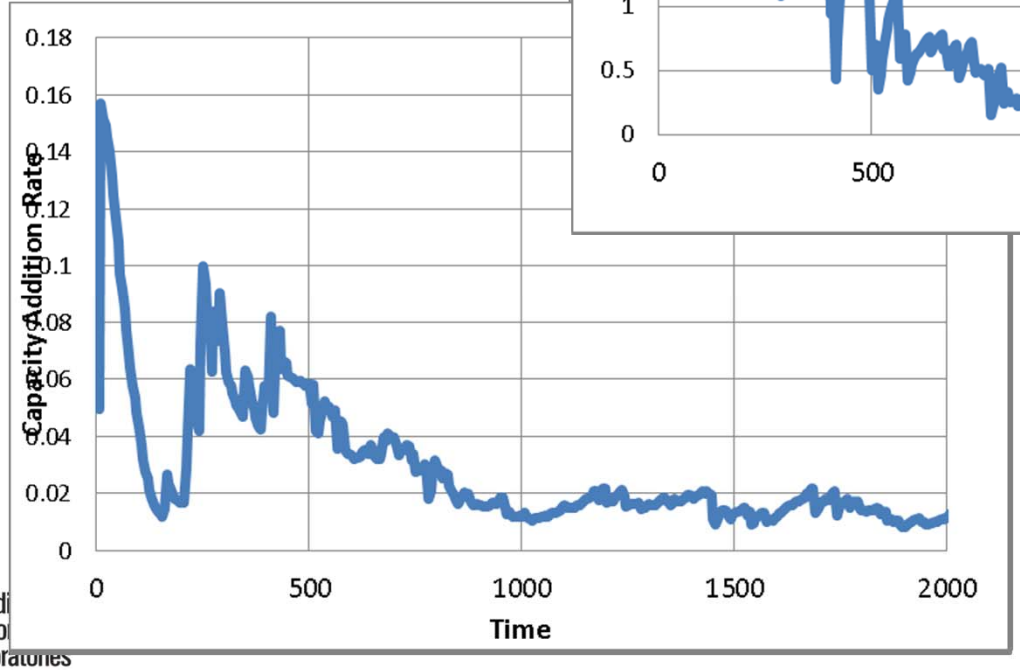
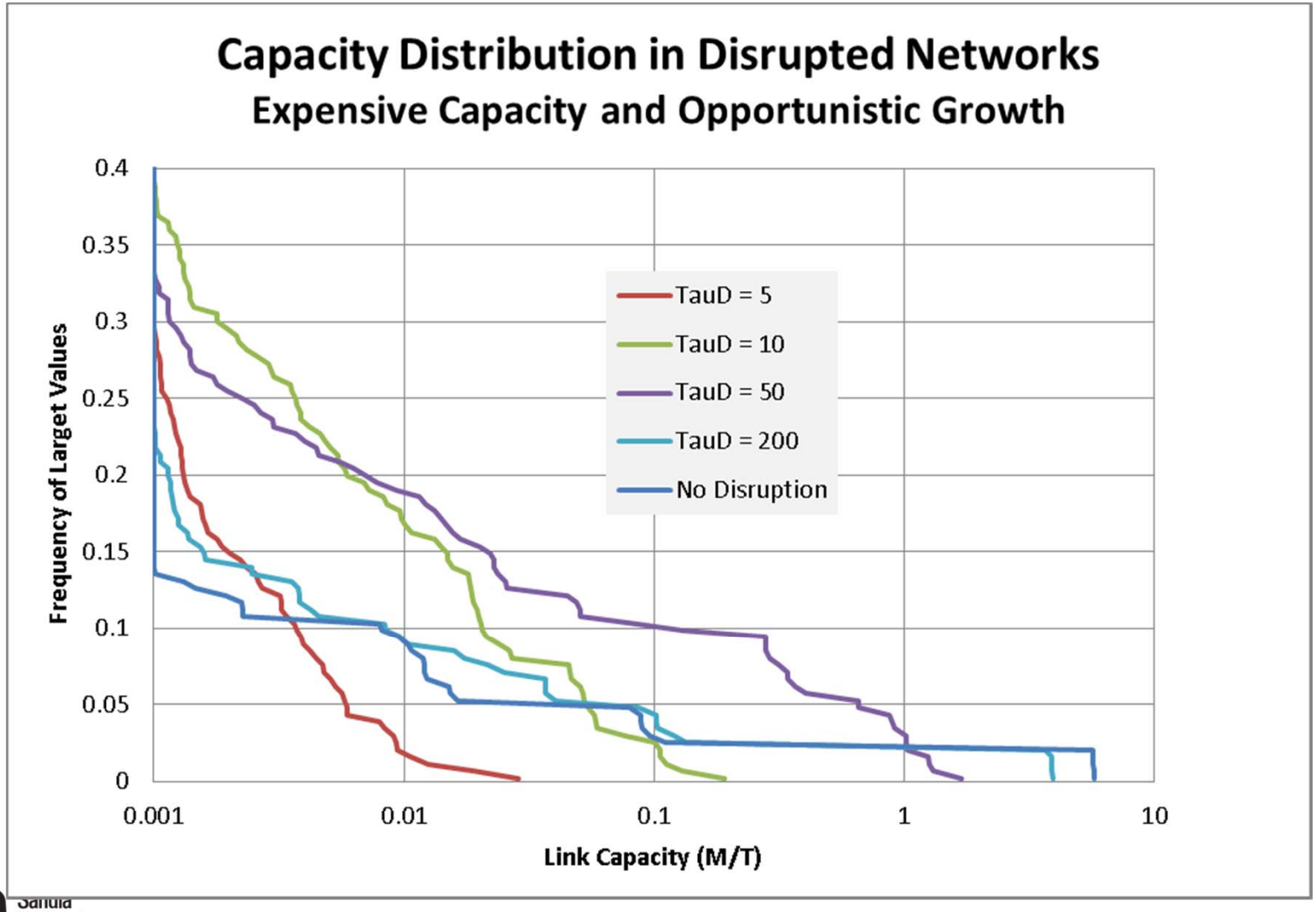
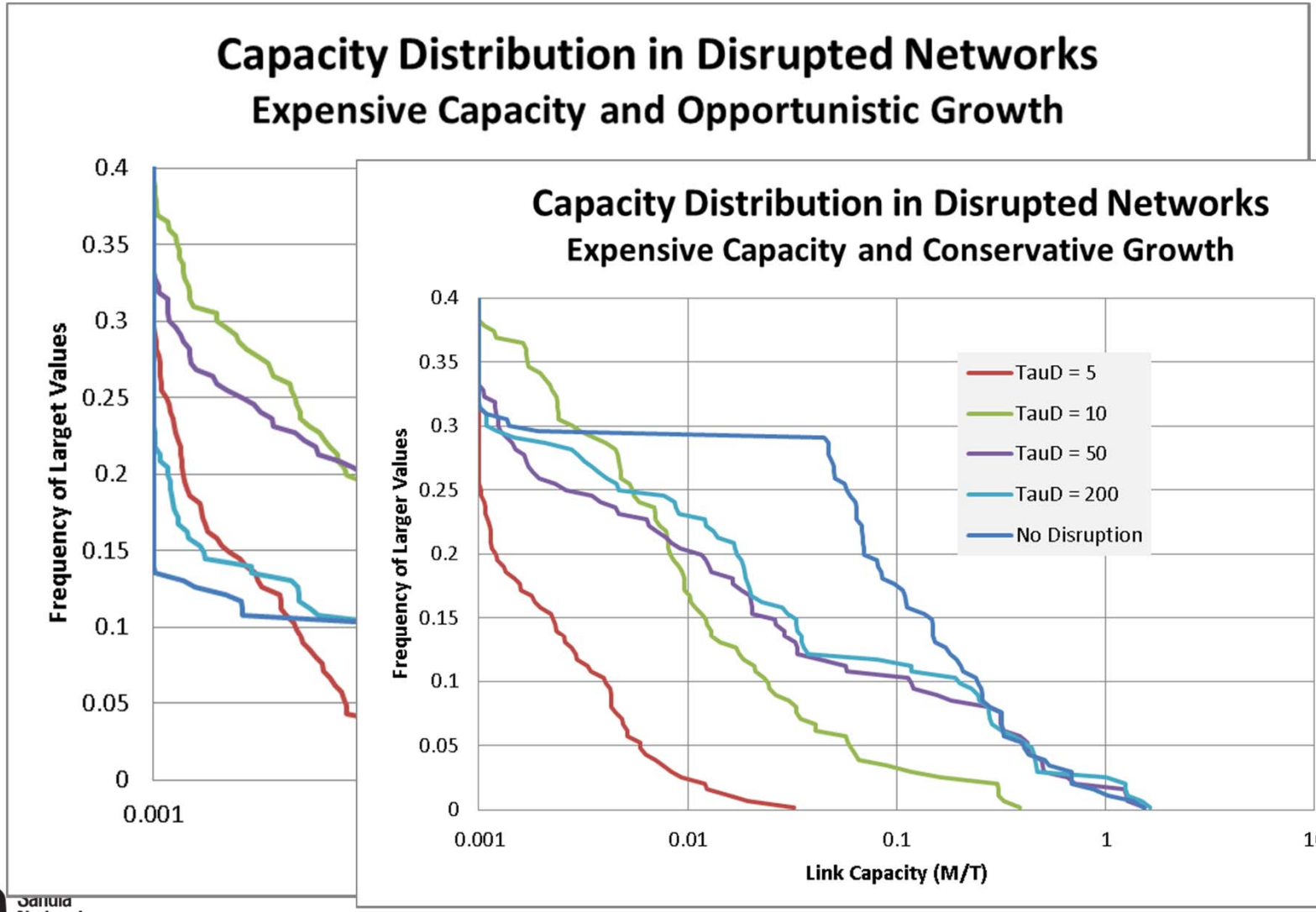




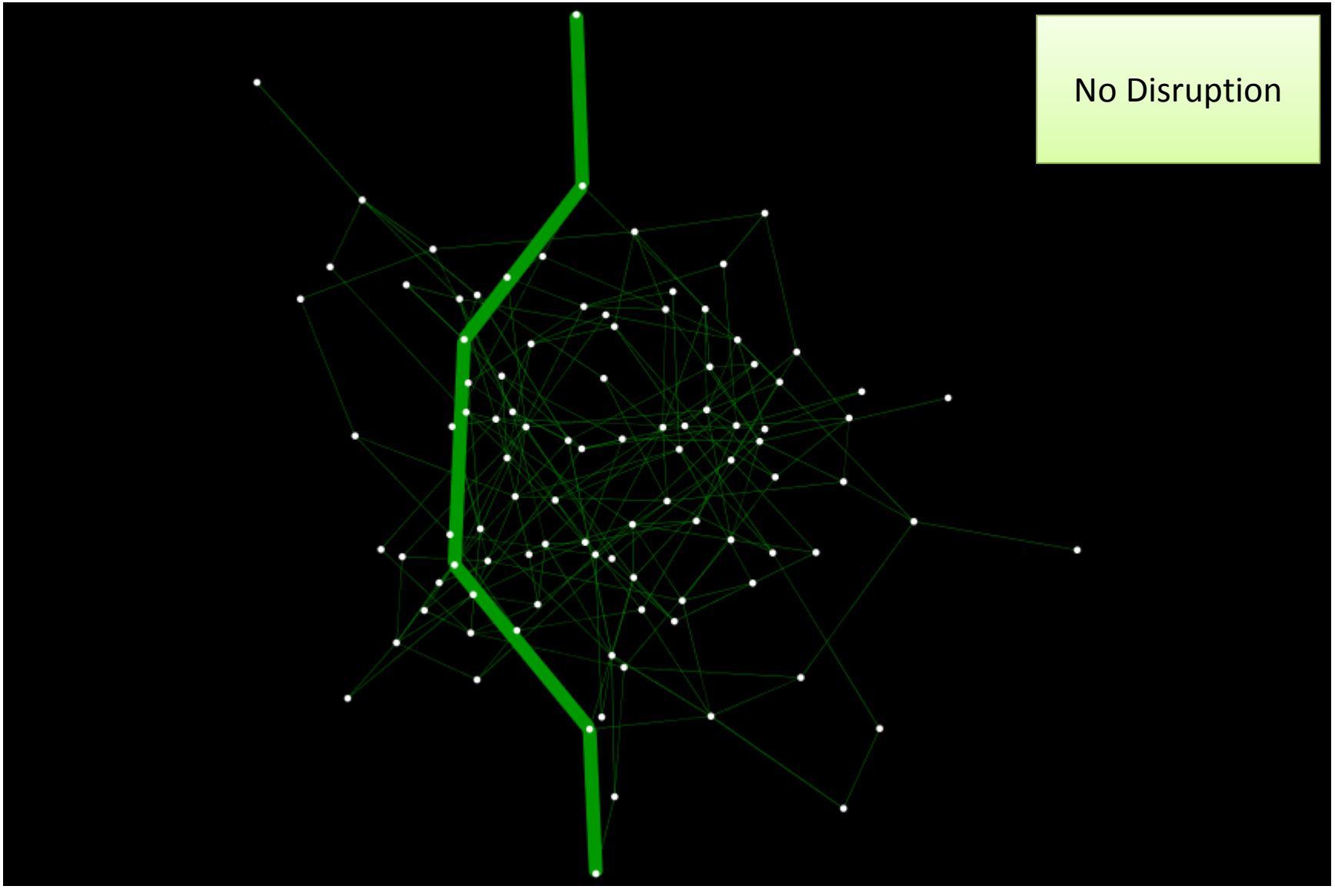
Influence of Disruption on System Structure
Opportunistic Strategy with Expensive Capacity



Influence of Disruption on System Structure
Opportunistic Strategy with Expensive Capacity



Influence of Disruption on System Structure
Opportunistic Strategy with Expensive Capacity



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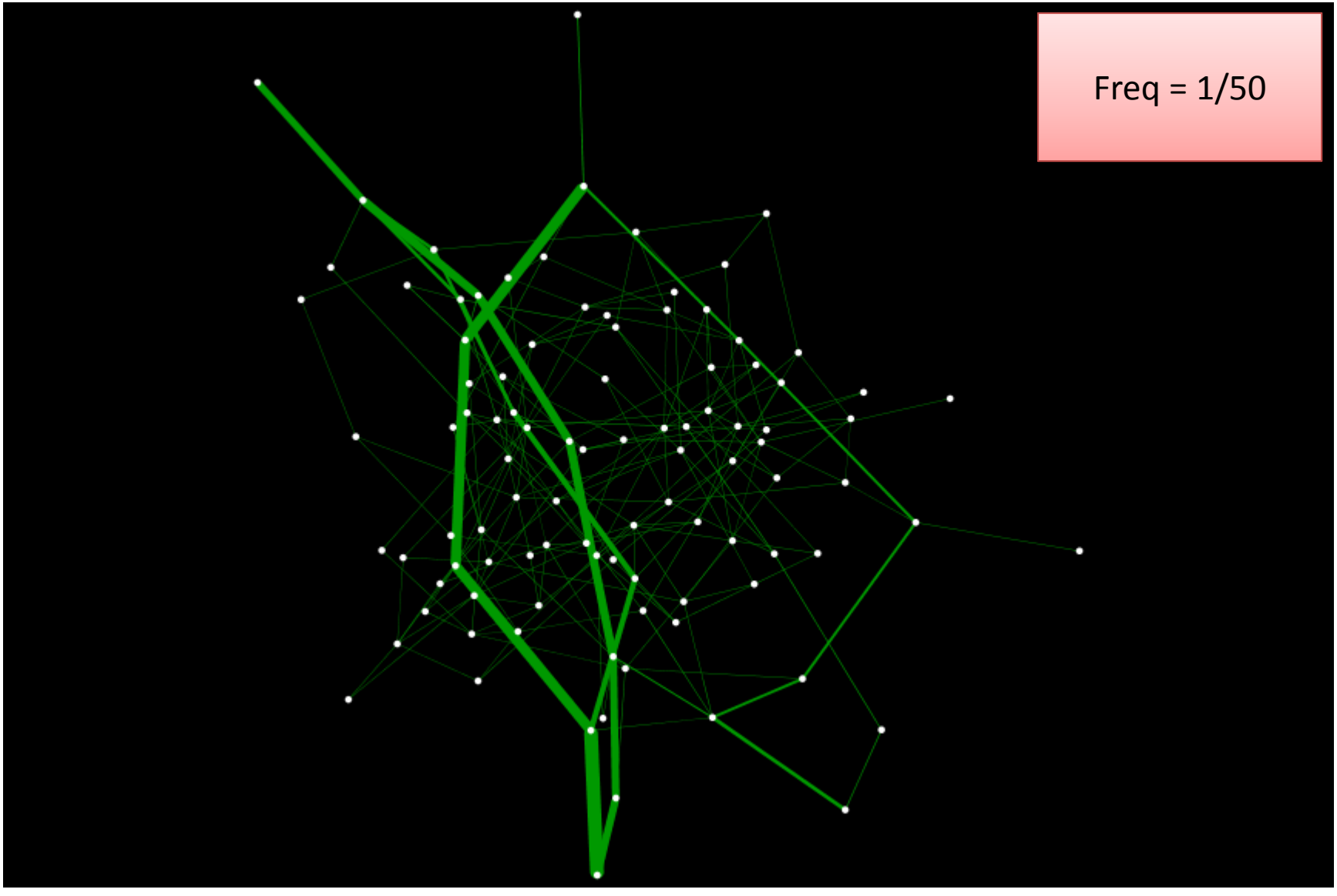
Opportunistic Strategy with Expensive Capacity



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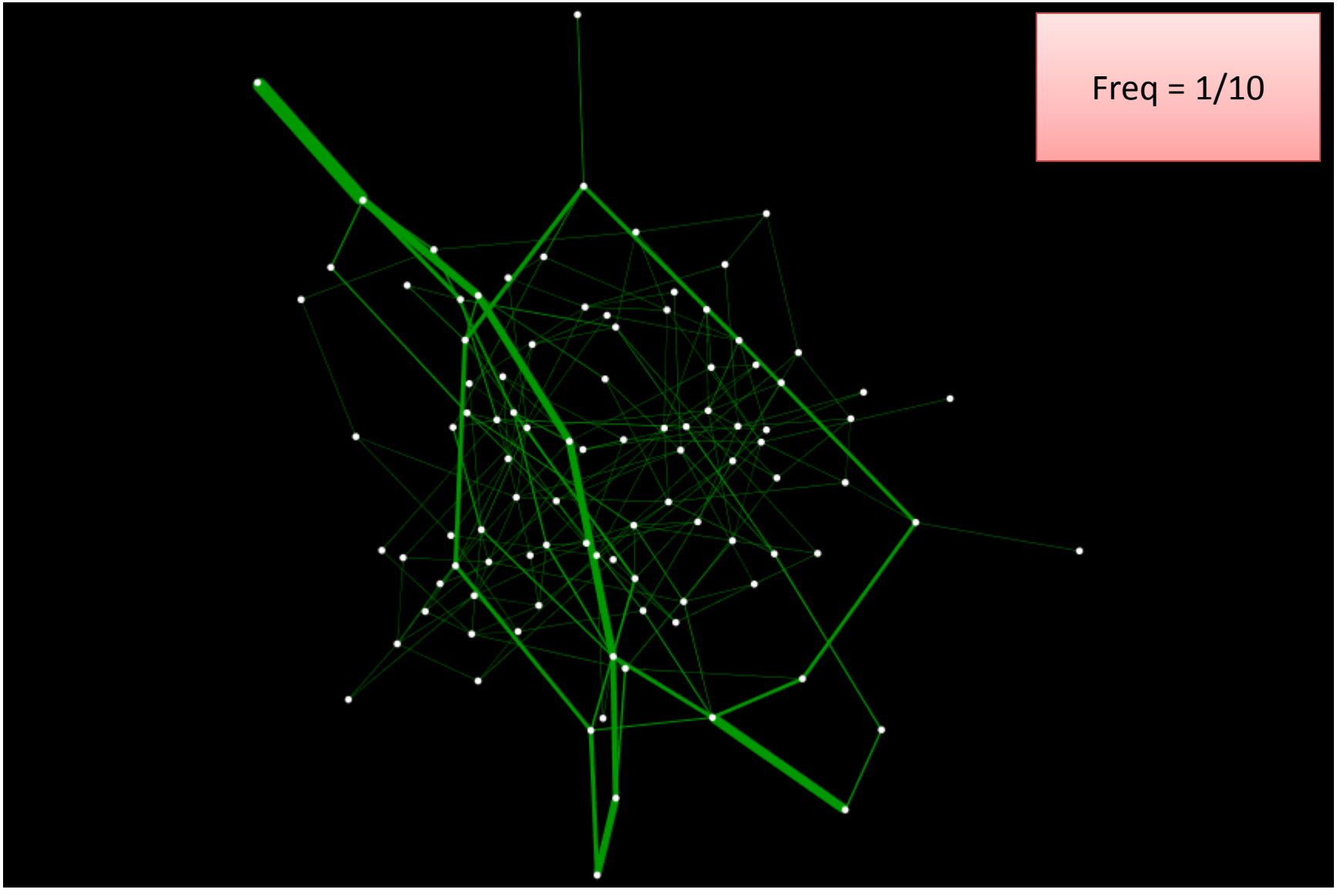
Opportunistic Strategy with Expensive Capacity



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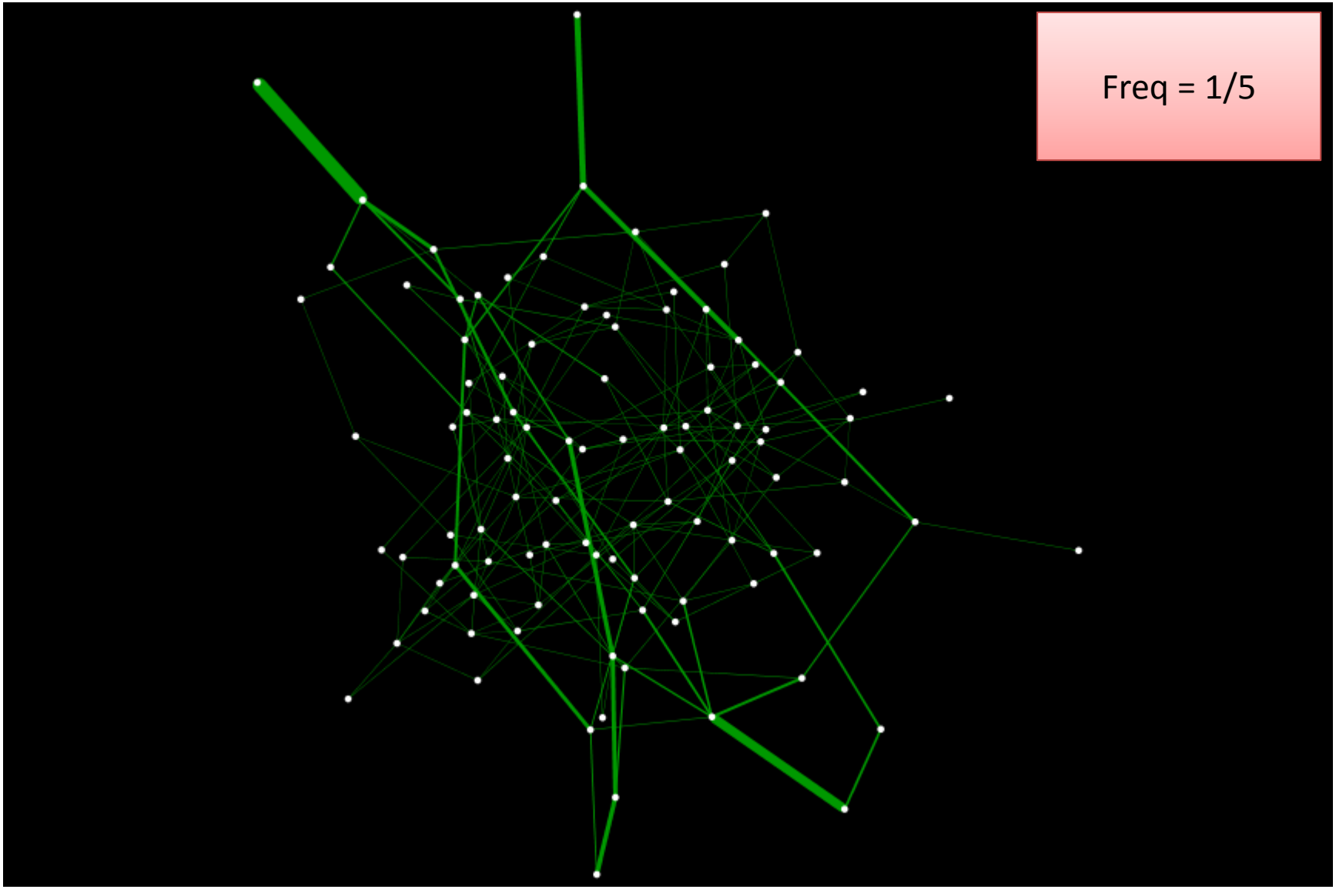
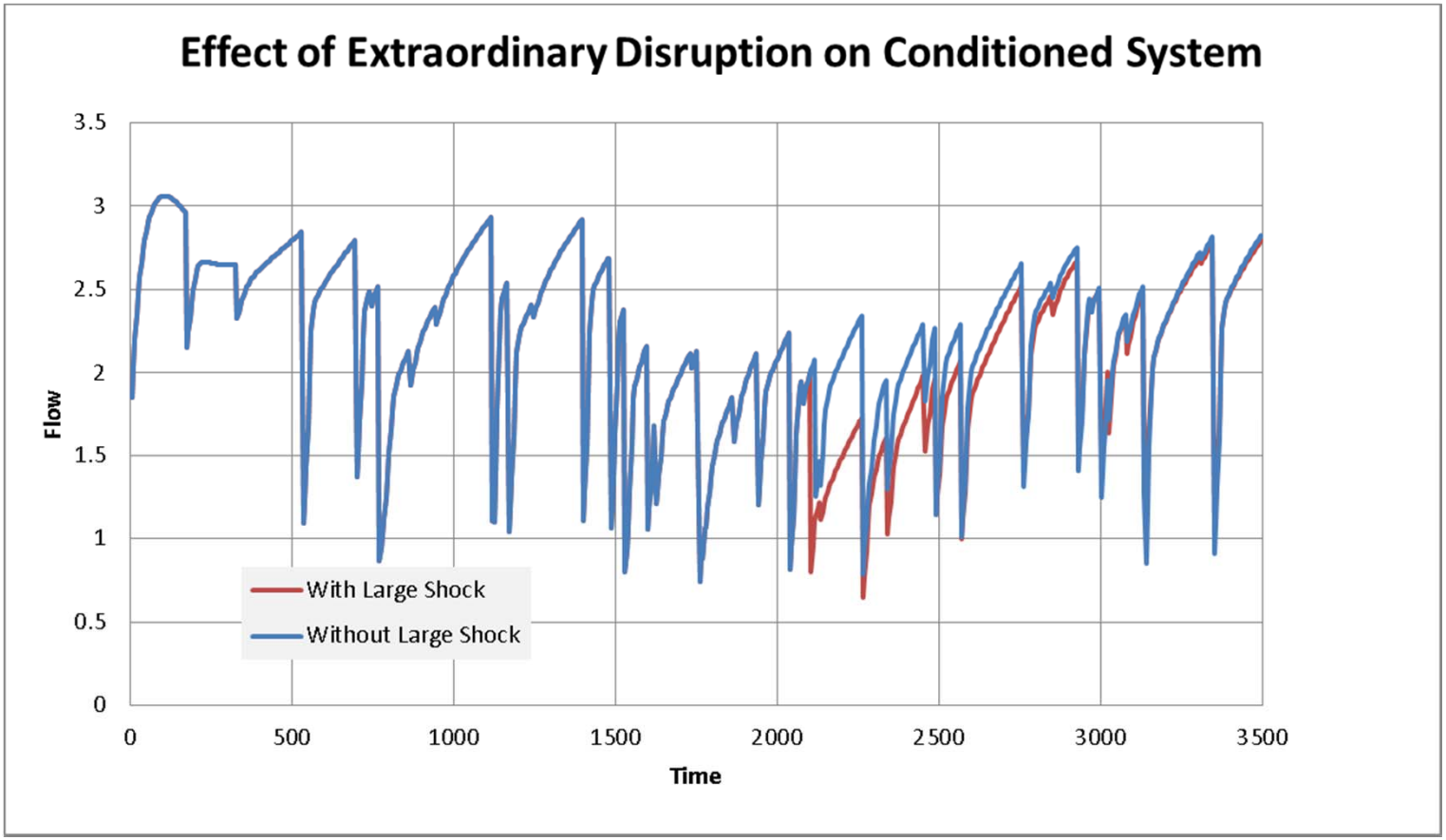
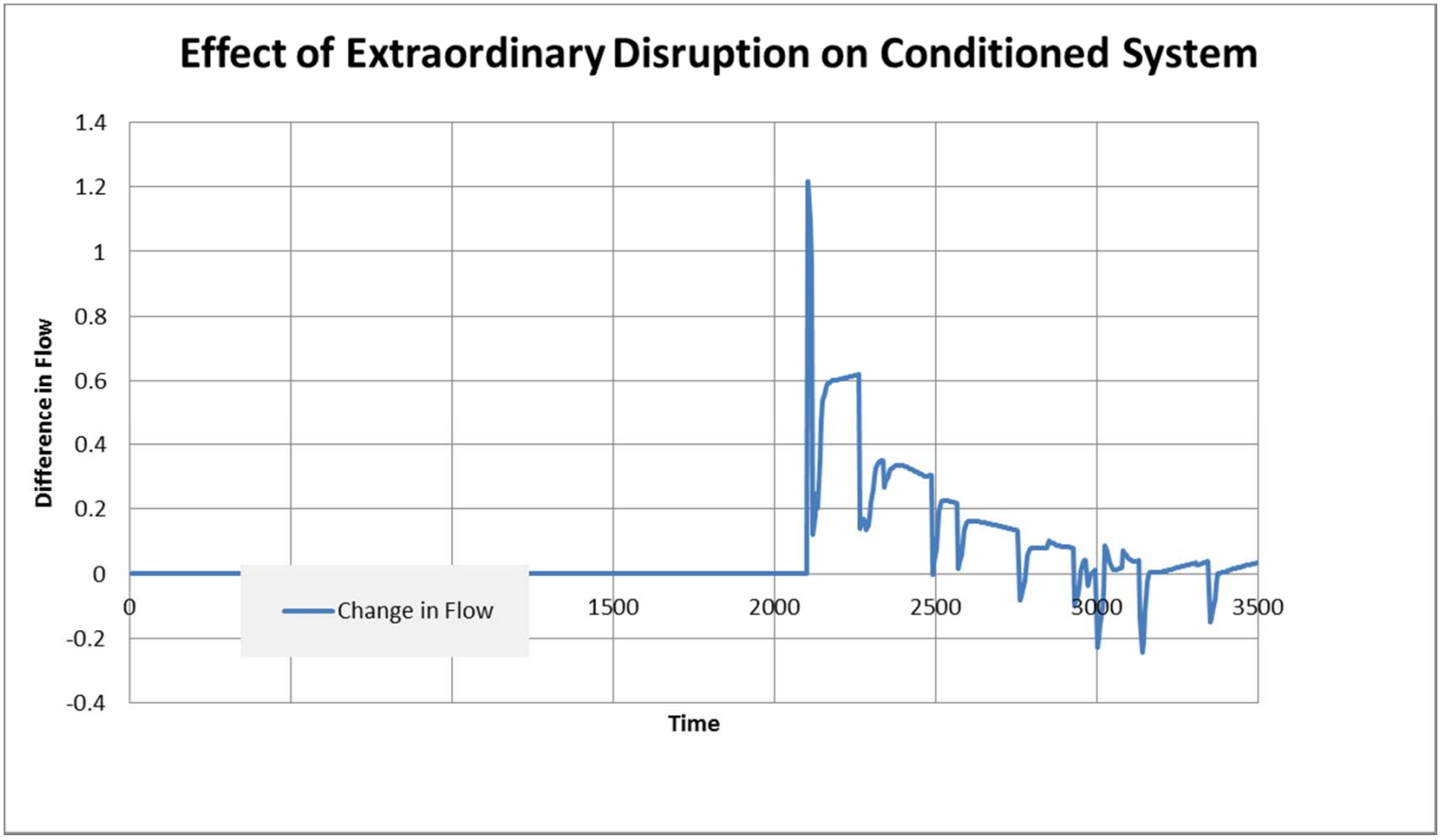


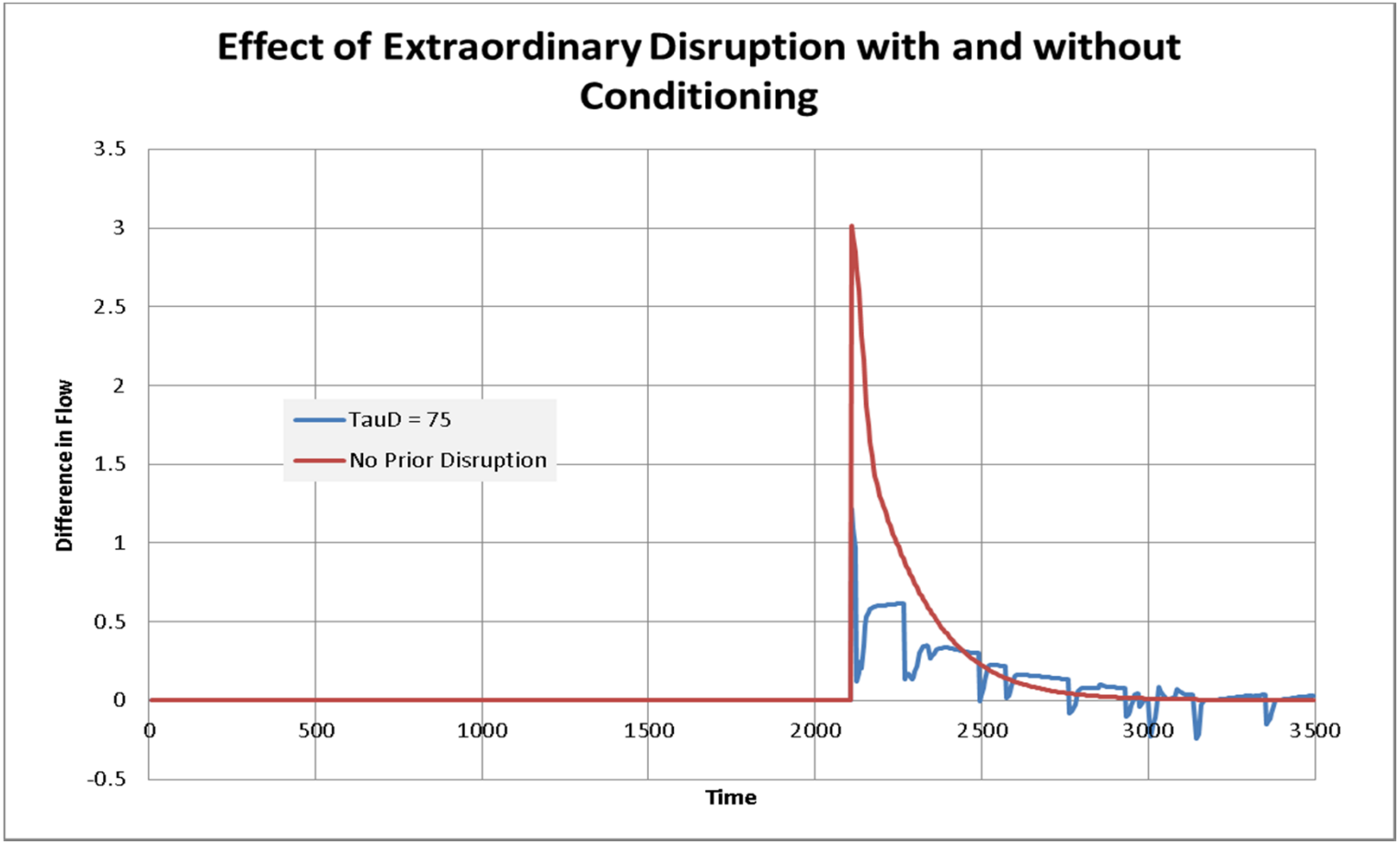
Assessing Resilience to Extraordinary Disruptions



Assessing Resilience to Extraordinary Disruptions



Assessing Resilience to Extraordinary Disruptions



Summary

- 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)