Improving the resilience of symbiotic networks via permutable nodes

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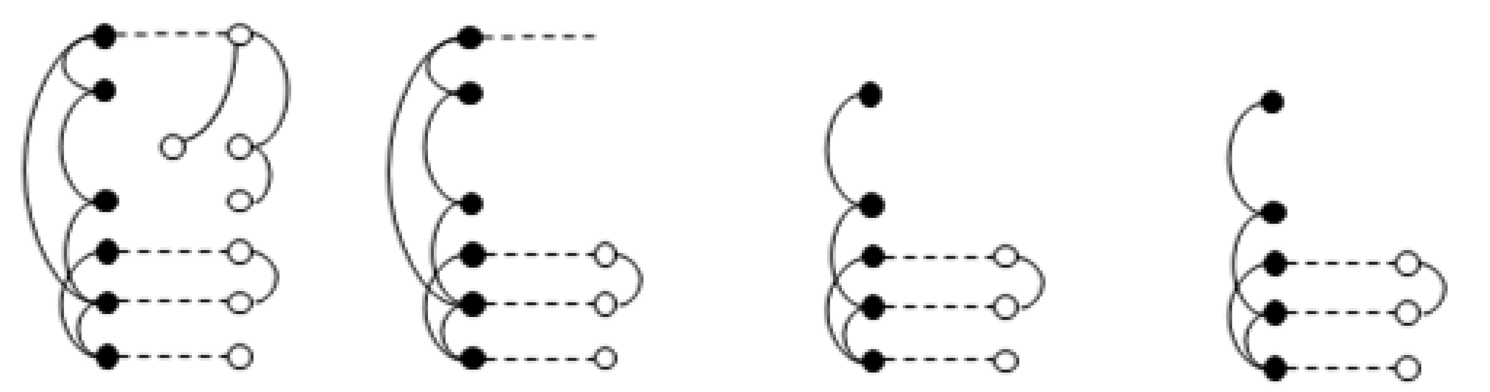
Introduction

- Infrastructure systems can be represented (in an idealised manner) by a *network of networks*.
- Such systems are vulnerable to *cascading failure*.
- Here we explore the influence of *permutable* network nodes that can switch from playing a role in one system to playing a role within another, but may not play both roles simultaneously, e.g., traffic tunnel ⇔ flood water
- *Symbiotic networks* are those for which inter-network dependencies are critical to their operation meaning that network components that become isolated due to cascading failure are no longer viable.
- We demonstrate that symbiotic networks featuring permutable nodes can enjoy a significantly increased resilience, especially where attacks are large or the degree of symbiosis is significant.

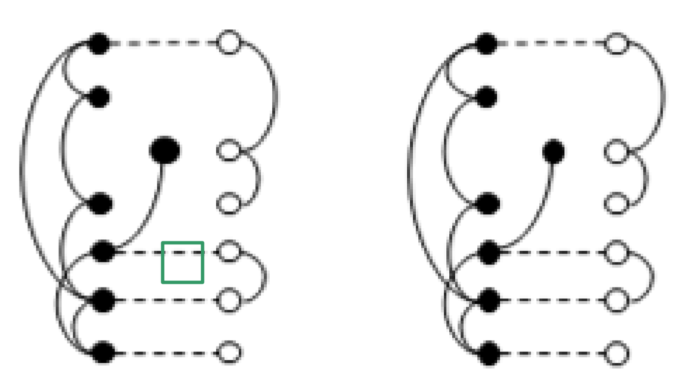
Method

- Consider two infrastructure networks, *A* and *B*.
- *A* and *B* have are *scale-free*, i.e., they are structurally similar to the Western US power grid or the Internet.
- *A* and *B* are *symbiotic*: in order for a fragment of *A* to operate, the proportion of its nodes connected directly to a working fragment of network *B* must be above some *threshold*, and vice versa. Here the threshold is 1/3:



Step 1: Initial state — Step 2: White component fails due to isolation — Step 3: Dependent node fails — Final State: Surviving Network

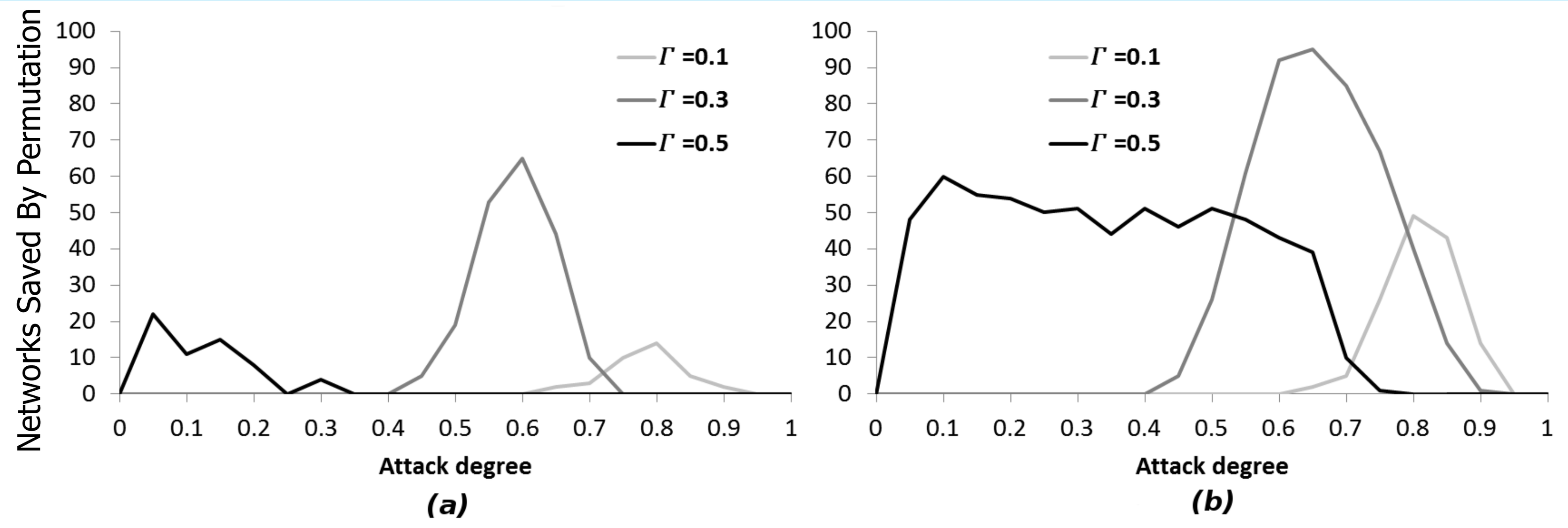
- Some nodes are *permutable*, i.e., they may switch roles in order to take part in the alternative network, potentially altering the resilience of the network as a whole:



Step 1: Initial state — Final State: Network Survives

- To assess network robustness:
  - Some randomly chosen network *A* nodes are disabled.
  - This causes some network *B* nodes to fail, which in turn causes some network *A* nodes to fail, and so on.
  - Network robustness is the total size of the surviving fragments once cascading failure has run its course.
- Where networks contain permutable nodes we explore how swapping their roles changes network robustness and treat this as a measure of resilience.

Results



Networks saved as a result of role permutation for different attack sizes, using permutation between (a) uncoupled nodes and (b) coupled nodes, for low (=0.1), medium (=0.3), and high (=0.5) symbiotic interdependency thresholds.

- We evaluate symbiotic network pairs. Each 100-node Barabási-Albert network has 50 nodes directly coupled to the other network, and 40% of its nodes permutable.
- Networks are limited to 100 nodes due to computational demands introduced by the exponential increase in the number of possible networks due to permutation.
- Two types of permutation are considered: uncoupled and coupled. The former involves a permutable node where each of its roles is uncoupled, i.e., in neither of its roles is it directly dependent on the operation of a complementary network node. The latter involves a permutable node where one of its roles is coupled to the complementary network.
- In each case, we explore the percentage of coupled networks saved from cascading failure by permutation.
- ***Permutation saves the most networks when attacks are of a moderate size and symbiosis is of medium strength.***

Discussion

- In interdependent infrastructure systems, failure may spread iteratively during periods of stress/perturbation.
- Our results show that the risks of cascading failure are reduced by *functionally permutable* infrastructure nodes.
- These nodes do not offer multiple simultaneous services (e.g., dual infrastructures that can potentially be a liability), but switch between different types of service.
- While our simulation results provide some insight, there are limitations to their applicability and generality:
  - We considered paired networks, but real infrastructure can involve a large number of interconnected systems.
  - Network interdependencies are *not random*, but may be correlated with degree, betweenness, proximity, etc.
  - Attacks may disable nodes non-randomly, according to centrality, proximity to a geographic attack location, etc.
  - Role permutation can be implemented *during* the process of cascading failure rather than afterwards.
- However, studies like this one are useful as a starting point for more sophisticated models when trying to understand, e.g., the vulnerability of coupled energy networks, the robustness of transport networks, etc.

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