Vulnerability Analysis of Interdependent Infrastructure Systems

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Resilient Futures

Global Uncertainties — Security for all in a Changing World

Introduction

- Infrastructure systems depend on each other to function properly and they have evolved into a network of networks.
- Interdependencies between these systems allow disruptive events to propagate across networks.
- Advances have been made in studying relatively simple, spatially constrained systems, and improved techniques are required to understand the role of interdependencies and the risks associated with them.
- This research studies interdependent networks featuring a range of complex coupling modes, and investigates the influence of these interdependencies on the behaviour and performance of interconnected systems.

Method

A network modelling framework for exploring cascading failure of interdependent systems has been developed.

Interdependent Network Model

- Coupling two or more networks, which can be spatial or aspatial.
- Various networks topologies, *e.g.* grid, scale free, random, centralised, decentralised *etc.* that represent different infrastructure types.
- A range of interdependency coupling modes, *e.g.* random links, favoured according to number of existing connections, preferential according to distance, which can be configured by:
  - *Directionality*: bi-directional or uni-directional
  - *Extent*: fraction of interdependent nodes
  - *Redundancy*: number of supporting connections for each interdependent node

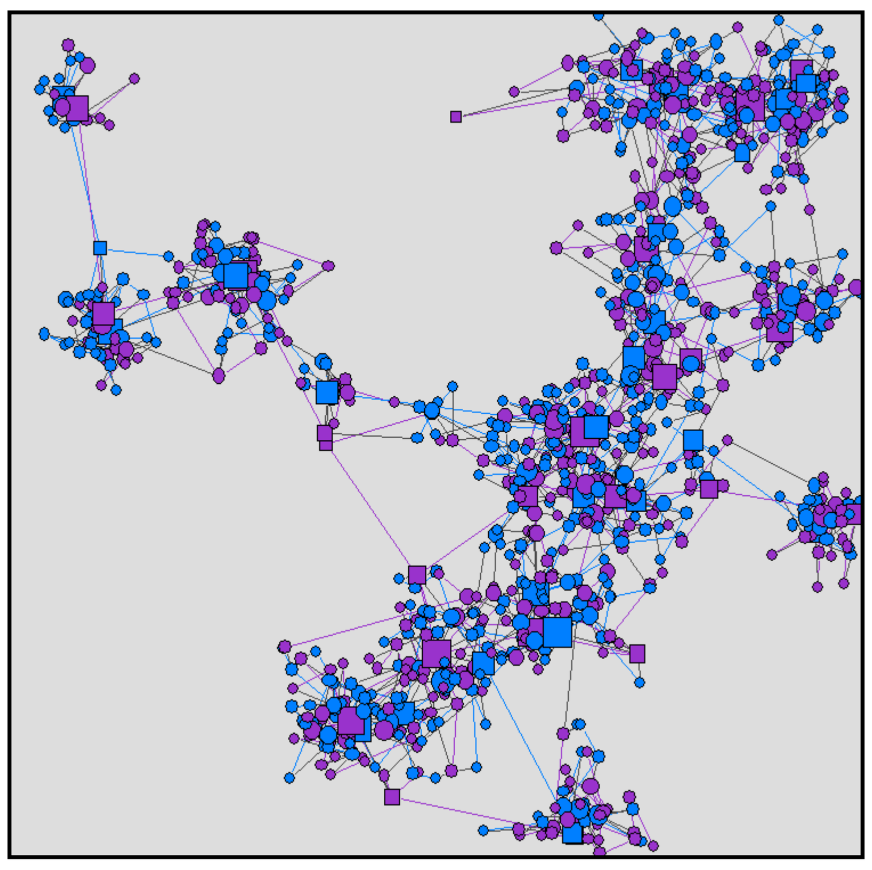


Fig. 1 An interdependent system of two networks (blue and purple). Larger nodes have more network connections. Interdependencies between each network are influenced by distance.

Cascading Failure Model

We model an attack by disabling some proportion of the network nodes directly, which indirectly brings about a cascade of additional node failures in the system as a consequence of compromised interdependencies. An attack can be random, targeted at the most important nodes (e.g. largest number of connections), or spatially explicit (e.g. a flood, or windstorm). Node failures happen recursively and may result in system failure extending far beyond the original attack footprint, as shown in Figure 2.

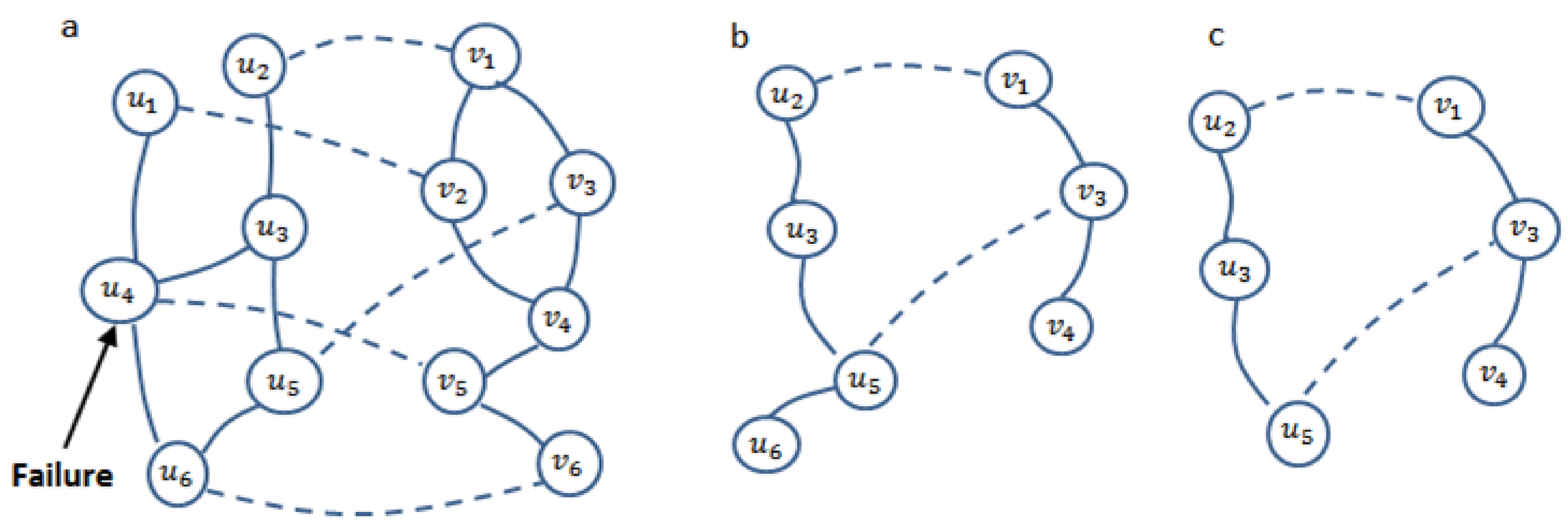


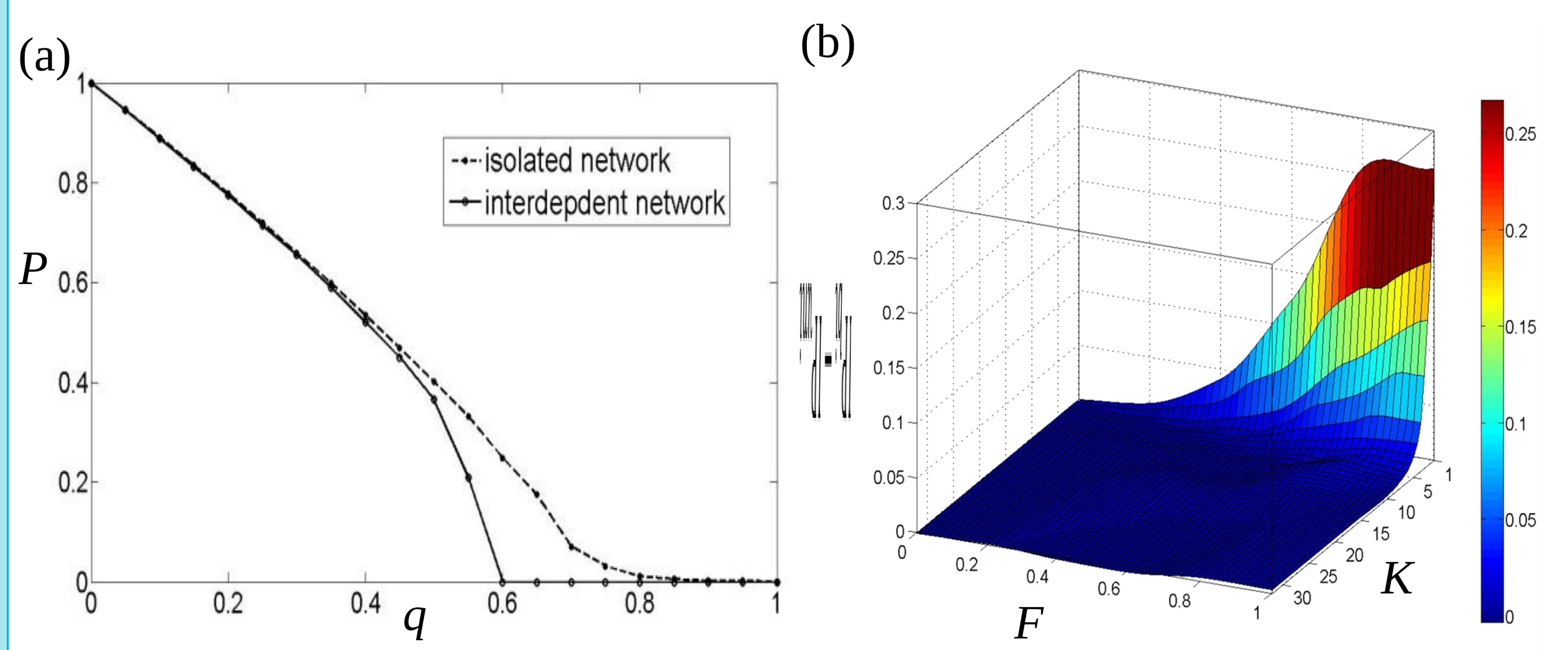
Fig. 2 An interdependent system and the cascading failure when the node u_4 is attacked (a) the initial system (b) the system after the first iteration of cascading failure (c) the stabilised system.

Results

Extensive experiments were carried out on modelled systems for a range of coupling modes. A selection of results, in each case for two coupled networks of 10,000 nodes, are reported here.

The relative size, *P*, of the largest connected component survived after cascading failure, is used as a measure of system performance for a given network disruption size *q*. The aggregate performance, *IP*, characterises the behaviour of an interdependent system when network disruptions of different magnitude are considered and is calculated as the integral of *P*.

Figure 3(a) shows how, for the system modelled here, that the introduction of interdependencies to a single infrastructure network increases its vulnerability. Figure 3(b) shows interdependencies that are uni-directional (i.e. if Network A node *v* relies upon a Network B node *u*, *u* does not have to rely on *v*) results in a more vulnerable system. This is further reinforced in Figure 3(c) which shows how increasing the fraction of bi-directional interdependencies system performance increases.



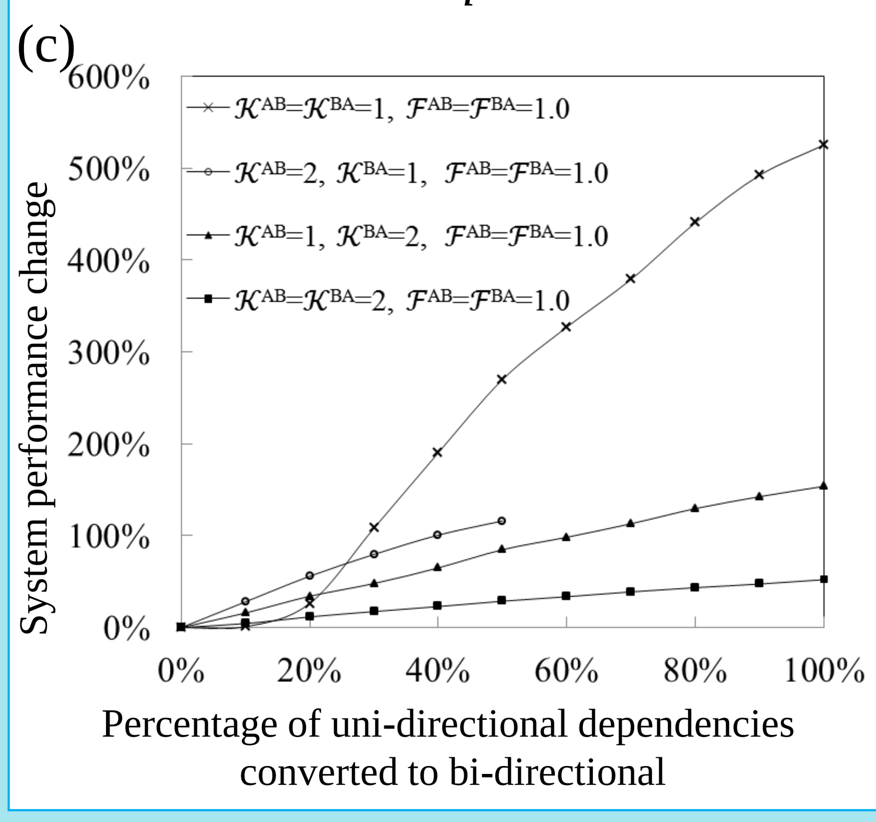


Fig. 3 Performance of interdependent systems.
(a) Performance is compared against an isolated system.
(b) Performance of systems with bi-directional interdependencies is compared against those with uni-directional connections: difference between aggregate performance ($IP_{bi} - IP_{uni}$) is reported against the fraction of nodes with interdependent connections, F, and the number of interdependent connection per node, K.
(c) Performance change when proportion of uni-directional dependencies are turned into bi-directional.

Conclusions

- Interdependent extent, directionality and redundancy mediate the performance of interdependent infrastructure systems.
- The disruption to interdependent systems can be disproportionate to attack size when inter-network dependencies are sub-optimal.
- Networks with directed dependencies are less robust than those with undirected dependencies.
- The degree of redundancy in inter-network dependencies can have a differential effect on robustness dependent on their direction.
- The robustness of an interdependent system can be improved by optimising inter-network dependencies in a cost effective way.
- Further work is exploring the mediating influence of other network attributes, such as flow, capacity, resistance *etc.* and the development of potential transition and adaptation strategies for making interdependent networks more resilient.

References

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Funded by the EPSRC and ESRC 'Global Uncertainties' initiative

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