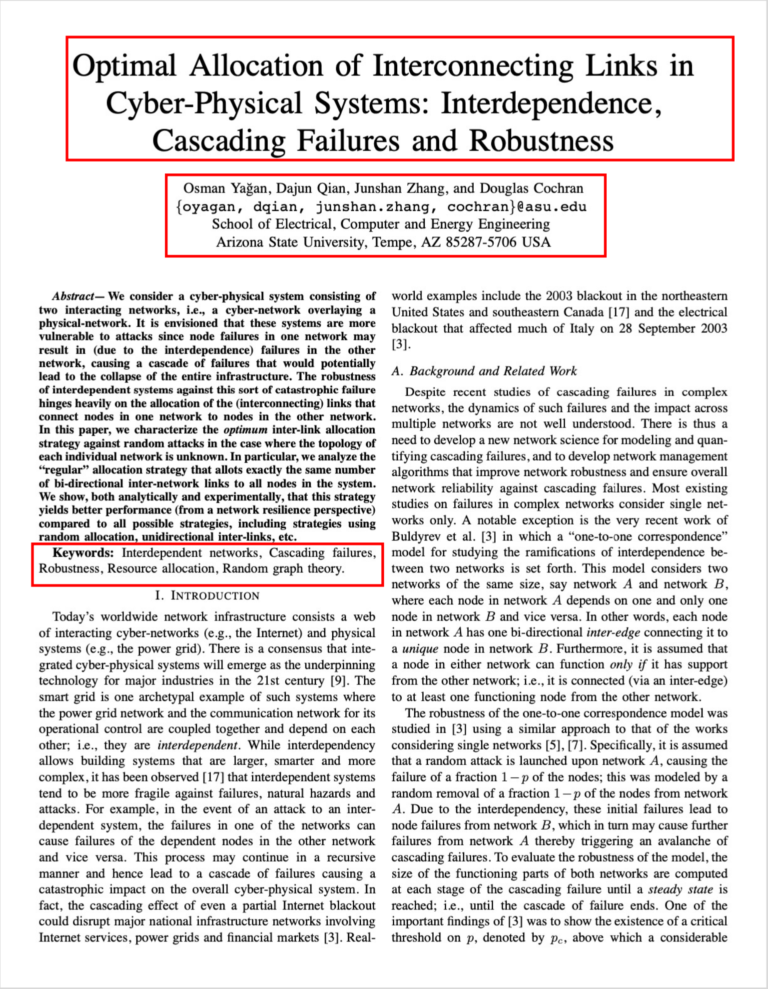
18-755 – Paper Review Presentation

November 9, 2022

Vikas Kashyap, Tony Huang (Group 8)

TABLE OF CONTET

Overview of the Paper



Optimal Allocation of Interconnecting Links in Cyber-Physical Systems: Interdependence, Cascading Failures and Robustness

Osman Yağan, Dajun Qian, Junshan Zhang, and Douglas Cochran
{oyagan, dqian, junshan.zhang, cochran}@asu.edu
School of Electrical, Computer and Energy Engineering
Arizona State University, Tempe, AZ 85287-5706 USA

***Abstract*— We consider a cyber-physical system consisting of two interacting networks, i.e., a cyber-network overlaying a physical-network. It is envisioned that these systems are more vulnerable to attacks since node failures in one network may result in (due to the interdependence) failures in the other network, causing a cascade of failures that would potentially lead to the collapse of the entire infrastructure. The robustness of interdependent systems against this sort of catastrophic failure hinges heavily on the allocation of the (interconnecting) links that connect nodes in one network to nodes in the other network. In this paper, we characterize the *optimum* inter-link allocation strategy against random attacks in the case where the topology of each individual network is unknown. In particular, we analyze the "regular" allocation strategy that allots exactly the same number of bi-directional inter-network links to all nodes in the system. We show, both analytically and experimentally, that this strategy yields better performance (from a network resilience perspective) compared to all possible strategies, including strategies using random allocation, unidirectional inter-links, etc.**

Keywords: Interdependent networks, Cascading failures, Robustness, Resource allocation, Random graph theory.

I. Introduction

Today's worldwide network infrastructure consists a web of interacting cyber-networks (e.g., the Internet) and physical systems (e.g., the power grid). There is a consensus that integrated cyber-physical systems will emerge as the underpinning technology for major industries in the 21st century [9]. The smart grid is one archetypal example of such systems where the power grid network and the communication network for its operational control are coupled together and depend on each other; i.e., they are *interdependent*. While interdependency allows building systems that are larger, smarter and more complex, it has been observed [17] that interdependent systems tend to be more fragile against failures, natural hazards and attacks. For example, in the event of an attack to an interdependent system, the failures in one of the networks can cause failures of the dependent nodes in the other network and vice versa. This process may continue in a recursive manner and hence lead to a cascade of failures causing a catastrophic impact on the overall cyber-physical system. In fact, the cascading effect of even a partial Internet blackout could disrupt major national infrastructure networks involving Internet services, power grids and financial markets [3]. Real-world examples include the 2003 blackout in the northeastern United States and southeastern Canada [17] and the electrical blackout that affected much of Italy on 28 September 2003 [3].

A. Background and Related Work

Despite recent studies of cascading failures in complex networks, the dynamics of such failures and the impact across multiple networks are not well understood. There is thus a need to develop a new network science for modeling and quantifying cascading failures, and to develop network management algorithms that improve network robustness and ensure overall network reliability against cascading failures. Most existing studies on failures in complex networks consider single networks only. A notable exception is the very recent work of Buldyrev et al. [3] in which a "one-to-one correspondence" model for studying the ramifications of interdependence between two networks is set forth. This model considers two networks of the same size, say network A and network B, where each node in network A depends on one and only one node in network B and vice versa. In other words, each node in network A has one bi-directional *inter-edge* connecting it to a *unique* node in network B. Furthermore, it is assumed that a node in either network can function *only if* it has support from the other network; i.e., it is connected (via an inter-edge) to at least one functioning node from the other network.

The robustness of the one-to-one correspondence model was studied in [3] using a similar approach to that of the works considering single networks [5], [7]. Specifically, it is assumed that a random attack is launched upon network A, causing the failure of a fraction $1-p$ of the nodes; this was modeled by a random removal of a fraction $1-p$ of the nodes from network A. Due to the interdependency, these initial failures lead to node failures from network B, which in turn may cause further failures from network A thereby triggering an avalanche of cascading failures. To evaluate the robustness of the model, the size of the functioning parts of both networks are computed at each stage of the cascading failure until a *steady state* is reached; i.e., until the cascade of failure ends. One of the important findings of [3] was to show the existence of a critical threshold on p, denoted by p_c, above which a considerable

Paper Title

Optimal Allocation of Interconnecting Links in Cyber-Physical Systems: Interdependence, Cascading Failures and Robustness

Author

Osman Yagan, Dajun Qian, Junshan Zhang, and Douglas Cochran

Publication & Date

IEEE, (Volume: 23, Issue: 9, September 2012)

Key Topics

Interdependent networks, cascading failures, network robustness, resource allocation and random graph theory

Background and Objective of the Paper

Background

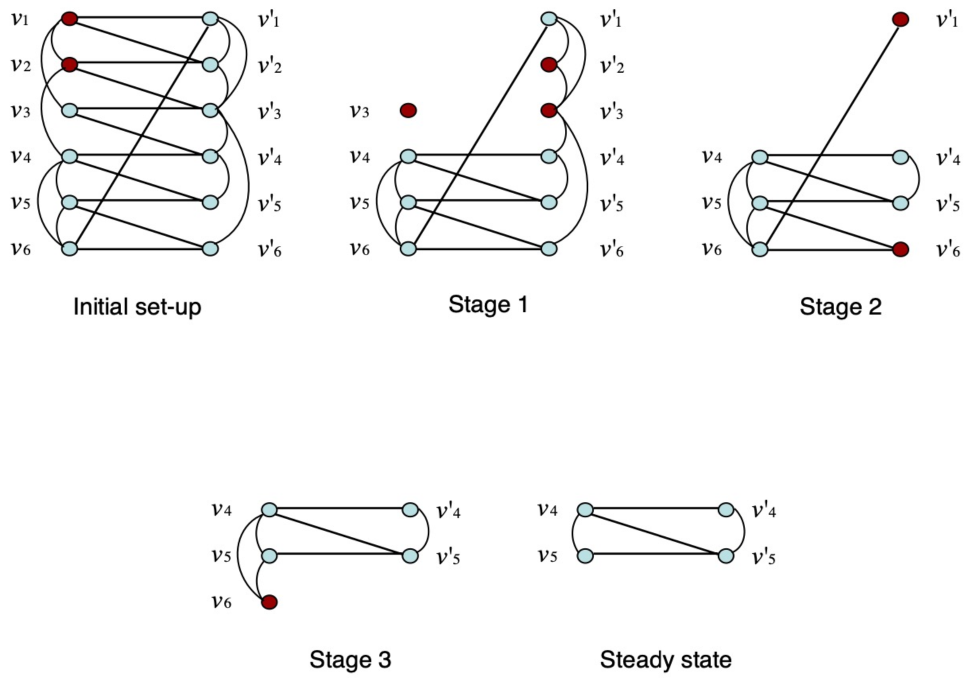
Real-world networks are complicated and connected. Failures in one network have cascading effect on other networks.

Objective

The objective is to investigate how edges should connect for maximum robustness and the threshold at which networks collapse

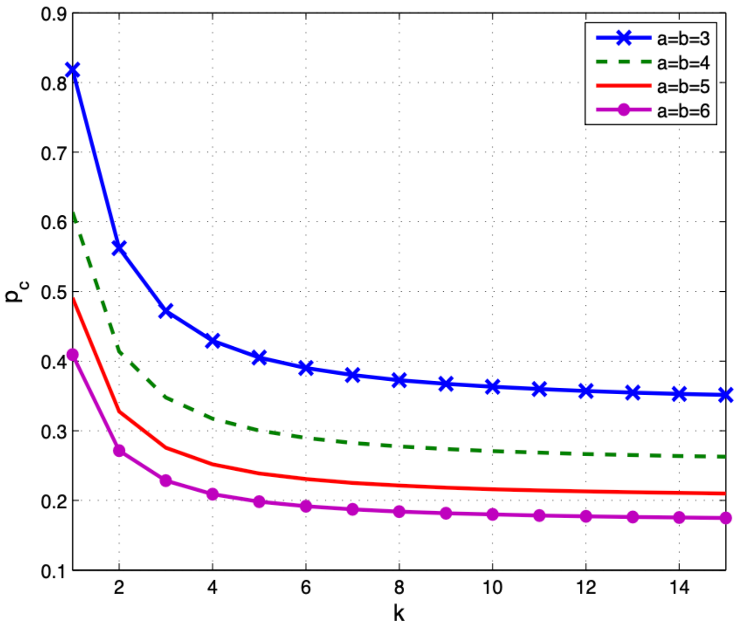
Setting

Two interdependent networks are considered, and the effects of regular and random allocation are simulated.

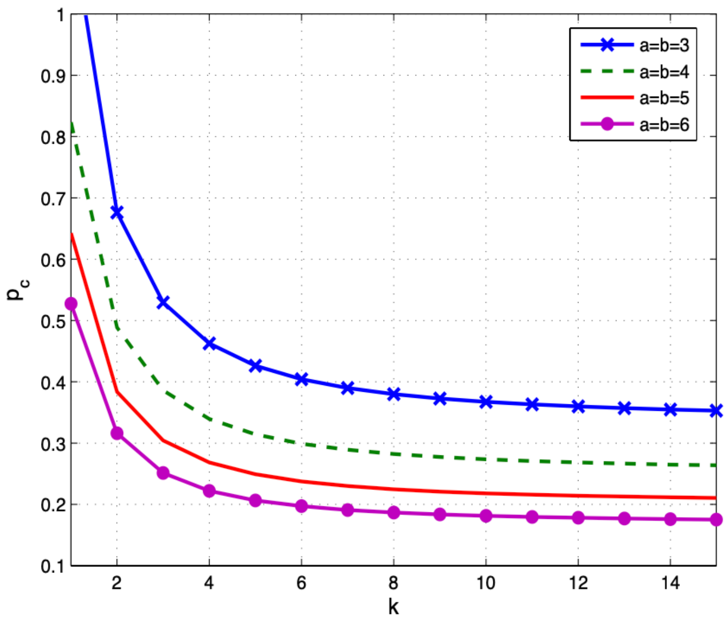


Key Results and Conclusion

Critical Value for Regular Allocation



Critical Value for Random Allocation

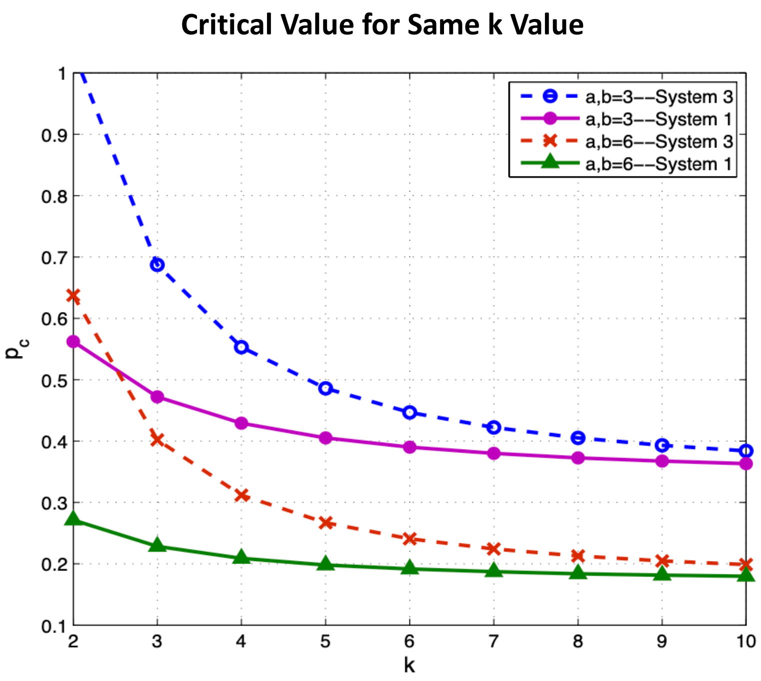


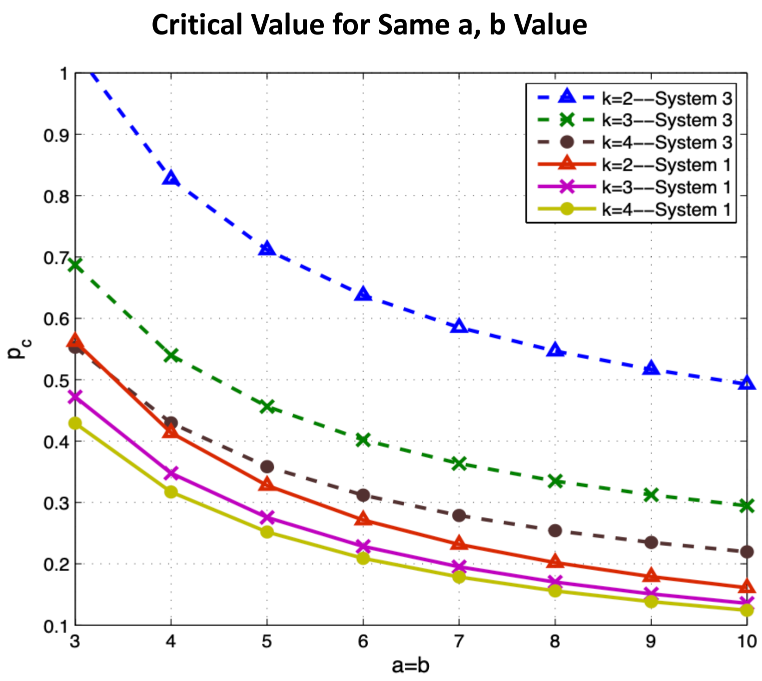
Key Findings and Impact

- As k increases, the robustness of the system increases for both regular and random allocation
- For random allocation, in some cases, the system collapses without attacking any node
- The results conclude that regular allocation (i.e., all nodes have same number of bi-directional inter-edges) is more robust than random allocation

Note: P_c denotes the threshold below which the network collapses, k the number of nodes in each network, a and b the mean intra-degrees

Key Results and Conclusion





Key Findings and Impact

- Holding the value of k constant, bi-directional inter-edge yields higher robustness
- Holding the values of a and b constant, bi-directional inter-edge yields higher robustness
- The result concludes that regular allocation with bi-directional inter-edge is more robust than regular allocation with unidirectional inter-edge

Note: System 1 denotes the bi-directional inter-edge regular allocation strategy, and system 3 denotes unidirectional inter-edge regular allocation strategy

Strengths of the Paper

STRENGTH 1

Explicit Derivation of the Critical Threshold

This recursive process stops at an "equilibrium point" where we have $p'_{B2m-2} = p'_{B2m}$ and $p'_{A2m-1} = p'_{A2m+1}$ so that neither network A nor network B fragments further. Setting $x = p'_{A2m+1}$ and $y = p'_{B2m}$, this yields the transcendental equations

$$x = p\left(1 - (1 - P_B(y))^k\right) \quad y = 1 - (1 - pP_A(x))^k. \quad (14)$$

- Previous papers on similar topics use simulation to show the existence of critical threshold
- This paper mathematically determine the "equilibrium point," which can be solved explicitly given the intra-structures of the networks

STRENGTH 2

Mathematical Proof of Relative Robustness of Networks

Theorem 4.1: Under the condition

$$k = \sum_{j=0}^{\infty} \alpha_j j, \quad (20)$$

we have

$$\begin{aligned} P_{A^1_\infty}(p;k) &\geq P_{A^2_\infty}(p;\boldsymbol{\alpha}), \\ P_{B^1_\infty}(p;k) &\geq P_{B^2_\infty}(p;\boldsymbol{\alpha}); \end{aligned} \quad (21)$$

and furthermore

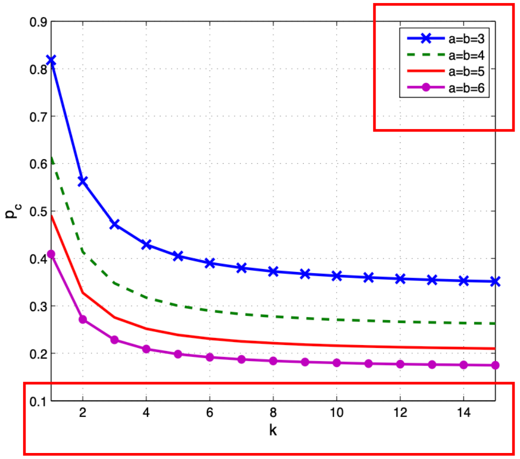
$$p_{c_1}(k) \leq p_{c_2}(\boldsymbol{\alpha}). \quad (22)$$

- The relative robustness between regular and random allocation, and between bi-directional and unidirectional networks are mathematically proven
- The results are generic and is applicable to other network scenarios

Weaknesses and Future Directions

WEAKNESS 1

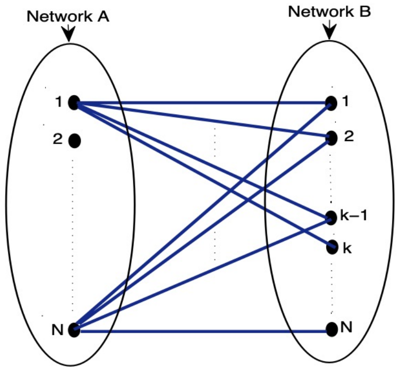
Limited Sets of Parameters were Tested



- The value of k ranges between 0 to 15, while the values of a/b ranges between 3 to 10
- The networks have relatively small-size and may not be representative of real-world networks

WEAKNESS 2

Topology Information is not Assumed



- This paper assumes the absence of topological information about the networks (e.g., the intra- and inter-edges are all equal weighted)
- In the presence of information, optimal strategy may be different

References

1. ***Optimal Allocation of Interconnecting Links in Cyber-Physical Systems: Interdependence, Cascading Failures and Robustness***
https://ieeexplore.ieee.org/document/6148227