Robustness of Interdependent Cyber-Physical Networks

Marzieh Parandehgheibi; Massachusetts Institute of Technology

Two massive blackouts in northeast America and Italy in 2003, each affecting around 50 million people and costing billions of dollars [1,2], showed that it is essential to have a smarter grid that detects autonomously faults and allows self-healing [3]. Smart grids are a new paradigm for future energy systems that integrate electrical power networks and information networks. This integration creates a strong interdependency between the cyber and physical networks and opens a new area for investigation of such complex networks.

The control of today's power grid relies on a supervisory control and data acquisition (SCADA) system. However, the SCADA system does not have the capability to collect real-time data from the entire grid and analyze it efficiently to make control decisions. It is expected that future smart grid will need a wide-area measurement system (WAMS) that uses new technologies such as Phasor Measurement Units (PMUs) and Sensor and Actuator Networks (SANETs) to collect synchronous data, send it to control centers for making online control decisions, and apply changes to the grid using devices such as actuators. On the other hand, elements in control network such as routers should receive power from power grid to operate. The increased dependency of power grid on communication network and vice versa gives rise to the necessity of analyzing and designing robust cyber-physical networks [4].

There have been a few attempts at introducing and modeling interdependent infrastructure networks. Rinaldi et al. [5] described the concept of interdependencies among major infrastructure networks including the power grid and communication networks. Later, Rosato et al. [6] studied the Italian blackout of 2003 and by using the real data explained that this blackout was the result of a cascade of failures between the power grid and the communication network.

For the first time, in 2009, Buldyrev et al. [7] presented a model for analyzing the robustness of interdependent random networks and investigated the existence of a giant connected component in the case of random removal of a fraction of nodes. They showed that the interdependent networks are more vulnerable to failures than single networks. A review of follow-up works on Buldyrev's model can be found in [8].

However, three critical issues arise in the context of the interdependent power grid and control network. First is the issue of cascading failures inside the power grid which leads to significant power loss. We implemented the model of cascading failures from [9] in conjunction with the random model introduced by Buldyrev et al. We observed that no giant component exists for any size of node removal and none of the results in Buldyrev et al. holds anymore. Therefore, it is critical to consider the actual power flow in analyzing the power grid.

The second issue is related to the concept of control and self-healing. It was shown in [8] that the interdependency between the networks decreases the robustness; however, the power grid is dependent on the communication network, because it should be monitored and controlled by the control system implemented using the communication network. We can show that by implementing a centralized control policy one can mitigate the cascading failures inside power grid and preserve a minimum amount of power at all power nodes that are still connected to the generator. This policy helps decrease the cascade of failures both inside and between the two networks.

The third issue is that the power grid and communication networks are not really random and they have known topologies. Therefore, it is necessary to develop metrics for analyzing the robustness of such networks considering their interdependency. In order to accomplish this, we have developed a deterministic interdependency model where a control node fails if it loses power and a power node fails if it loses its control. We introduced two metrics MTFR (minimum node removal for total failure) and MPFR (minimum node removal for partial failure) for measuring the robustness of networks. Measuring these metrics in networks with given topologies helps us to find the areas that are more vulnerable to failures. It also provides valuable insights for designing a robust interdependent network [10].

These observations lead to the following research areas for further investigation:

1. **Developing Optimal Control Policies:** Although one can come up with a simple centralized algorithm to control the smart grid, this policy cannot be implemented. The real power grid is divided into regions, and each region is controlled by different utility companies that do not tend to share information. Thus, although the future smart grid will collect very extensive information, this information will be kept locally. On the other hand, collecting such huge amount of data and making a fast centralized decision based on it, is not practical. Therefore, it is important to design fast and decentralized control algorithms that rely on a small amount of localized information and can avoid the failures in each region optimally.

2. **Modeling Interdependency:** Although our deterministic model can express some behaviors of interdependent networks, it is not an accurate model. In reality, control nodes may have backup batteries that help them operate for a while after disconnection form power grid. Moreover, a power node may not fail instantaneously after the loss of control node. Therefore, a probabilistic model may be a more accurate model for interdependency where power and control nodes fail according to some probability distributions. It is also possible to improve the model by considering the delay in failure propagation between the networks. Having an accurate interdependency model helps understand the behavior of networks more precisely.

3. **Designing Robust Topologies:** We observed that no control policy can survive the power nodes that are disconnected from the generators; thus, the failure can still propagate inside and between the two networks. Similarly, control nodes that become disconnected from the control centers will fail and lead to extra failures in other networks. Therefore, it is critical to design interdependent topologies that have high redundancy and are robust to certain failure events.

We believe that despite the importance of interdependent cyber-physical networks such as smart grids, this area is very new and there is very little known about such complex systems. Therefore, it is critical to study the behavior of interdependent networks under accurate models, develop control policies and design network topologies that are robust to both natural failures and physical/cyber attacks.

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