How They Interact? Understanding Cyber and Physical Interactions against Fault Propagation in Smart Grid

Zhuo Lu, University Of South Florida

Mingkui Wei, Sam Houston State University

Xiang Lu, Institute Of Information Engineering

Outline

1. Introduction
2. Problem statement and model
3. Analytical formulation and results
4. System level simulation
5. Conclusion

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Cascading Failure in the Power Grid

- The propagation of a single fault can cause wide-area, large-scale system failure.

Initialization:
  Random transmission line failure;
  Power redistribution;
while *Overloaded line exists* **do**
  Fail overloaded lines;
  Power redistribution;
end

Algorithm 1: How to take down a power grid

Cascading Failure in the Power Grid

- The propagation of a single fault can cause wide-area, large-scale system failure.

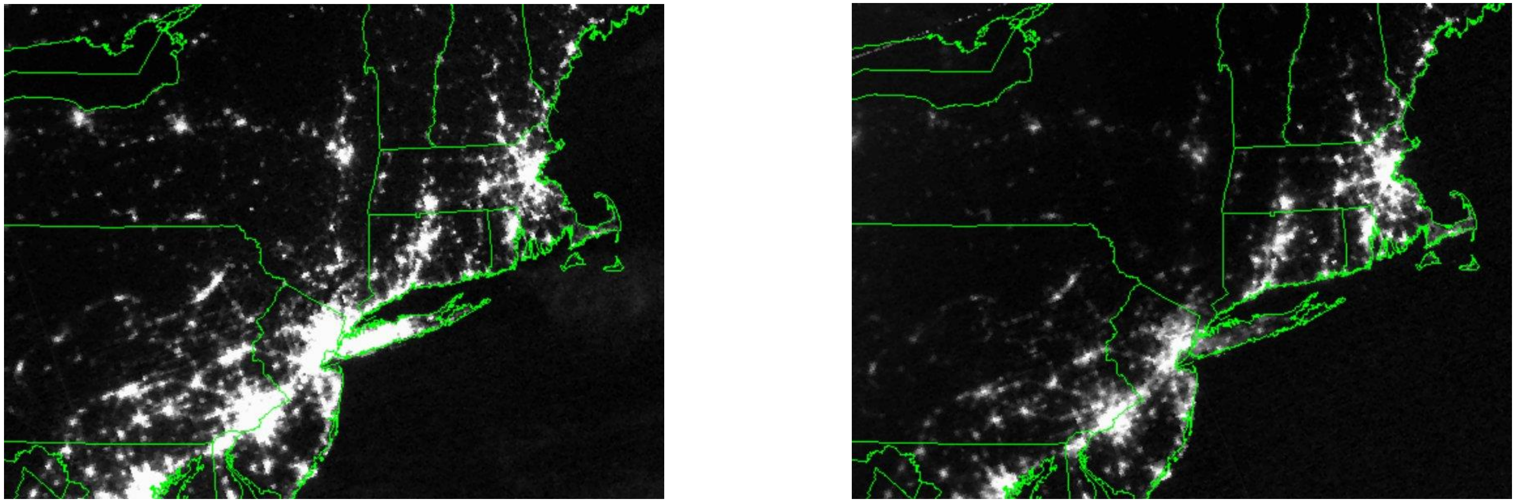
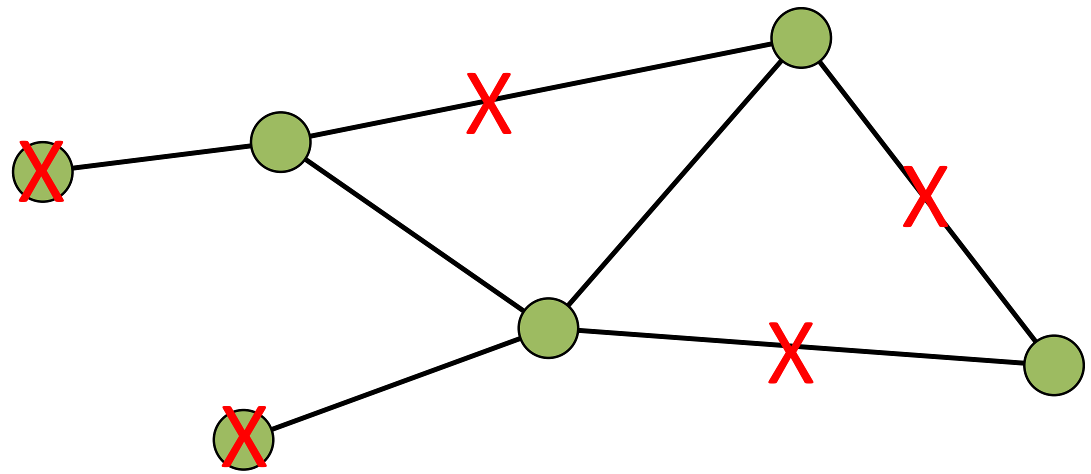


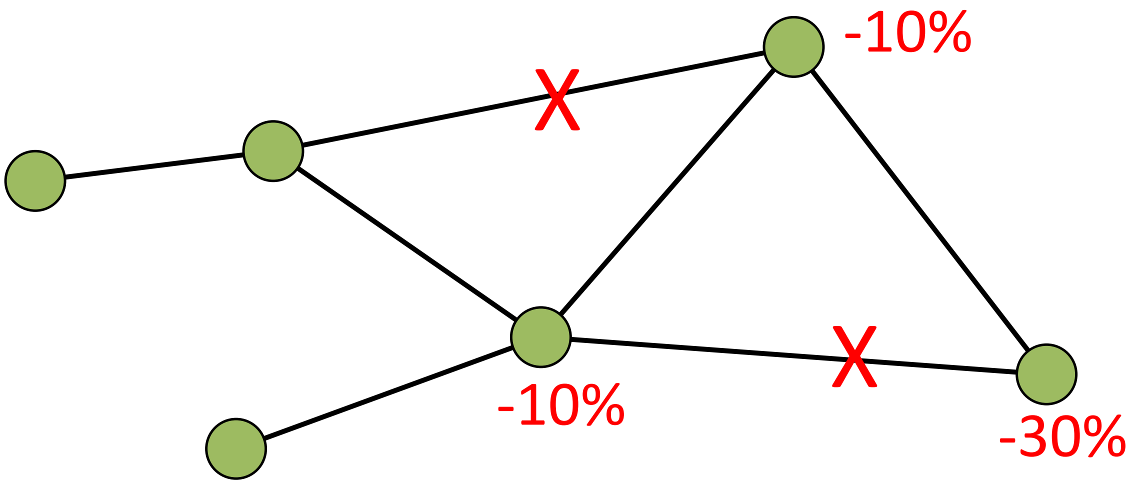
Figure: 2003 US northeast blackout, before and after the event.

Shedding Load to Stop Cascading Failure



- Legacy grid approach
  - Load is pre-configured with priority
  - Load is shed according to priority, rather than its contribution in stopping fault propagation
  - **Local load shedding**

Shedding Load to Stop Cascading Failure



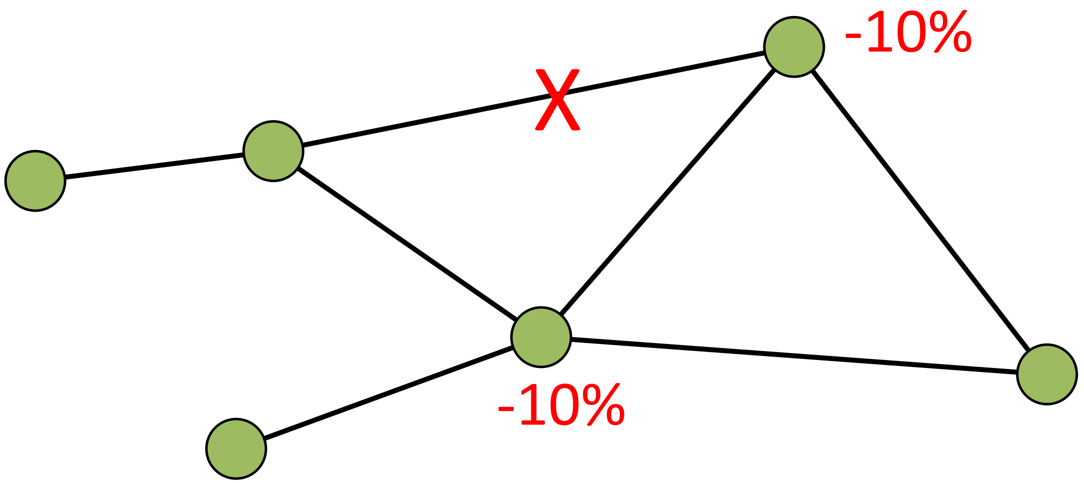
- Smart grid approach
  - Shed load and eliminate over with the least cost
  - Relies on *communication networks*
  - **Global load shedding**

Existing Works

- Analytic modeling
  - Is based on complex/interdependent network theory
  - Does not necessarily accommodate power factors

- Event or simulation based analysis
  - Has more realistic power system setting
  - Studies the result and impact of fault propagation
  - **Implicitly assumes the communication is ideal**

Motivation



- Global load shedding with message delay
  - What if the load is shed too late?
  - Is communication always a helpful factor?

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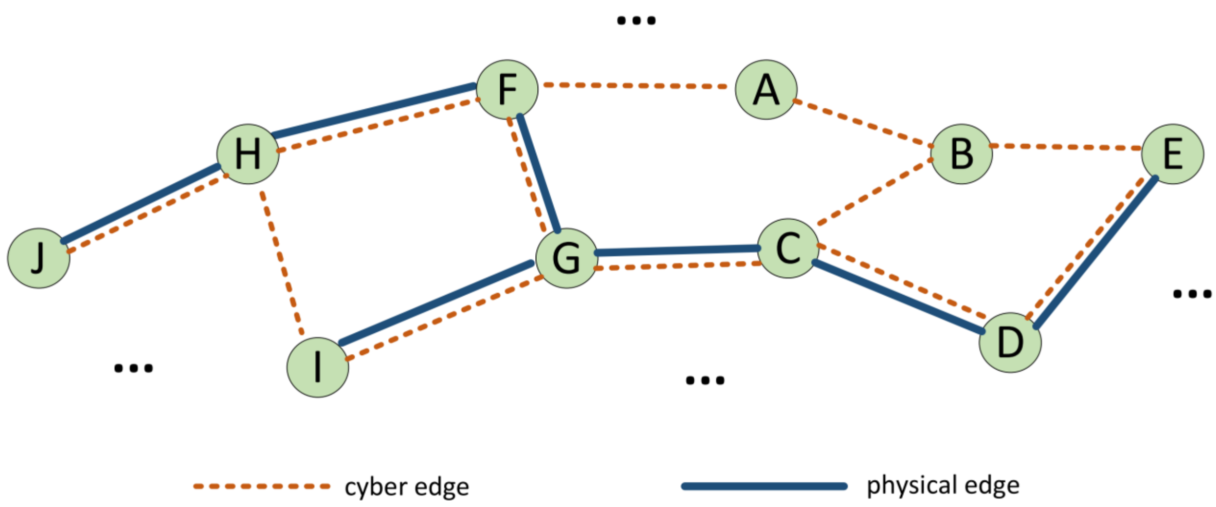
System Model

- Smart grid and network architecture

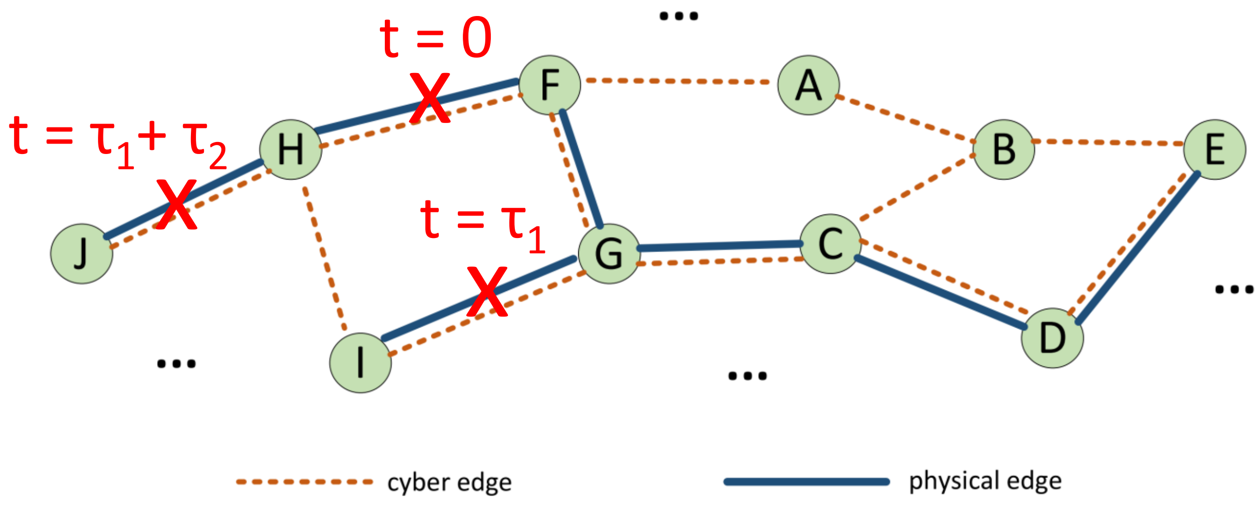


Smart grid as a multigraph: $\mathcal{G} = (\mathcal{N}, \mathcal{E}_c, \mathcal{E}_p)$

- $\mathcal{N}$ is the set of all nodes;
- $\mathcal{E}_c$ and $\mathcal{E}_p$ are the set of cyber and physical edges
- Cyber system $\mathcal{G}_c = (\mathcal{N}, \mathcal{E}_c)$, and power system $\mathcal{G}_p = (\mathcal{N}, \mathcal{E}_p)$

System Model

- Fault propagation in the physical domain

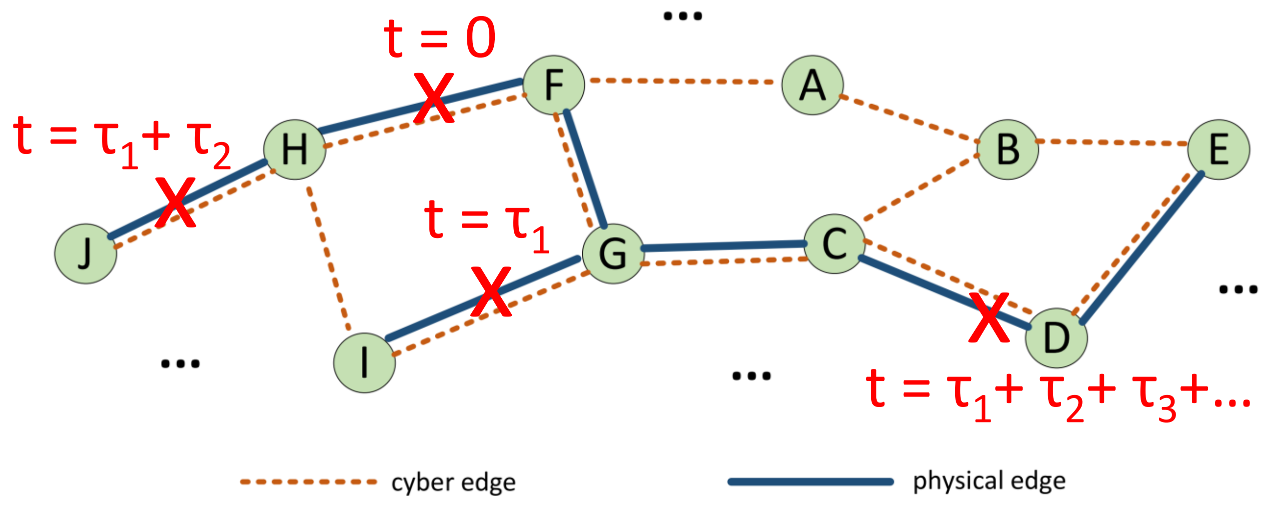


Definition 1:

The total number of failed lines $\{M(t); t \geq 0\}$ is an inhomogeneous counting process with the i-th random counting interval τ_i depends on i.

System Model

- Fault propagation in the physical domain

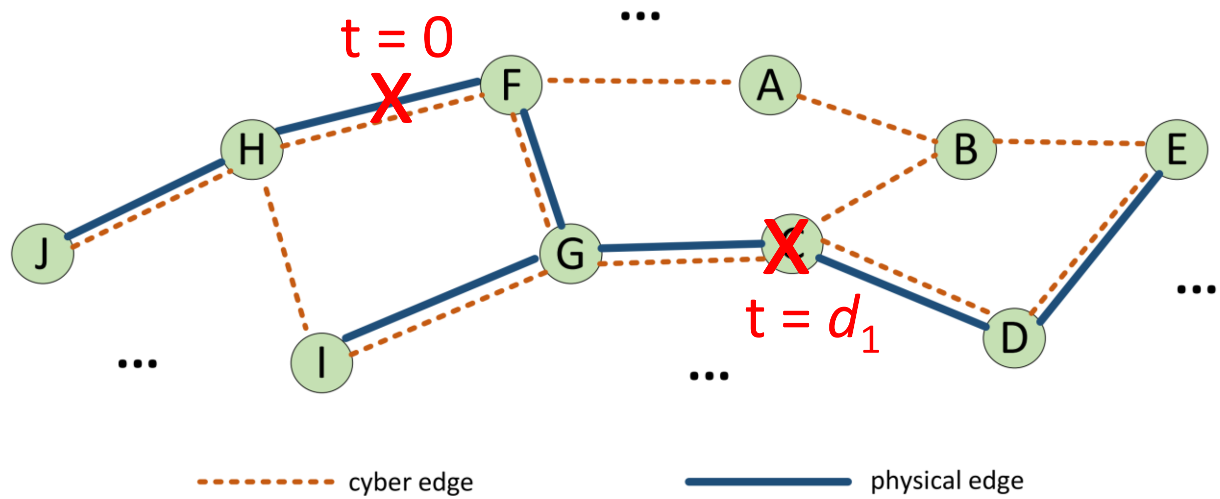


Definition 2:

The failure probability, denoted as $P(M(\infty) \geq m)$, is the probability that at least m lines eventually fail.

System Model

- Fault propagation in the physical domain



Definition 3:

The action of load shedding is triggered at each epoch in the process $\{M(t); t \geq 0\}$ with delay d_i denote the duration between the i-th load shedding procedure starts, and the corresponding load is shed in the physical domain.

Problem Statement

- How to formulate and characterize the failure probability $P(M(\infty) \geq m)$?

- What are the most important factors to use global and local load shedding to stop failure propagation?

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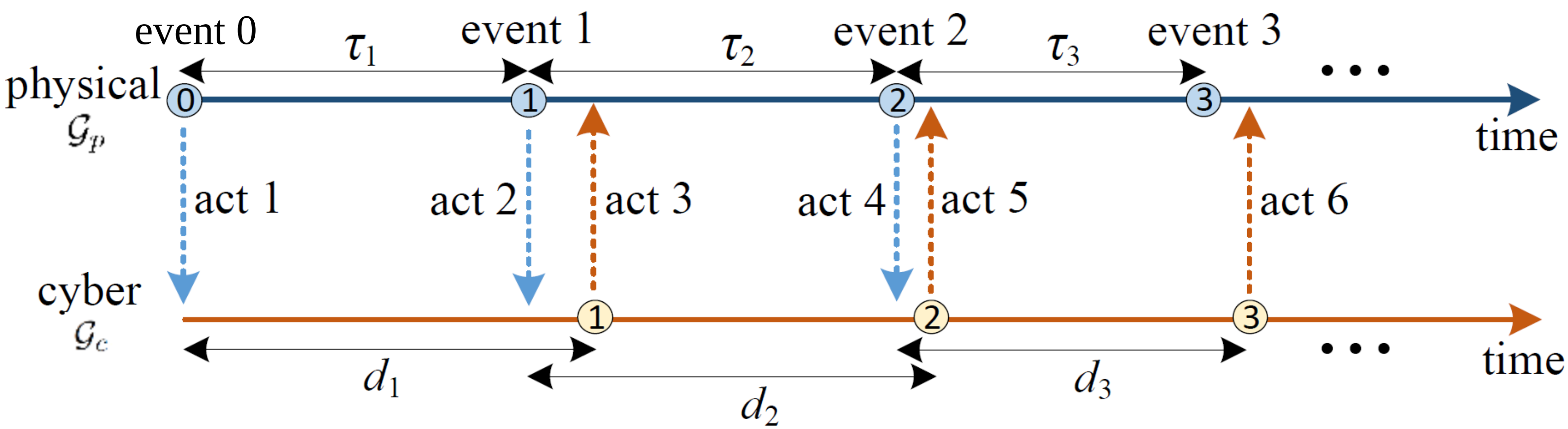
Cyber-Physical Interactions during Fault Propagation



Why fault propagation won't be stopped by global load shedding?

- act 1: detection of fault in event 0.
- act 3: delivering of control message in reaction to fault in event 0.
- Problem: act 3 is delivered after new fault (event 1) has been caused.

Analytical Results

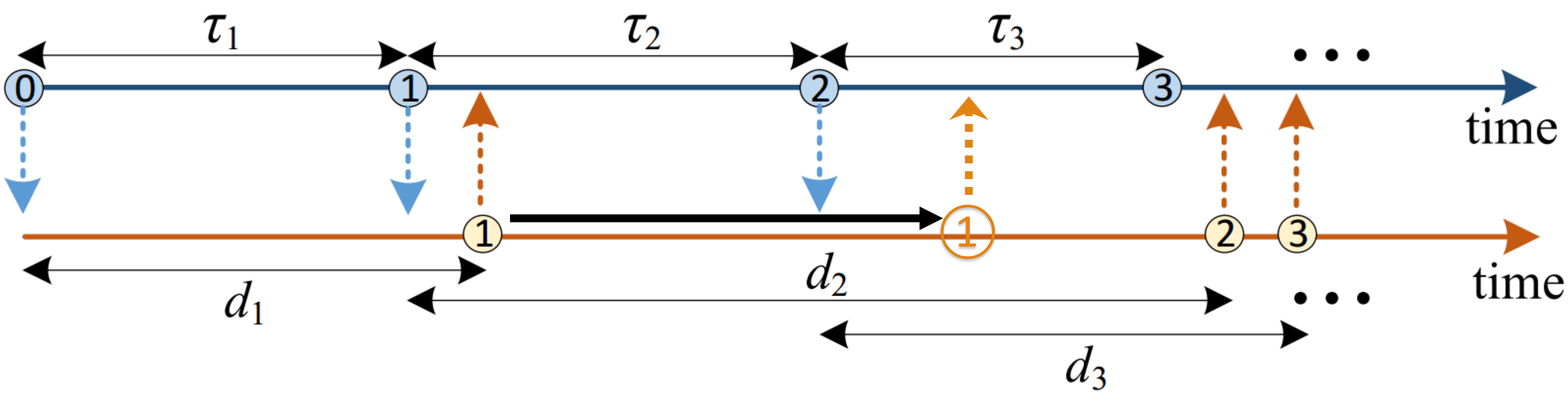
Theorem 1

Given the physical and cyber interactions in Definition 1 and 3, the failure probability $P(M(\infty) \geq m)$ satisfies:

$$P(M(\infty) \geq m) = 1 - \sum_{l=1}^{m} (-1)^{l-1} \sum_{(x_1,\ldots,x_l) \in R_{l,m}} P(\bigcap_{k=1}^{l} \bigcap_{l=x_{k-1}}^{x_k} A_{i,x_k})$$

where $R_{l,m} = \{x_1, x_2, \ldots, x_l | 1 \leq x_1 \leq x_2 \ldots \leq x_l \leq m\}$.

Analytic Results



- $A_{i,j}$ is the event that *j-th* load shedding happens after the *i-th* failure.
  - $A_{1,1}$ means the 1st load shedding occurred after the 1st failure, i.e., $d_1 > \tau_1$.
  - $A_{1,2}$ means the 1st load shedding occurred after the 2nd failure, i.e., $d_1 > \tau_1 + \tau_2$.

Analytic Result

Theorem 2

Denoted by $n = |\mathcal{N}|$ the number of nodes in the network. If the delay in the cyber domain is exponentially distributed, with mean denoted in the asymptotic notation as $E(d_i) = \Theta(g(n))$ for some function $g(\cdot)$, and τ_i has a finite mean, it holds that:

$$P(M(\infty) \geq m) \geq e^{-\Theta(\frac{mf(\{\tau_i\})}{g(n)})},$$

where $f(\{\tau_i\})$ is a function of $\{\tau_i\}$.

Analytical Result

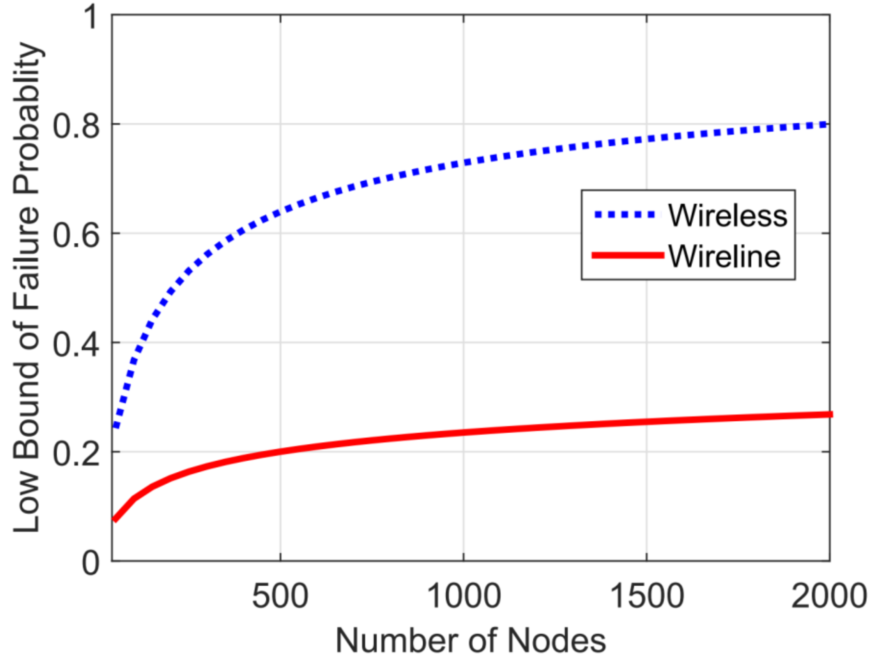


Figure: a numerical example comparing lower bound of wired and wireless.

- For a wired network, $g(n) = \Theta(\log n)$.
- For a wireless network, $\mathrm{g(n)} = \Theta(\sqrt{n})$.
- For local shedding, $\mathrm{g}(n) = \Theta(1)$.

Global shedding is not uniformly better than local shedding!

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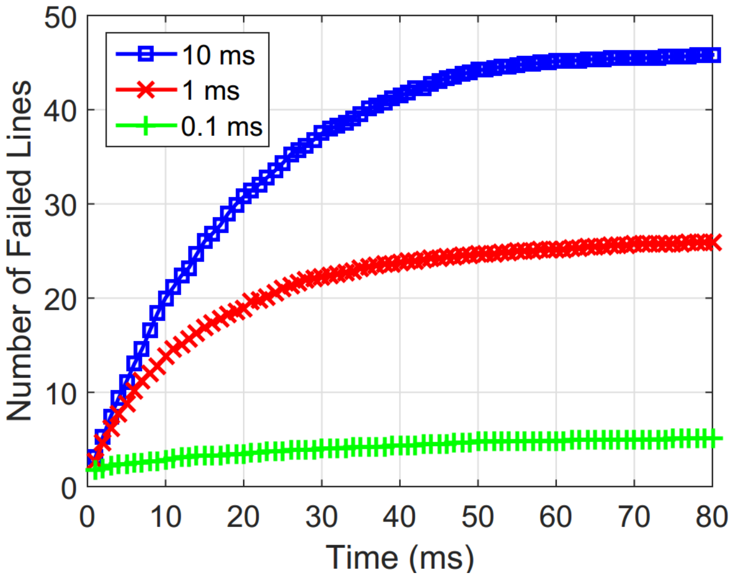
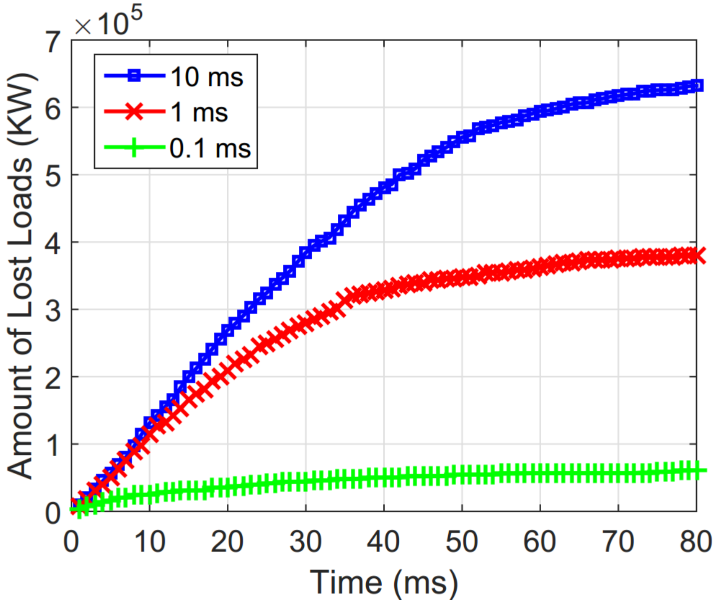
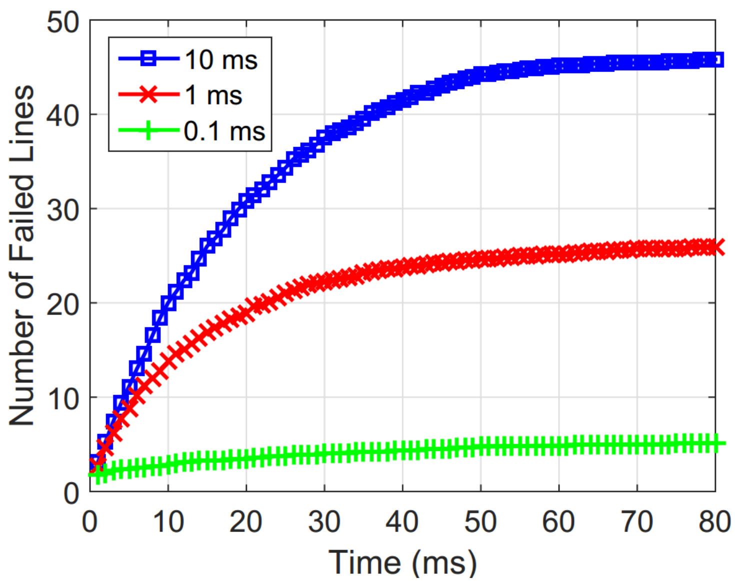
Global Load Shedding with Practical Link Performances

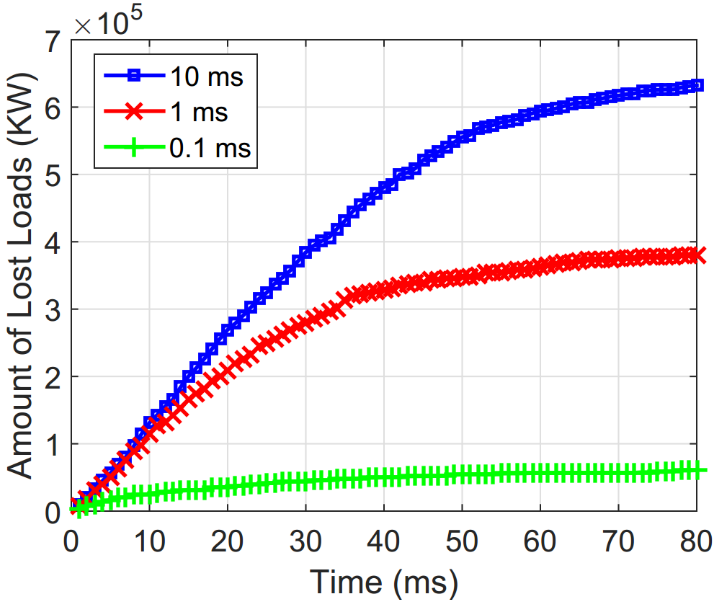




- Simulation is conducted on the IEEE 57-Bus system
  - 57 buses, 80 transmission lines, 1,250,800 Kilowatts load.
- Average communication delay is set to be 0.1, 1, and 10 ms.

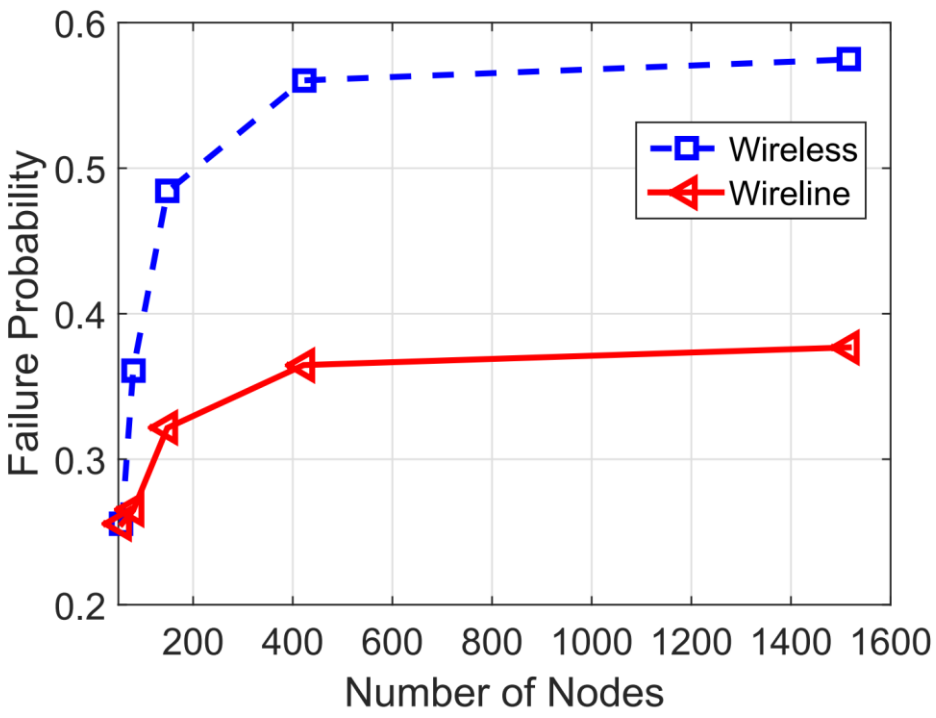
Global Load Shedding with Practical Link Performances





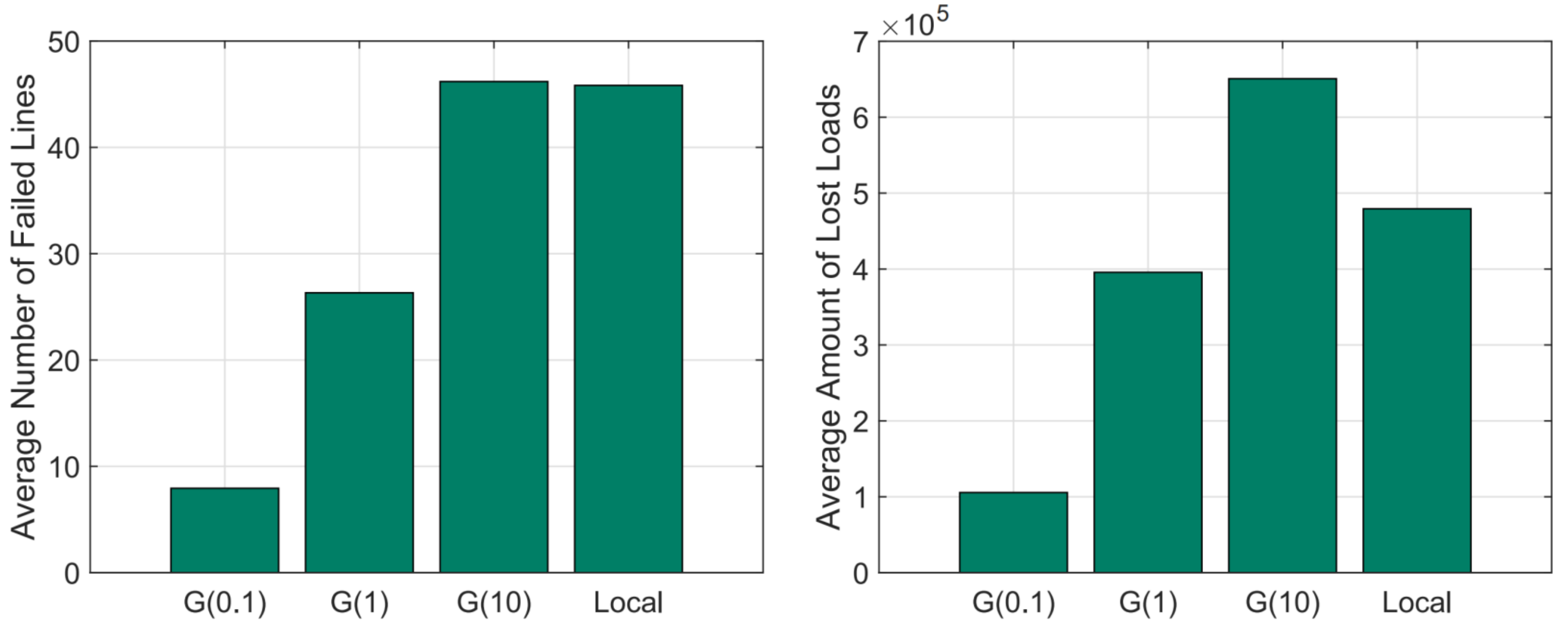
1. 10 ms delay results in more than half line failure and about half load lost.
2. Shorter delay brings better result.
3. Even very small delay can still not completely prevent fault propagation.

Global Load Shedding in Wired and Wireless Networks



- Change of $P(M(\infty) \geq m)$ as number of nodes increase, while m is fixed to be m=*32.*
- Follows analytical results.
- Wireless incurs much higher failure probability.

Global v. Local Load Shedding



- Delay in Global load shedding is set to 0.1, 1, and 10 ms.
- Local load shedding without communication.
- Local load shedding outperforms the 10 ms case.

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Conclusion

- Characterized the cyber-physical interaction of fault propagation using analytical modeling and system-level simulation.
- Demonstrated that:
  - Global load shedding is sensitive to the performance in the cyber domain;
  - Local load shedding may perform better in the presence of an imperfect cyber domain.
- Necessitate a joint view for any design in the smart grid.

Thank you!