LIDS

Massachusetts Institute of Technology

Role of Communication Network in Real-Time Control of Power Grid: Benefits & Risks

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Joint work with Eytan Modiano, Kostya Turitsyn & David Hay

TCIPG reading group – UIUC
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Overview

- **Part I:** Introduction- Why the current control is not enough for emergency control? How to improve it?
- **Part II:** Interdependency between Power Grid and Communication Networks
- **Part III:** Modeling Impact of Communication Loss on Power Grid
- **Part IV:** Using Real-Time Control for Normal Operation

Part I: Introduction

Why Current Controls in the Power Grid are not enough for Emergency Situations? How to Improve it?

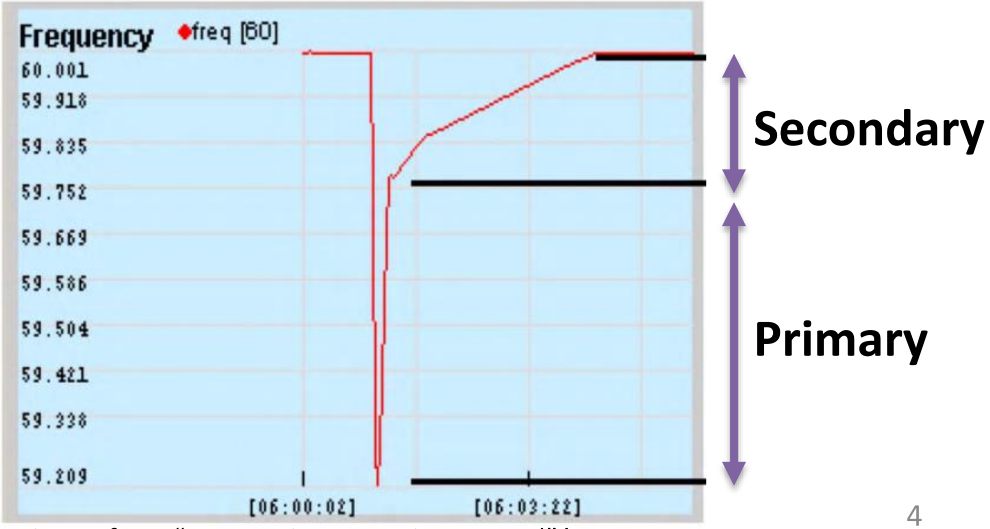
Current Control of Grid

Power must be always balanced inside the grid
All elements inside the grid operate in one frequency: 60Hz in US

Failure causes imbalance in the system

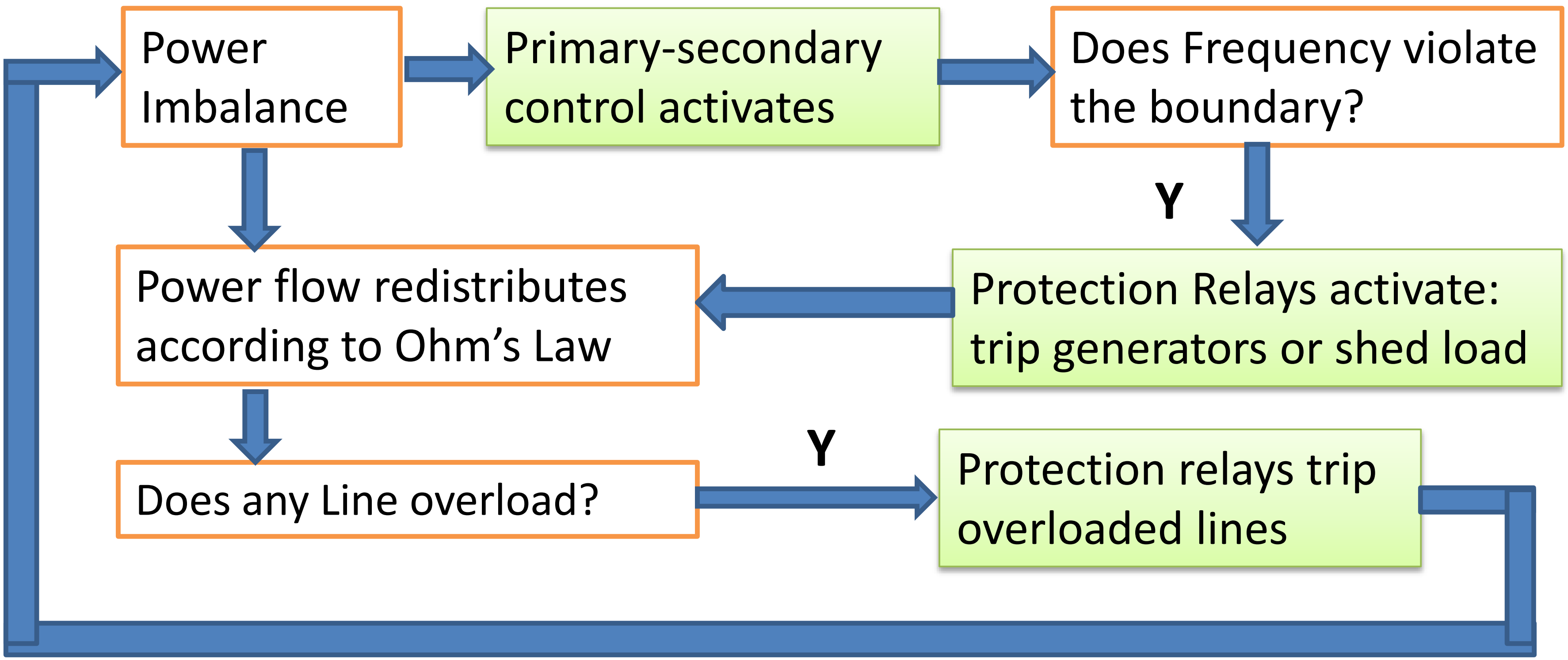
if extra generation in the system: frequency increases
if extra load in the system: frequency drops

To re-balance the power:
Primary Frequency Control
Primary Frequency Control



Picture from "Automatic Generation Control" by Murty

Cascading Failures



If a large disturbance occurs, failures cascade in the power grid

Large Blackouts due to Cascading Failures

Date	Location	Notable consequences
1988 to 2003	Western India	29 large cascading failures over 15 years, millions of customers: 1.9 per year
14 Aug. 2003	Northeast America	50 million customers Economic damage: $6 to $10 billion
27 Sep. 2003	Italy	50 million customers, at least 5 deaths, 30,000 passengers stranded in trains for hours
25 May 2005	Moscow	2 million customers. Tens of thousands stuck in trains
8 Sep. 2011	Southwest America	1.4 million customers in San Diego, 1.1 million customers in Mexico
30-31 July 2012	India	600 million customers

Souce: http://tppserver.mit.edu/2005_tmp_consortium/conversion/hines.pdf
"Large blackouts in North America: Historical trends and policy implications" by Paul Hines, Jay Apt and Sarosh Talukdar

Large Blackouts due to Cascading Failures

Date	
1988 t	
14 Aug	
27 Sep	ours
25 Ma	ck in
8 Sep. 2	lion
30-31 J	

Renewable Sources of Energy
→ increases the fluctuations in the system
→ increases the Risk of Power Blackout

How to control the power blackouts?

Real-Time Monitoring and Control of Grid: Requires a Communication Network

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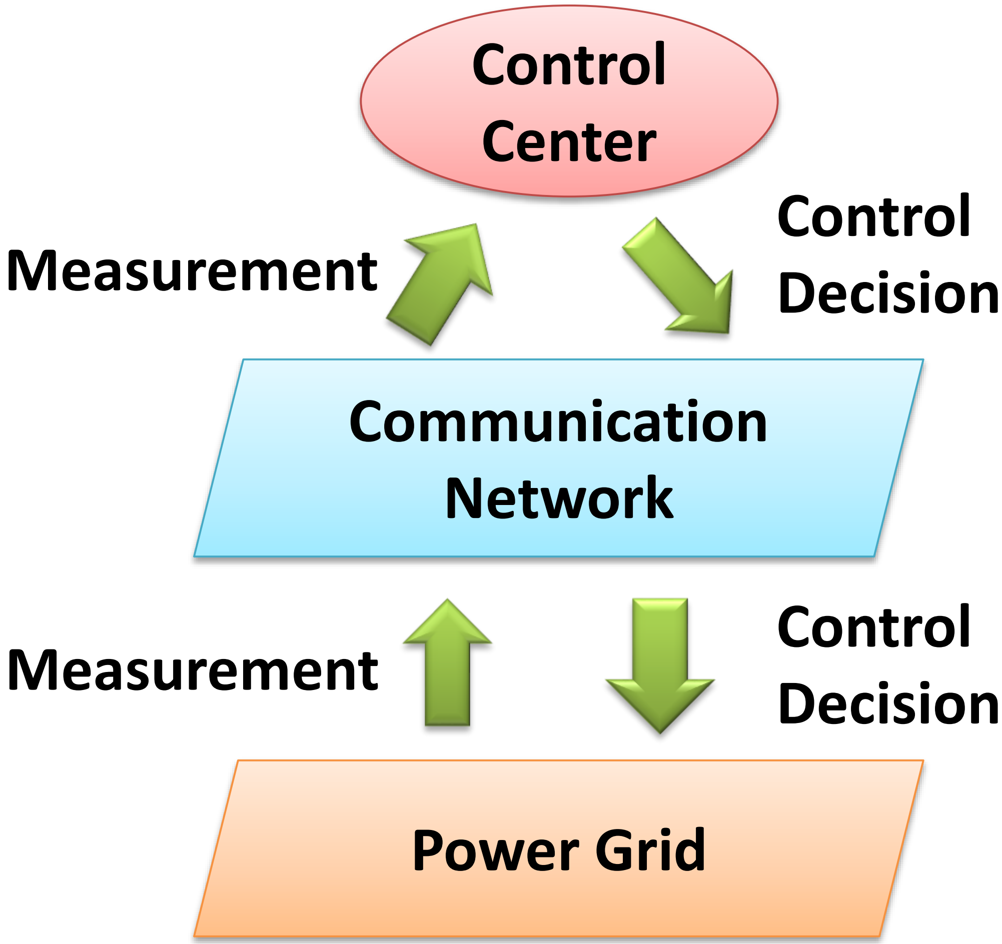
Adding Control/Communication Layer



Available Information & Control Through Communication Network

Information collected by Communication Network

$V_k(t)$	Magnitude of voltage at node k
$\theta_k(t)$	Phase of voltage at node k
$\omega_k(t)$	Frequency of Power at node k if it is a generator
$f_{kj}(t)$	Flow in power line (k,j)

Observe the state of the entire system instead of local frequency

Control Actions

Centralized Control Requires Communication	**Decentralized** control-protection Performs locally- No Need to Communication
Ramping down generators	5% droop control at generators
Intelligent load shedding	Over-frequency generator tripping - protection
Intelligent line tripping	Under-frequency load shedding - protection
	Overloaded line tripping – protection

Real-Time Control with Full Communication

$$\min \sum_{i \in V_L} PL_i$$

$$\sum_{j \in E} f_{ij} - \sum_{j \in E} f_{ji} = PG_i - \alpha_i(\omega_i - \omega_s) \quad \forall i \in V_G$$

$$\sum_{j \in E} f_{ij} - \sum_{j \in E} f_{ji} = PL_i \quad \forall i \in V_L$$

$$\sum_{j \in E} f_{ij} - \sum_{j \in E} f_{ji} = 0 \quad \forall i \in V_B$$

$$-M(1\text{-}z_{ij}) \le X_{ij} f_{ij} - \Delta\theta_{ij} \le M(1\text{-}z_{ij}) \quad \forall (i,j) \in E$$

$$-z_{ij} f_{ij}^{\max} \le f_{ij} \le z_{ij} f_{ij}^{\max} \quad \forall (i,j) \in E$$

$$-M(1\text{-}z_{ij}) \le \omega_i - \omega_j \le M(1\text{-}z_{ij}) \quad \forall (i,j) \in E$$

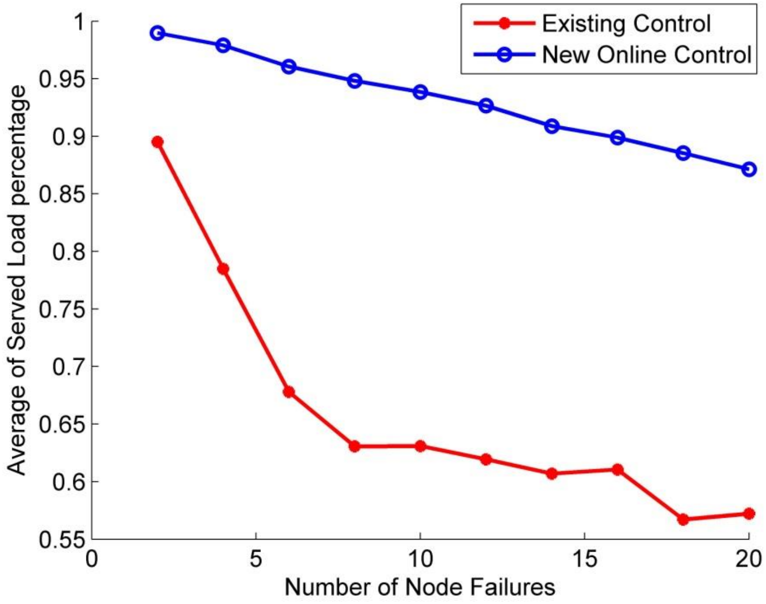
$$\omega_i^{\min} \le \omega_i \le \omega_i^{\max} \quad \forall i \in V_G$$

$$PG_i^{\min} \le PG_i - \alpha_i(\omega_i - \omega_s) \le PG_i^{\max} \quad \forall i \in V_G$$

$$PL_i^{\min} \le PL_i \le PL_i^{\max} \quad \forall i \in V_L$$

$$z_{ij} \in \{0,1\} \quad \forall (i,j) \in E$$

Compare the performance of Real-Time control with the conventional control



Risks of Communication Network

- Cyber Security
  - Bad Data
  - Denial of Service
    - Loss of Data
    - Congestion in communication network: Delay
- Physical Failure
  - Lines or routers
    - Loss of Data
    - Congestion in communication network: Delay

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- Cyber Security
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- Physical Failure
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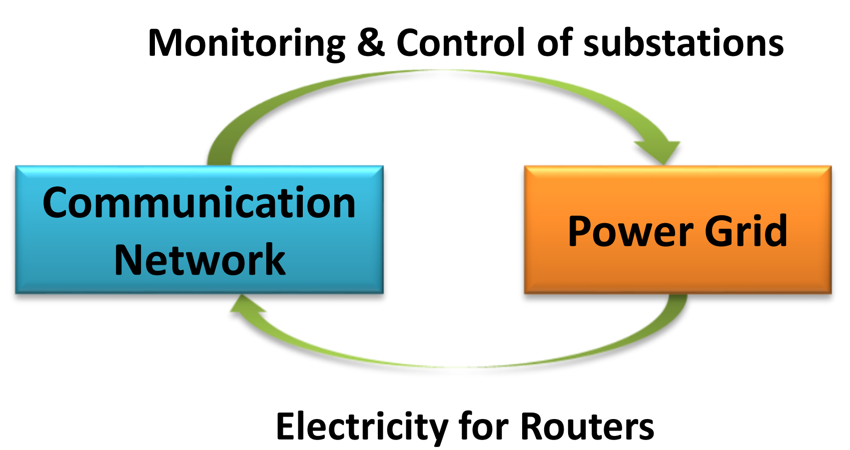
Impact of Data Loss

- No Significant Disturbance in the grid:
  - System continues to operate with the conventional control
- What if there is simultaneous failure in the grid?
  - Could lead to extra disturbance in the grid
- **Chances of simultaneous failures in** Power & Communication:
  - local geographical failure
  - Attack
  - Interdependency



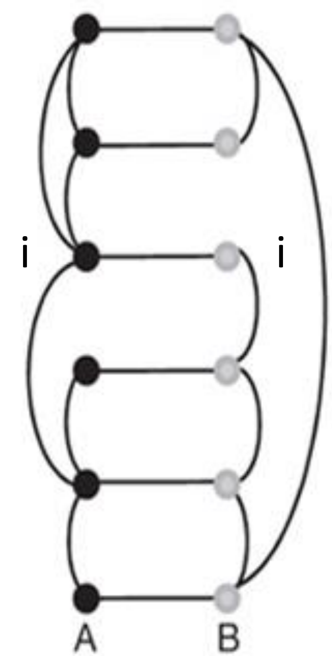
Part II: Interdependency between Power Grid and Communication Networks

Abstract Interdependency Model

by Buldyrev *et. al.*, 2010

- Two Random Networks A and B with N nodes
- One-to-One interdependency

Node i in network A operates if
(1) it is connected to the giant component in network A
(2) it is connected to node i in network B



Cascading Failures in Interdependent Networks

Node i in network A operates if
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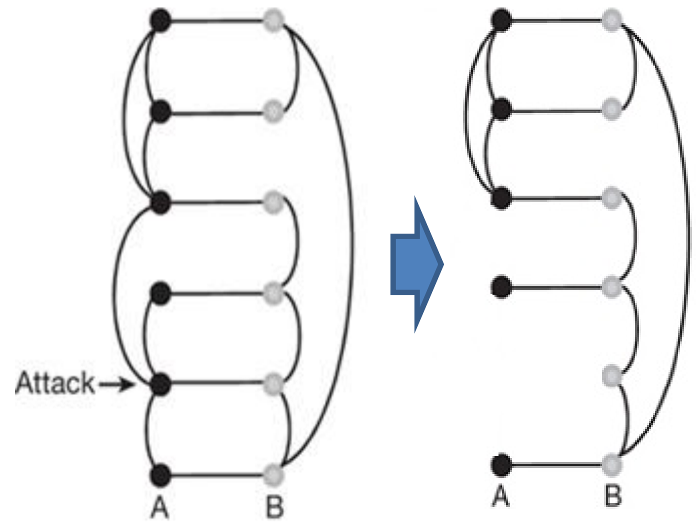
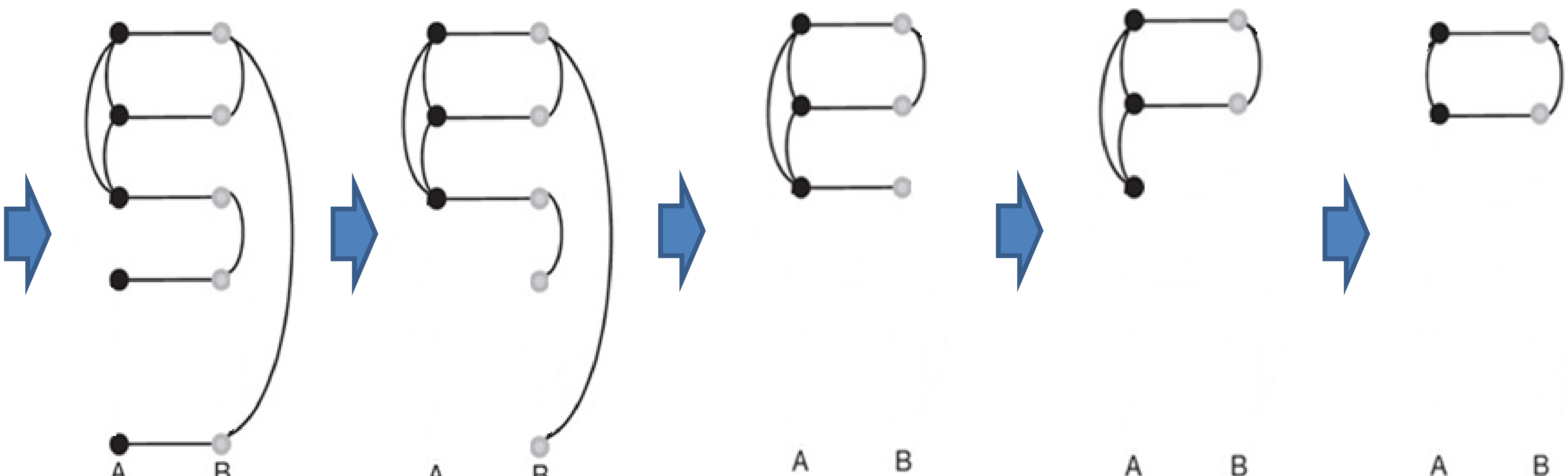
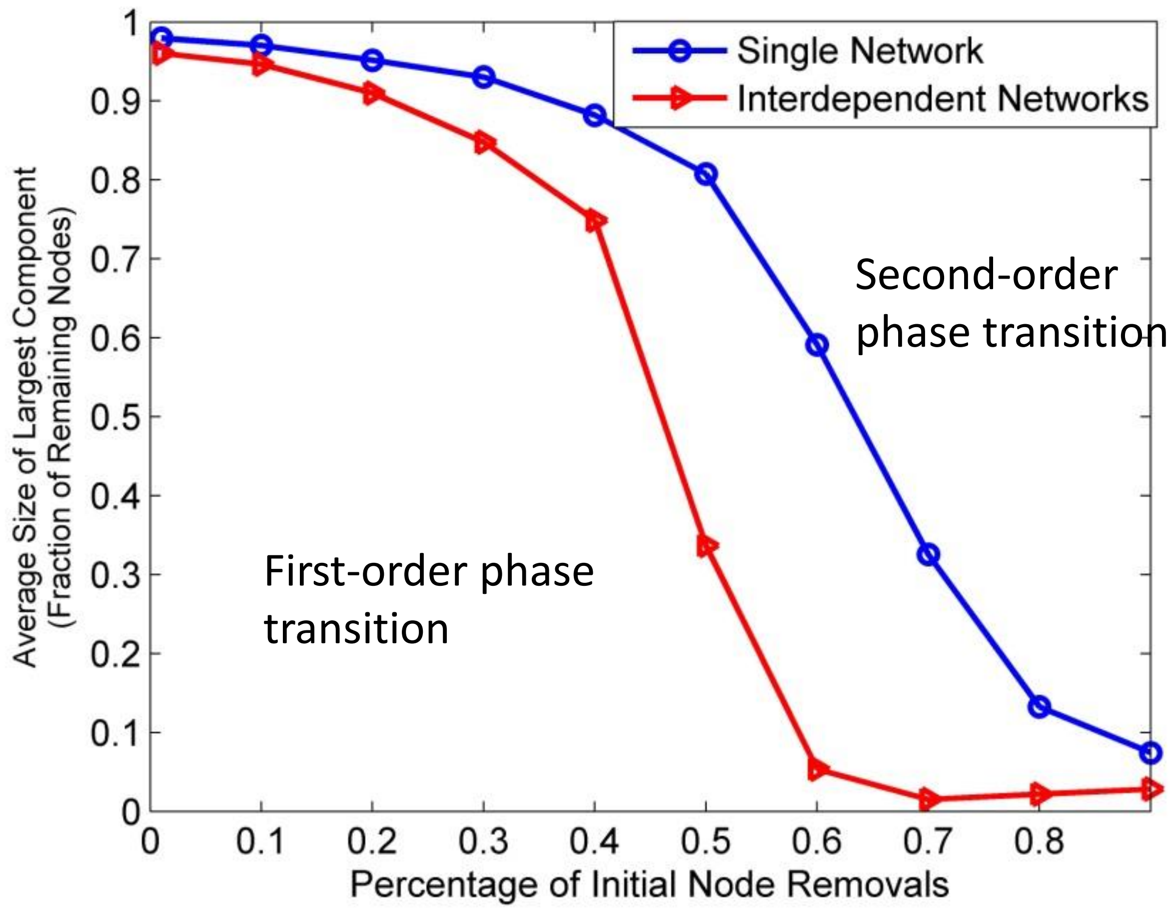




Interdependent vs. single Networks

Erdos-Renyi Graph with 500 nodes and expected degree of 4



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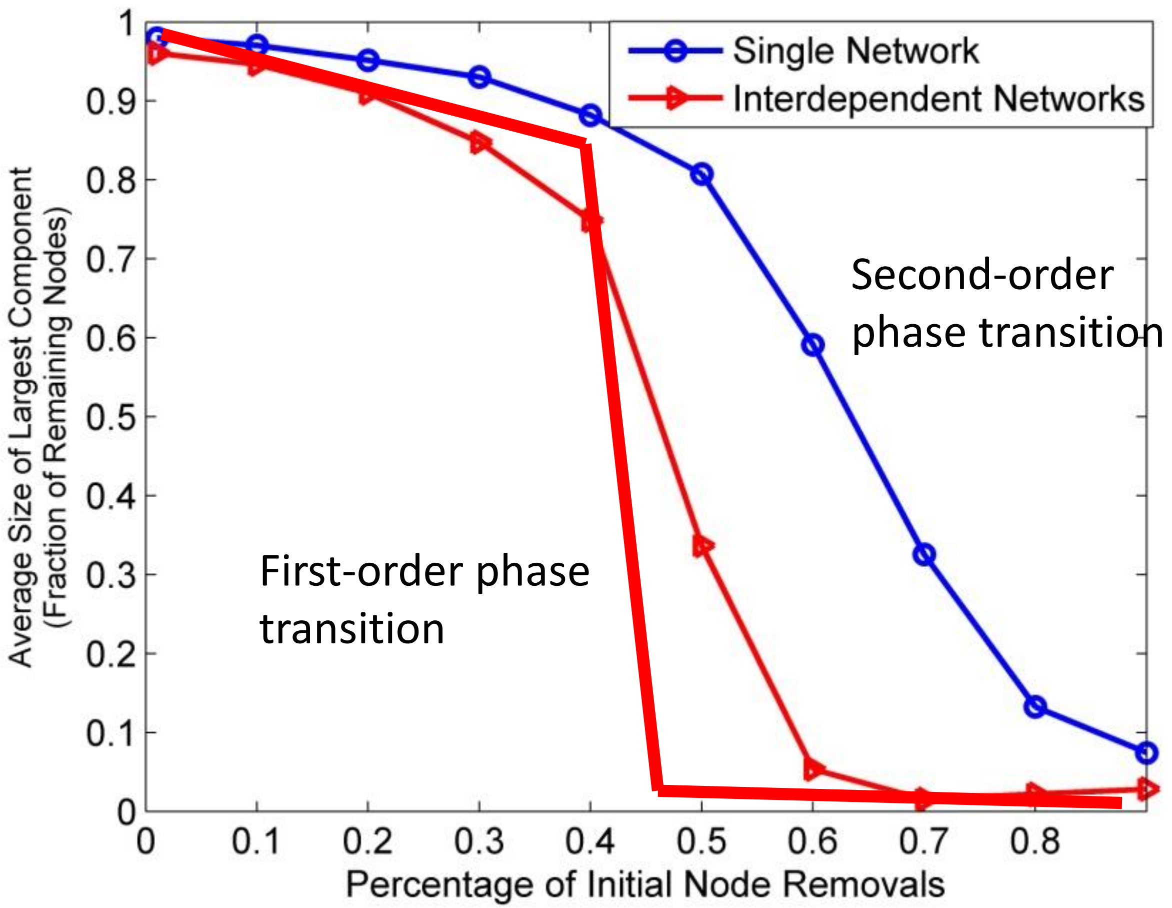
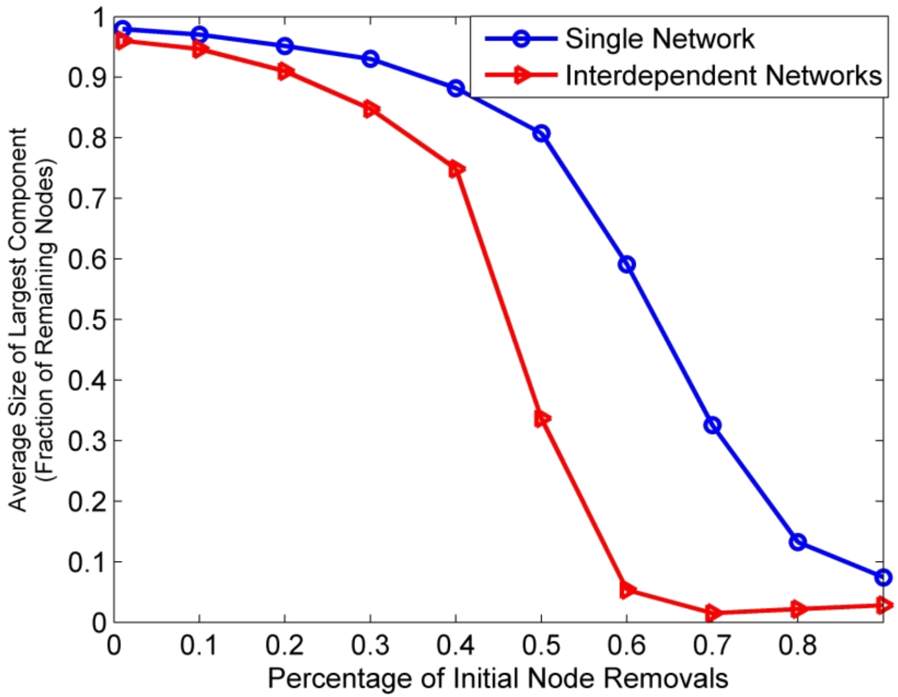
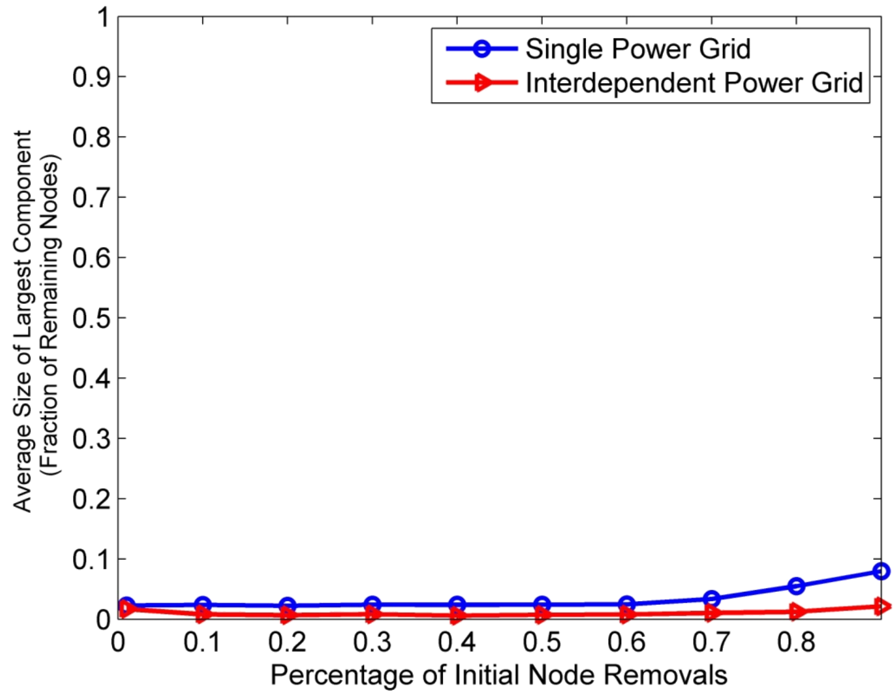


Compare Interdependency in Abstract Model and Power Grid



Erdos-Renyi Graph with 500 nodes and expected degree of 4

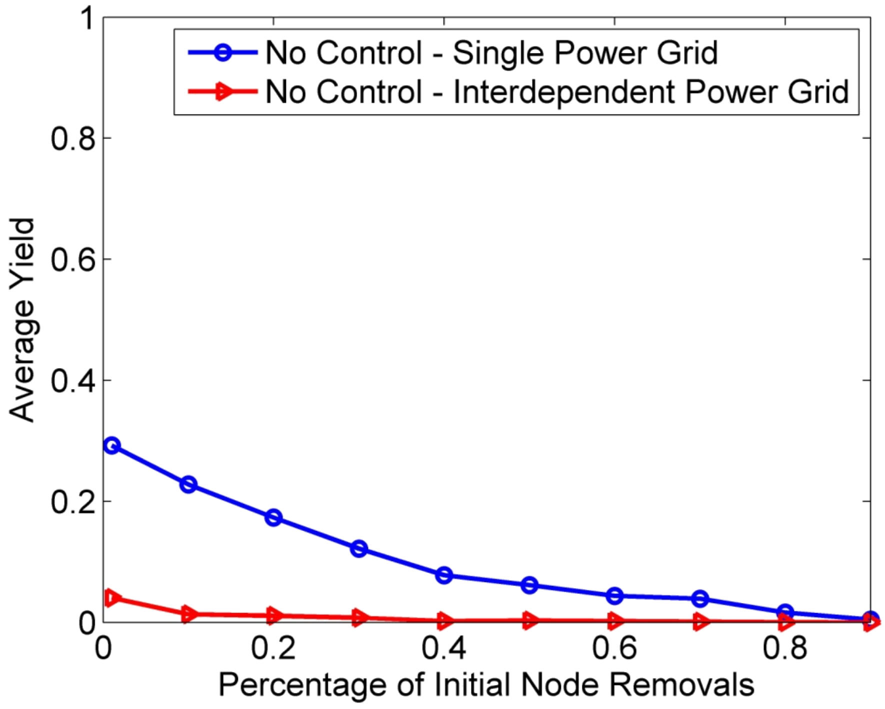


Random Power Grid - Erdos-Renyi with 500 Nodes and average degree of 4; 1/5th of the nodes are generators and 1/5th are loads with random value in range [1000,2000]; unit reactance

Power Grids are More Vulnerable to Failures due to Cascading Failures

Interdependent Power Grid

Metric in Power Grid: Fraction of Served Load; i.e. Yield



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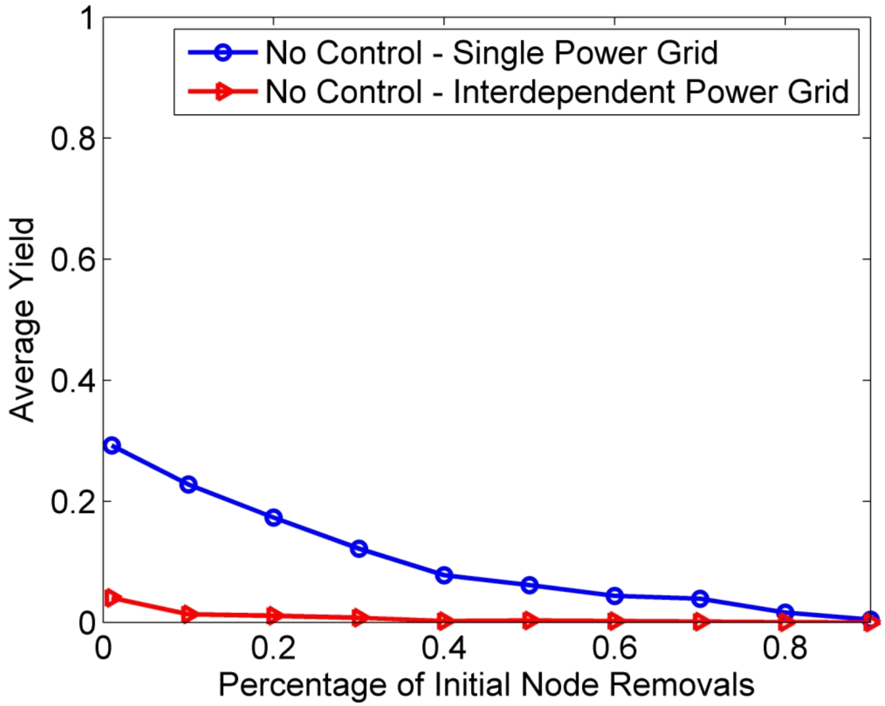
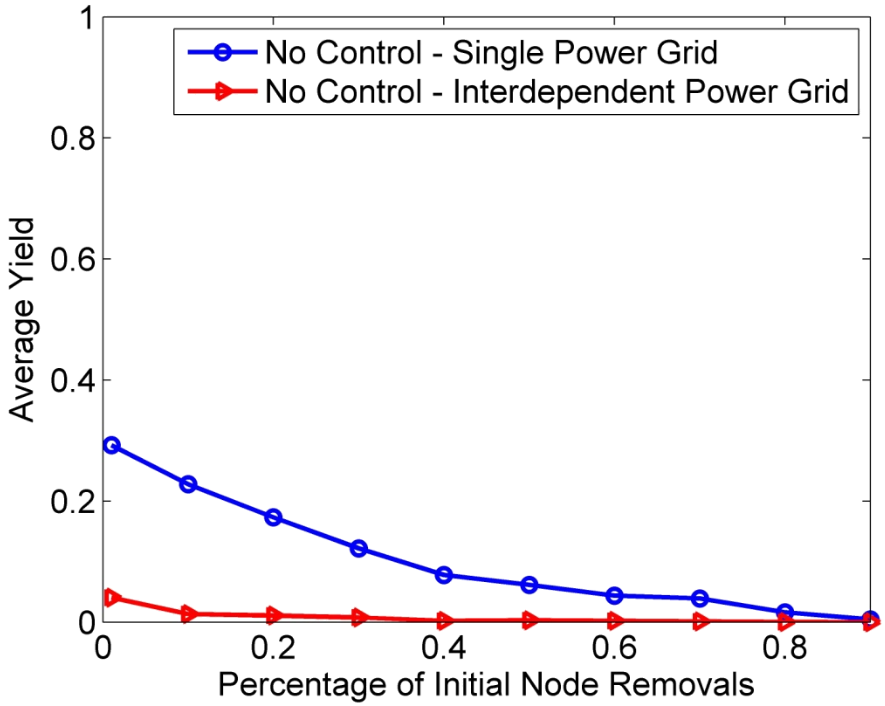


The purpose of designing a communication network intertwined with the power grid is to **provide real-time monitoring and control for the grid**.

Interdependent Power Grid

Metric in Power Grid: Fraction of Served Load; i.e. Yield



The purpose of designing a communication network intertwined with the power grid is to **provide real-time monitoring and control for the grid**.

a proper analysis of interdependent networks should account for the availability of **control schemes that can mitigate cascading failures**.

Load Control Policy

Objective: A control policy that sheds load "intelligently" to avoid the failure of critical communication nodes

<u>Load Control Policy</u>

- Phase 1) Find the Set of all unavoidable failures (i.e., disconnected nodes)
- Phase 2) Re-dispatch the generators and loads so that
  - All remaining communication nodes can operate (receive enough power)
  - Minimum amount of load is shed; i.e. Maximize Yield

Load Control Mitigation Policy

- Phase 1) Find the Set of all unavoidable failures
- Phase 2) Re-dispatch the generators and loads

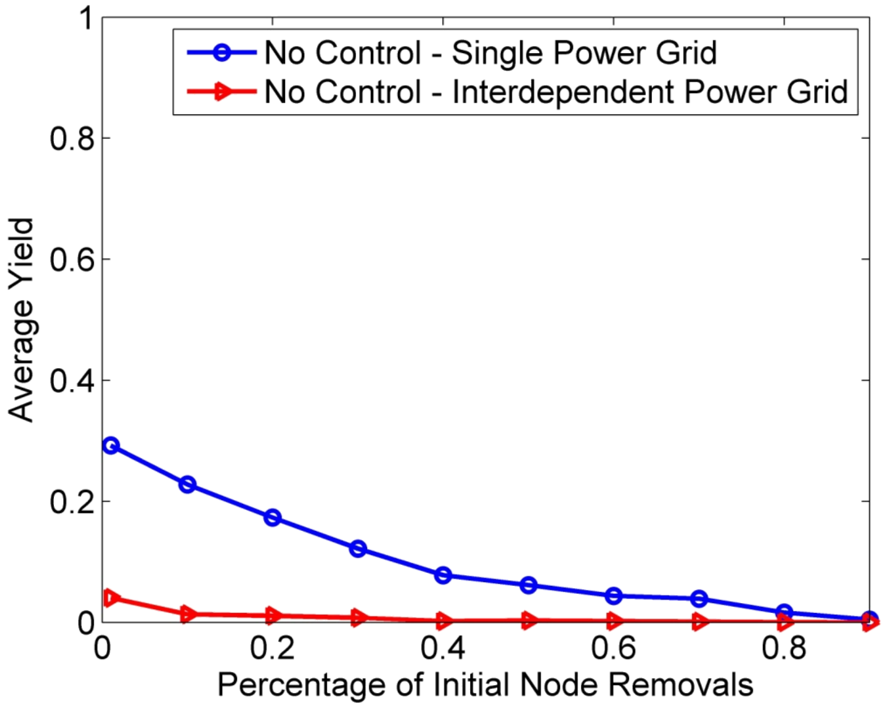
$$
\begin{aligned}
\text{minimize} \quad & e^T(|P^{new} - P^{old}|) \\
\text{subject to} \quad & A^{updated} f = P^{new} \\
& (A^{updated})^T \theta = X f \\
& f \le f^{max}, \quad \forall (i,j) \in E_P^{updated} \\
& 0 \le P_i^{new} \le P_i^{old} \quad \forall i \in V_{P,gen}^{updated} \\
& P_i^{old} \le P_i^{new} \le 0 \quad \forall i \in V_{P,load}^{updated} \\
& P_{C_j} \le -P_C^{req} \quad \forall j \in V_C^{updated} \\
& \sum E_{CP}^{updated} h = b \\
& h \ge 0
\end{aligned}
$$

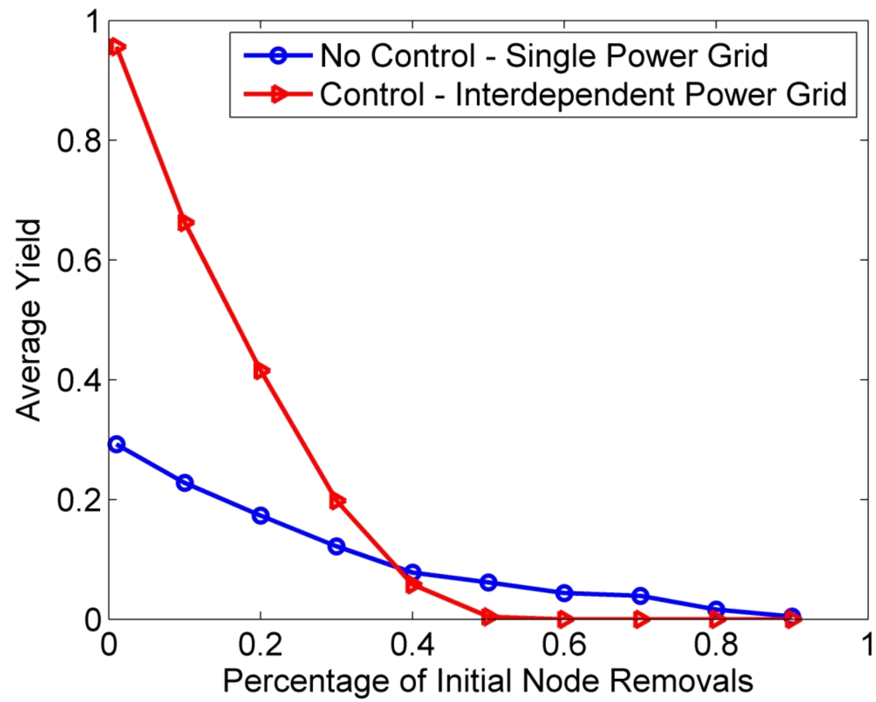
Minimum Load Shedding

Communication Nodes receive enough Power

Connecting communication and power grid

Interdependent Power Grid without & with Control

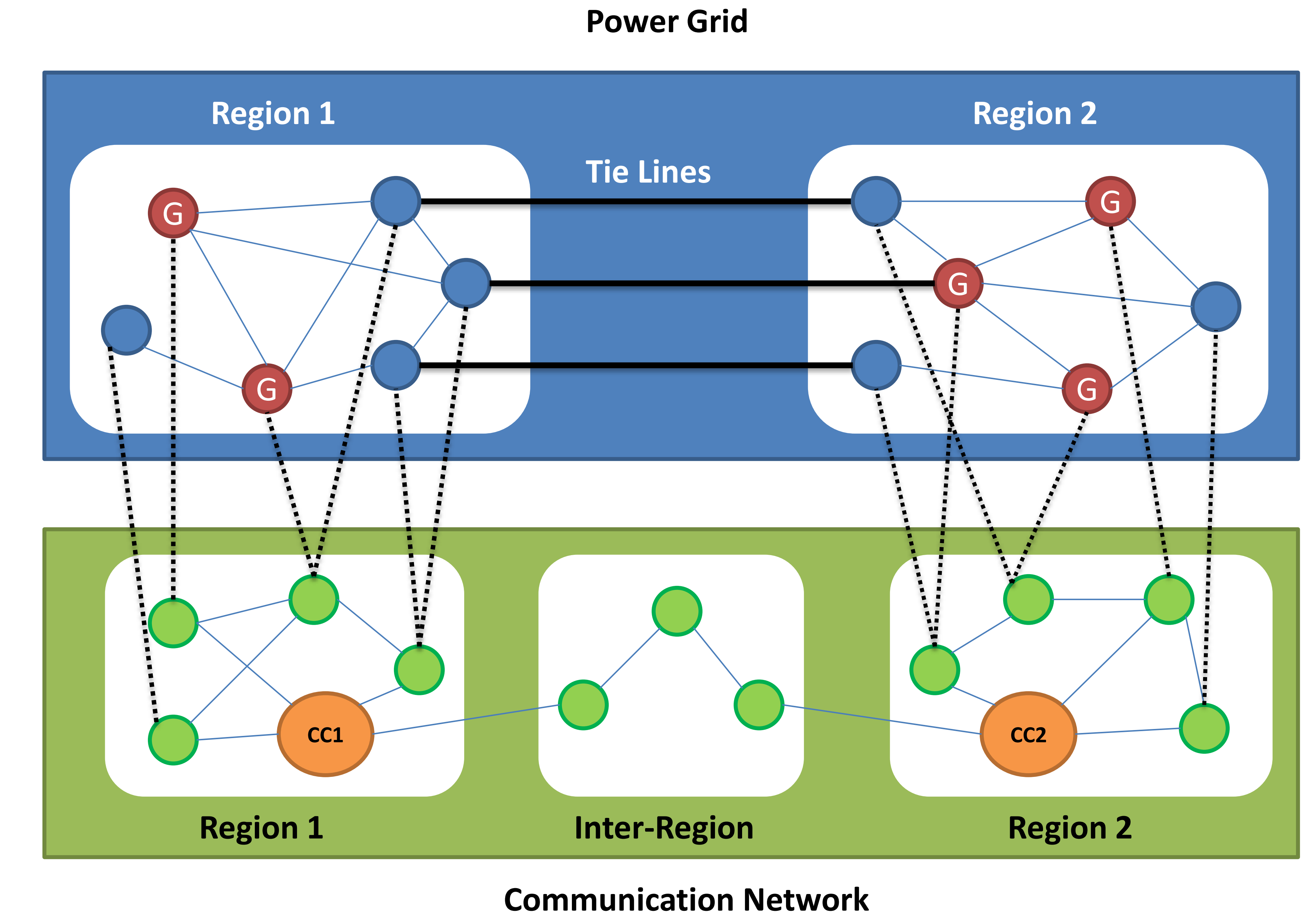




By applying mitigation control policy, Interdependency makes the Power Grid more Robust

Too simplistic Assumption: If a power node loses control, it will definitely fail

Part III: Modeling the Impact of Communication Loss on Power Grid during a Large Disturbance


Power Grid
Region 1
Region 2
Tie Lines
G
G
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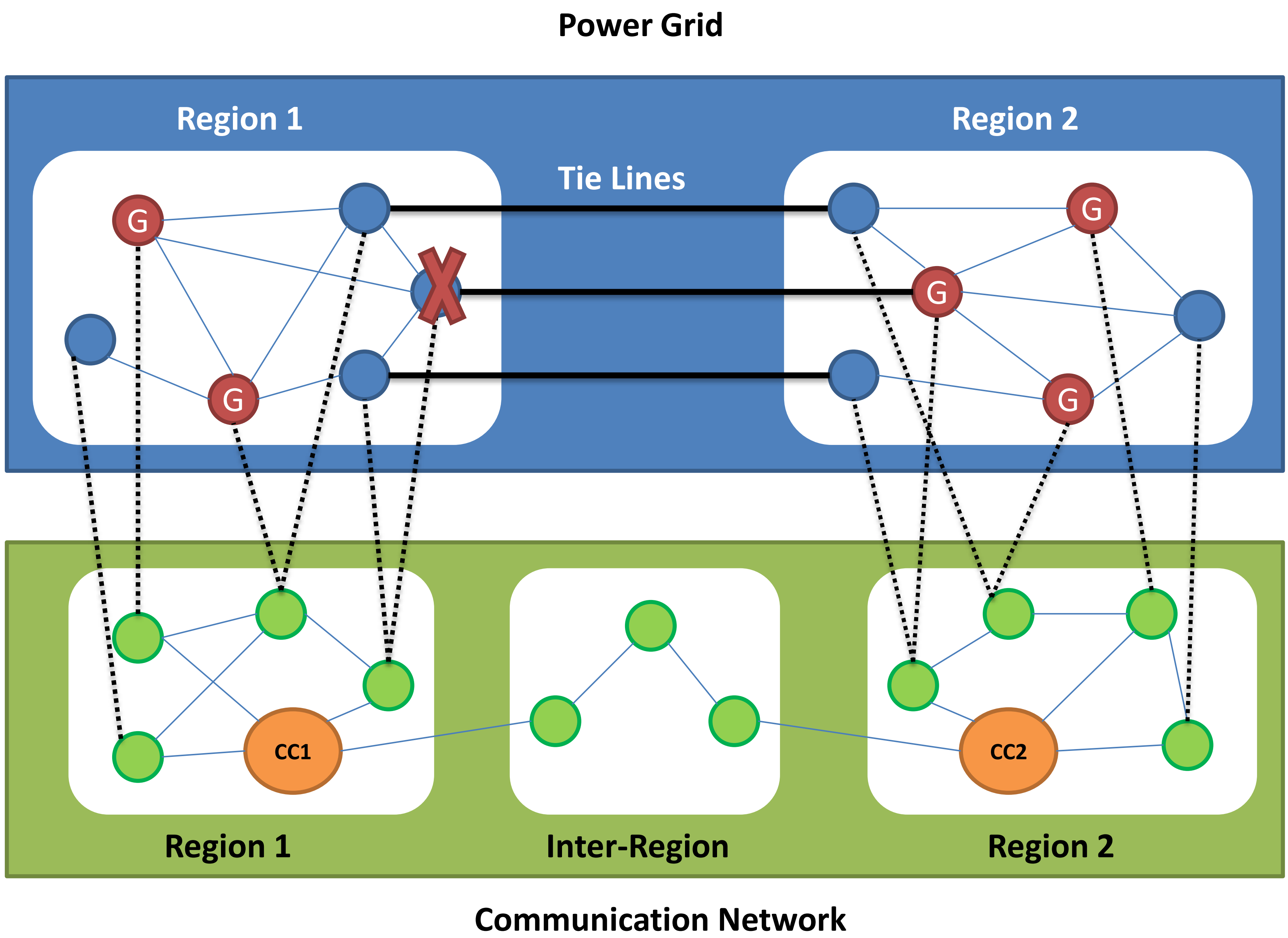
CC1
CC2
Region 1
Inter-Region
Region 2
Communication Network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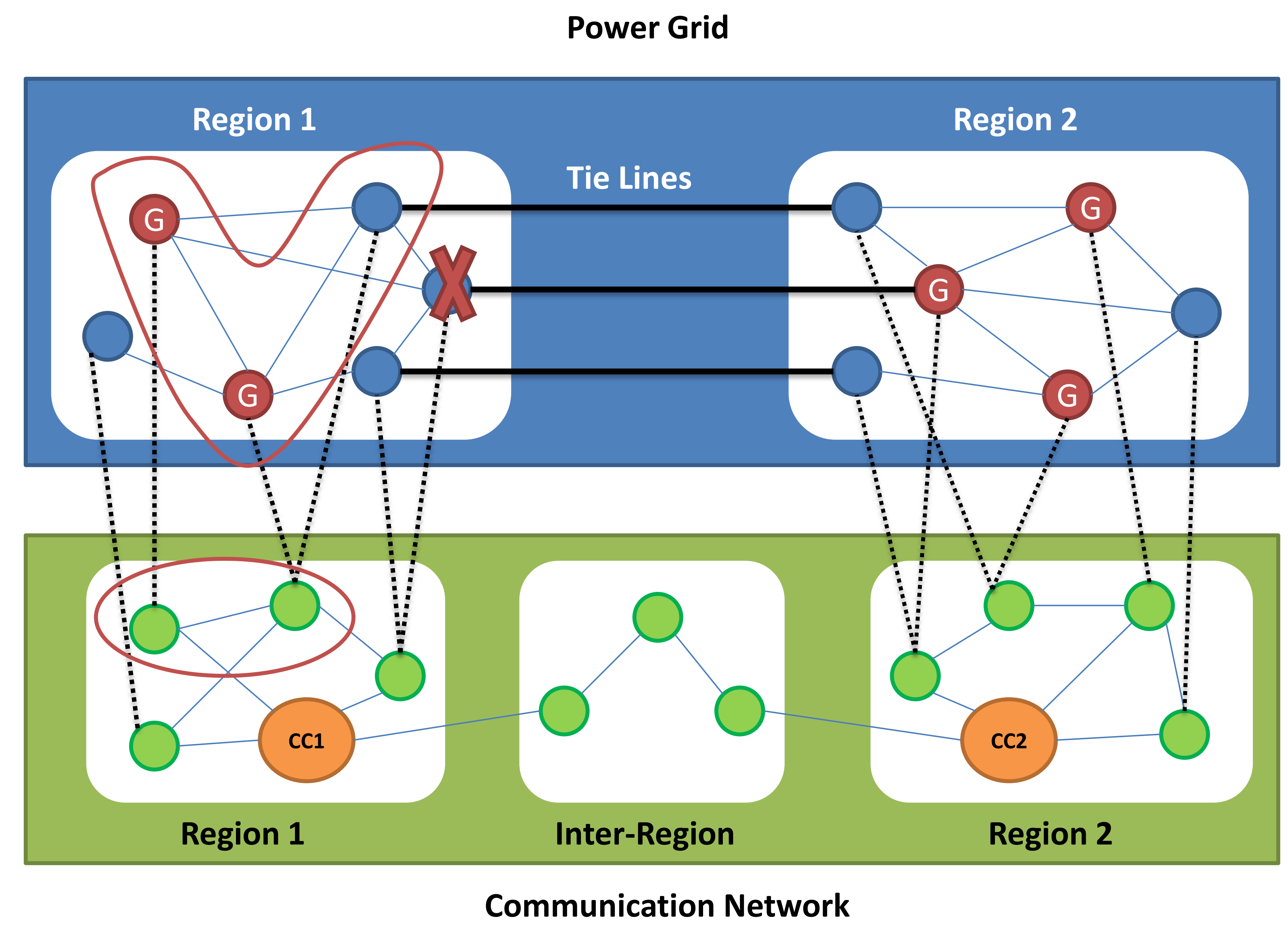
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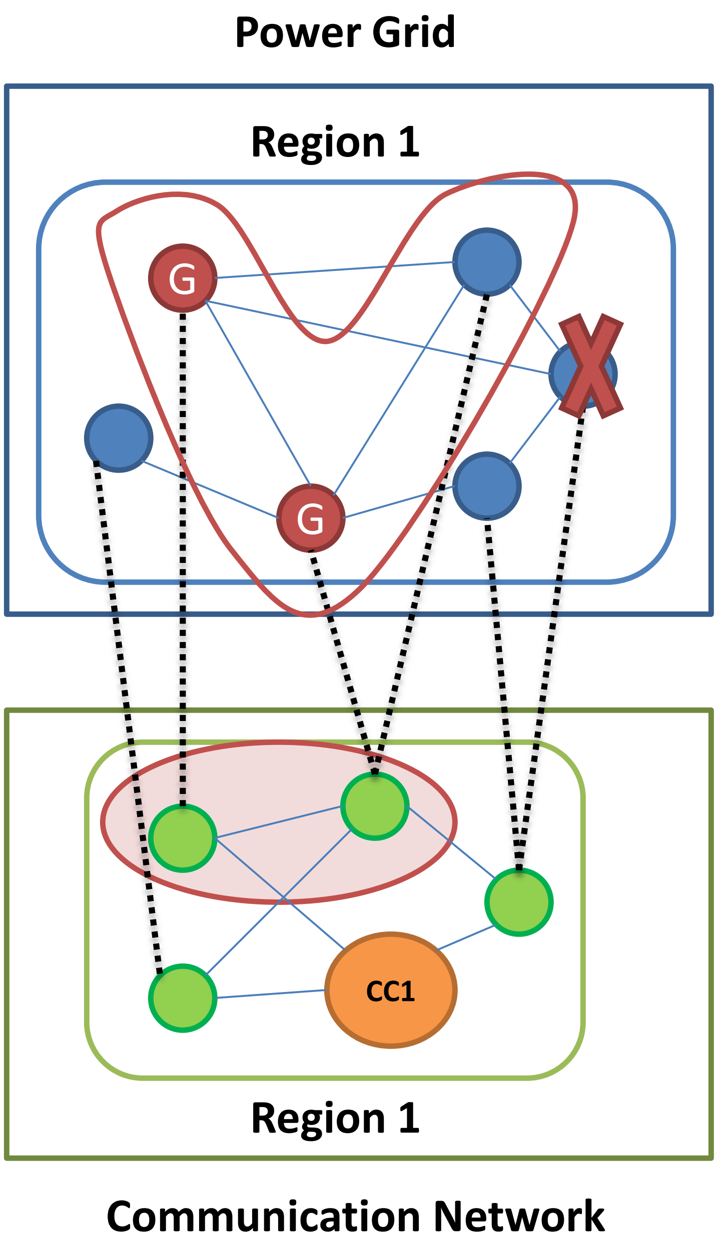

Inside Region

Two Scenarios:

1) Set of Uncontrollable nodes (G1) and set of Power Failures (G2) are disjoint
   - **Complete Information** about the last state of Grid
   - **Partial Control**

2) Set of Uncontrollable nodes (G1) and set of Power Failures (G2) overlap
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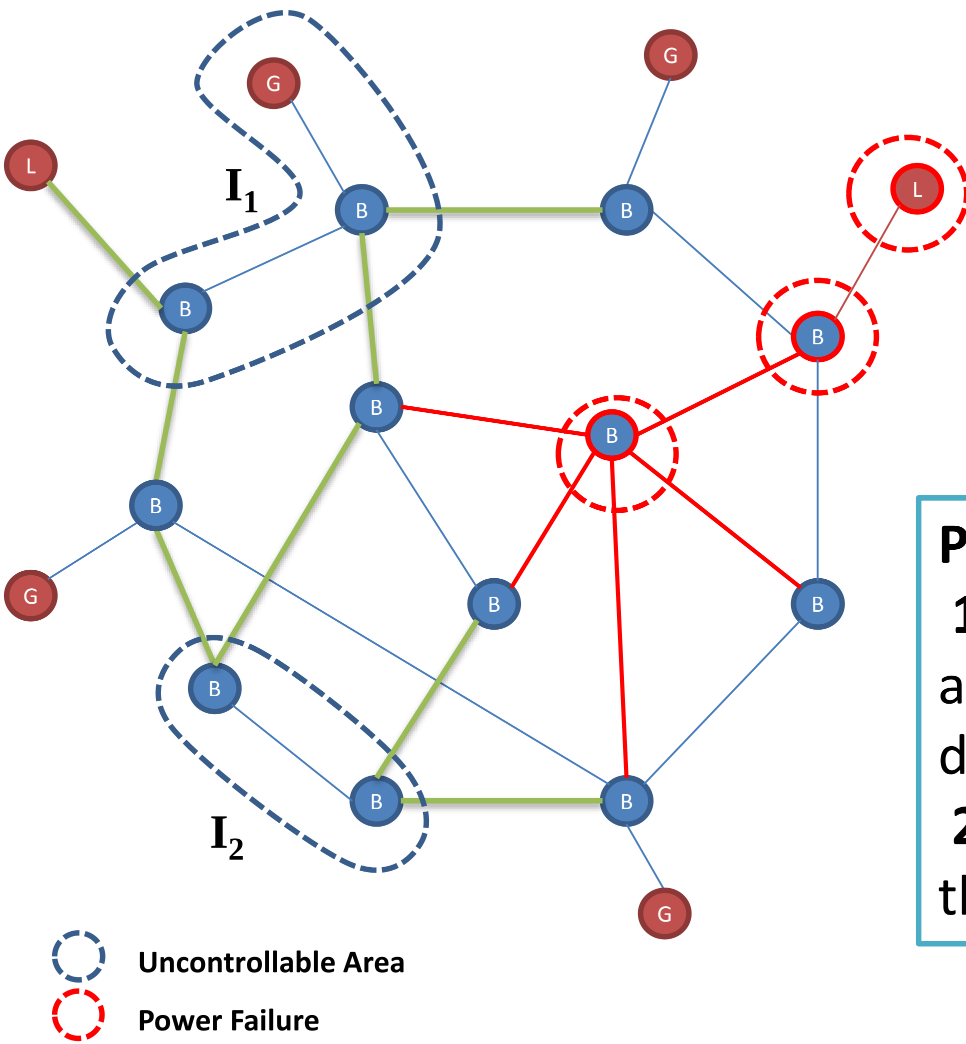
Comm Loss Inside Region – Scenario 1



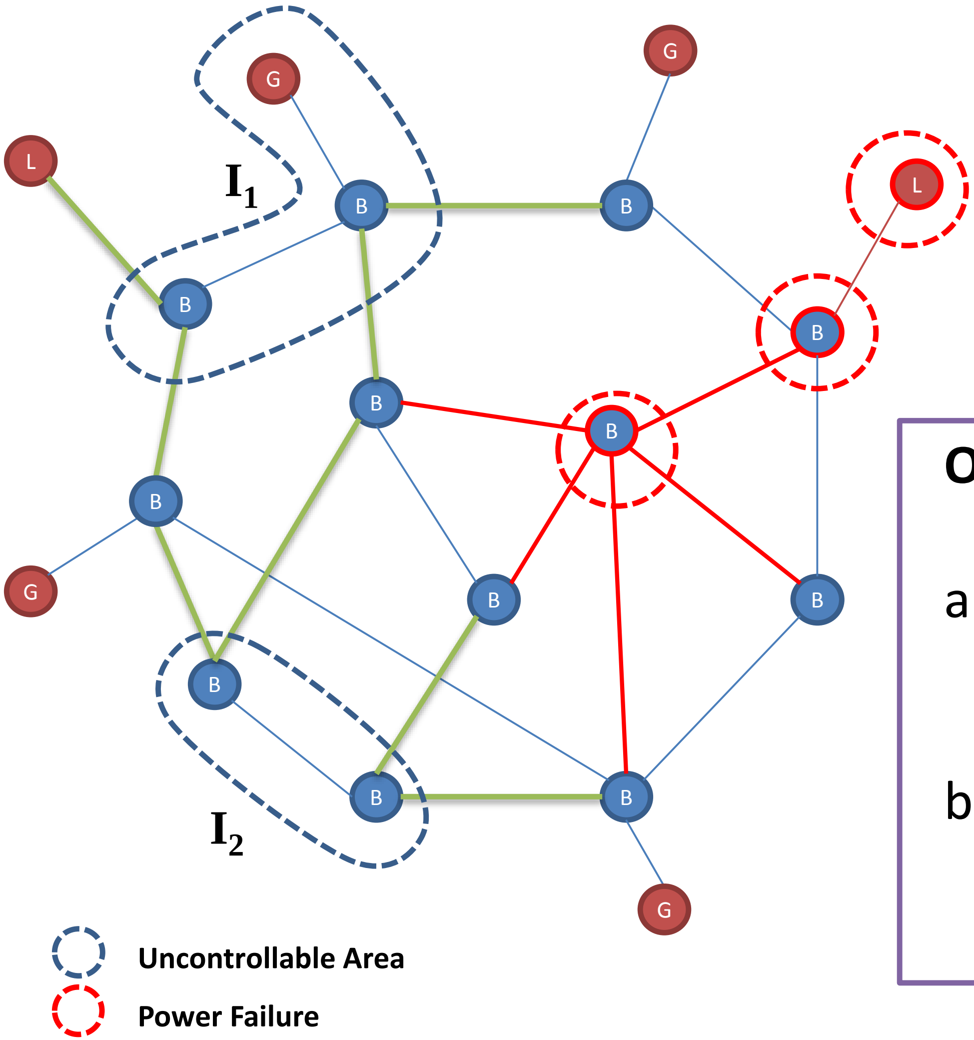
Assumption: All the Generators and Loads in the Uncontrollable Area switch to a <u>predefined strategy</u>

Pre-defined Strategy:

1) P_{init}: Keep the generators and loads at their last state right before disconnection

2) P_{zero}: Trip the generators and shed the loads

Comm Loss Inside Region – Scenario 1



Controllable Areas: Full control

Uncontrollable areas:

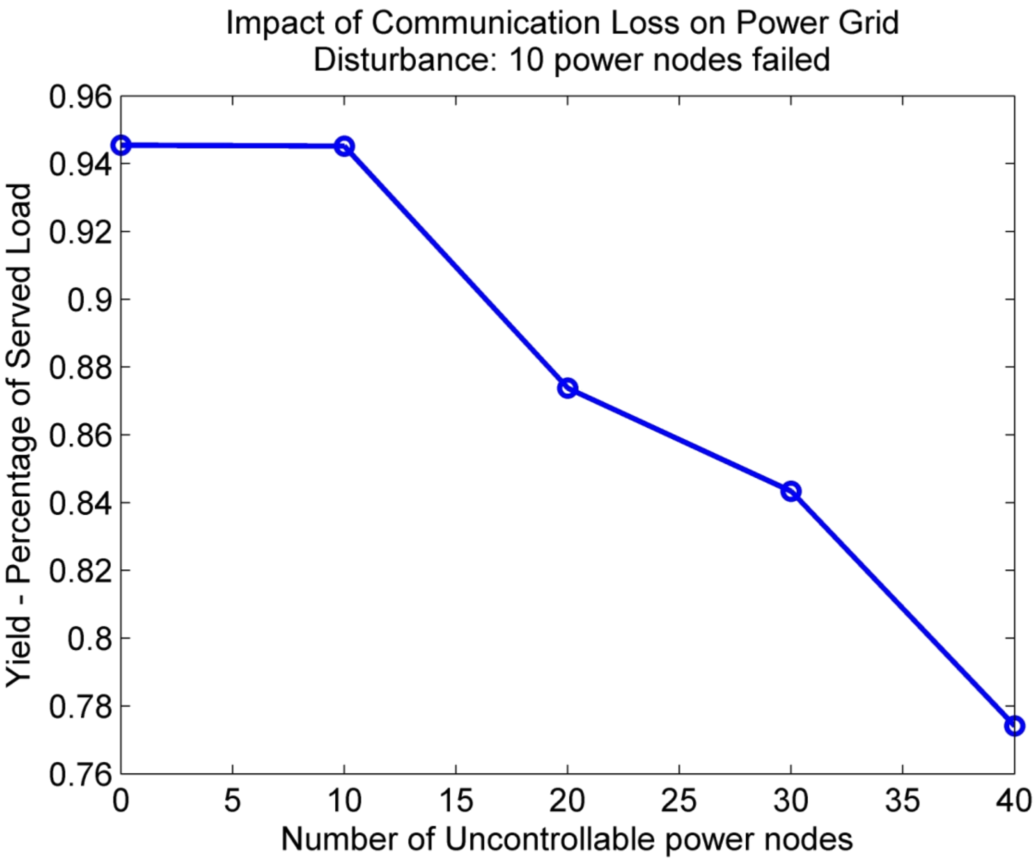
- Allow Trip border lines
- Decentralized Controls

Objective: Stabilize Grid

a) Minimize Load Shedding while keeping the uncontrollable area

b) If keeping an uncontrollable area connected to the rest of grid is not optimal: Trip all border lines

Communication loss results in smaller yield



6% load shedding due to pow dist
17% load shedding due to comm loss

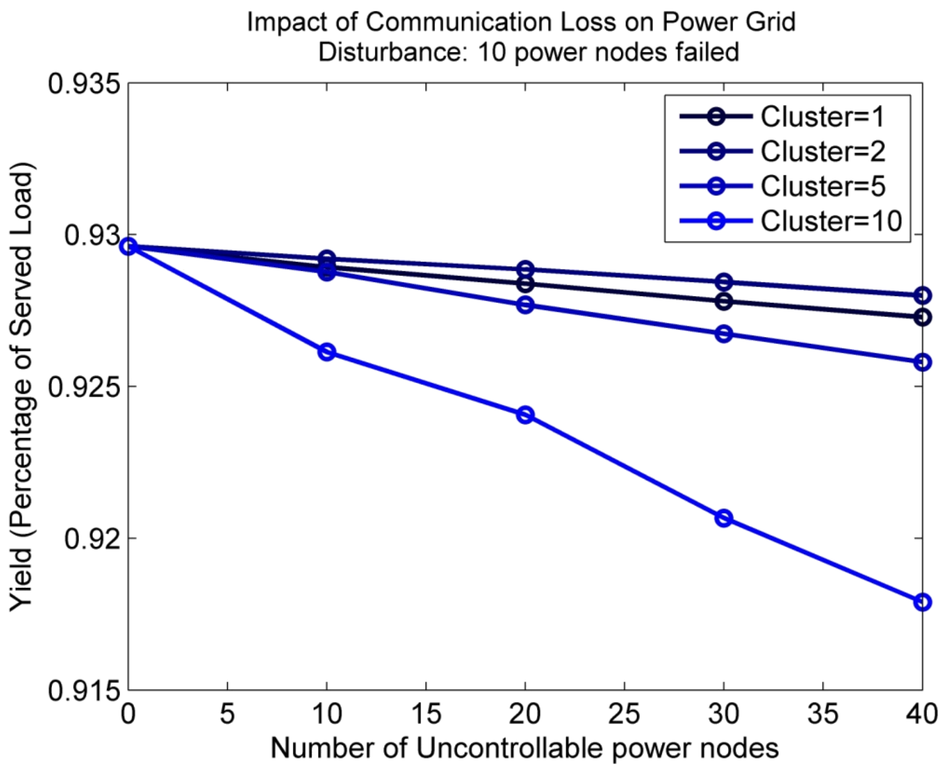
Average power consumption of a house: 30KWh per day

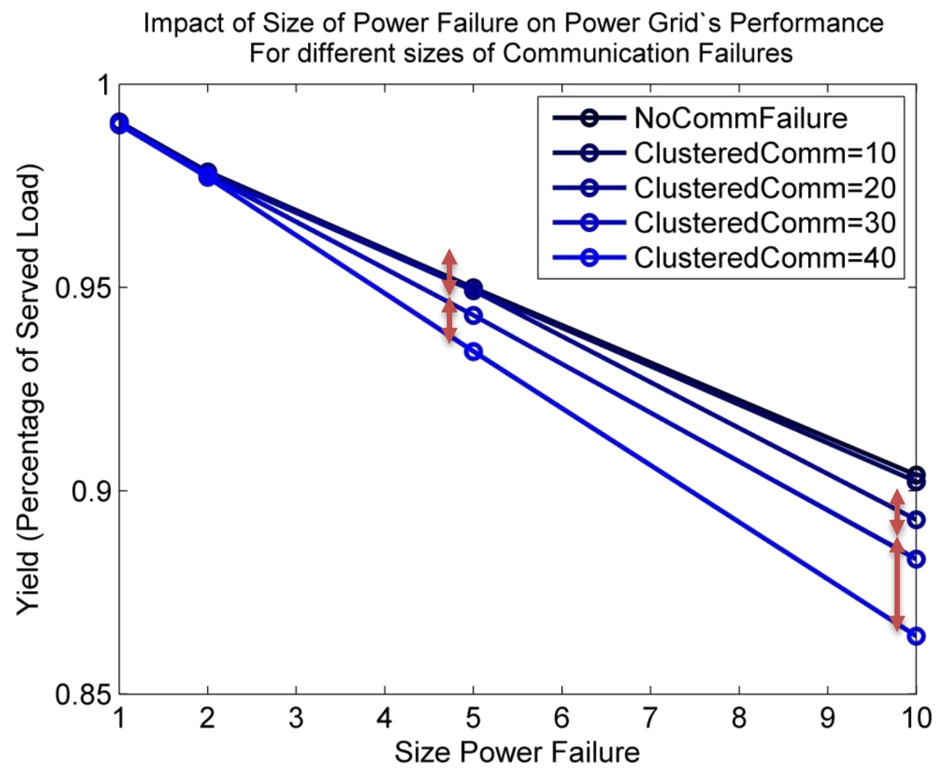
Power Loss due to comm:
0.17*24000MW≈4100 MW
≈ 140,000 houses

Source: http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3

Impact is a function of many parameters:

1) number of uncontrollable nodes (size of communication loss)
2) size of uncontrollable clusters (connectivity of uncontrollable area)
3) Size of Power Failure

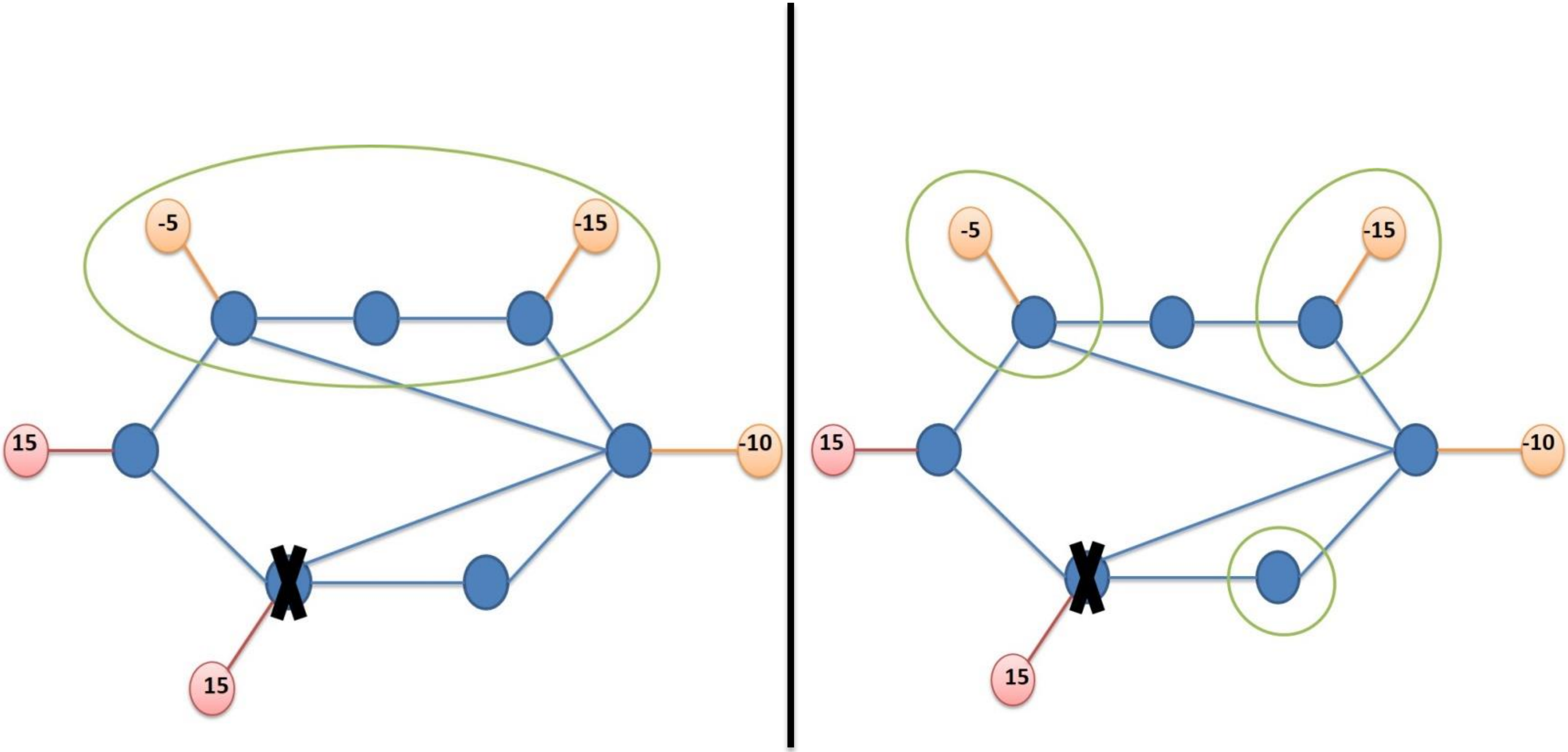




Nodes outside the uncontrollable area could be affected

Pinit Strategy is not always optimal

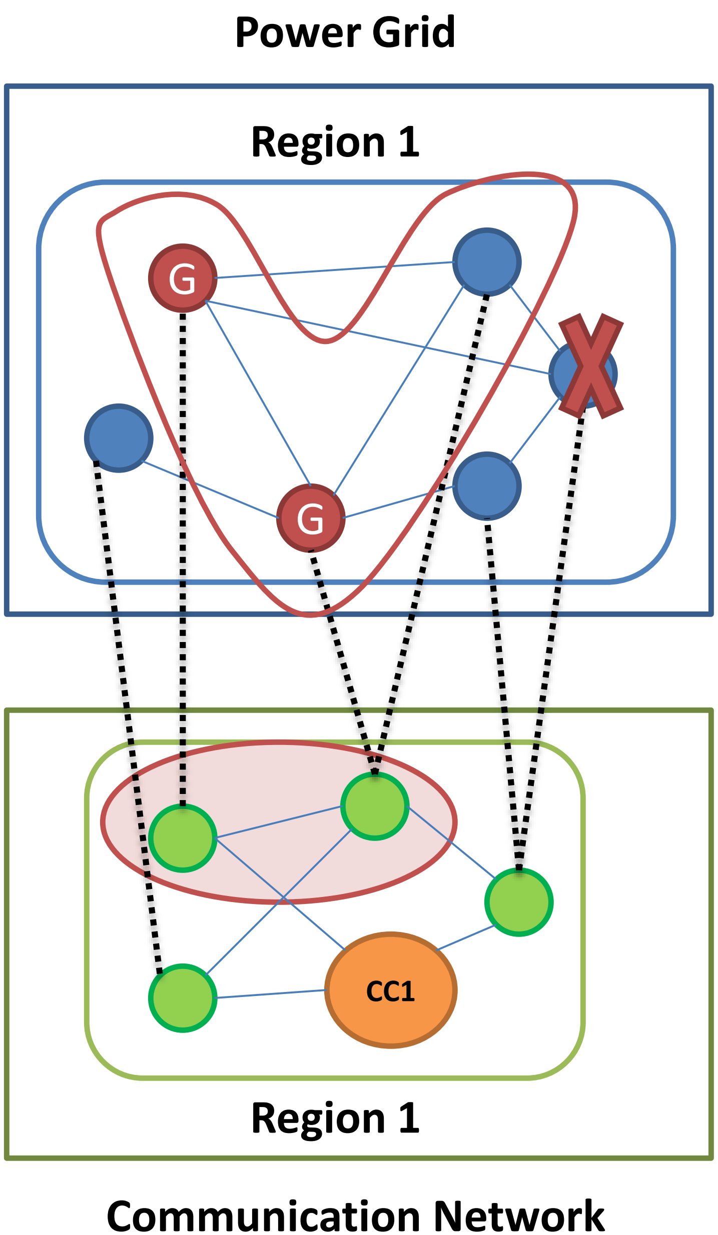
Example:



Open Questions – Future Work

1) What is the Optimal Pre-defined Strategy?

2) For a given communication network and power grid, what is the optimal allocation of communication nodes to power nodes to minimize the negative impact of communication loss?



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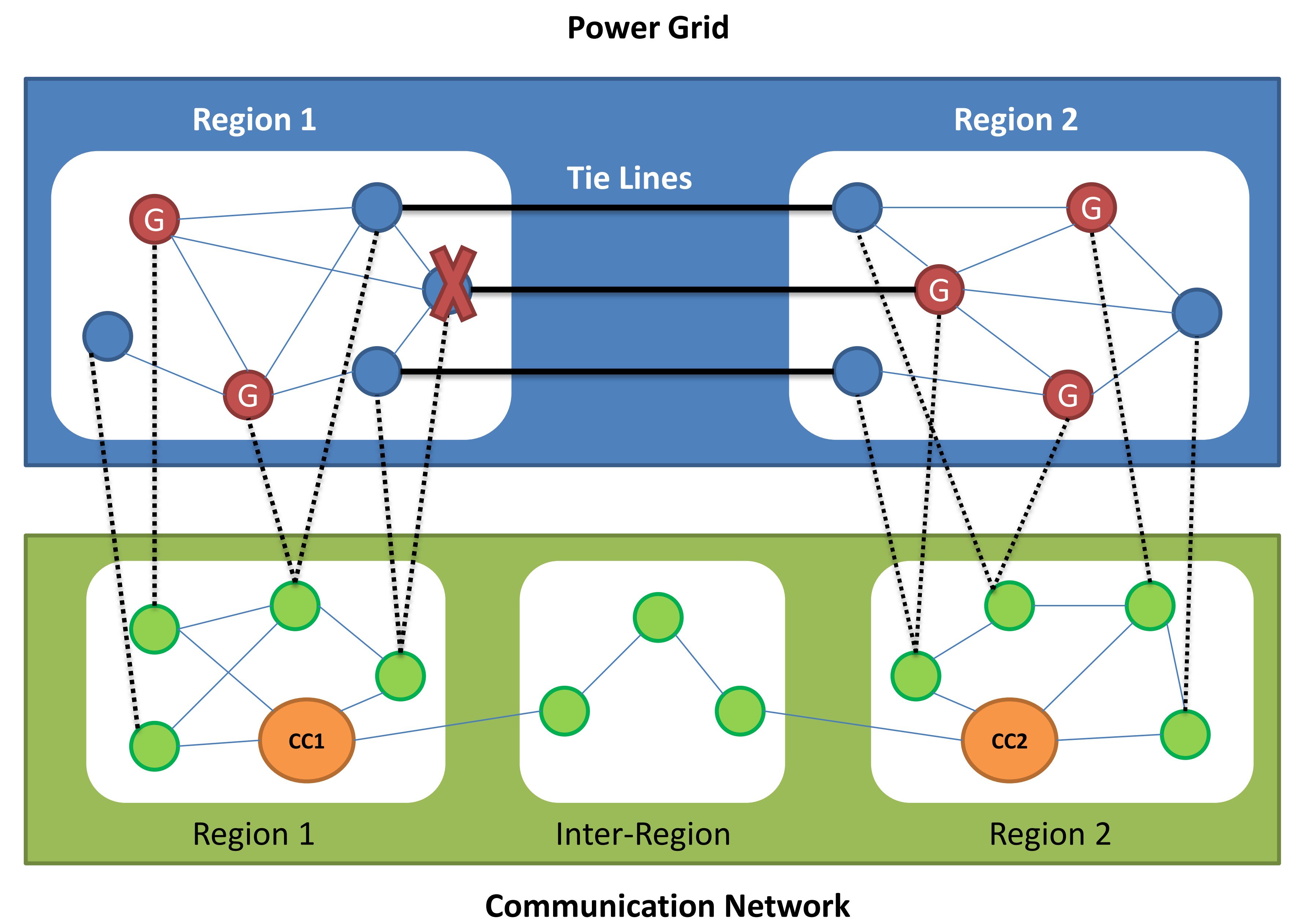
Open Questions

- **Definition–** An area is called K-Observable area if failure of K elements inside the area can be identified using the information from nodes outside of the area.

- What are the topological properties of a K-observable area?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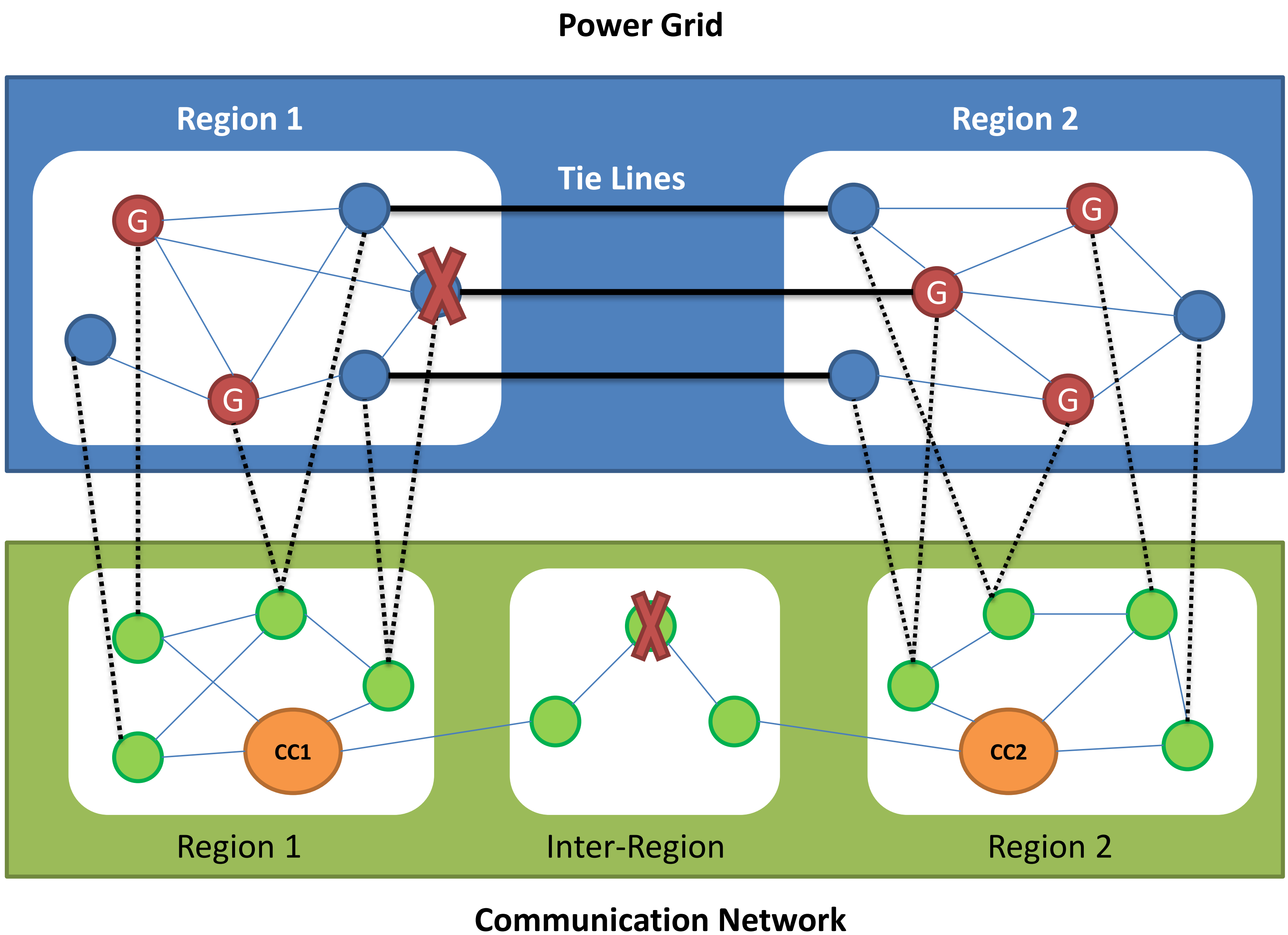
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Part IV: Using Real-Time Control for Normal Operation of Power Grid

Reducing the cost of Generators reserves as well as transmission lines margins

Generator Dispatch for Normal Operation

Unit Commitment	Which generators are ON
Economy Dispatch	Minimize Cost of Generation to Satisfy the load and line capacities
N-1 Secure Operation	Decide on Generators reserved power to ramp up rapidly in the case of a single failure

Joint Economy Dispatch & N-1 Security Analysis

Dispatch generators such that in the case of a single failure the grid remains stable:

Primary Frequency Control

1) Frequency does not violates the limits
2) No Transmission Line is overloaded

Secondary Frequency Control

1) AGC changes generator set-points: generators have enough reserve to respond
2) No Transmission Line is overloaded

AGC versus Real-time adjustment

- **AGC:**
  - Changes the set points proportional to the second derivative of cost of generation $C_1(i)$;
    i.e. $\Delta P(i) = \frac{c1(i)}{\sum_i c1(i)} \Delta P(\text{tot})$

$\text{Cost}(i,P) = C_1(i)P^2 + C_2(i)P + C_3(i)$

- **Real-time Control:**
  - Depending on the failure scenario changes the set points of generators

Source: Power Generation, Operation and Control, wood & Wollenberg, sec 3.8

Benefits & Risks

- Reduces the cost of generation reserve and deployment as well as the security margins for transmission lines

- Loss of communication leads to the loss of control over some generators
  – AGC exists: constant coefficient for set point change
  – AGC doesn't exists: generators set point is fixed

Summary

1) Designed a real-time control that minimizes the load shedding while balancing the power and keeping power within the line capacities

2) Interdependency between Power Grid and Communication Networks increases the risk of using real-time control

3) Proposed a framework for modeling the impact of Communication Loss on Power Grid: Analysis and Design of dependency

4) Decrease the reserve costs using Real-Time Control for Normal Operation