Modeling Impact of Communication Network Failures on Power Grid Reliability

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Cascading Failure in Power Grid

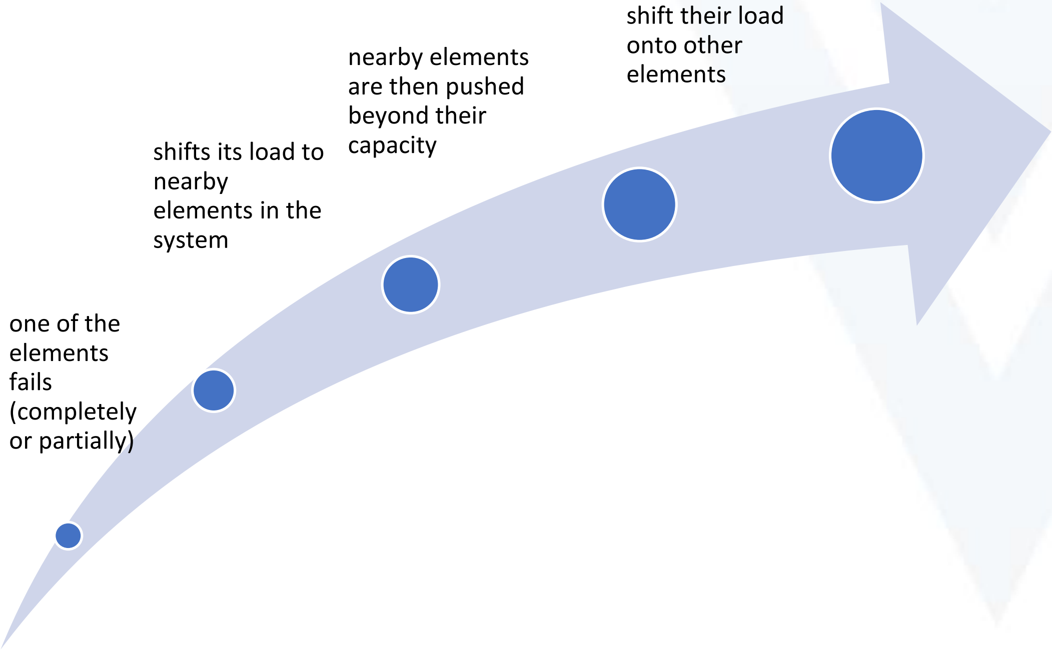
one of the elements fails (completely or partially)

shifts its load to nearby elements in the system

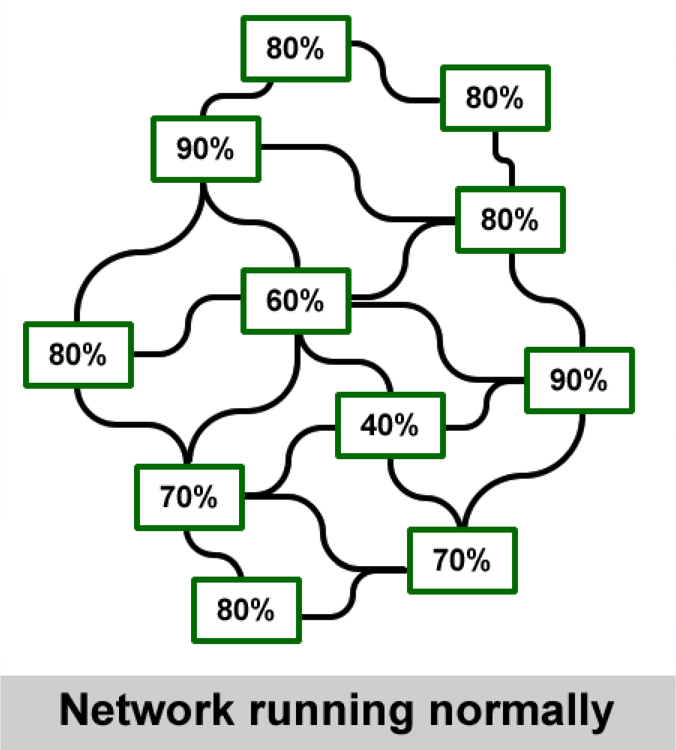
nearby elements are then pushed beyond their capacity

become overloaded and shift their load onto other elements

Cascading chain of event starts and can lead to system blackout



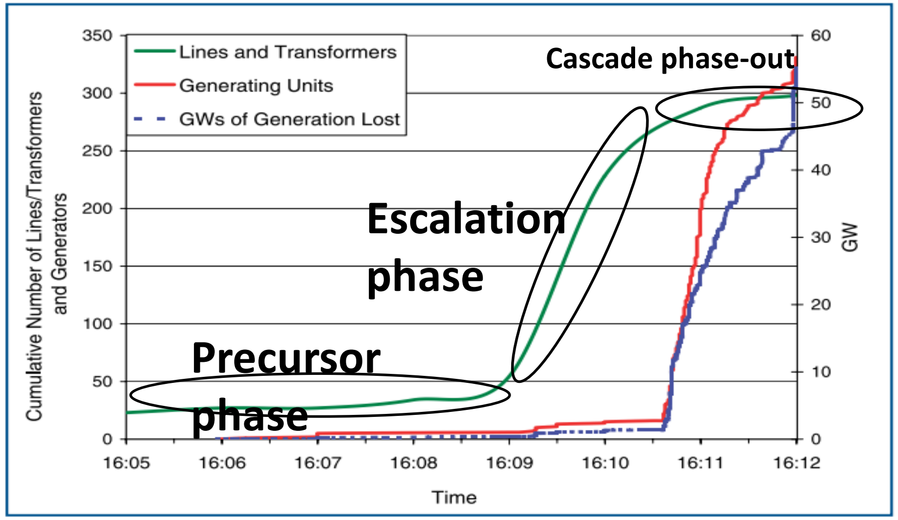
balancing generation and load is critical



Source : Wikipedia

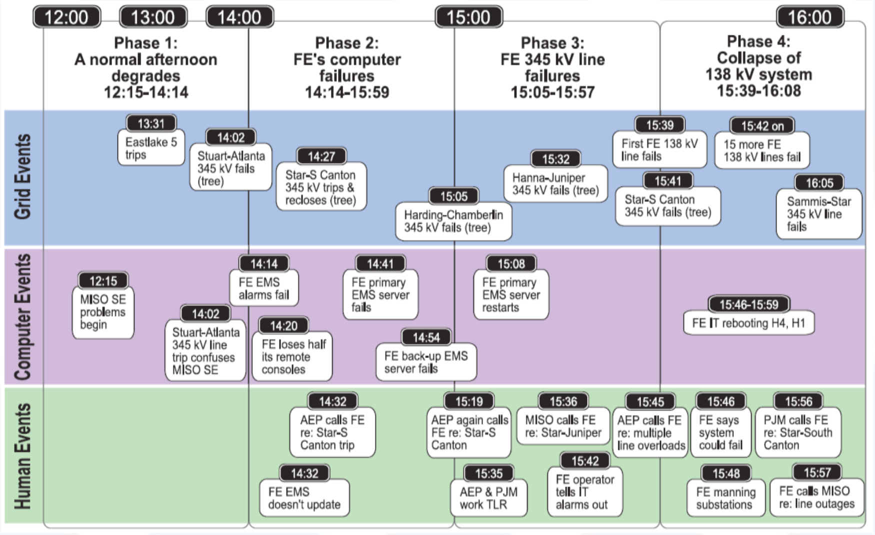
Why do cascading failures and blackouts occur?

- Large blackouts result from the cascade of component failures in the transmission grid triggered by **initial disturbances:**
  - Natural disasters and human-related events such as unintentional human faults, sabotage occurrences and WMD attack.
  - Cascading failure exhibit three phases where during escalation phase high number of transmission lines fails in a small time window



Time evolution of 2003 blackout in US and Canada exhibit three phases. [Online]. [3]

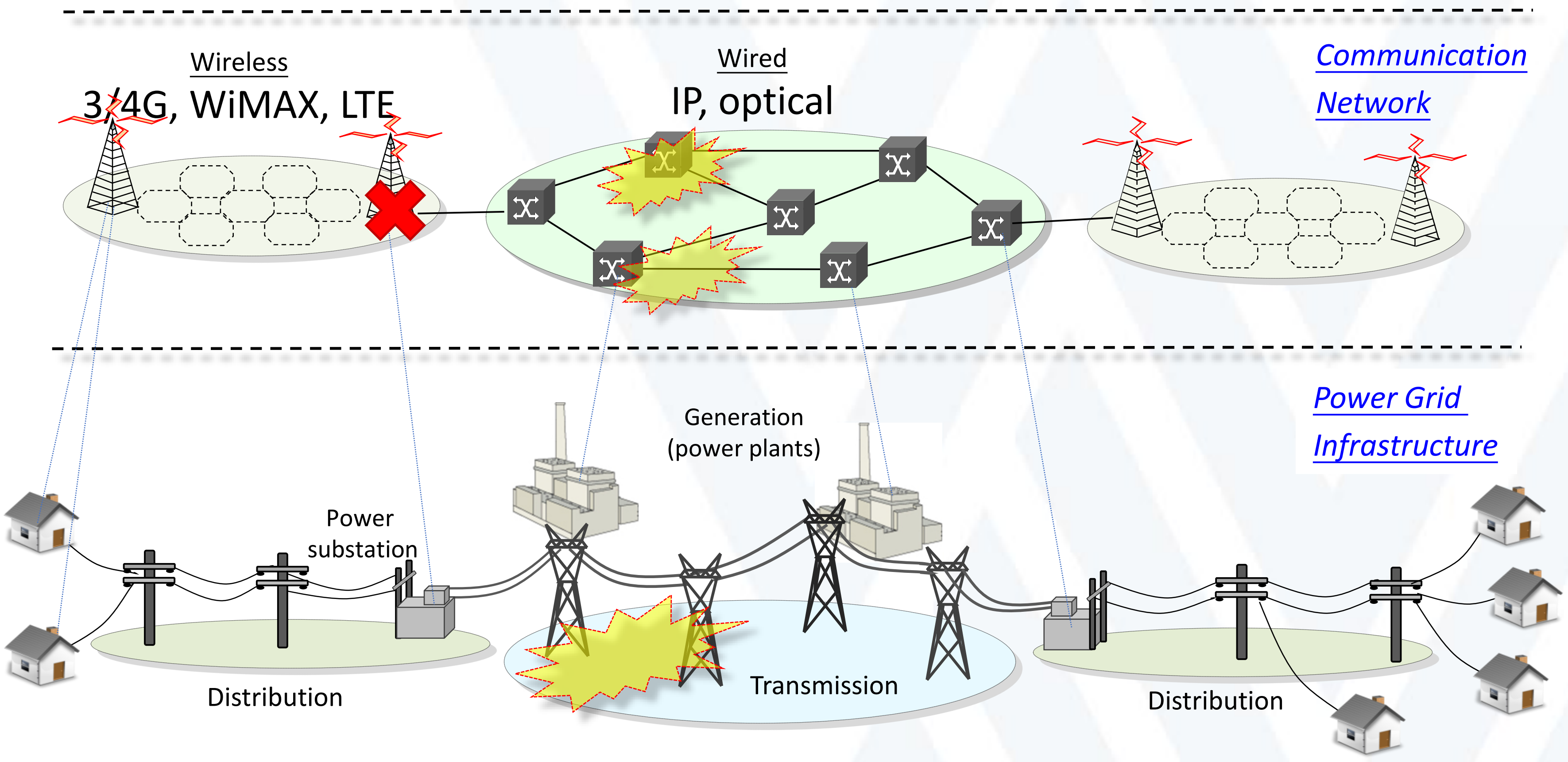
- **Example: 2003 Northeast Blackout**:
  - Occurred due to a combination of transmission-line failure and communication network failure
  - Alarm software failed leaving the human operators unaware of the transmission-line outage which contributed the cascading failure [1]



- **Example: 2003 Italy Blackout**:
  - During Power blackout at Italy, an unplanned power shutdown eventually led failures in the communication network, which in turn initiated a series of cascading failures in the power grid [2].

2003 blackout: sequence of events [online] [3]

Modeling requires a multi-layer view of the electric infrastructure



Earlier work

We used the following two models to define interdependency between power grid and communication network:

- ***Stochastic abstract-state evolution (SASE)*** [5] model *:*

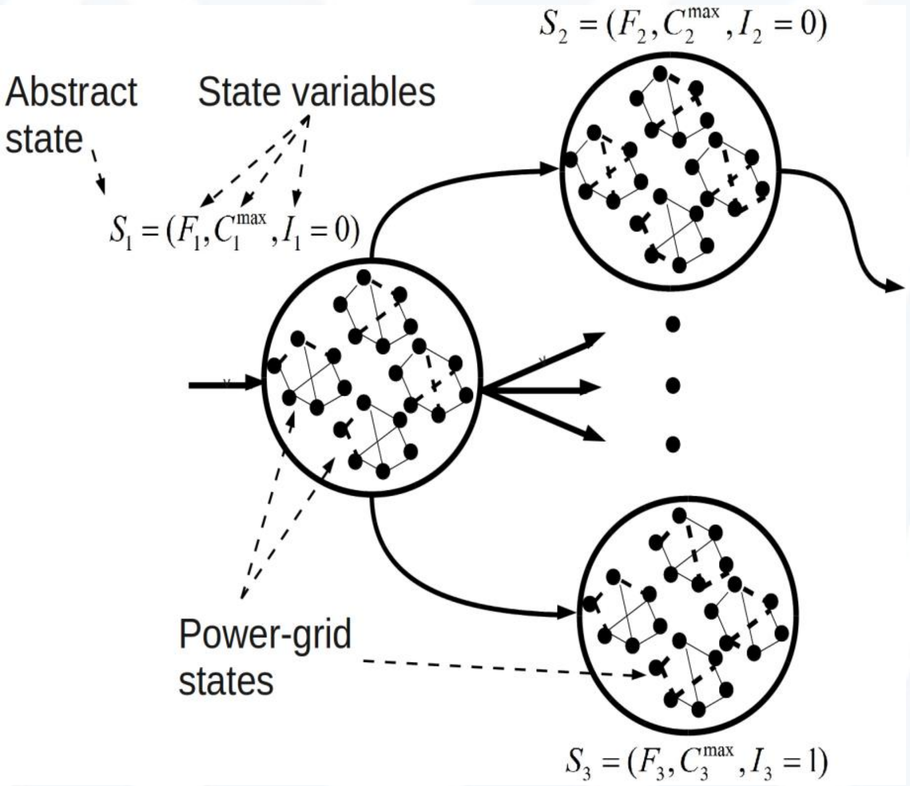
  - Describes the dynamics of cascading failures based upon Markov chains

- ***Interdependent Markov-chain (IDMC)*** [4] model**:**

  - A minimal MC that encompasses the individual MC for each physical system and their interdependencies

Review of SASE model

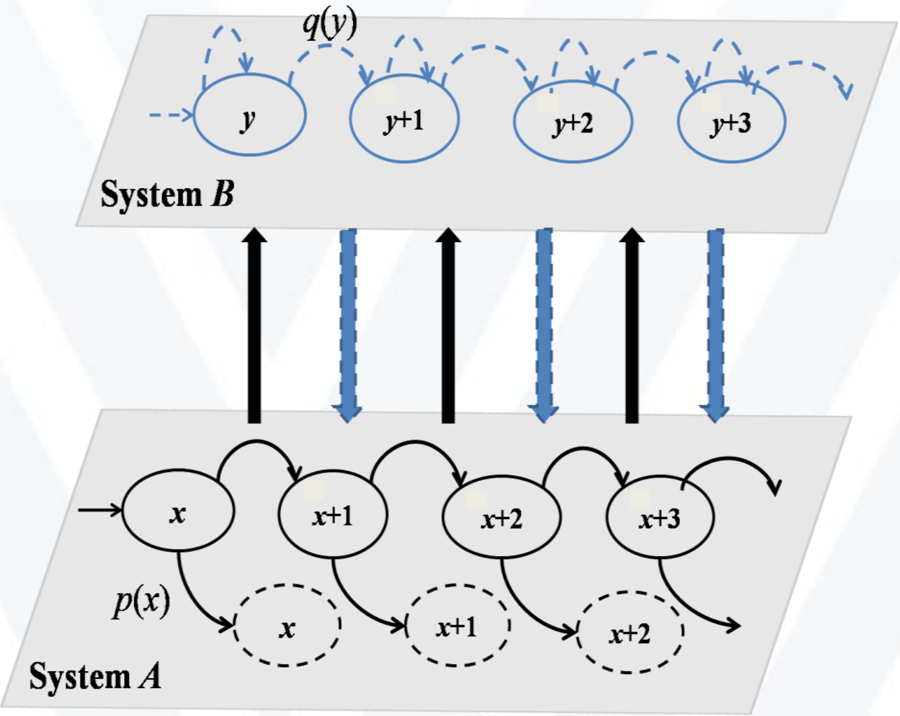
- Main ideas of the *stochastic abstract-state evolution (SASE) approach:*
    - Simplify the state space of the complex power system (**equivalence classes**)
    - Capturing the effects of the omitted variables through the transition probabilities and their parametric dependence on physical attributes and **operating characteristics** of the system.



- Aggregate state variables: $\boldsymbol{S_i = (F_i, C_i^{\max}, I_i)}$
    - ***F***: number of failed lines
    - $\boldsymbol{C_{max}}$: maximum capacity of failed lines
    - ***I***: Cascade-stability of power grid

Review of Interdependent Markov-chain (IDMC) model

- Each network is represented by a Markov chain
  - Number of failures in the power grid: ***x***
  - Number of failures in the communication system: ***y***
- Failure in one chain is correlated with failure in the other chain via state-dependent coupling variables
- Transition probabilities are influenced by communication-network topology via state-dependent variables representing significance of failed nodes/links

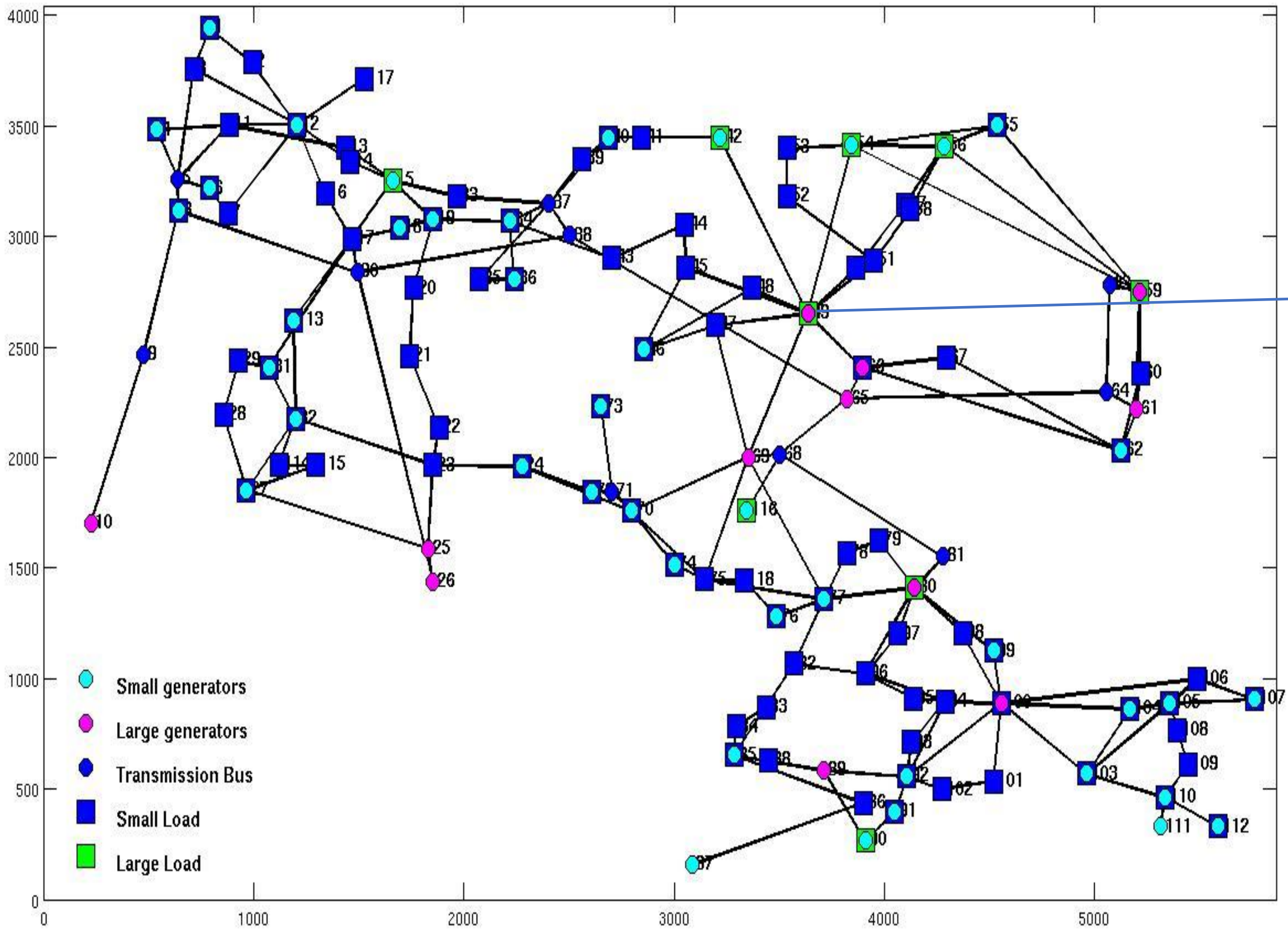


Inter-dependent Markov chains (IDMC) refers a coupling parameter to characterize the influence of communication network in power grid but simply considered it as a constant

Proposed model to capture the impact of interdependency between power grid and communication network

- We introduce the coupling parameter *d* in terms of the minimum hop distance and the maximum node degree of the failed communication nodes.
- Our observations illustrate that, a decrement in the minimum hop distance or an increment in the maximum node degree of the failed communication nodes increase the cascading-failure probability in the power grid.
- By characterizing the coupling parameter *d*, we study the communication topology and identify it’s impact on cascading-failures in power grid in an interdependent system environment.

Communication/control network over-layed on IEEE-118 bus topology



center connected
with 12 nodes

control
center

- We selected the 49th node as the center node. Its node degree is 12, which is the highest
- Maximum hop distance from the center node is 8

Coupling between communication/control and transmission networks

- **Consequence of power loss on communication:**
  - A failure in a transmission line triggers a communication-link failure in communication system with probability ***q***.
- **Consequence of communication-link failure on power loss:**
  - Without communication influence, cascading failures stop in the power grid with probability ***p*(*x*)**, which depends on the number of failures in the power grid: this is the cascade-stop probability. [earlier SASE model]

  - A communication-link failure reduces the cascade-stop probability in the power grid from ***p*(*x*)** to ***p*(*x*)(1-*d*(*y*))**, where ***d*(*y*)** (in [0,1])

  - ***d*(*y*)** is an interdependency function that depends on the dynamic functionality and topological attributes of the communication network.

  - ***d*(*y*)** should represent the “significance” of the failed communication links on the power grid

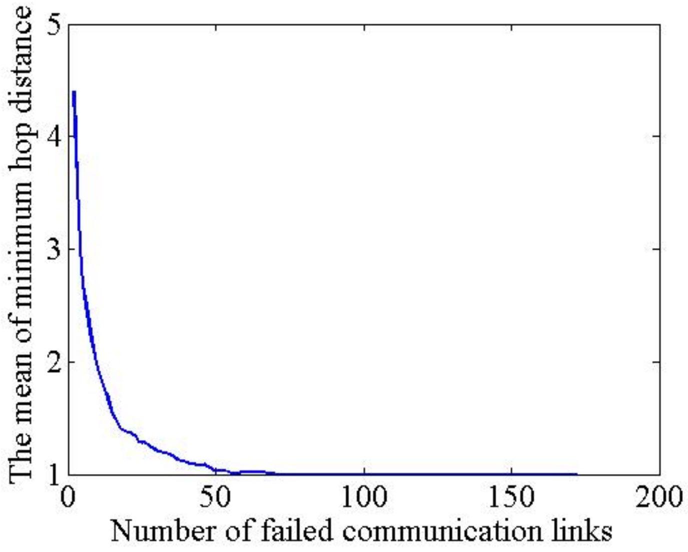
  - We represent “importance” by the:
    - Maximum degree of failed nodes
    - Minimum hop-distance between failed nodes and the central node.

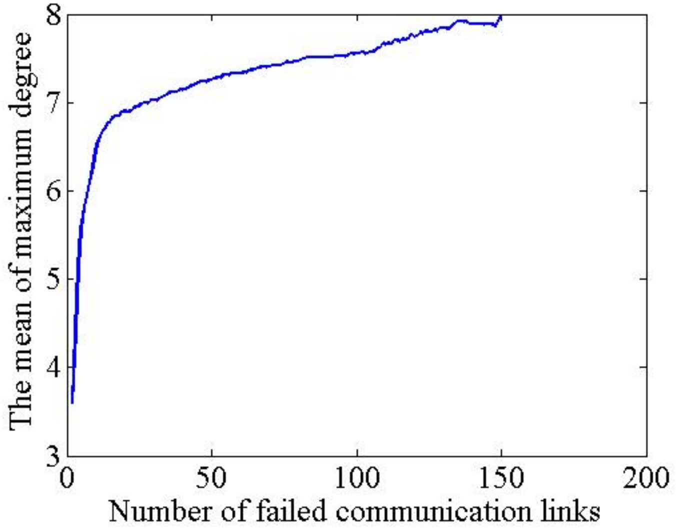
Role of communication/control topology

- Optimal power-flow simulations suggest that communication-link failure can be attributed to two main connectivity and topological factors:
  - Minimum hop-distance of the failed communication nodes to the central node
  - Maximum degree of failed communication nodes
- Hence, we can propose:
  - Interdependency variable, *d*, to be a weighted sum of two probabilities:
    - $\boldsymbol{p_{hop}^{fail}(h_n)}$: probability of communication-link failure resulting from the state of the connectivity to the central node (hop distance of the failed lines to the central node)
    - $\boldsymbol{p_{deg}^{fail}(d_n)}$: probability of communication-link failure resulting from the state of the degree of failed communication nodes
    - $d = w\, \boldsymbol{p_{hop}^{fail}(h_n)} + (1-w)\, \boldsymbol{p_{deg}^{fail}(d_n)}$; w is a weight factor between 0 and 1.

Role of communication/control topology (cont.)

- Optimal power-flow simulations suggest a relationship between:
  - Maximum degree of failed nodes in communication network and number of failed links in communication network.
  - Minimum hop-distance between central control node and failed nodes in communication network.



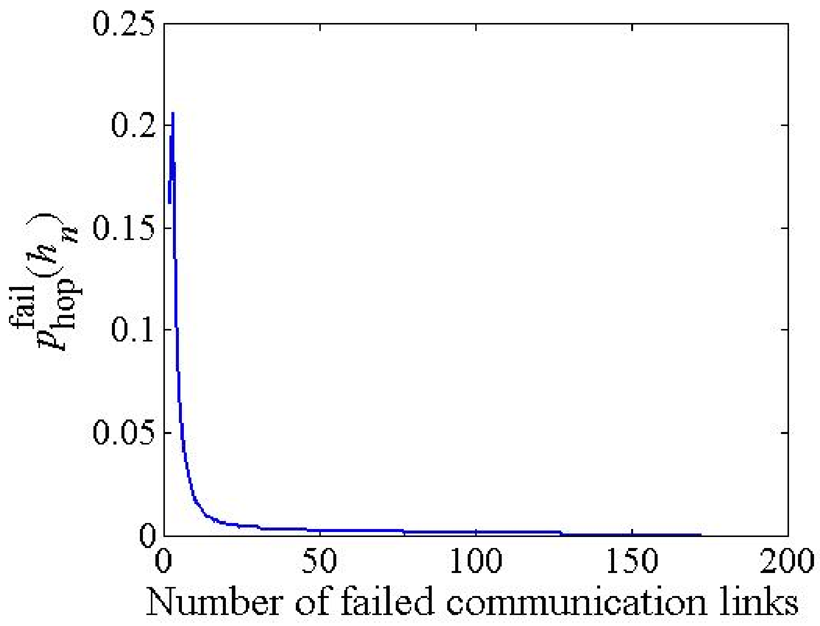


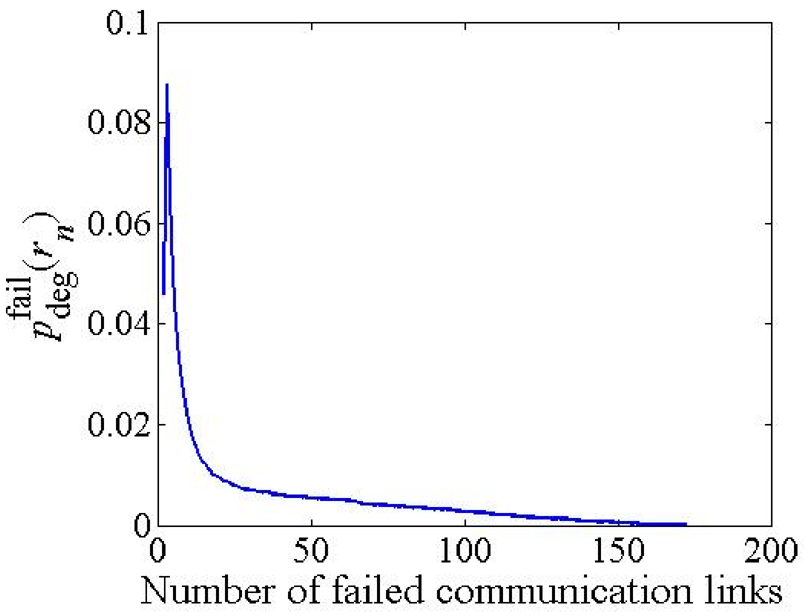
Parametric approximation

$$p_{hop}^{fail}(h_n) = \begin{cases} \dfrac{a_1}{{h_n}^4} + \epsilon & 1 \leq h_n \leq m \\ \epsilon & h_n > m \end{cases}$$

$$p_{degree}^{fail}(d_n) = \begin{cases} \epsilon & 1 \leq d_n < n \\ a_2 {d_n}^4 + \epsilon & d_n \geq n \end{cases}$$

Role of communication/control topology (cont.)





- Hence, we can represent the interdependency variable

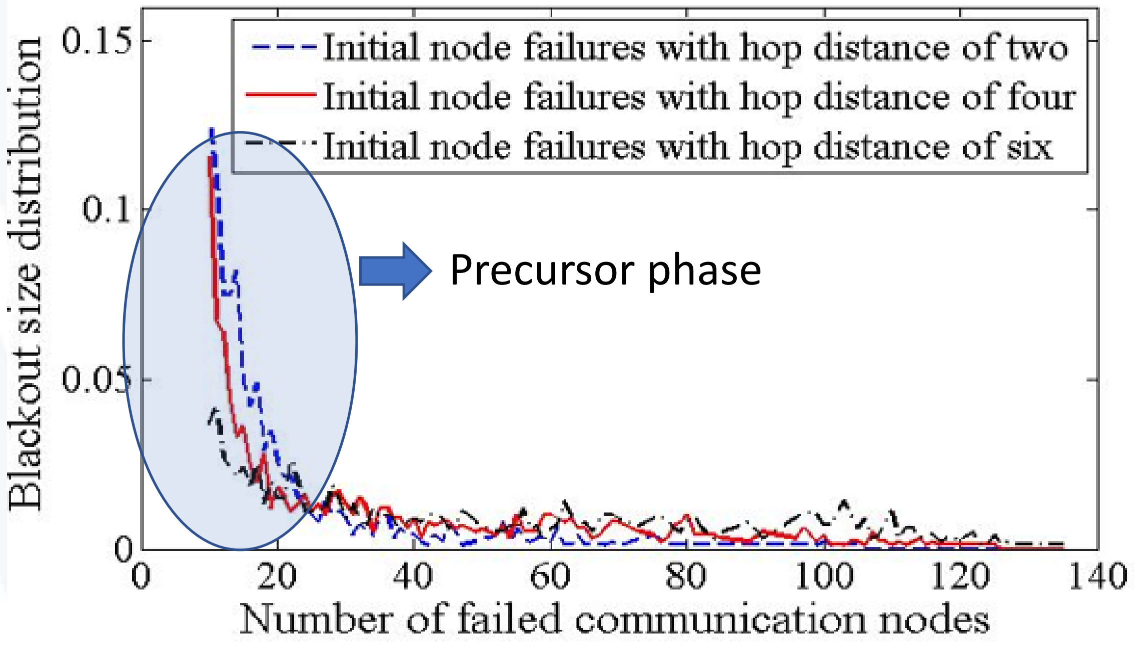
$$d = w\, \boldsymbol{p}_{hop}^{fail}(\boldsymbol{h}_n) + (1-w)\, \boldsymbol{p}_{deg}^{fail}(\boldsymbol{d}_n)$$

as

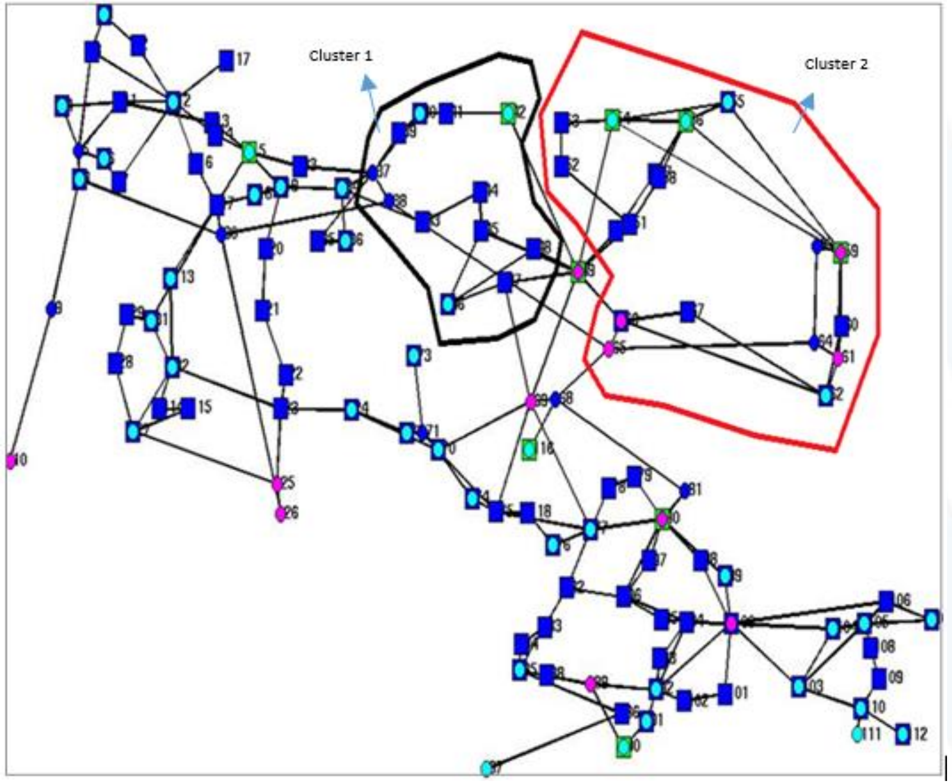
$$d\,(\boldsymbol{y}_n) = w\, \boldsymbol{p}_{hop}^{fail}(\boldsymbol{y}_n) + (1-w)\, \boldsymbol{p}_{deg}^{fail}(\boldsymbol{y}_n)$$

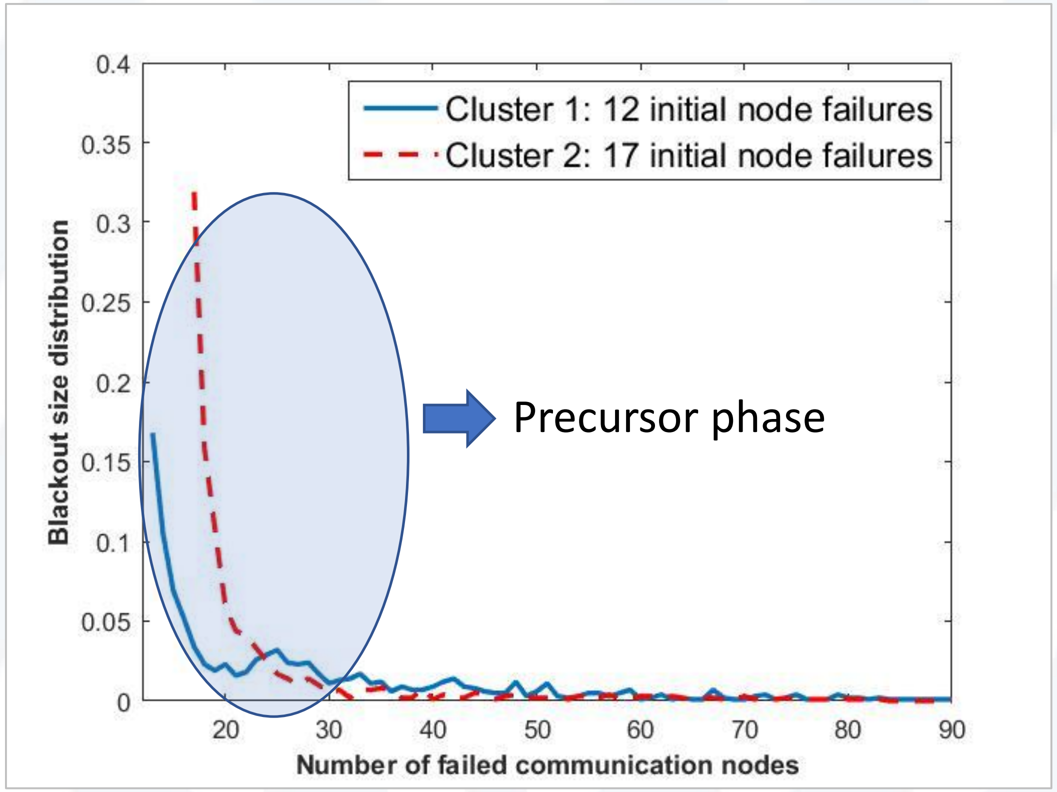
Blackout distribution comparison for ten initial communication node and power line failures having different minimum hop distances

- We have simulated the blackout distribution in power grid for ten initial communication node and power line failures
- We observed that failure in communication nodes with lower hop distances has higher blackout distribution as failures increase
- When the mean of the minimum hop distance is lower, power grid is more conducive to cascading failures in precursor phase



Blackout distribution comparison for two clusters having different minimum hop distance & maximum node degree





- Both the mean of the minimum hop and the mean of the maximum degree are higher in cluster two to those in cluster one
- Cluster two is more conducive to cascading-failure than cluster one with higher blackout distribution during the precursor phase of the communication network node failures

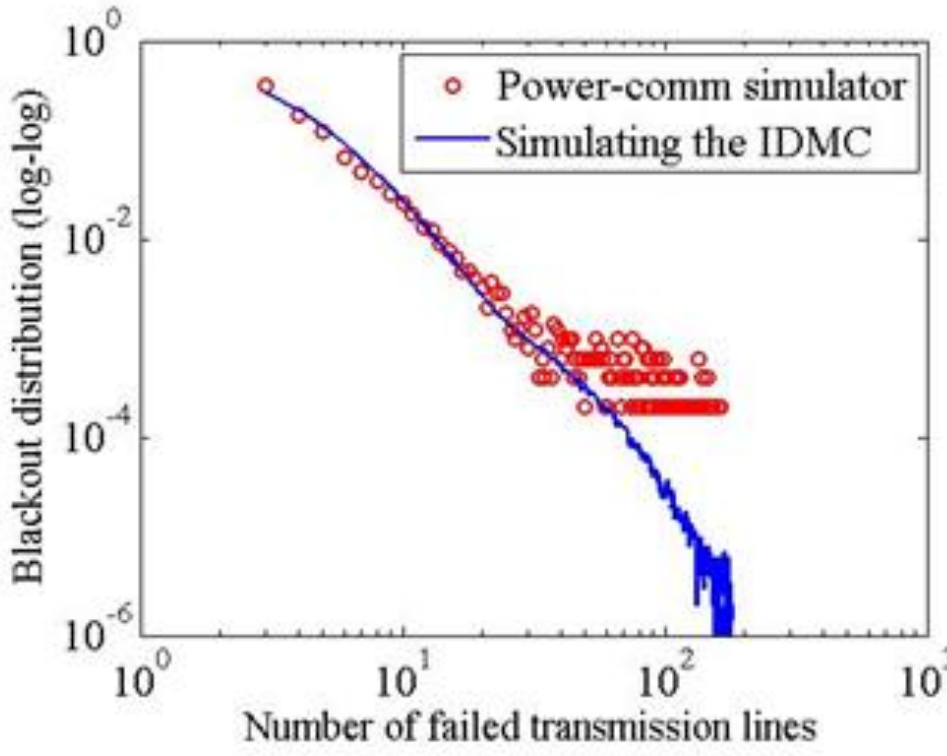
Simulating the Markov chain of the proposed model

- We simulated the Markov chain of the proposed model to validate the IDMC model by comparing its results to those obtained from the coupled communication and power-grid simulator.

- Two results agree in showing a similar trend in the blackout size distribution

- The results obtained from coupled simulator is not precise when the number of failed transmission-lines is large (e.g. over 100), which is due to the limited sample size of large blackouts

- Results validate that the proposed model is effective in capturing the impact of the interdependency between the power system and communication network on cascading-failures in the power grid.

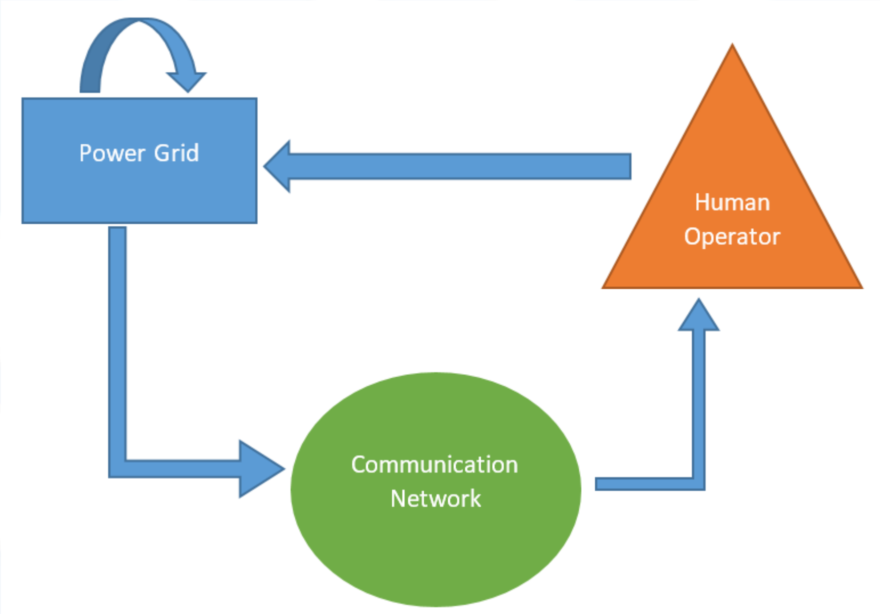


Conclusions

- We proposed a communication-power interdependency function, *d* that is determined by hop distance from a central node and the degree of the node in the communication network
- It captures the influence of communication network on the power system under different stress levels of the power grid during cascading failures.
- We devised a coupled power-communication simulator and conducted extensive simulations to validate the proposed model
- Blackout probability in the power grid can be significantly impacted by the failures in the communication network when the power grid is under stress.
- The computational time for simulating the proposed model is reduced by a factor of 10e7 to the time using the coupled simulator.

Ongoing Works

- Develop a comprehensive 3-layer Markov chain based model to characterize cascading failure in power grid with communication network and human operator error in the loop.(accepted in IGESSC 2017)
- Characterize the impact of initial failures in power grid due to natural disaster, WMD’s
- Analyze the impact of lost capacity of the failed transmission lines during cascading failure



References

[1] M. Amin and P. F. Schewe, “Preventing blackouts,” Scientific American, vol. 296, no. 5, pp. 60–67, 2007.

[2] A. Veremyev, A. Sorokin, V. Boginski, and E. L. Pasiliao, “Minimum vertex cover problem for coupled interdependent networks with cascading failures,” European Journal of Operational Research, vol. 232, no. 3, pp. 499–511, 2014.

[3] https://energy.gov/oe/downloads/blackout-2003-final-report-august-14-2003-blackout-united-states-and-canada-causes-and

[4] M. Rahnamay-Naeini and M. M. Hayat, “Cascading failures in interdependent infrastructures: An interdependent markov-chain approach,” IEEE Transactions on Smart Grid, vol. 7, no. 4, pp. 1997– 2006, 2016.

[5] Rahnamay-Naeini et al., “Stochastic analysis of cascading-failure dynamics in power grids,” IEEE Transactions on Power Systems, vol. 29, no. 4, pp. 1767–1779, 2014.

Thank you for your Attention

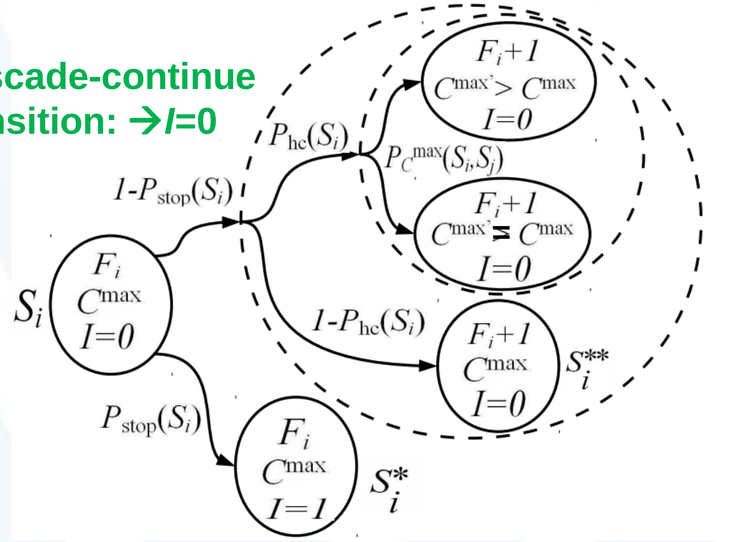
Questions?

Annex 1: SASE model state transition probabilities

Transition probabilities are state dependent

$$
p_{ij} = \begin{cases}
0 & F_j < F_i \quad or \quad F_j - F_i > 1 \\
0 & C_j^{\max} < C_i^{\max} \\
0 & I_i = 1 \quad and \quad j \neq i \\
1 & I_i = 1 \quad and \quad j = i \\
P_{stop}(S_i) & I_i = 0, I_j = 1, \quad F_j = F_i \quad and \quad C_j^{\max} = C_i^{\max} \\
P_{cont}(S_i, S_j) & I_i = I_j = 0, \quad F_j = F_i + 1 \quad and \quad C_j^{\max} \geq C_i^{\max}
\end{cases}
$$

Cascade-continue transition: → *I*=0



Cascade-stop transition (Absorbing state): → *I*=1

Annex 2: IDMC model state transition probabilities

$$f(s_{n+1}|s_n) = \begin{cases} 1 & \\ \quad if\ i_n = 1, x_{n+1} = x_n, l_{n+1} = l_n, & \\ \quad y_{n+1} = y_n & \\ q(y_n) & \\ \quad if\ i_n = i_{n+1} = 0, l_n = 0, & \\ \quad x_{n+1} = x_n, y_{n+1} = y_n + 1 & \\ 1 - q(y_n) & \\ \quad if\ i_n = i_{n+1} = 0, l_n = 0, & \\ \quad x_{n+1} = x_n, y_{n+1} = y_n & \\ 1 - \frac{p(x_n)(1-d(y_n,h_n,r_n))}{(k_n+(1-d(y_n,h_n,r_n)(1-k_n))} & \\ \quad if\ i_n = i_{n+1} = 0, l_n = 1, & \\ \quad x_{n+1} = x_n + 1, y_{n+1} = y_n & \\ \frac{p(x_n)(1-d(y_n,h_n,r_n))}{(k_n+(1-d(y_n,h_n,r_n))(1-k_n))} & \\ \quad if\ i_n = 0, i_{n+1} = 1, & \\ \quad l_n = 1, x_{n+1} = x_n, y_{n+1} = y_n & \\ 0 \quad otherwise & \end{cases}$$

IDMC state transitions

Power-communication interdependency: *q*(*x*)

Communication-power interdependency *d*(*y*)