Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

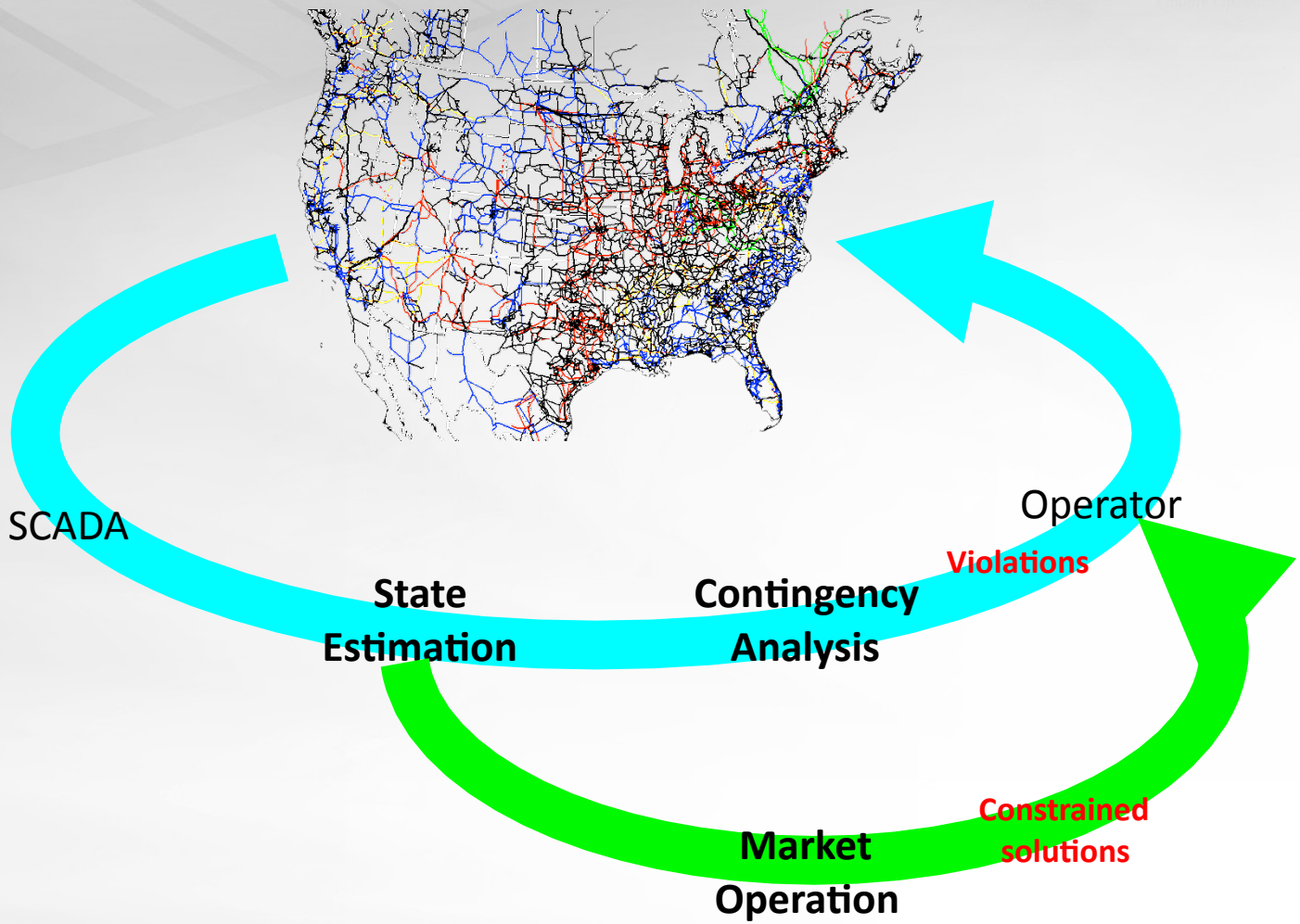
"Towards" N-x Contingency Selection Using Group Betweenness Centrality

MAHANTESH HALAPPANAVAR, YOUSU CHEN, ROBERT ADOLF, DAVID HAGLIN, ZHENYU (HENRY) HUANG, & MARK RICE

JOHN FEO, DANIEL CHAVARRIA, & SHUANGSHUANG JIN

Salt Lake City, Utah. November 11, 2012

Contingency Analysis: Context

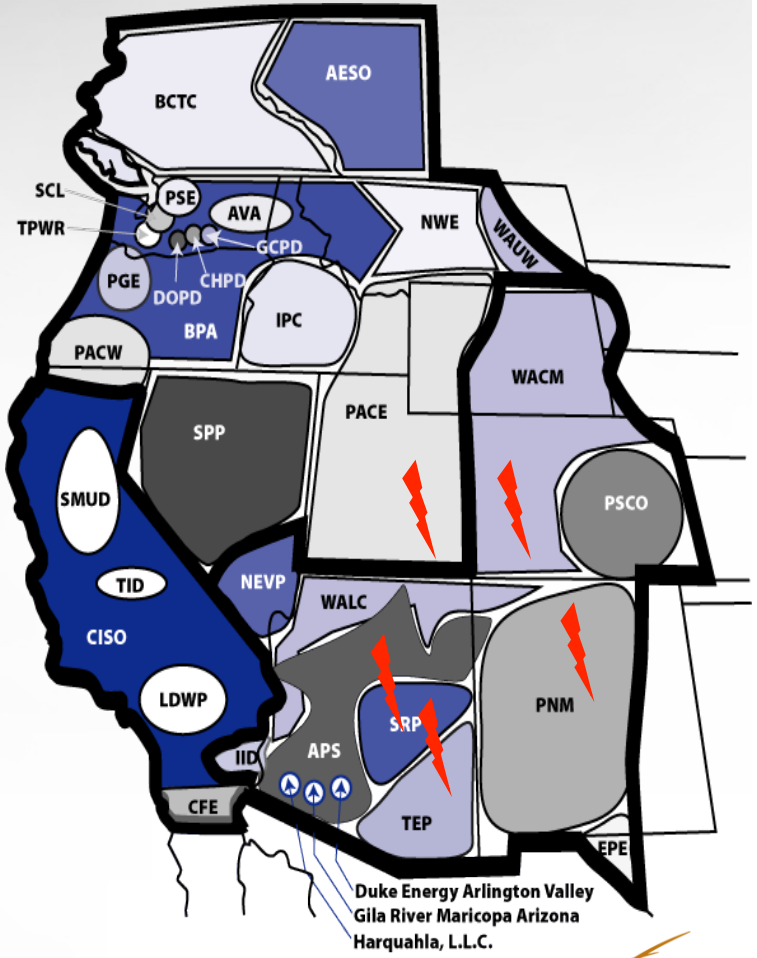


Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

Contingency Analysis

- Study the impact of individual component failures on the overall system based on power system state estimation
- "N-1" Contingency Analysis
  - Impact from *single* failures
- "N-x" Contingency Analysis
  - Different combinations of "x" concurrent failures
- Why N-x?
  - Regulatory restrictions
  - Balancing Authorities
    - Example: 35 BAs in west



Pacific Northwest
NATIONAL LABORATORY

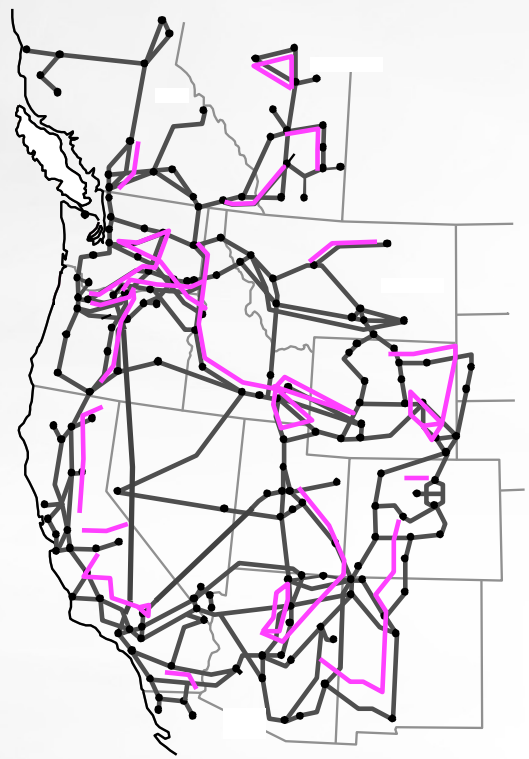
Proudly Operated by Battelle *Since 1965*

"N-x" Contingency Analysis: The Challenge

Western Power Grid: ~20,000 components

- *"N-1"* ➔ C_1^{20000} ~ 10^4
- *"N-2"* ➔ C_2^{20000} ~ 10^8
- *"N-3"* ➔ C_3^{20000} ~ 10^{12}

"N-x" ➔ C_x^N



➔ C_x^{N-b}

A potential solution:

non-critical elements: *ignore*

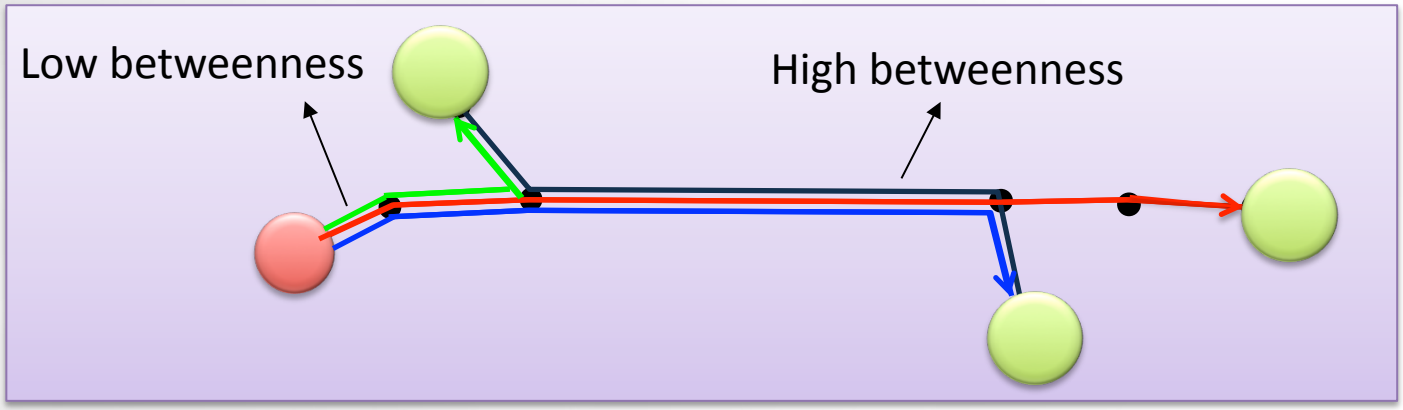
Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

Graph Centrality: Betweenness

- *Betweenness*: captures influence of a node on connectivity in a graph
- Consider paths between all pairs of nodes
- Edge betweenness identifies heavily traversed edges in a graph

$$C_B(e) = \sum_{s,t \in V \setminus e} \frac{\sigma(s,t \mid e)}{\sigma(s,t)}$$



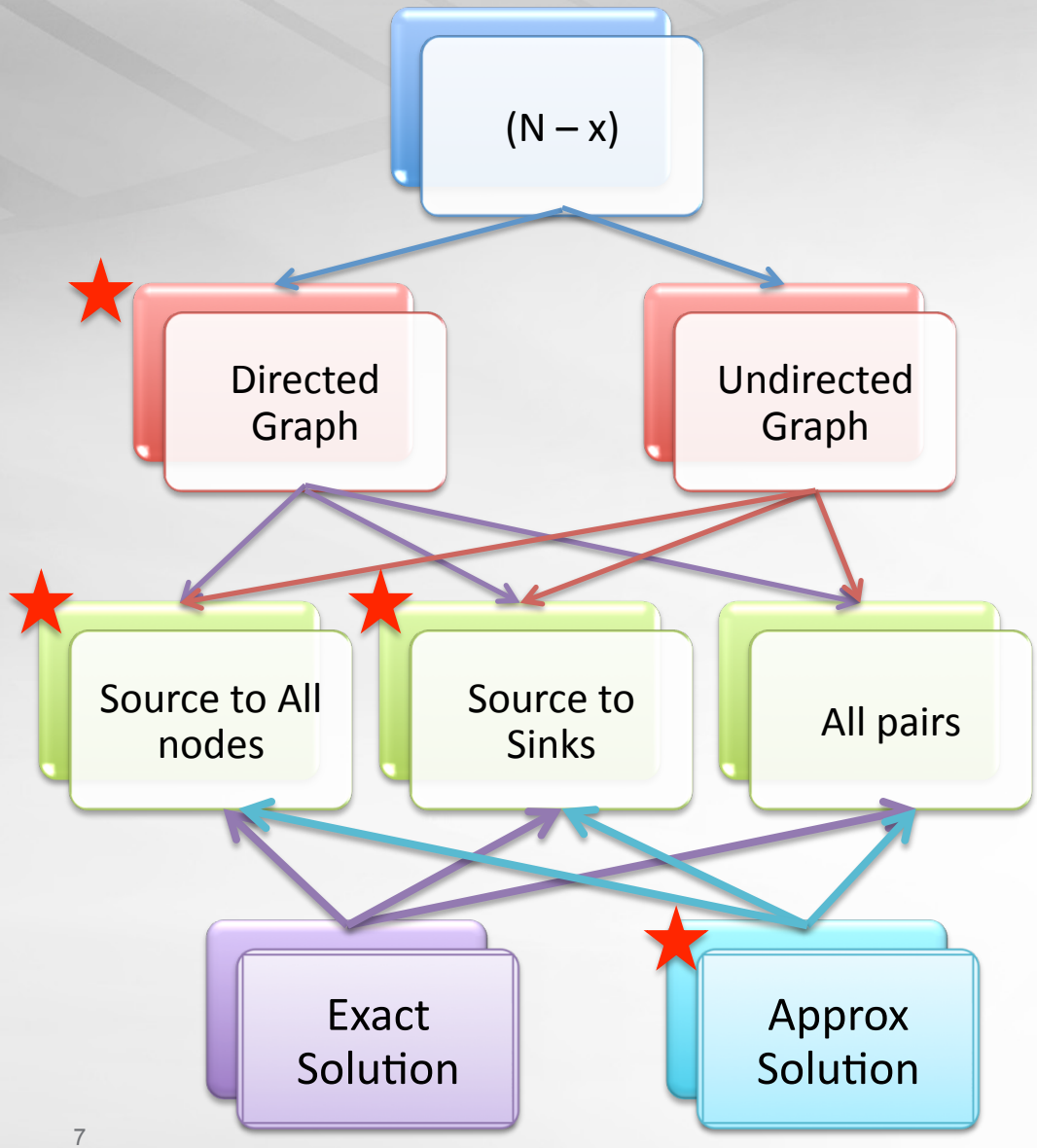
Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Graph-based Approach: Issues and Challenges

- Graphs are powerful, but simplistic
  - Power grid is a continuous/dynamic system, but graphs are discrete
  - Heterogeneity of entities, electrical properties are hard to model
- Centrality is an abstract concept from sociology
  - Emulating the behavior of electrons is not easy
- “N-x” analysis is a group-based problem
  - Combinatorial explosion of possibilities
  - Temporal aspect: fast computations are needed
- Validation of results is difficult
  - Lack of readily available large-scale datasets
  - Computational infeasibility of known methods (ground truth)

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

A Framework for "N-x" Contingency Selection



- Search Restrictions
  - All-pairs; Source-to-All; Source-to-Sink
- Graph Type
  - Directed; Undirected
- Metric
  - Edge betweenness
  - Group betweenness centrality
- Edge weights
  - 1/P; Pmax/P; (Pmax/P)^2
- Algorithms
  - Exact; Approximate

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

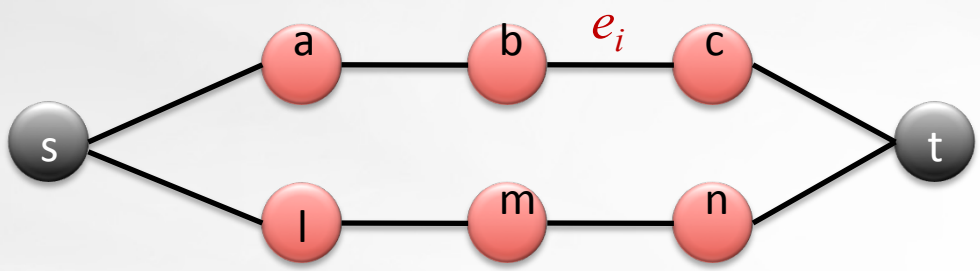
N–x Contingency Selection

- Goal: Identify groups of *x* edges that have maximal influence on the connectivity in a graph
- Importance of a group depends on:
  1. The weight of an edge,
  2. The relationship of the individual edges with other edges in the graph, and
  3. The mutual relationship of edges within a group
- How can we identify all these factors?
  - Technical Approach: Group betweenness centrality

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

N–x Contingency Selection: Group betweenness

- Goal: Identify important groups of *x* edges whose failure would cause the most severe problems to the power grid:

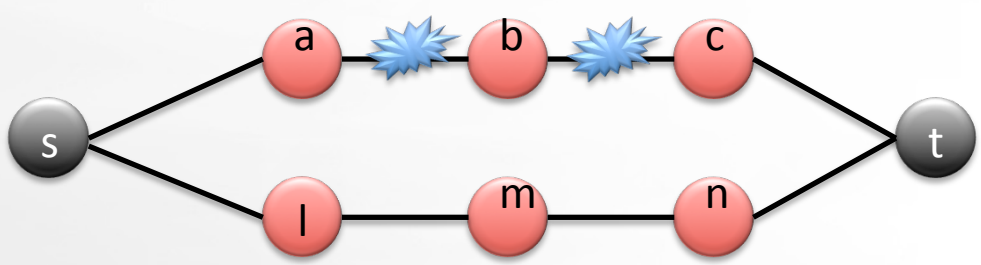


$$C_B(E_G^i) = \sum_{s,t \in V \setminus E_G^i} \frac{\sigma(s,t \mid E_G^i)}{\sigma(s,t)}$$

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Computing Group Betweenness: Intuition

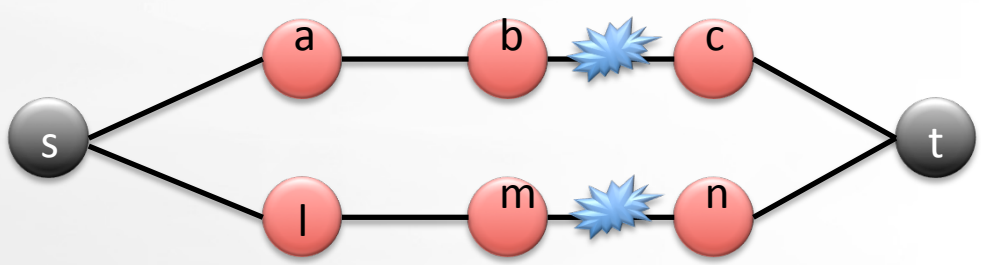
- Consider the complete influence of the first edge, but only consider additional influences of the subsequent edges in a group
- *Example*: if edge e_1 is part of N paths and edge e_2 is part of M paths, the influence of a group consisting of edges e_1 and e_2 is $(N + M - \delta)$, where δ is the number of paths that contain both e_1 and e_2.



Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Computing Group Betweenness: Intuition

- Consider the complete influence of the first edge, but only consider additional influences of the subsequent edges in a group
- *Example*: if edge e_1 is part of N paths and edge e_2 is part of M paths, the influence of a group consisting of edges e_1 and e_2 is $(N + M - \delta)$, where δ is the number of paths that contain both e_1 and e_2.



Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Computing Group Betweenness: Naïve Approach

1) Identify all groups of *x* edges
2) For each group E_{Gi}
   - Run Brandes's algorithm

- *Inefficient*: Combinatorial in nature
- Goal 1: Minimize number of groups to consider
  - Identify important edges (application/graph theory)
- Goal 2: Minimize the computational cost
  - Use memory to minimize computation (precompute)

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

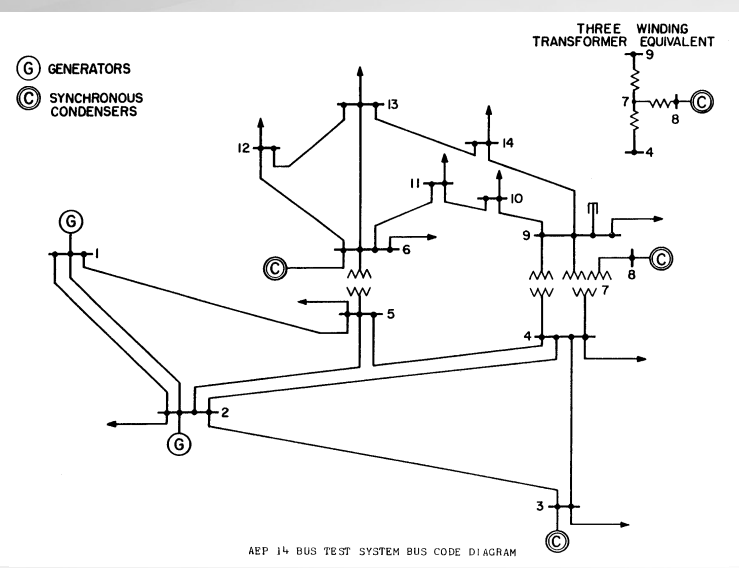
Computing Group Betweenness: Better Approach

1) Identify X ($<< E$) important edges
2) Precomputation based on X
3) Build groups of x edges from X
4) For each group E_{Gi}
   - Run modified GBC algorithm

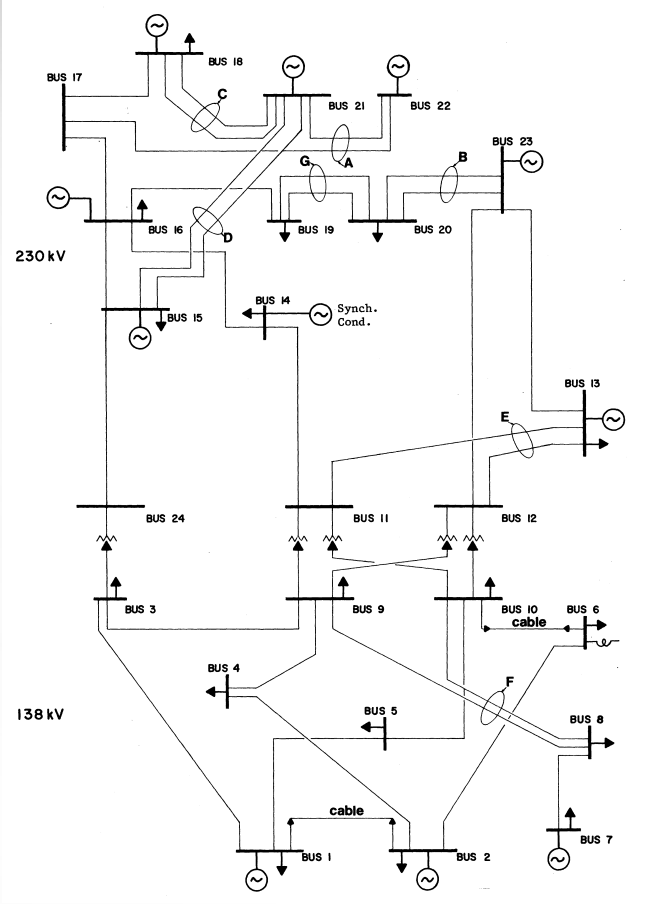
Puzis, R., Elovici, Y. and Dolev, S., Fast algorithm for successive group betweenness centrality computation. *Phys. Rev*. E. v76. 056709.

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Case Study: IEEE 14-bus and 24-bus systems



14-bus system



24-bus system

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

14-bus: “N-1” and “N-2” Analysis

Outage	Violations	Rank		Score	
		PI	GBC	PI	GBC
1-2	(no solution)	1	1	∞	13.00
2-3	4	2	2	7.56	10.00
2-4	3	3	5	5.23	9.00
1-5	2	4	4	4.91	9.00
4-5	2	5	7	3.58	4.00
5-6	1	6	3	4.32	10.00
2-5	1	7	10	3.19	0.00
3-4	1	8	11	3.02	0.00
6-13	0	9	14	2.28	0.00
6-11	0	10	12	2.27	0.00

N-1 Contingency Cases

Outages	Violations	Rank		Score	
		PI	GBC	PI	GBC
1-2, 2-3	4	1	4	7.56	11.00
1-5, 2-3	4	2	13	7.56	9.00
1-2, 2-4	3	3	2	5.23	12.00
1-5, 2-4	3	4	7	5.23	10.00
2-3, 2-4	3	5	14	5.23	9.00
1-2, 1-5	2	6	5	4.91	10.00
1-2, 4-5	2	7	6	3.58	10.00
1-5, 4-5	2	8	30	3.58	7.00
2-3, 4-5	2	9	31	3.58	7.00
2-4, 4-5	2	10	32	3.58	7.00

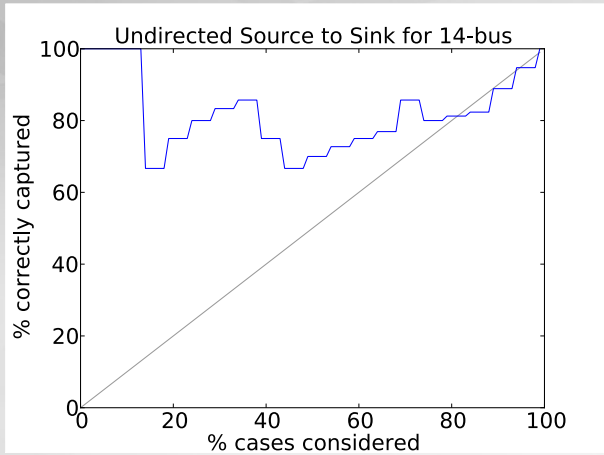
N-2 Contingency Cases

Performance Index: Sum of normalized branch flows (Σ(actual/capacity)^2)

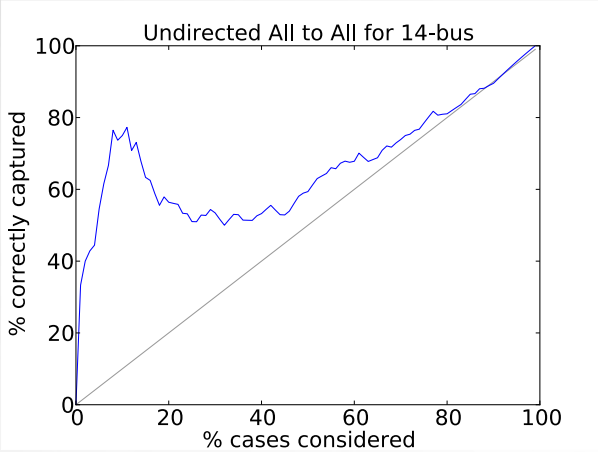
Data: Source-to-sink

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

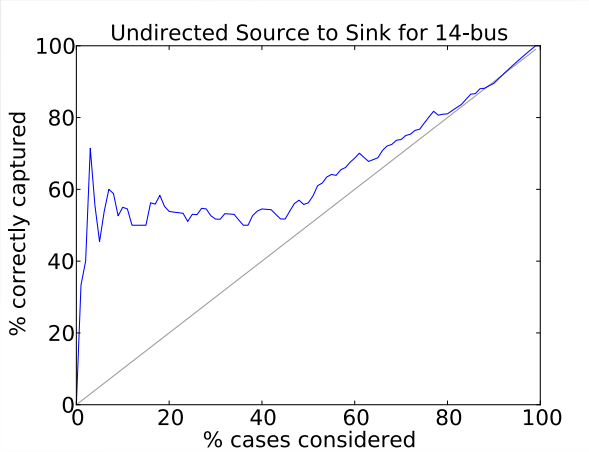
14-bus: “N-1” and “N-2” -- Capture plots



(a) Edge betweenness (N-1)



(b) All-to-all group betweenness (N-2)



(c) Source-to-sink group betweenness (N-2)

“N-1”

“N-2” (all pairs)

“N-2” (src-sink)

Capture rate: Percentage of cases correctly captured by centrality w.r.t. Performance Index.

X-axis: Number of cases considered

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

24-bus: “N-1” and “N-2” Analysis

Outage	Violations	Rank		Score	
		PI	GBC	PI	GBC
6-10	1	1	1	2.59	42.00
2-6	1	2	2	2.23	35.00
15-24	0	3	31	3.05	0.00
14-16	0	4	6	3.05	22.00
3-24	0	5	12	3.04	11.00
16-17	0	6	19	2.72	8.00
13-23	0	7	21	2.52	4.00
12-23	0	8	32	2.47	0.00
16-19	0	9	10	2.37	15.00
15-21	0	10	24	2.35	3.50

N-1 Contingency Cases

Outages	Violations	Rank		Score	
		PI	GBC	PI	GBC
1-2, 6-10	2	1	15	2.33	35.00
1-3, 6-10	2	2	31	2.33	31.00
1-5, 6-10	2	3	32	2.33	31.00
2-4, 6-10	2	4	33	2.33	31.00
2-6, 6-10	2	5	21	2.33	33.00
3-9, 6-10	2	6	34	2.33	31.00
4-9, 6-10	2	7	35	2.33	31.00
5-10, 6-10	2	8	36	2.33	31.00
1-2, 2-6	1	9	69	2.28	27.00
1-3, 2-6	1	10	79	2.28	24.00

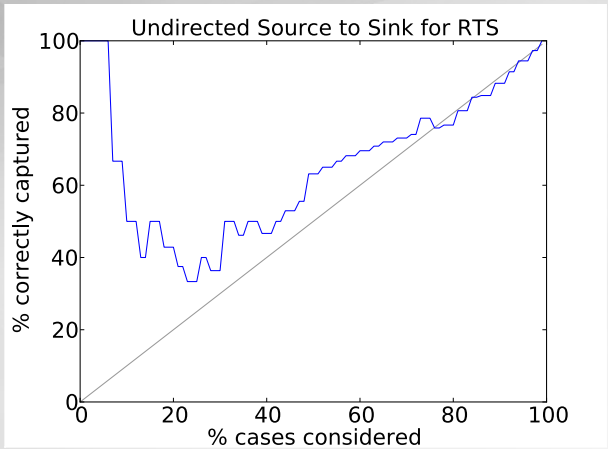
N-2 Contingency Cases

Performance Index: Sum of normalized branch flows (Σ(actual/capacity)^2)

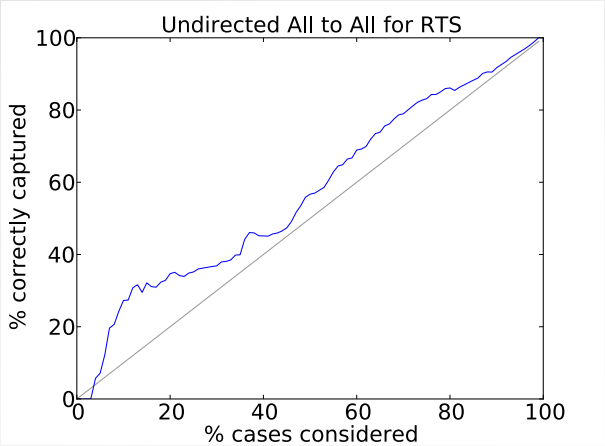
Data: Source-to-sink

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

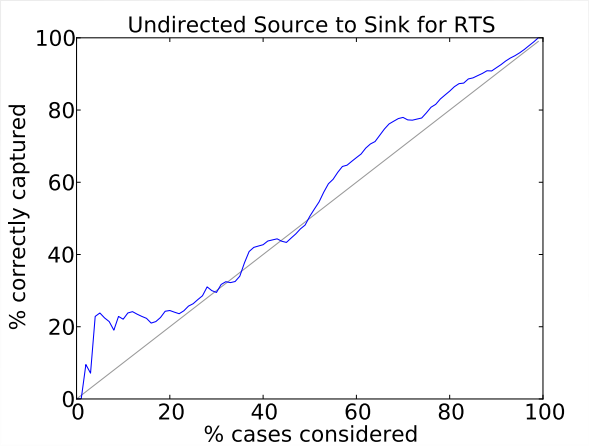
24-bus: “N-1” and “N-2” – Capture plots



(a) Edge betweenness (N-1)



(b) All-to-all group betweenness (N-2)



(c) Source-to-sink group betweenness (N-2)

“N-1”

“N-2” (all pairs)

“N-2” (src-sink)

Capture plots: Number of cases correctly captured by centrality w.r.t. Performance Index.

Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

Summary and Conclusions

- We presented a novel solution for “N-x” contingency selection via group betweenness centrality, and
- A framework to include different aspects of a power grid

- Conclusions:
  - Group betweenness can be computationally feasible with precomputations
  - Centrality measures are sensitive and should be used with care
  - Modeling a power grid using graphs is nontrivial
  - “N-x” contingency analysis is still in its infancy: opportunities

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965