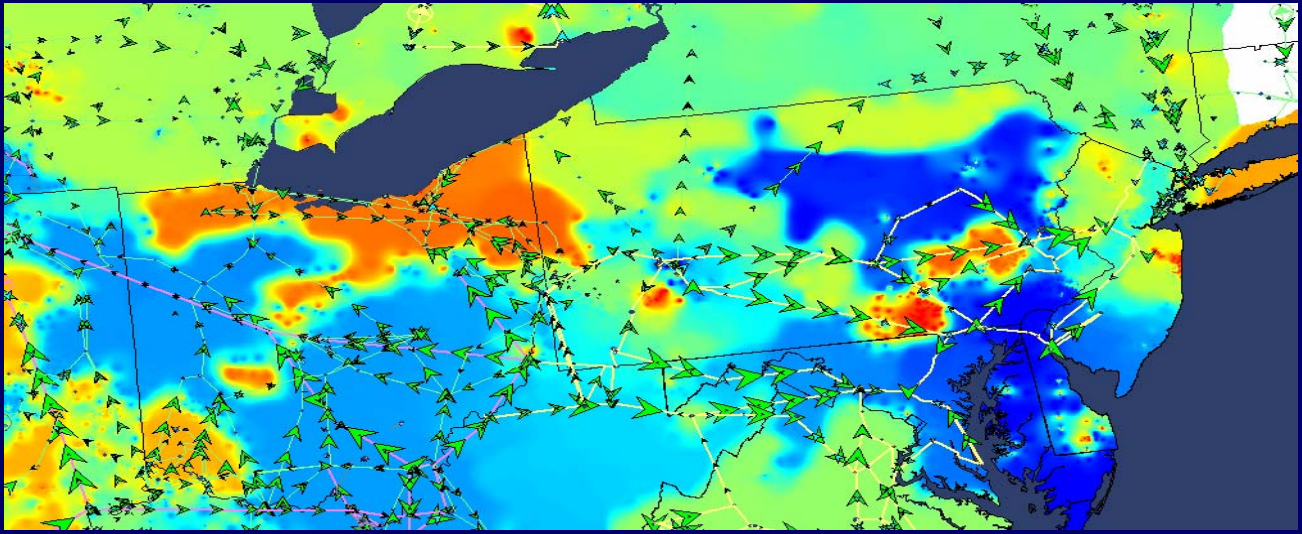
PENNSTATE



Clayton Barrows
Ph.D. Candidate – *Energy Management & Policy*
John & Willie Leone Department of Energy & Mineral Engineering
Pennsylvania State University

Dr. Seth Blumsack – Penn State

Dr. Russell Bent – LANL D-4

Computationally Efficient Transmission Switching: Solution Space Reduction

Optimal Power Flow (DC Model)

$$\min \sum_{g} c_{ng} P_{ng}$$ ← **Total Generation Cost**

$$s.t.$$

$$\theta_n^{min} \le \theta_n \le \theta_n^{max},$$
$$P_{ng}^{min} \le P_{ng} \le P_{ng}^{max},$$
$$P_{nk}^{min} \le P_{nk} \le P_{nk}^{max},$$

← **Voltage Angle Limits**
Generator Limits
Line Flow Limits

$$\sum_{i=n} P_{k_{ij}} - \sum_{j=n} P_{k_{ij}} - \sum_{g} P_{ng} - \sum_{d}$$ ← **Power Balance**

$$B_k(\theta_n - \theta_m) - P_{nk} = 0,$$ ← **Linearized DC Power Flow**

Optimal Transmission Switching

$$\min \sum_{g} c_{ng} P_{ng}$$ ← Total Generation Cost

$s.t.$

$$\theta_n^{min} \leq \theta_n \leq \theta_n^{max},$$
$$P_{ng}^{min} \leq P_{ng} \leq P_{ng}^{max},$$
$$P_{nk}^{min} z_k \leq P_{nk} \leq P_{nk}^{max} z_k,$$

← Voltage Angle Limits
Generator Limits
Line Flow Limits

$$\sum_{i=n} P_{k_{ij}} - \sum_{j=n} P_{k_{ij}} - \sum_{g} P_{ng} - \sum_{d}$$

← Power Balance

$$B_k(\theta_n - \theta_m) - P_{nk} + (1 - z_k)M_{}$$
$$B_k(\theta_n - \theta_m) - P_{nk} - (1 - z_k)M_{}$$

← Linearized DC Power Flow

← Line State

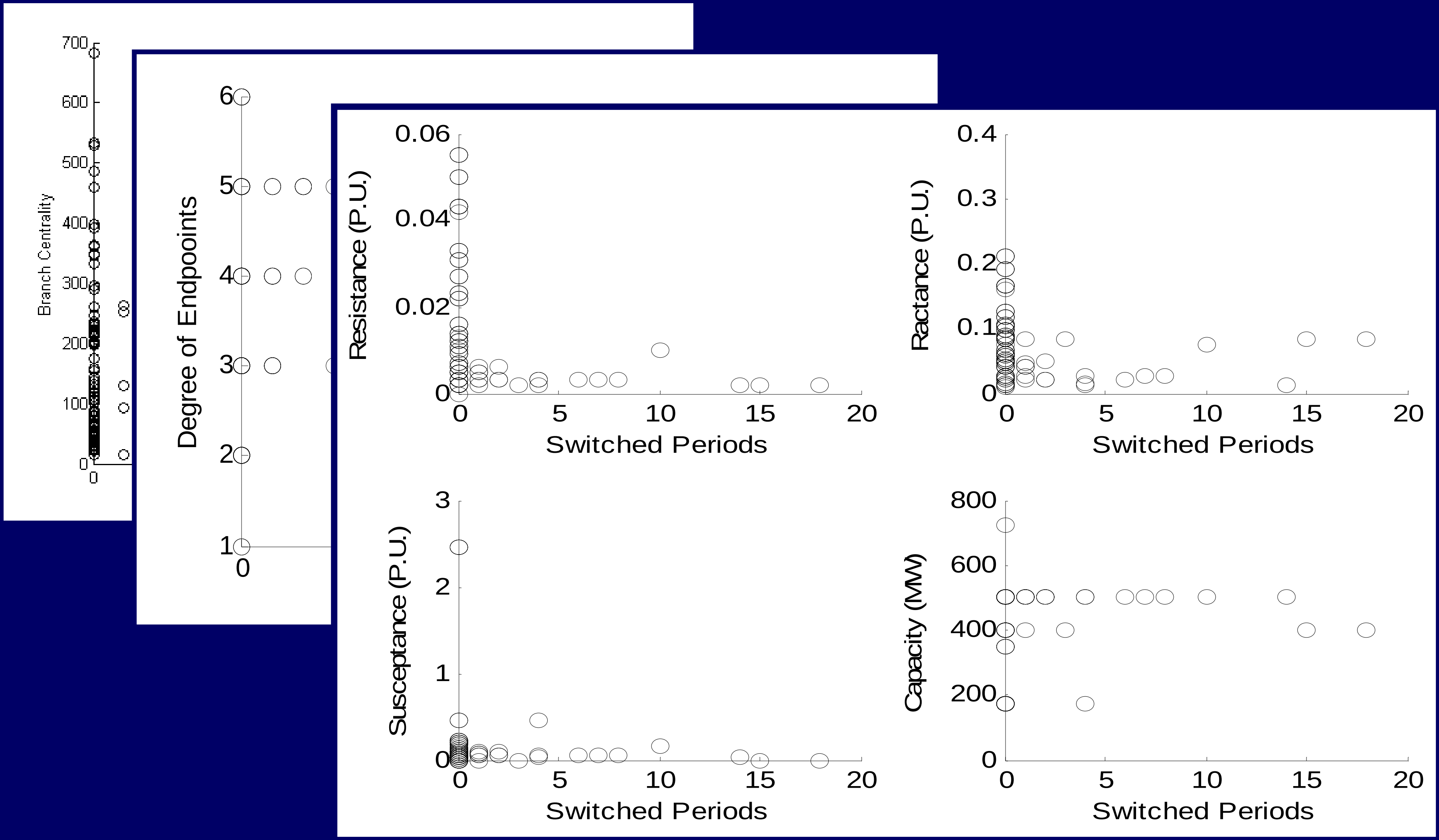
OTS on Test Networks

- Optimal Transmission Switching MIP
  - Integer variables representing line status
    - *2* $^{n\text{-}lines}$ possible network topologies
  - IEEE 118- Bus Model E. Fisher et al.
    - 22% Savings (7 lines switched)
  - IEEE RTS 96 Model (73 Busses) K. Hedman et al.
    - 3.7% Savings over 24 x 1hr periods
    - Computation time: Over 20 hours per period

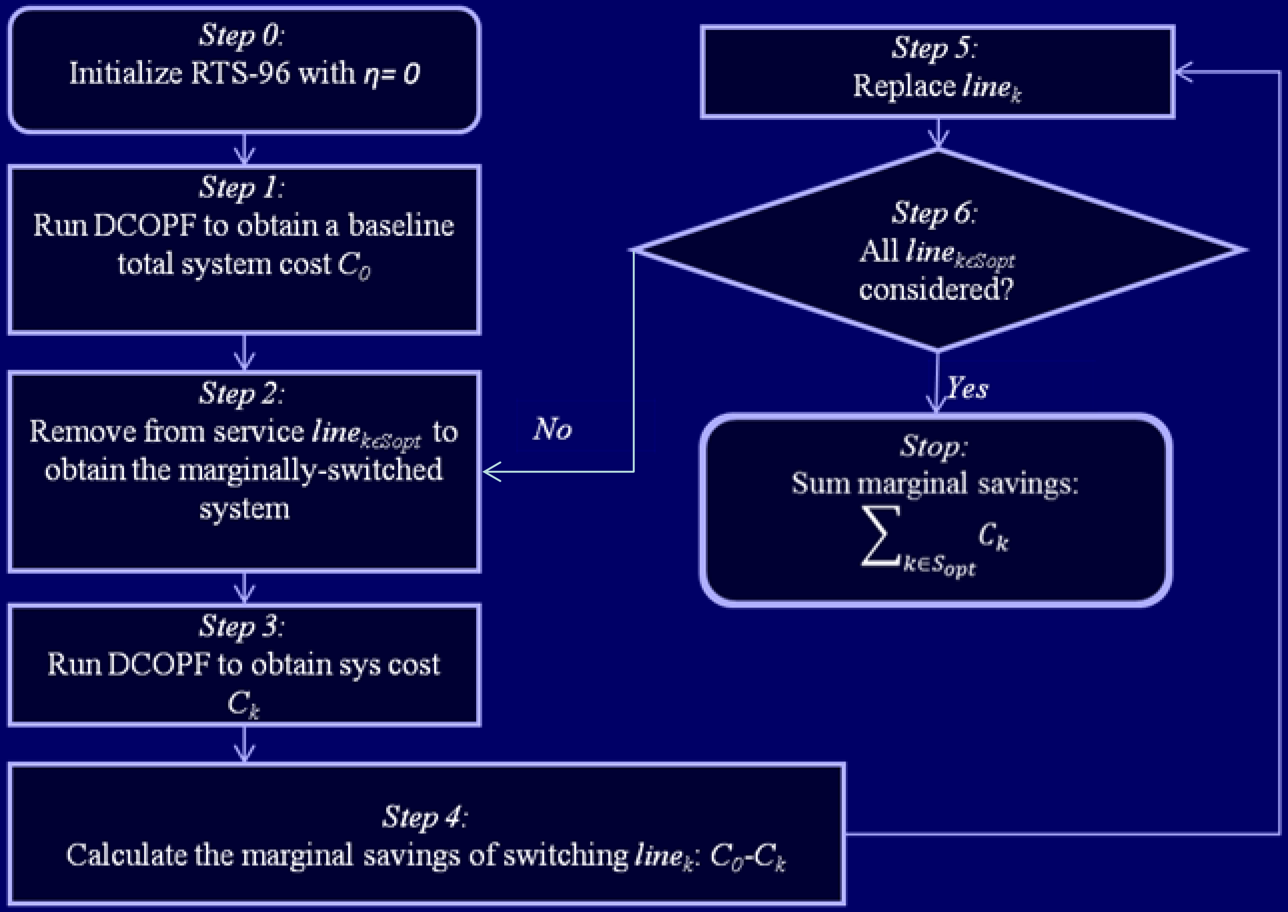
- Marginal Transmission Switching in the RTS-96
  - Savings are due to switching a relatively small number of lines
  - The effects of switching a line are somewhat localized

cpb155@psu.edu

Network Forensics



Marginal Switching Analysis



PENNSTATE

Marginal Switching

Lines	Periods (Hours)																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
109-111																								
112-113																								
113-215																								
201-202																								
209-211																								
215-216																								
215-221																								
217-218																								
218-221																								
218-221																								
219-220																								
219-220																								
220-223																								
220-223																								
309-311																								
310-311																								
318-321																								
318-321																								
320-323																								
320-323																								

Observations

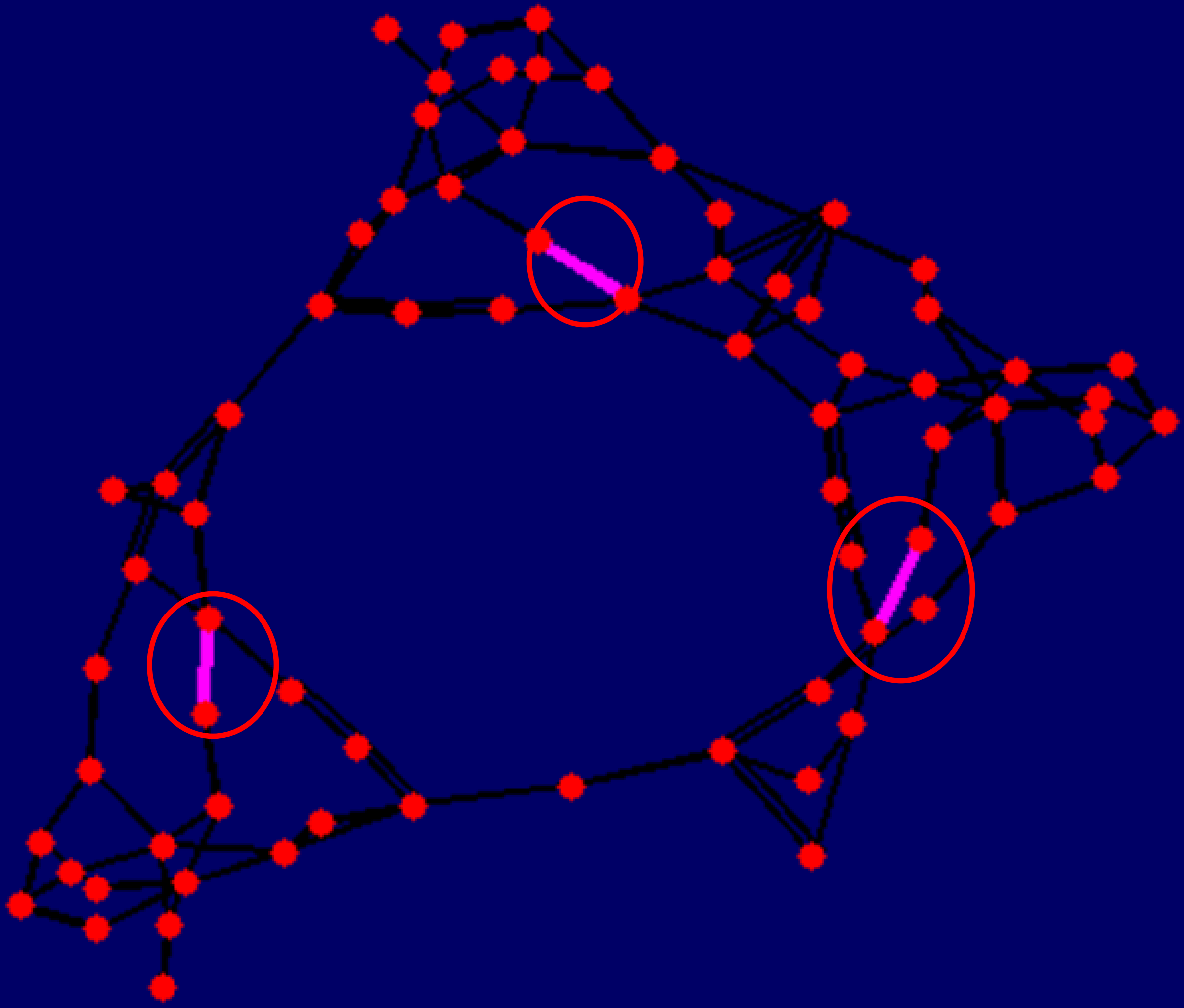
- **OTS savings are primarily due to the switching actions of a small number of lines**
  a) **The lines that contribute most to savings reside in separate areas**
  b) **The difference between the sum of Marginal Switching savings and OTS savings is small**

  The effects of switching a line are somewhat localized

- **Problem complexity scales by # of lines considered in optimization (*feasible topologies* = *$2^{\#\ lines}$*)**
  - **2 Strategies for complexity reduction**
    1. **Screen for Switchable Lines**
    2. **Network Partitioning**

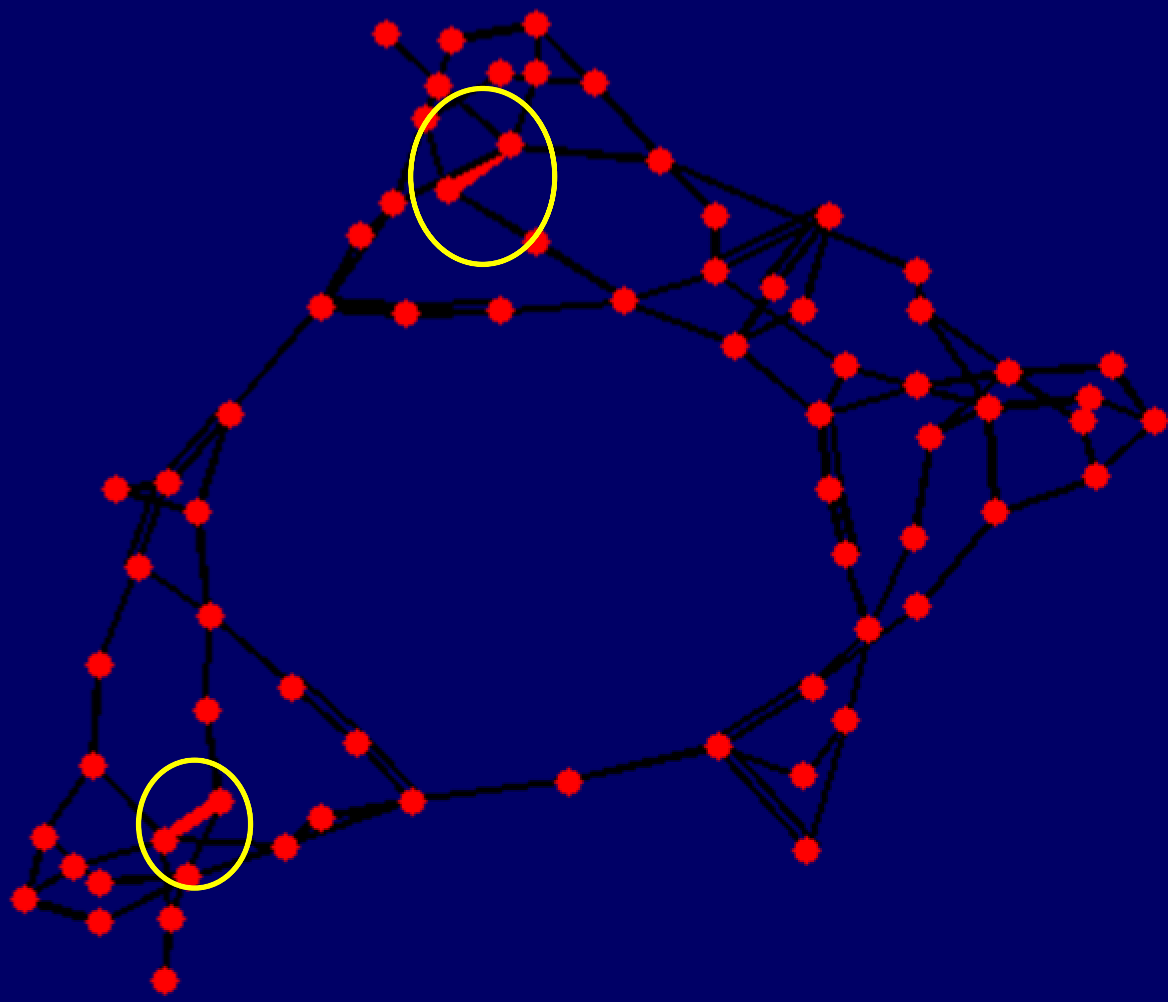
cpb155@psu.edu

RTS-96 Congestion (Hour 20)



cpb155@psu.edu

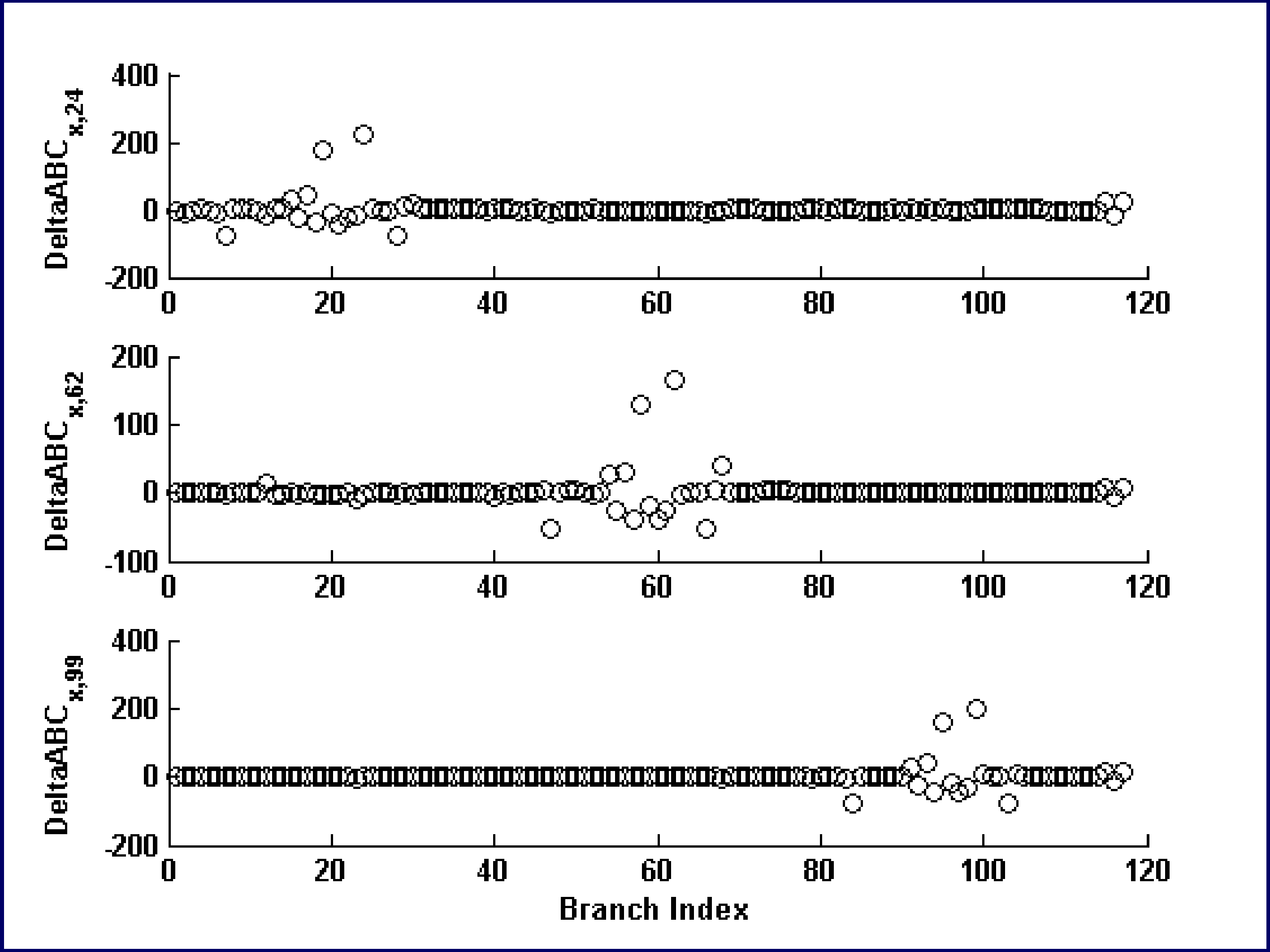
RTS-96 OTS Results (Hour 20)



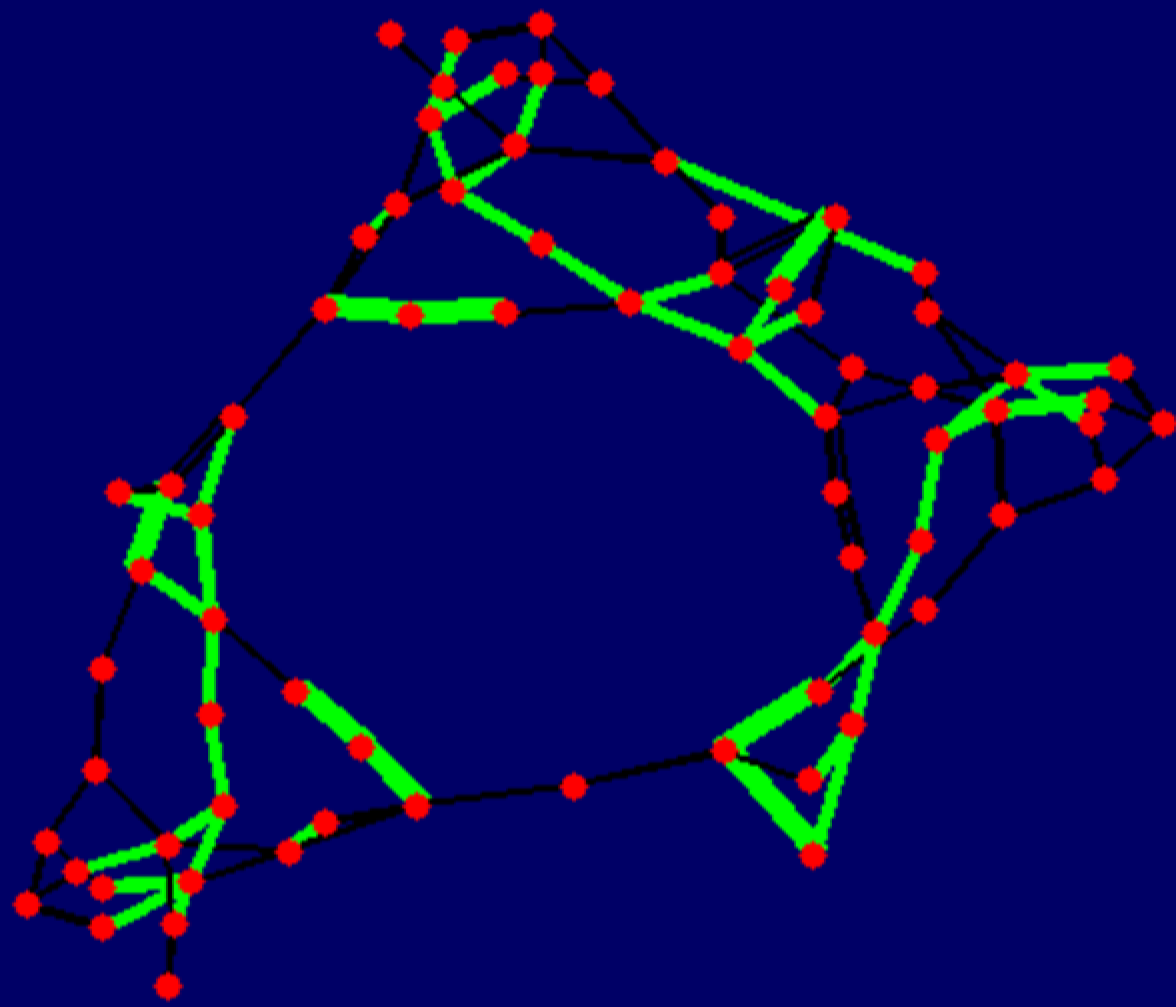
LODF

- $L_{ij,mn} = \frac{\Delta f_{ij}}{f_{mn}^{0}} = \frac{\psi_{ij}^{m} - \psi_{ij}^{n}}{1 - \psi_{mn}^{m} + \psi_{mn}^{n}}$
  - Δf_{ij}- Change in MW flow on *Line*$_{ij}$
  - f_{mn}^{0}- Original MW flow on *Line*$_{mn}$
  - ψ_{ij}^{m}- Δf_{ij} due to an injection at *node*$_{m}$
- $\Delta ABC_{mn} = \sum_{ij} L_{ij,mn} \cdot \left(f_{mn}^{0} \mu_{ij} + f_{nm}^{0} \mu_{ji} \right)$
  - Change in Available Branch Capacities due to a removal of *Line*$_{mn}$
  - μ – LaGrange multiplier on the line flow constraints
- $Line_{\mathbf{mn}}|_{\Delta ABC_{mn} > \mathbf{0}} \in \boldsymbol{S}_{\boldsymbol{switchable}}$

ΔABC in the RTS-96: Hour 20

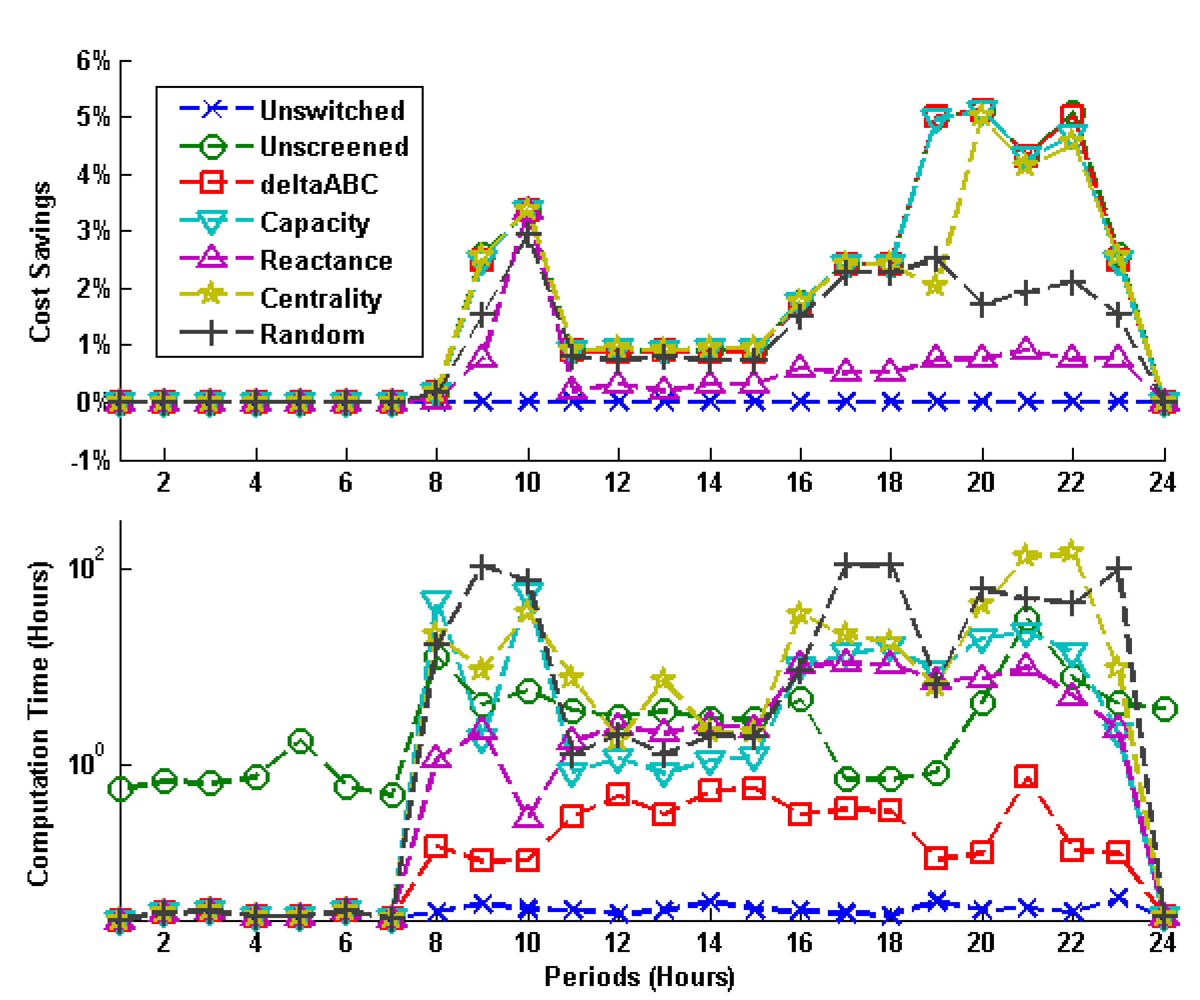


RTS-96 ΔABC Screen (Hour 20)



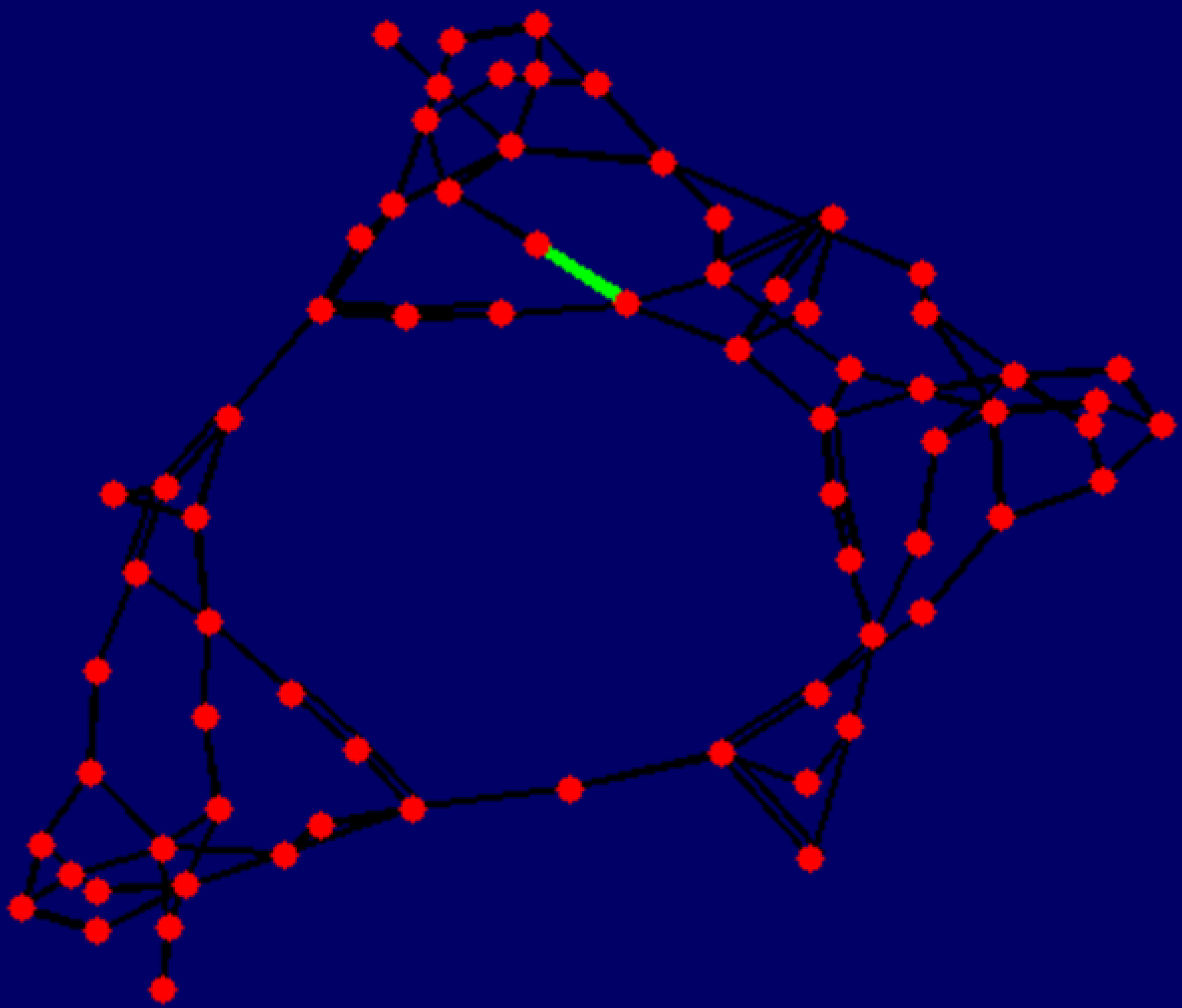
PENNSTATE

RTS-96 Screened OTS Results



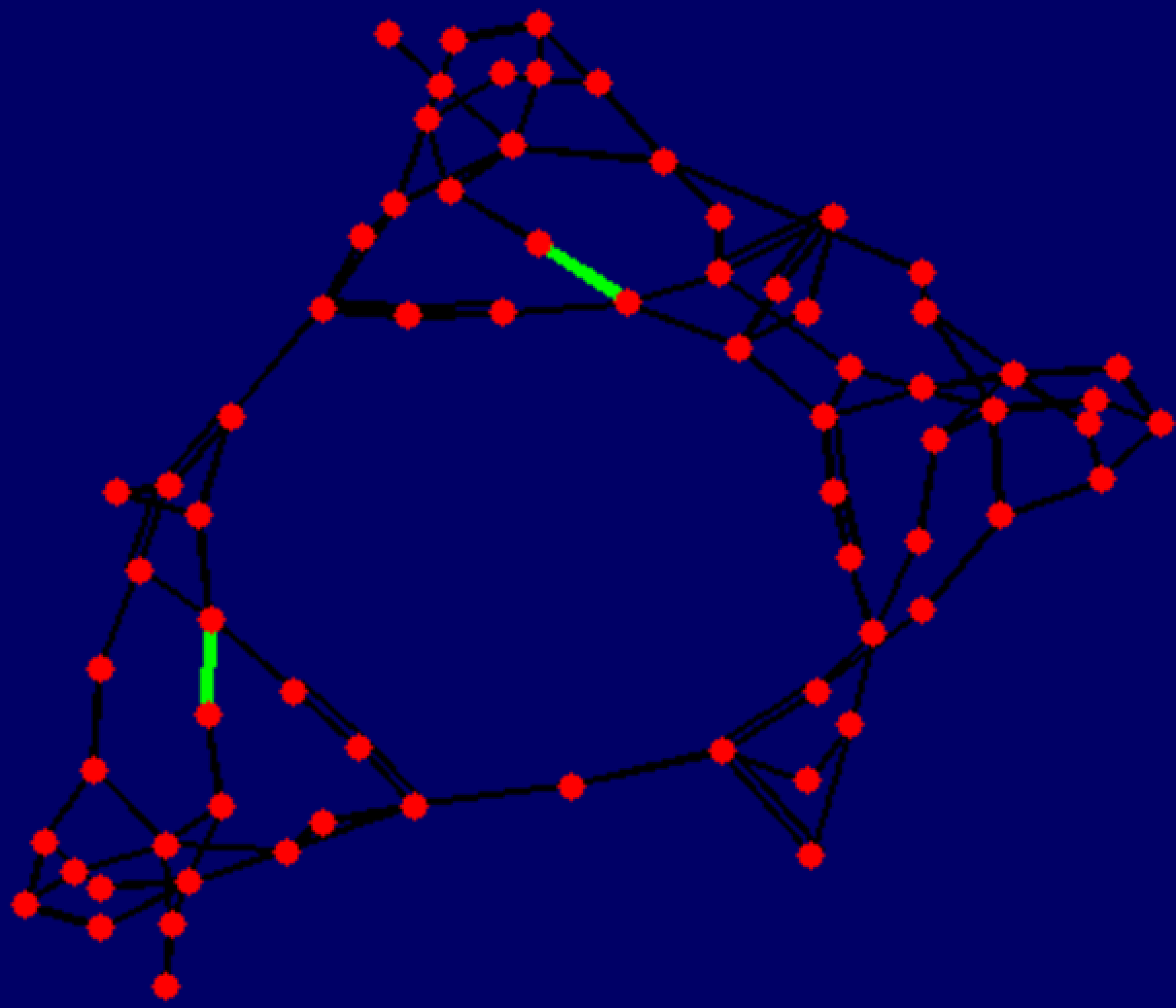
cpb155@psu.edu

RTS-96 ΔABC Screen (Hour 20)

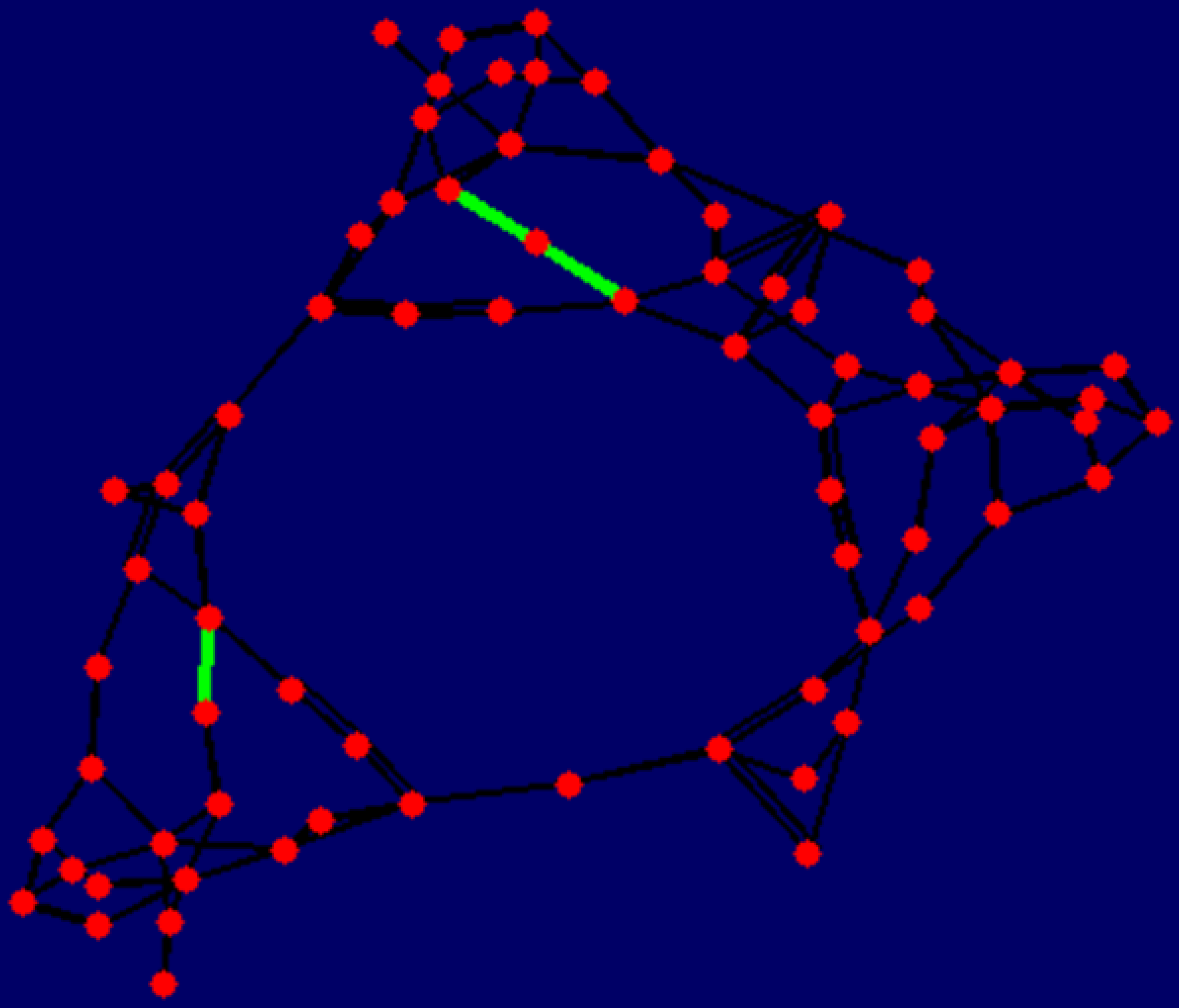


cpb155@psu.edu

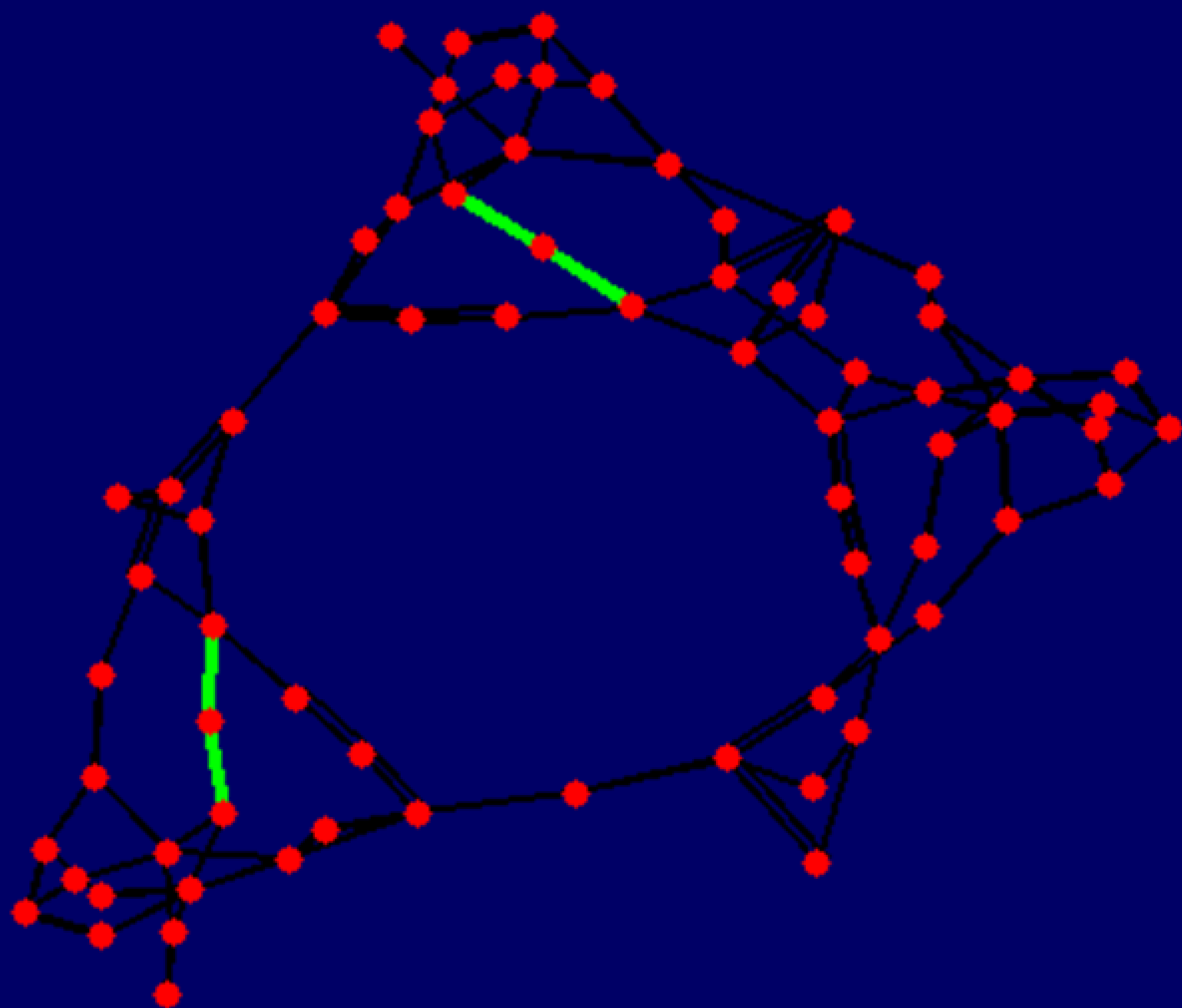
RTS-96 ΔABC Screen (Hour 20)



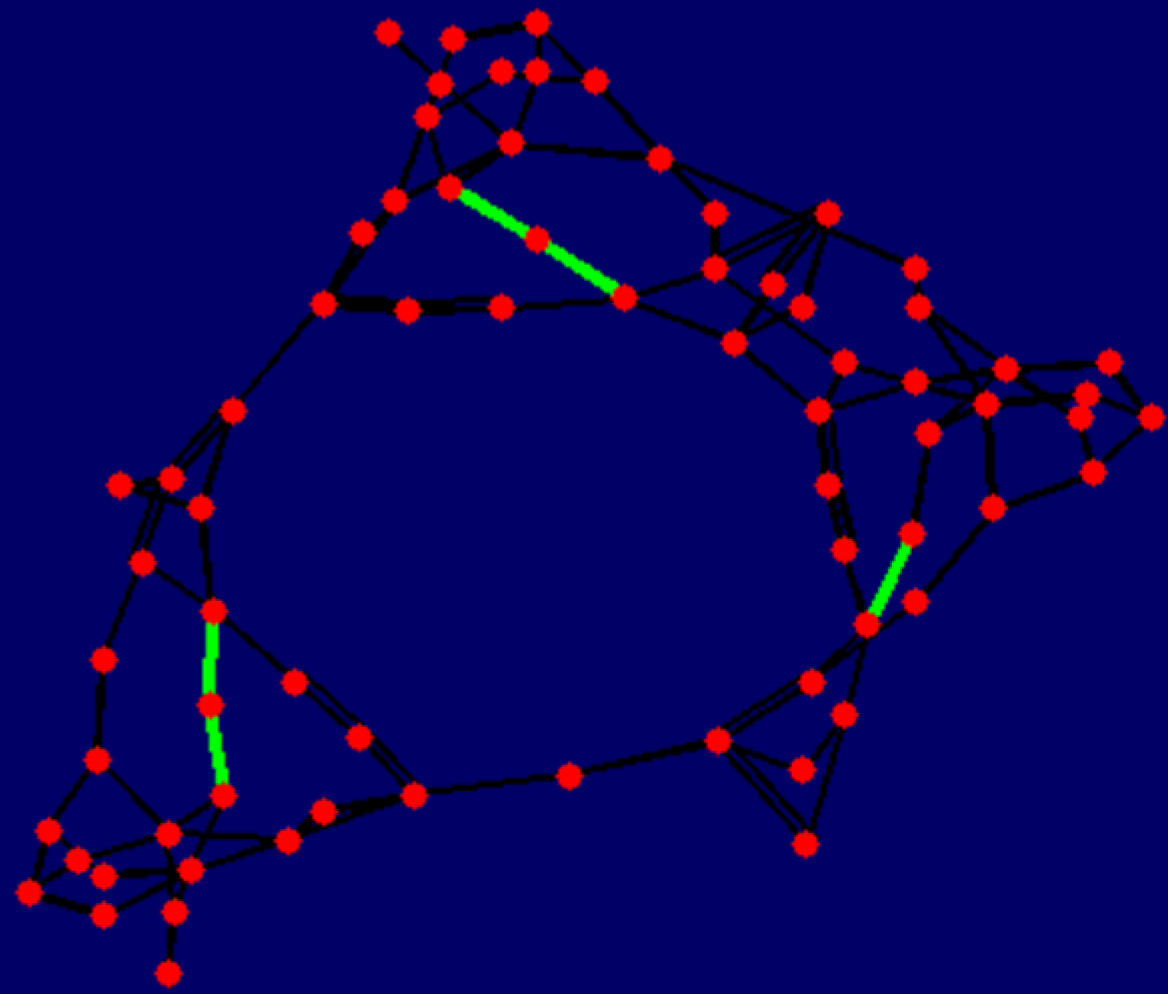
RTS-96 ΔABC Screen (Hour 20)



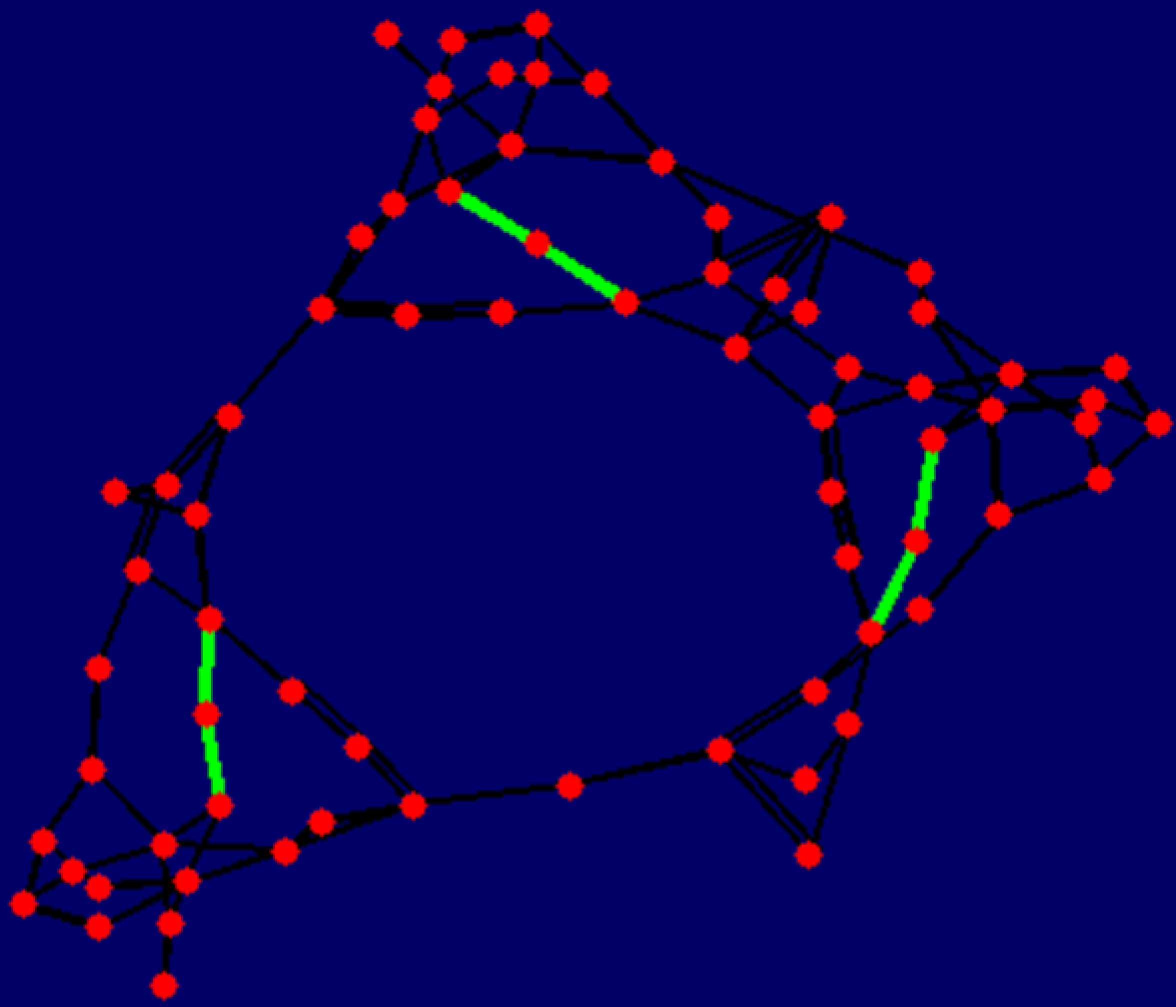
RTS-96 ΔABC Screen (Hour 20)



RTS-96 ΔABC Screen (Hour 20)

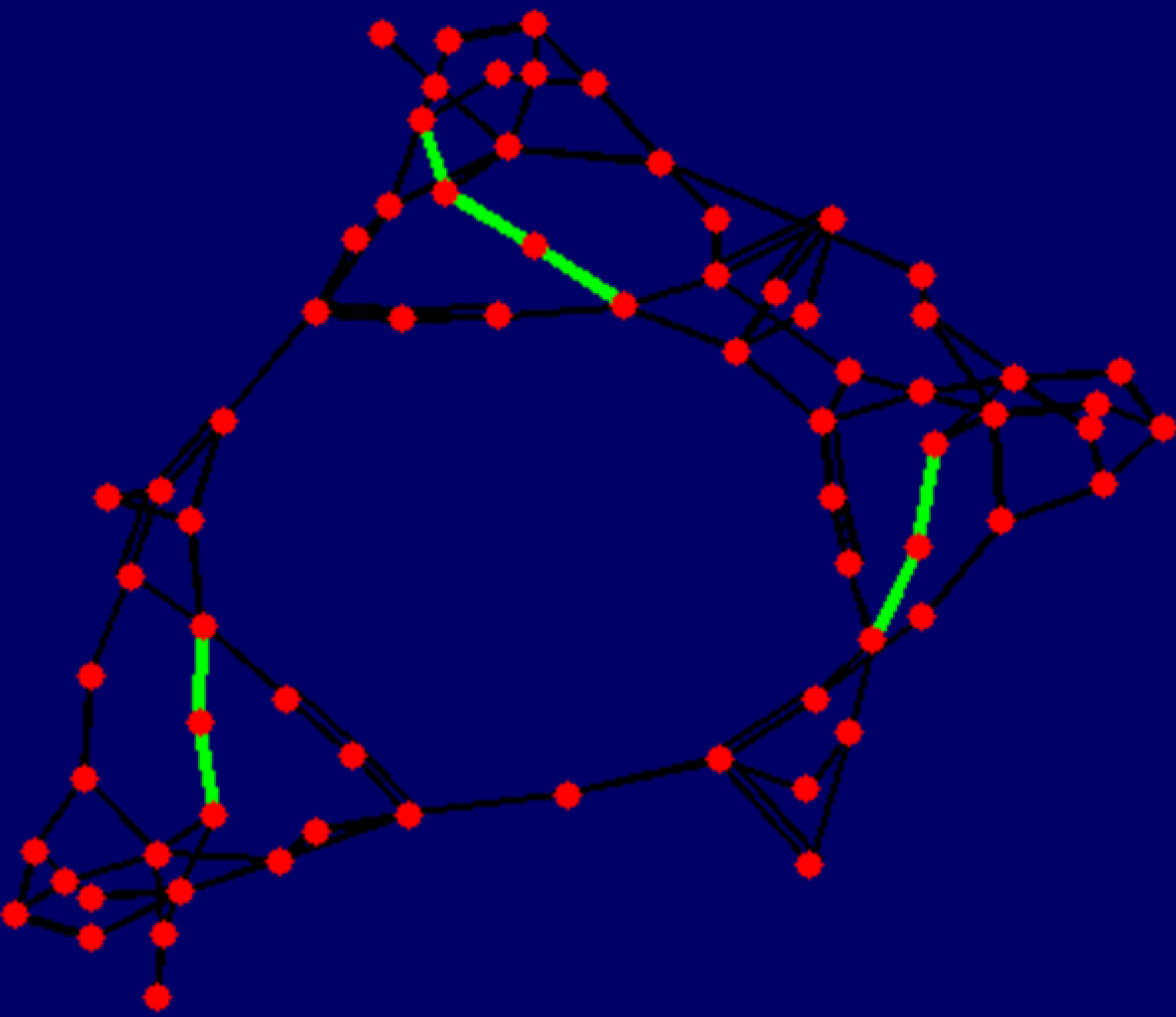


RTS-96 ΔABC Screen (Hour 20)

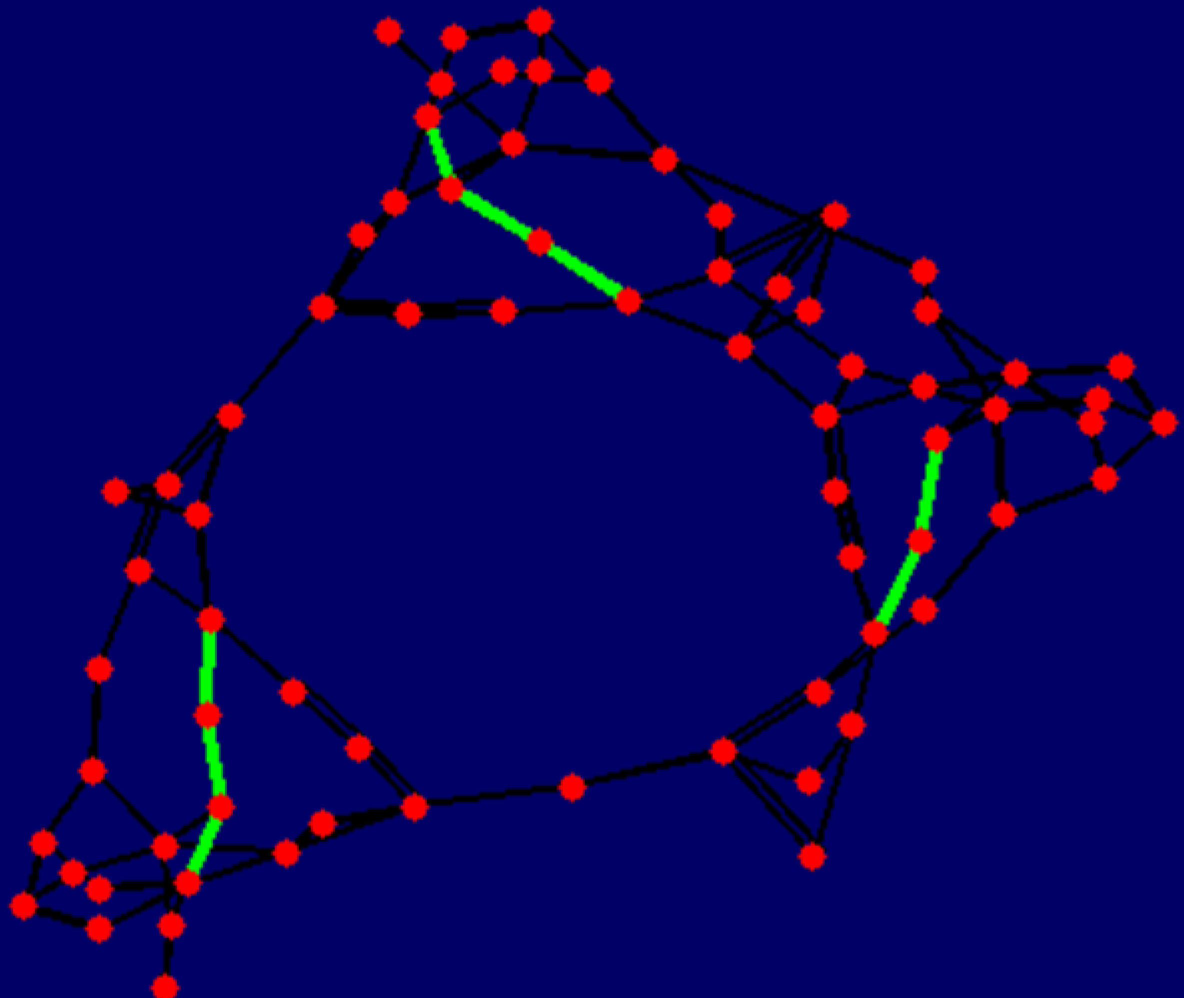


cpb155@psu.edu

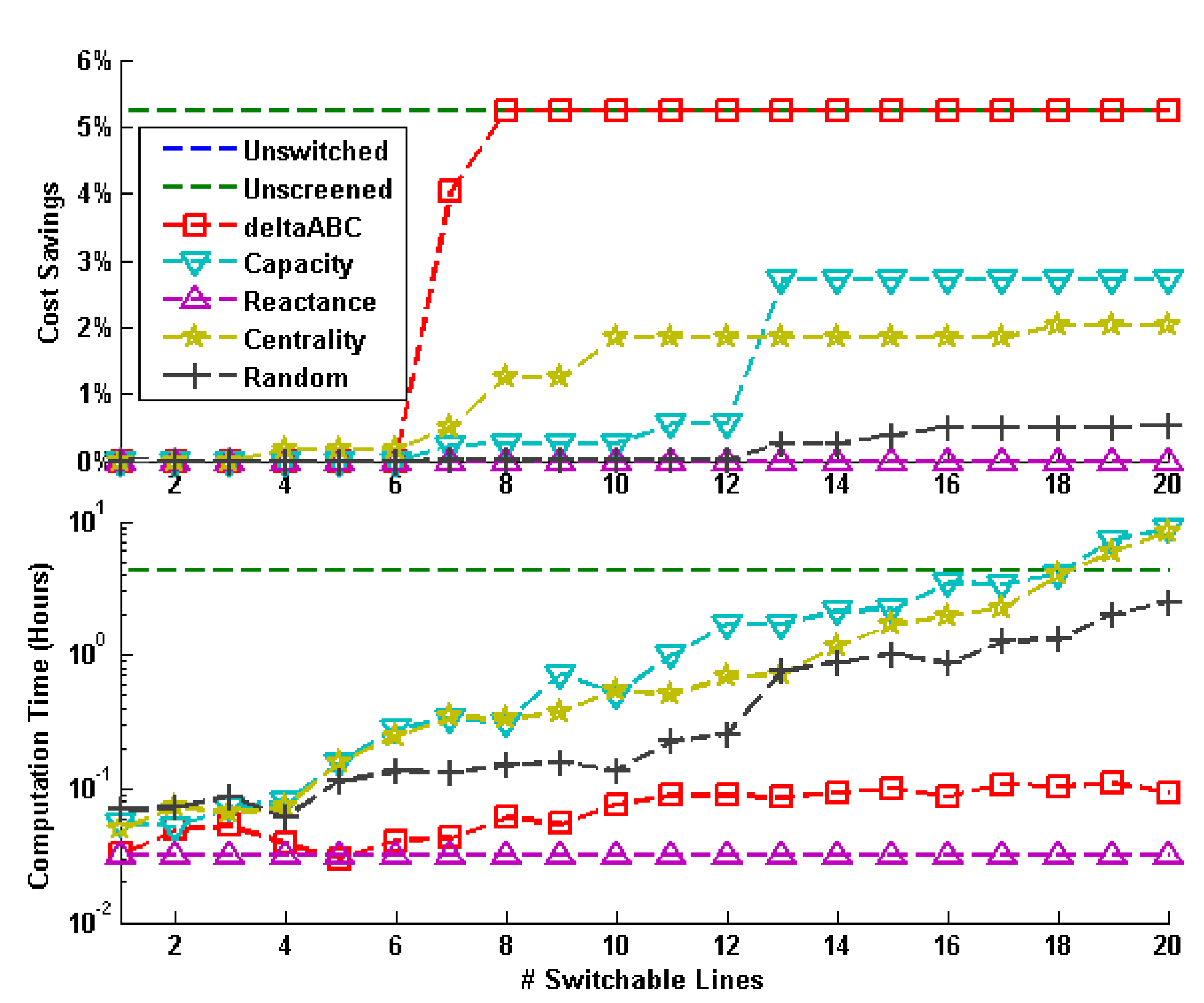
RTS-96 ΔABC Screen (Hour 20)



RTS-96 ΔABC Screen (Hour 20)

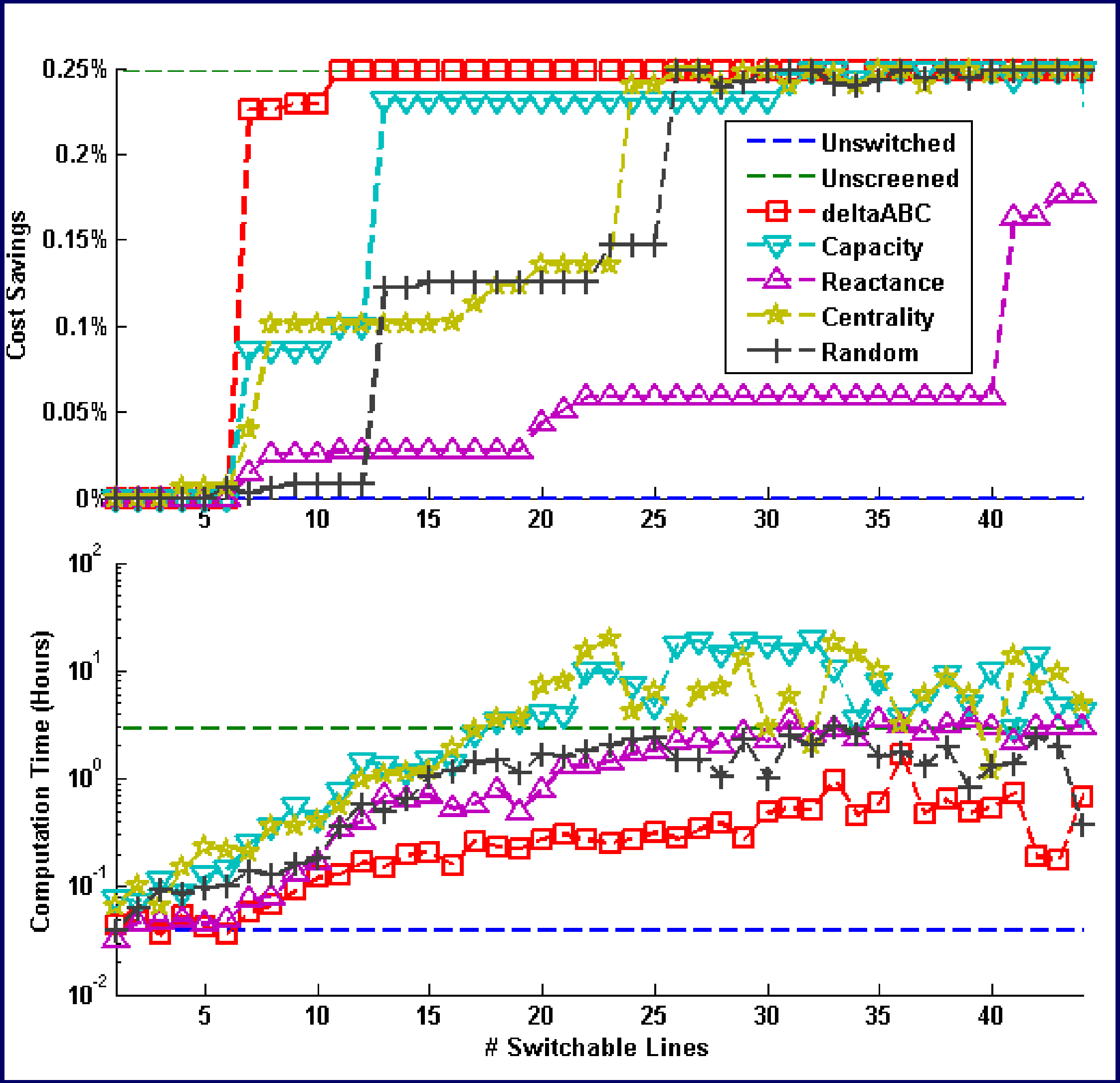


RTS-96 Progressive Screen (Hour 20)

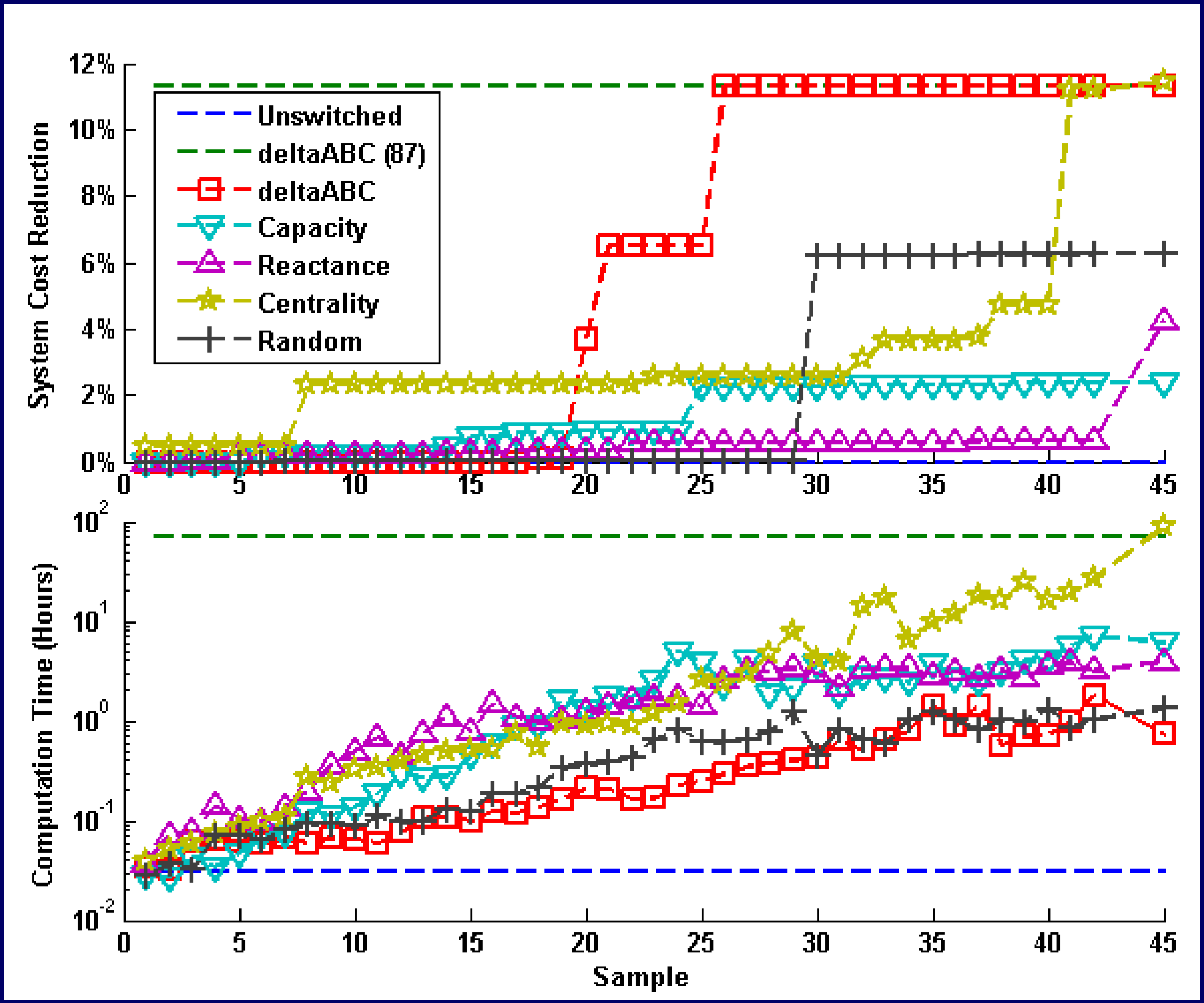


cpb155@psu.edu

RTS-96 Progressive Screen (Hour 14)



IEEE 118-Bus Network



cpb155@psu.edu

Summary

	RTS-96			IEEE 118-BUS (26 SWITCHABLE LINES)	
Screen	**Avg Hourly Savings (Sav_h > 0)**	**Total Savings**	**24hr Solution Time**	**Savings**	**Solution Time**
DCOPF	0%	0%	0.76 hr	0%	0.03 hr
OTS	1.71%	2%	100.93 hr	15.8%*	213 hr*
ΔABC	**2.43%**	**1.98%**	**4.97 hr**	**11.3%**	**0.29 hr**
Capacity	2.42%	1.97%	216.94 hr	2.3%	2.23 hr
Reactance	0.69%	0.58%	78.5 hr	0.59%	2.58 hr
Centrality	2.21%	1.8%	491.65 hr	2.55%	2.31 hr
Random	1.52%	1.25%	692.22 hr	0.01%	0.62 hr

*Suboptimal result

- **OTS has large savings potential**
  - **Problem is too complex to solve quickly**
  1. **Partitioning enables solutions on parallel sub-networks**
  2. **Screening reduces the set of candidate switchable lines and facilitates faster solutions**

Ongoing Work

- **OTS and Screened OTS application to larger networks**
    - **Polish Power Models: ~2000 buses**
    - **Eastern Interconnect**
- **Network Partitioning**
    - **Partition network and apply OTS to distinct sub networks**
- **Verify AC power flow feasibility under reconfigured topology**

Acknowledgements

- This work was supported in part by a student research fellowship provided by LANL and CNLS

References

- S. Blumsack, "Network Topologies and Transmission investment Under Electric-Industry Restructuring," PhD Thesis, Carnegie Mellon, 2006.
- E. Fisher, R. O'Neill, and M. Ferris, "Optimal Transmission Switching," *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 1346-1355, Aug. 2008
- K. Hedman, M. Ferris, R. O'Neill, E. Fisher, and S. Oren, "Co-Optimization of Generation Unit Commitment and Transmission Switching With N-1 Reliability," *IEEE Transactions on Power Systems*, vol. 25, no. 2, pp. 1052-1063, May 2010.