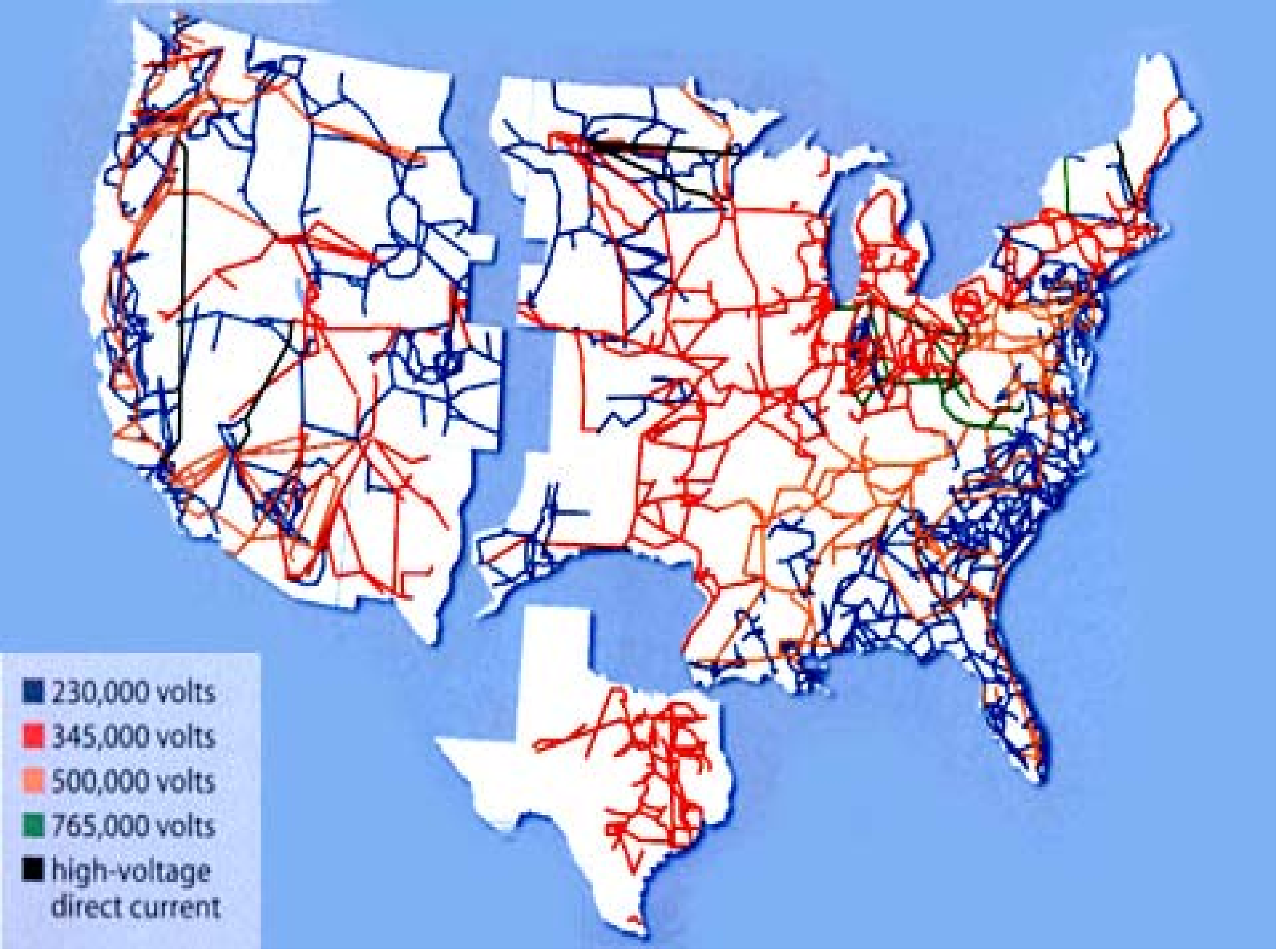
Optimization and Control Theory for Smart Grids

- So what? Impact.
  - savings: (a) 30b$ annually is the cost of power losses,
    10% efficiency improvement=> 3b$ savings,
    (b) cost of 2003 blackout is 7-10b$, 80b$ is the total cost of blackouts annually in US
  - further challenges (more vulnerable, cost of not doing planning, control, mitigation)
- Grid is being redesigned [stimulus]

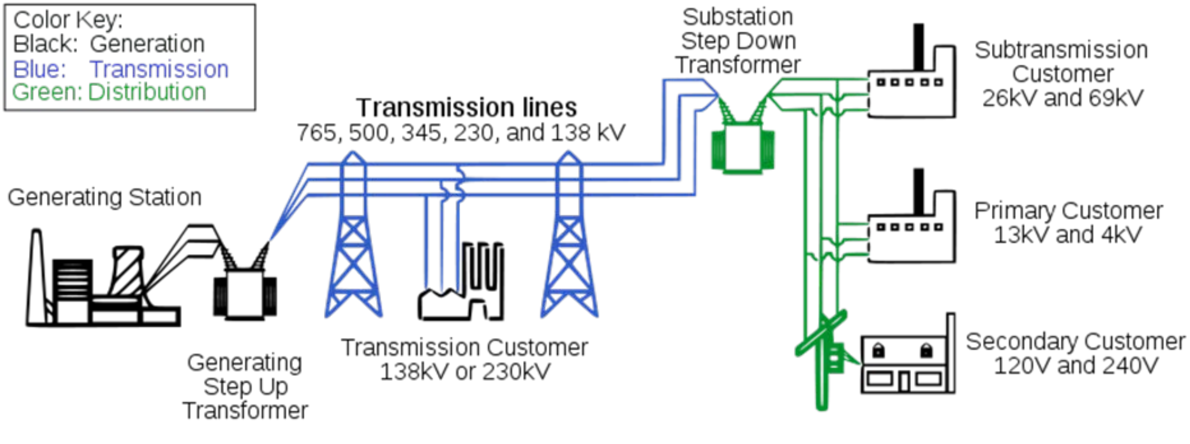
  The research is timely.

  -2T$ in 20 years (at least)



US power grid

Greatest Engineering Achievement of 20^{th} century



will require smart revolution in 21^{st} century

Smart Grid as an Opportunity for LANL

Green Grid
(NM, smart metering)
25M,50M,100M

LANL is DOE-OE/EERE/OS
Lablet (beyond DHS,
->DOE, D + T)

Our DR provides

Information Science Foundation

for the future programmatic efforts!!

Our (LANL) *Road Map* for Smart Grids

New Systems

- Renewables
- PHEV & Storage
- Metering

Grid Stability

- distance to failure
- dynamic stability
- outages/rare events
- cascading
- signature detection

Grid Control

- load balancing
- queuing and scheduling
- optimal power flows
- feeder lines control
- distribution and switching with redundancy

Grid Design

- placement of generations and storage
- intermittent wind as an integrated capacity
- accounting for outages and intermittency in planning

New Challenges

All of the above also requires scientific advances in

- Analysis & Control
- Stability/Reliability Metrics
- State Estimation
- Data Aggregation & Assimilation
- Middleware for the Grid
- Modeling Consumer Response

Grid Design (I)

Pilot study

Toole,Fair,Berscheid,Bent '09

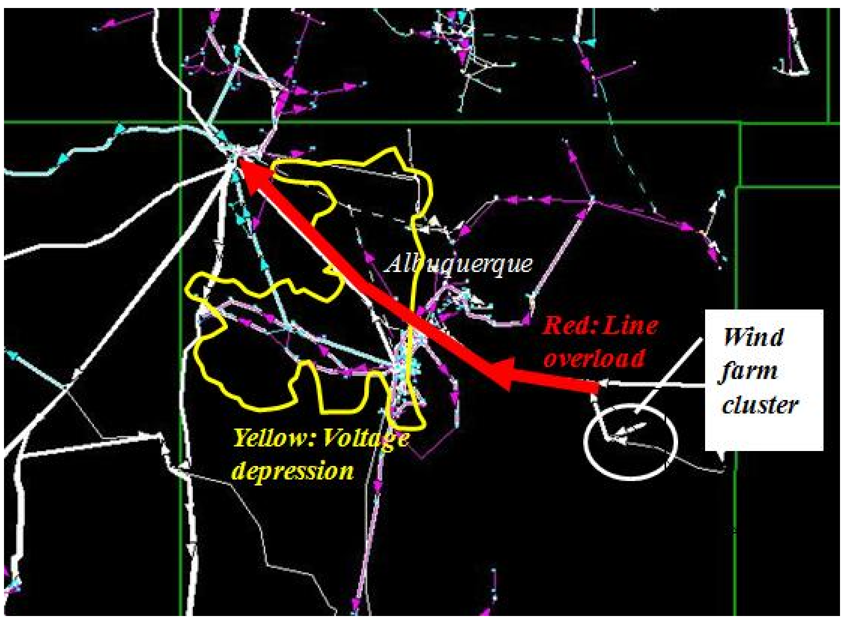
extending NREL ``20% by 2030"

LAUR 09-03-164

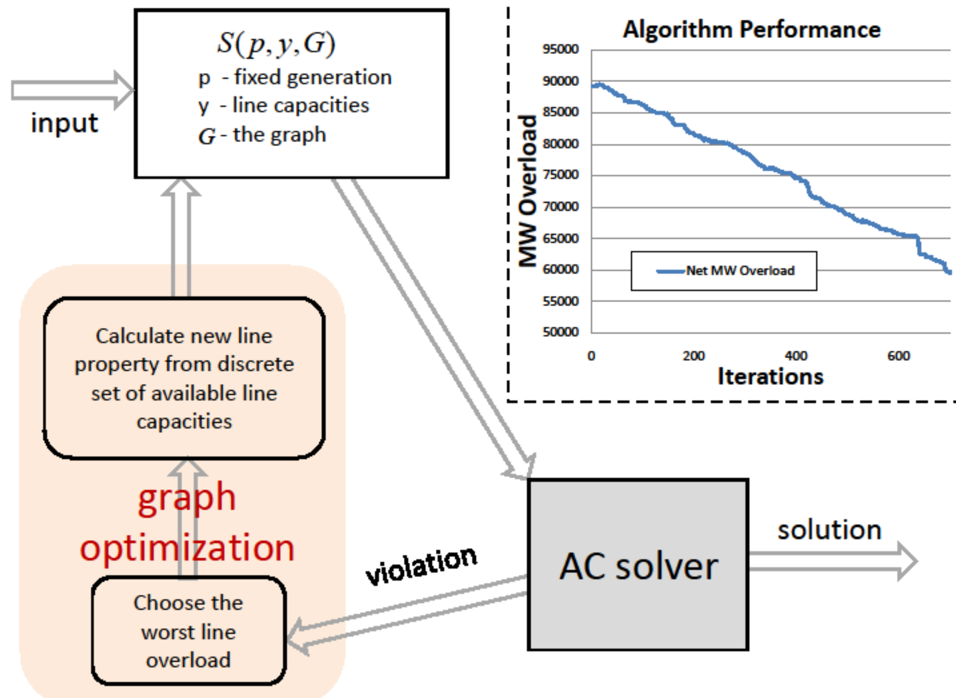
- design grid of the future
- account for costs
- account for power flow
- incremental growth
- plan for renewables/intermittency
- account for stability/contingency

NREL:

- Cost dispatch only
- Power flows highly approximate
- Unstable solutions
- Intermittency in Renewables not accounted



An unstable Grid Example



Our IT Suggestions: Hybrid Optimization (discussed with S. Chu last month)

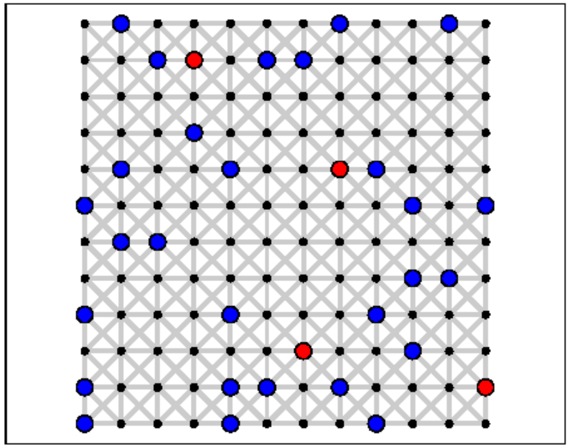
Grid Design (II)

Pilot study

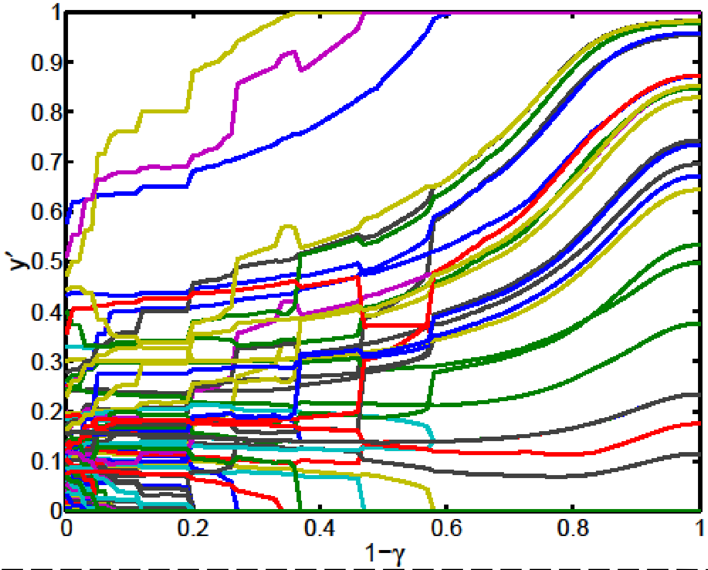
Johnson, Chertkov '09

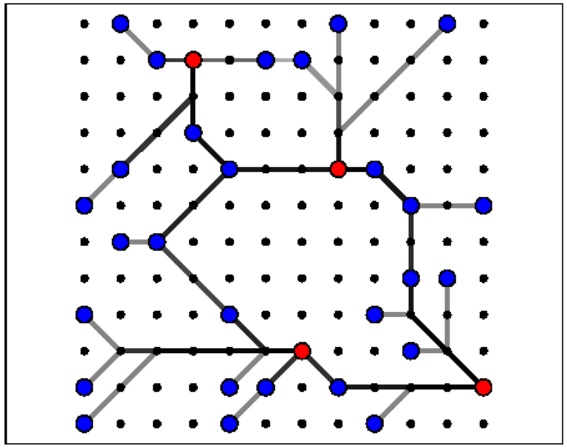
Network Optimization

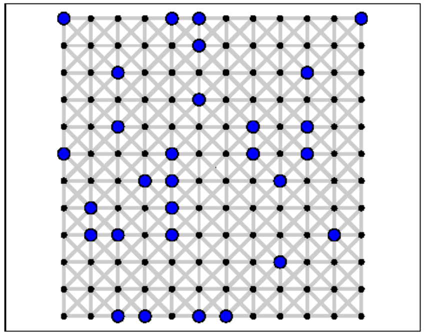
Generators – red dots
Loads – blue dots

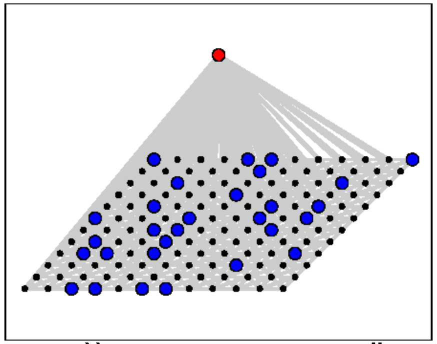

original graph for line optimization

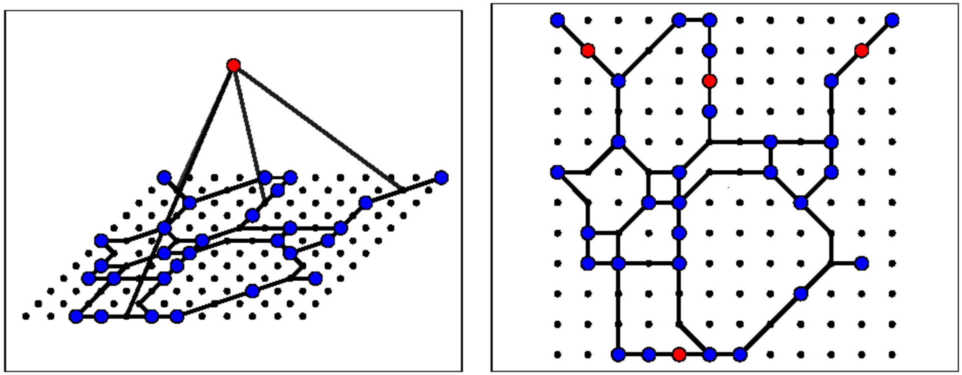
edge weights annealed




resulting sparse solution


original graph for generation placement


``master generator" connected to possible sites.

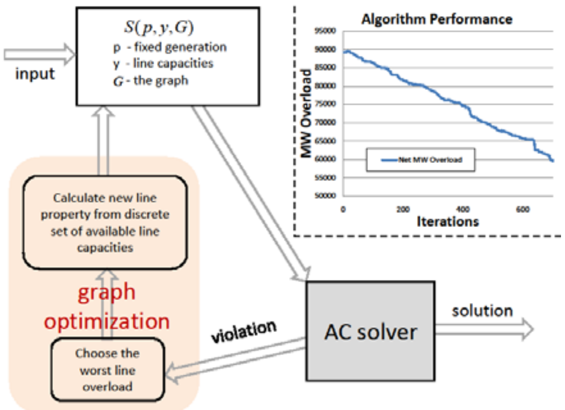

Resulting Sparse Network

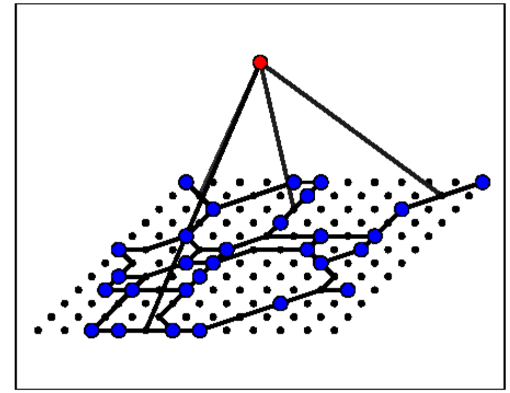
$$\text{minimize} \quad \mathrm{Tr}(K(y)^{-1}W) + \textstyle\sum_{\ell \in G} c_\ell \left(\frac{y_\ell}{\hat{y}_\ell}\right)^\gamma$$
$$\text{subject to} \quad 0 \le y_\ell \le \hat{y}_\ell \text{ for all } \ell \in G$$

y – vector of conductances (subject to optim.)
K(y) – capacitance matrix of the graph G
W- matrix of demand (input)
c – vector of costs (input)

Grid Design : Milestones

Thrust leader: *Bent*





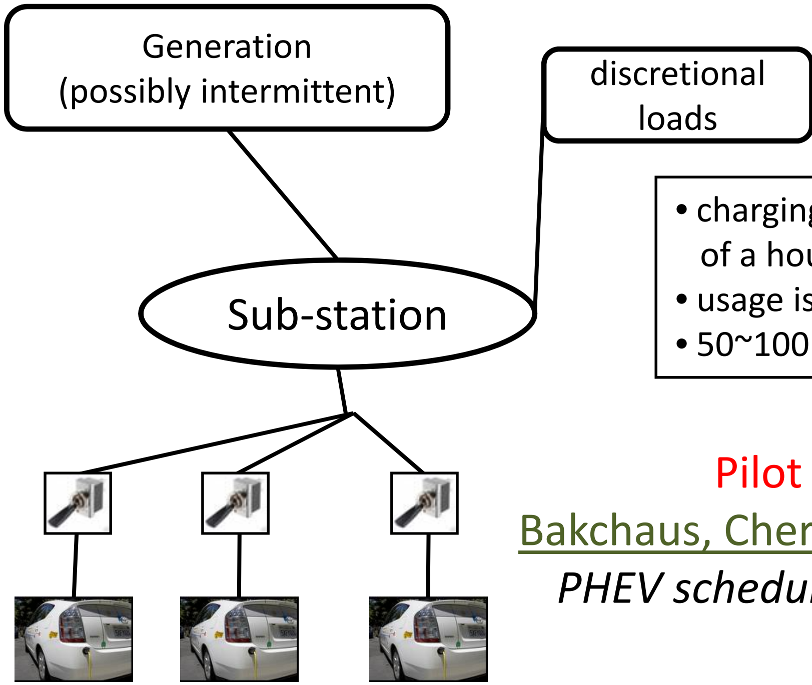
Lower Risks,
high computation time requirements

Higher Risks, with strong
theory support

- Develop comprehensive theory and algorithms for network optimization (accounting for intermittency in renewables)
- Develop Hybridization & Simulation approach, first tests on NREL models
- <u>*Combine and Compare Network Optimization & Hybrid Optimization approaches*</u>
- Develop a set of realistic cost functions, e.g. accounting for geography
- Apply Developed Algorithms to Placement of Renewables in the Rocky Mountain Belt
- Account for Stability Metric in planning and effects of Control <u>*[connects to other two thrusts]*</u>
- <u>*Develop and Calibrate LANL toolbox for power grid planning*</u>

Grid Control (I)

- Load Balancing (shave peeks fill valleys)
- Scheduling of loads, generators, storage
- Switching within the grid/graph
- Queuing of load arrival
- Distributed (in space-time) control

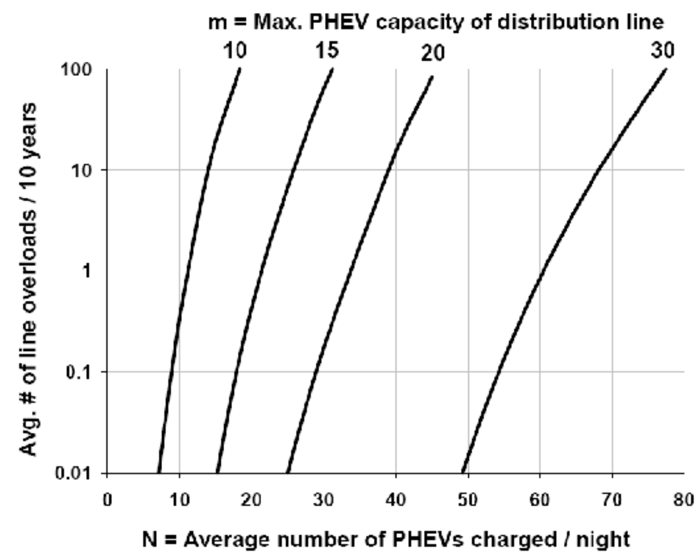


- charging a car will ~ double consumption of a household
- usage is correlated (6pm = back home effect)
- 50~100 users on a feeder line -> easy to overload

Pilot Study

Bakchaus, Chertkov, Gupta '09

PHEV scheduling & queuing



Questions

- How many cars can be charged without overload and with proper scheduling (overnight)
- What is an optimal scheduling algorithms without communications? [random number switch … distribution?]
- … with one-way or two-way communications?
- Utilizing some PHEV for storage? V-2-grid.
- How to control charging from Renewable Generation?

M/M/m queuing model.

Utilization can be improved with communication aware scheme

Grid Control (II)

- generators matched to loads
- generators have caps (limits). Overload means shedding.
- loads may be connected to more than one generator
- connections are controlled by switches

Pilot Study

Zdeborova, Chertkov '09

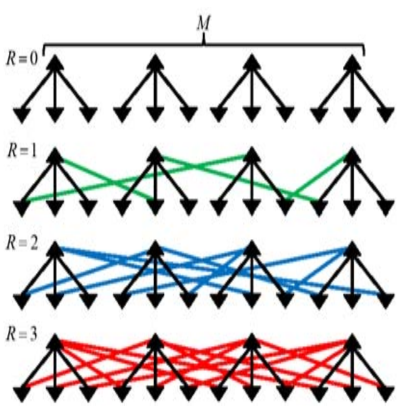
Optimal switching/control

arxiv:0904.0477

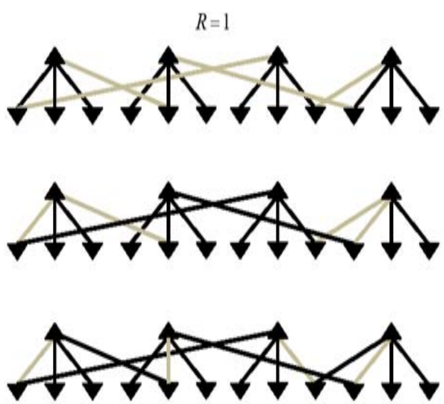
- Quantify advantage of redundancy for loads

- Suggest efficient and distributed control/switching algorithm

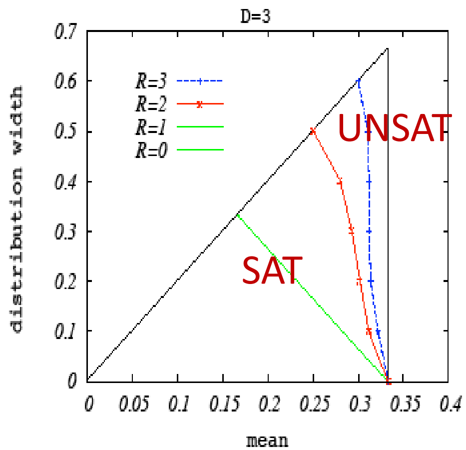
replica+population dynamics technique



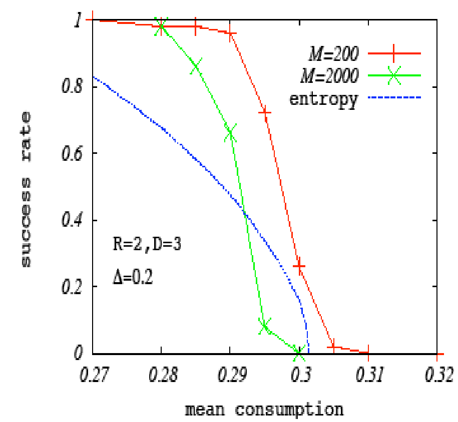
Graph samples.
Ancillary connections
shown in color



Valid configurations



Phase Space split into
SAT=good and UNSAT=bad

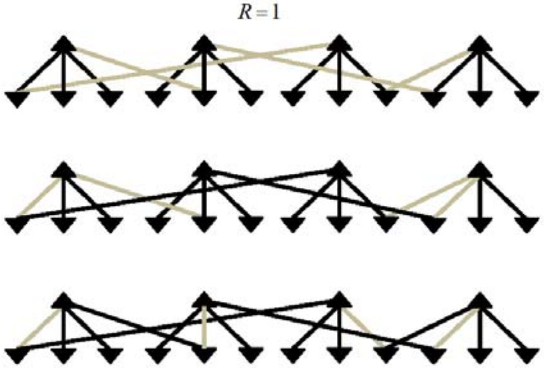


Performance of message
-passing switching algorithms

Grid Control : Milestones

Thrust leader: *Backhaus*

Queuing, scheduling of storage



Optimal and Efficient Switching

Distributed Automatic Control

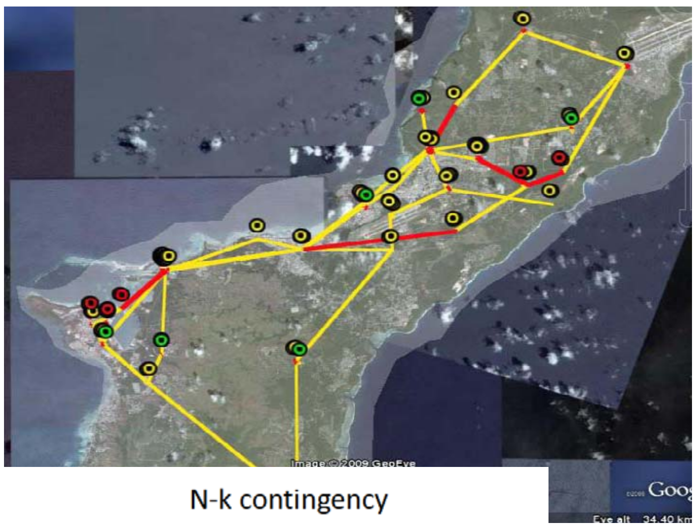
- manage renewables
- right proportion of control between different scales
- to be reconfigurable
- outages proof

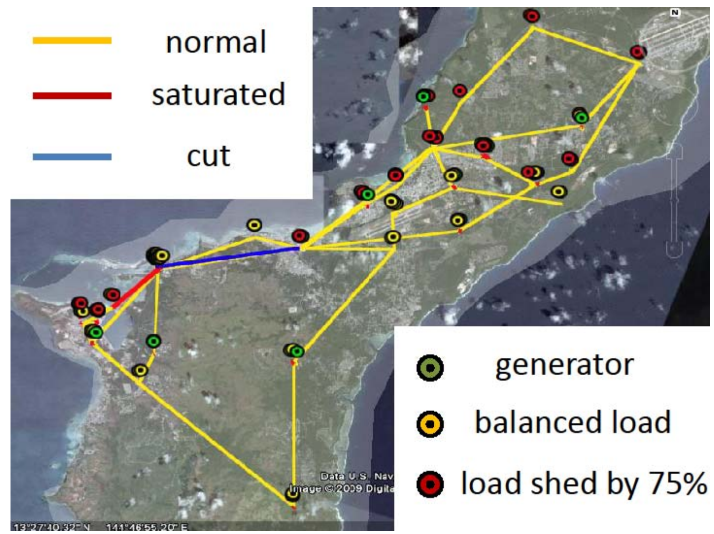
- Local Queuing for PHEV without communications (LANL county, PNM distribution)
- Control for Distribution Level with Renewables
- Feeder lines optimization & automatic control (switching of capacitor banks)
- Local Queuing for PHEV with Communications
- *Message-Passing based control across the layers*
- Adopt distributed model predictive control technique for power grid
- Distributed queuing for PHEV/storage across the grid
- *Implement control schemes on test beds (Green Grid, LA & LANL utility, PNM)*
- Incorporate effects of control into planning & analysis of failures *[connects to other two thrusts]*

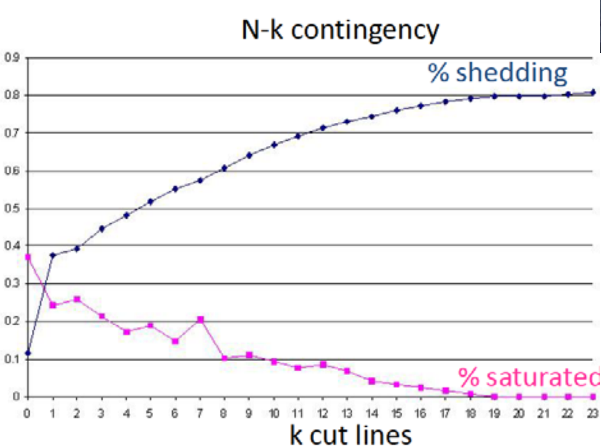
Grid Stability (I)

Static Contingency Analysis of the Grid

- metrics for failures
  [stable (a), non-stable (b), unstable (c)]
- linear, nonlinear, continuous, discreet
- distance to failure, signature detection
- static, dynamics, cascades





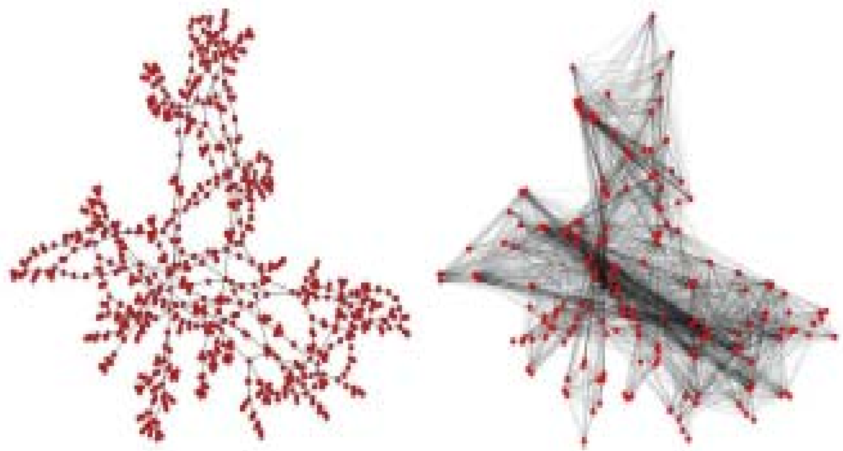


- Find a cut causing max damage, assuming a perfect load shedding control
- Difficult **max min** problem
- Future challenge – make the alg. efficient

Pilot Study
Pan, Chertkov '09
Contingency Analysis

Grid Stability (II)

Pilot Study
Anghel, et al '09
Dynamics & Control
LA-UR-09-02778

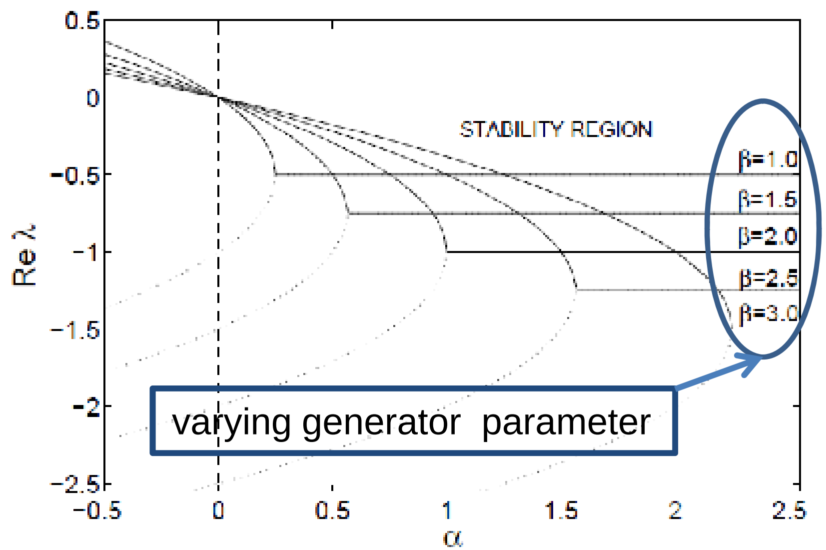


Grid and effective grid (generators only)

Dynamic Linear Stability of the Grid

eigen-value analysis

Domains of the grid stability

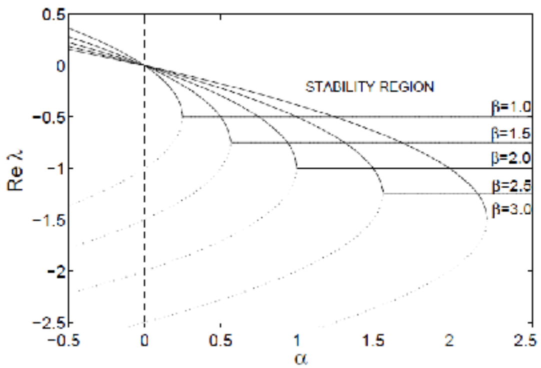


Smallest eigen-value of an effective grid matrix

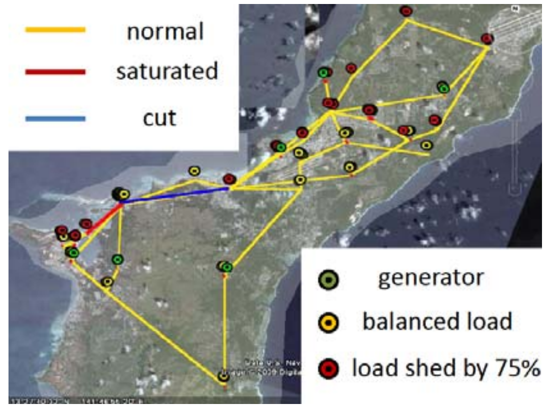
Dynamic Model:

- frequency droop control at any generator
- load is fixed
- sensitivity of the eigen-values to control schemes
- test on realistic (Northern Italy) grid

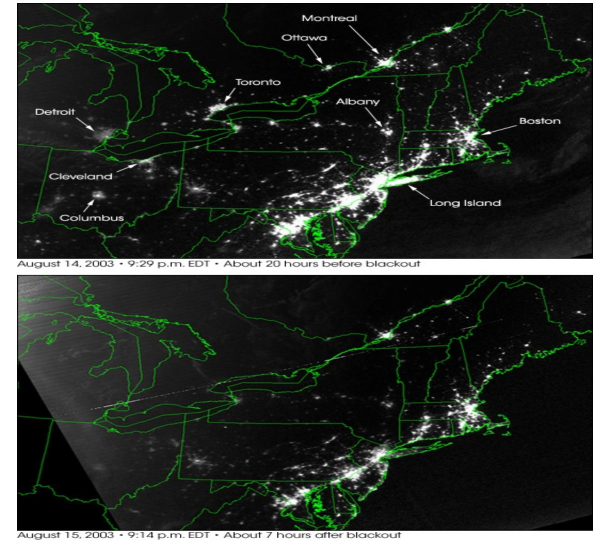
Grid Stability : Milestones



Stability

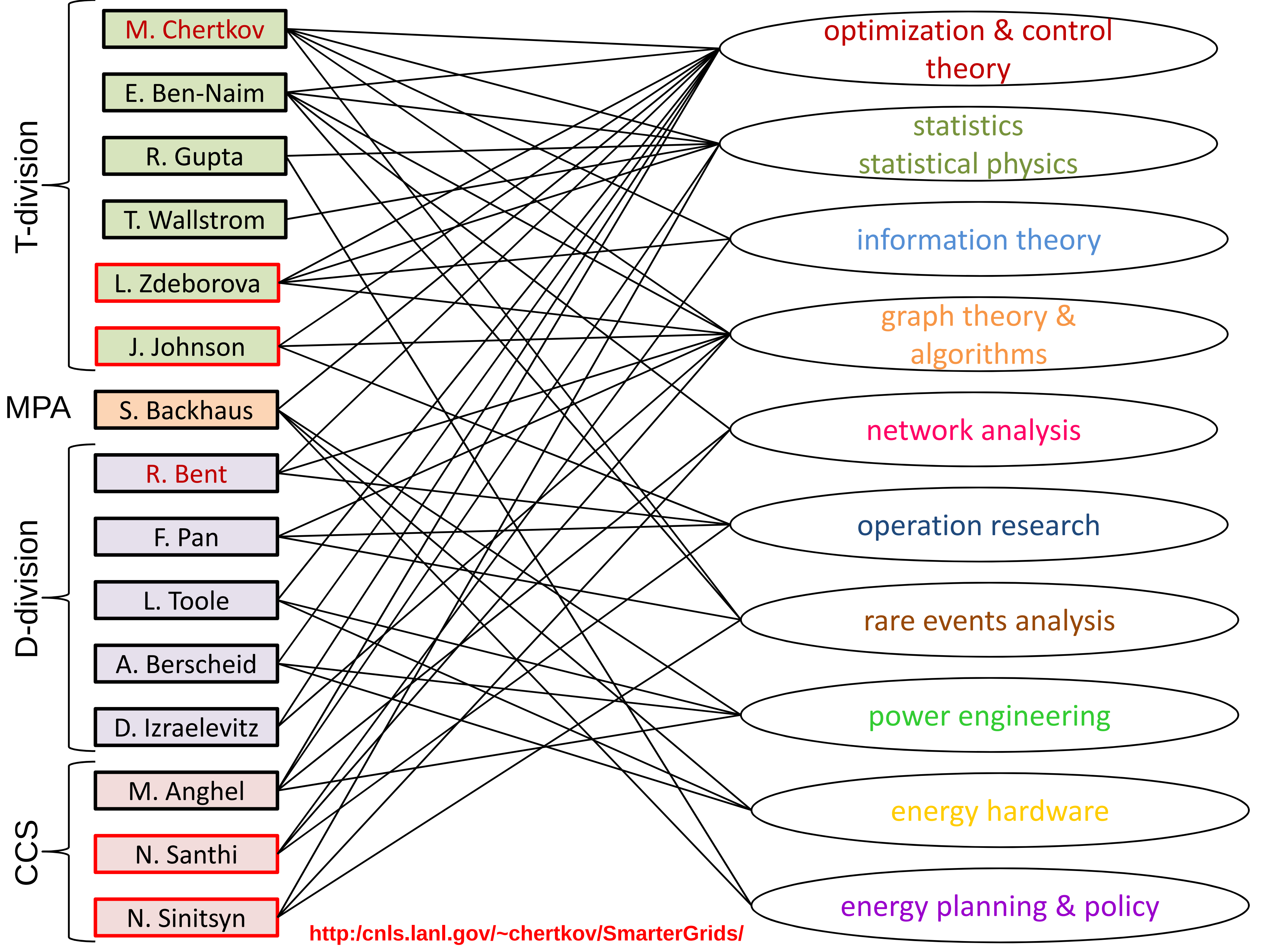


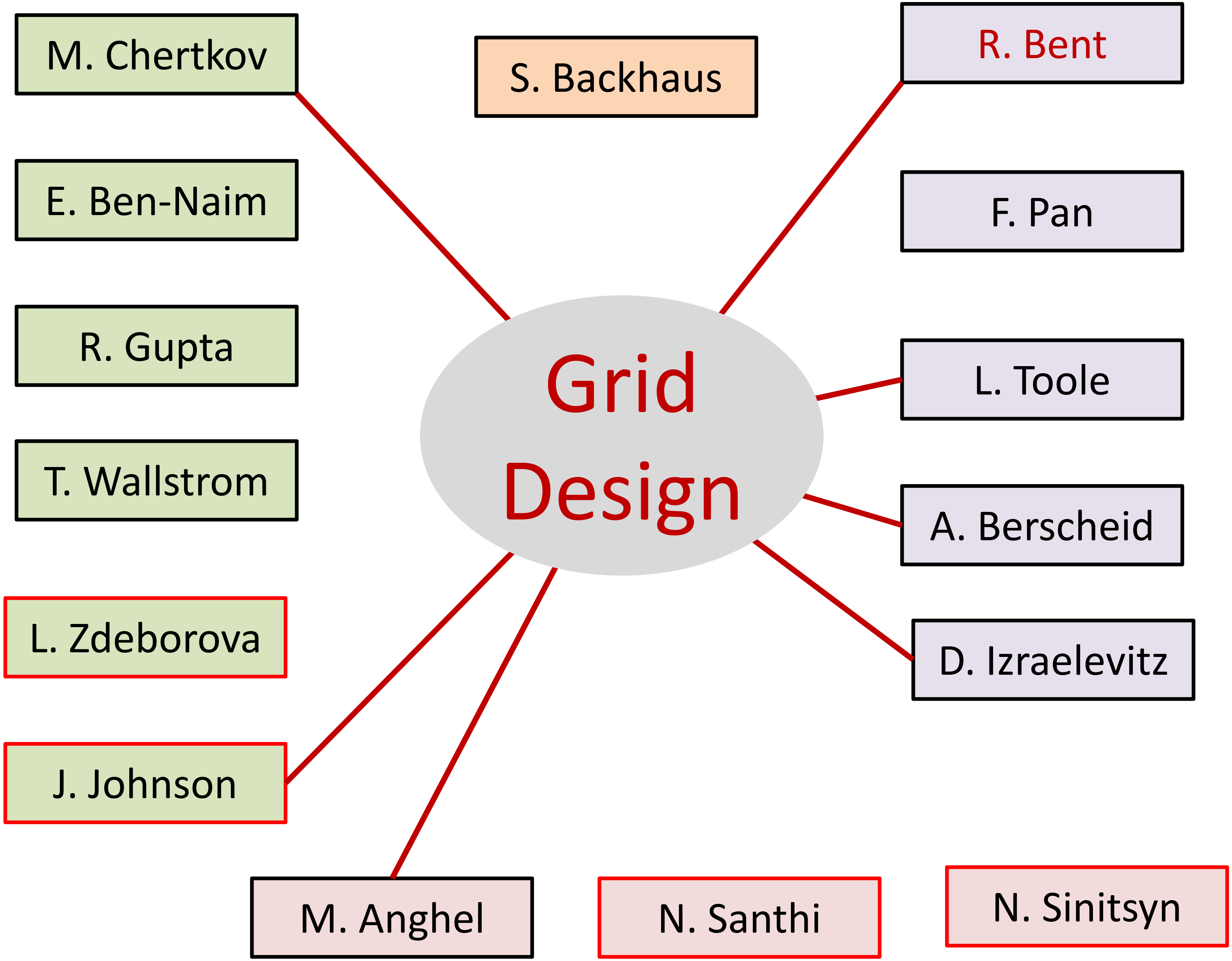
Rare-Events Analysis



Cascades

- Develop classification and metric for different failures
- Study N-k contingencies on the power grid
- *Develop Theory of Cascades*
- Algorithms for Stability within Quasi-Static Models of the Grid
- Damage-control algorithms
- Efficient Algorithms for detection of vulnerabilities within Dynamic Models
- Phase map of the grid as a troubleshooting signature
- Algorithms for cascades, testbed validations (PNM, LANL & county utilites)
- *Signature Detection for grid data-bases (Argonne, NREL, Oakridge)*
- Control & Failure Detection Toolbox for the Grid *[connects to other two thrusts]*


T-division
M. Chertkov
E. Ben-Naim
R. Gupta
T. Wallstrom
L. Zdeborova
J. Johnson
MPA
S. Backhaus
D-division
R. Bent
F. Pan
L. Toole
A. Berscheid
D. Izraelevitz
CCS
M. Anghel
N. Santhi
N. Sinitsyn
optimization & control theory
statistics
statistical physics
information theory
graph theory & algorithms
network analysis
operation research
rare events analysis
power engineering
energy hardware
energy planning & policy
http:/cnls.lanl.gov/~chertkov/SmarterGrids/



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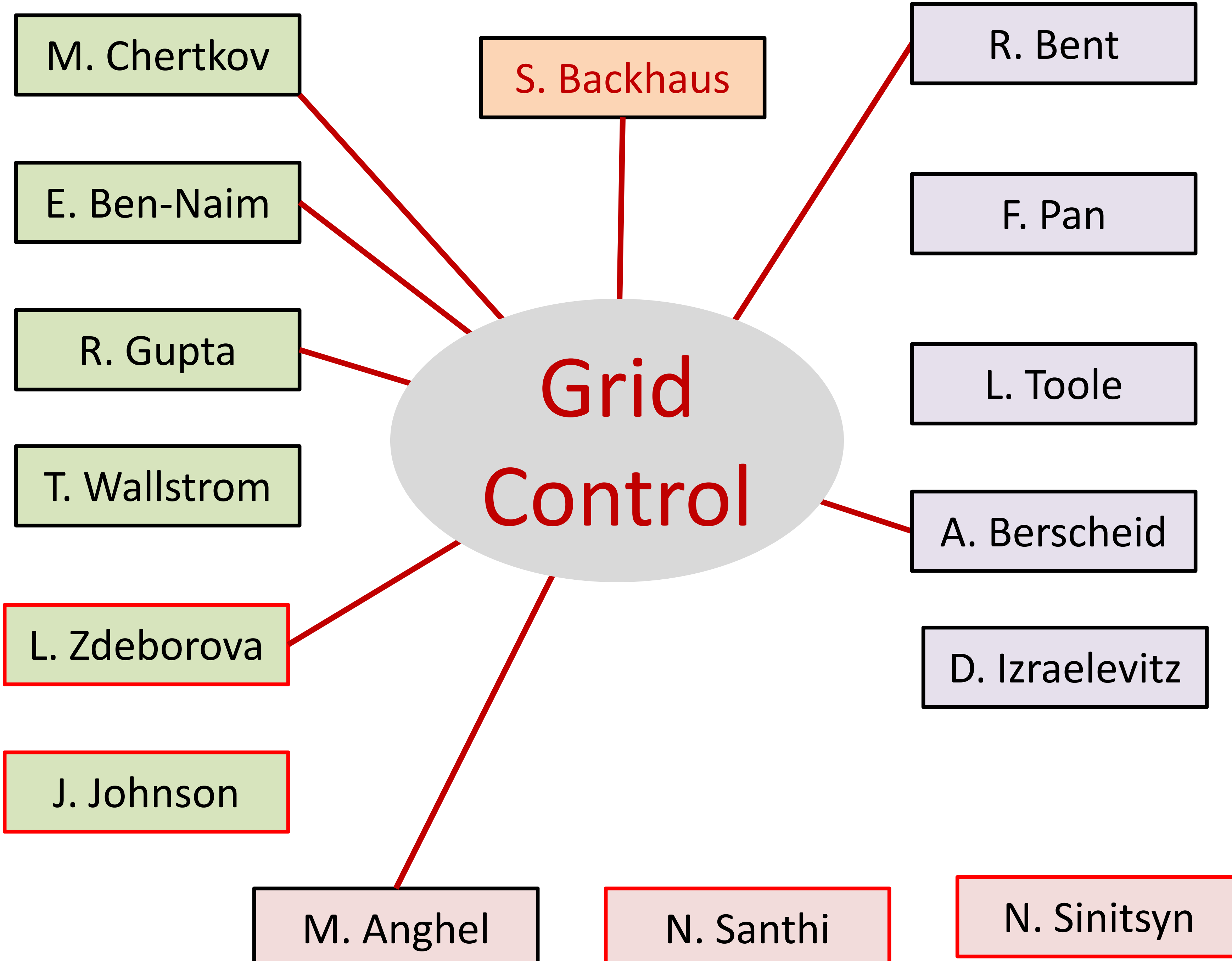
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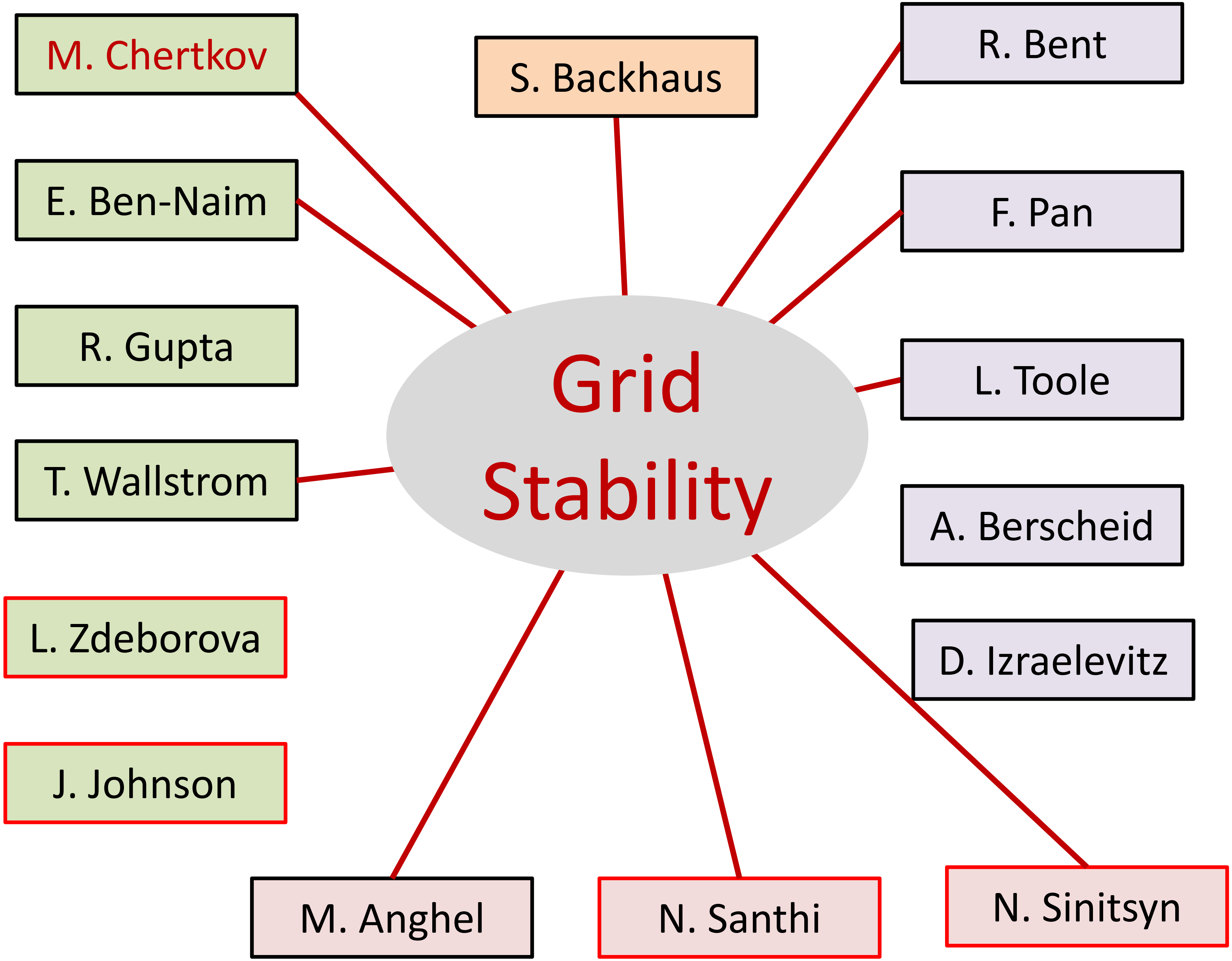
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N. Sinitsyn

Our Collaborators & Competitors

Collaborators:

- MIT/LIDS (control, queuing theory)
- U of Minnesota (power engineering)
- U of Wisconsin (outages, cascades)
- U of Vermont (grid stability)
- Penn State (grid optimization and planning)
- LANL utility & LANL county, PNM (data, test-beds)
- possibly NREL (renewables, data)

Smart Grid Seminar Series

Competitors (as of yet – our strategy => turn into collaboration):

- *PNNL, ORNL, ANL, SNL* (data/grid centers, middleware, +)
- U of Columbia & Berkeley (contingency, mixed optimiz.)
- Boston U (economics of the grid)
- Carnegie Mellon U (control theory for the grid)
- Industry, e.g. *GE, Google, IBM, XCEL Energy*, etc

Thank You!