Toward Optimal Operations

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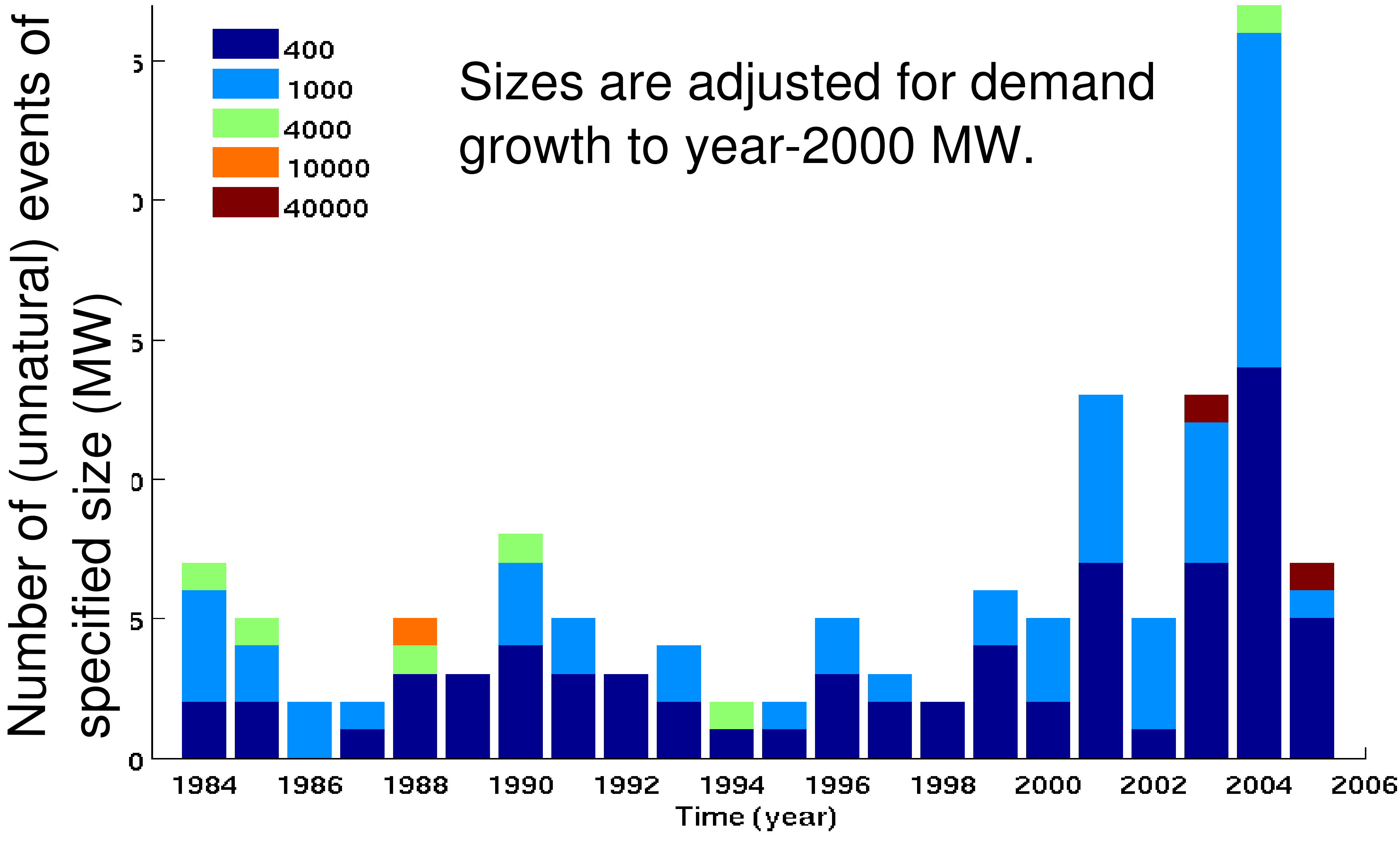
Outline

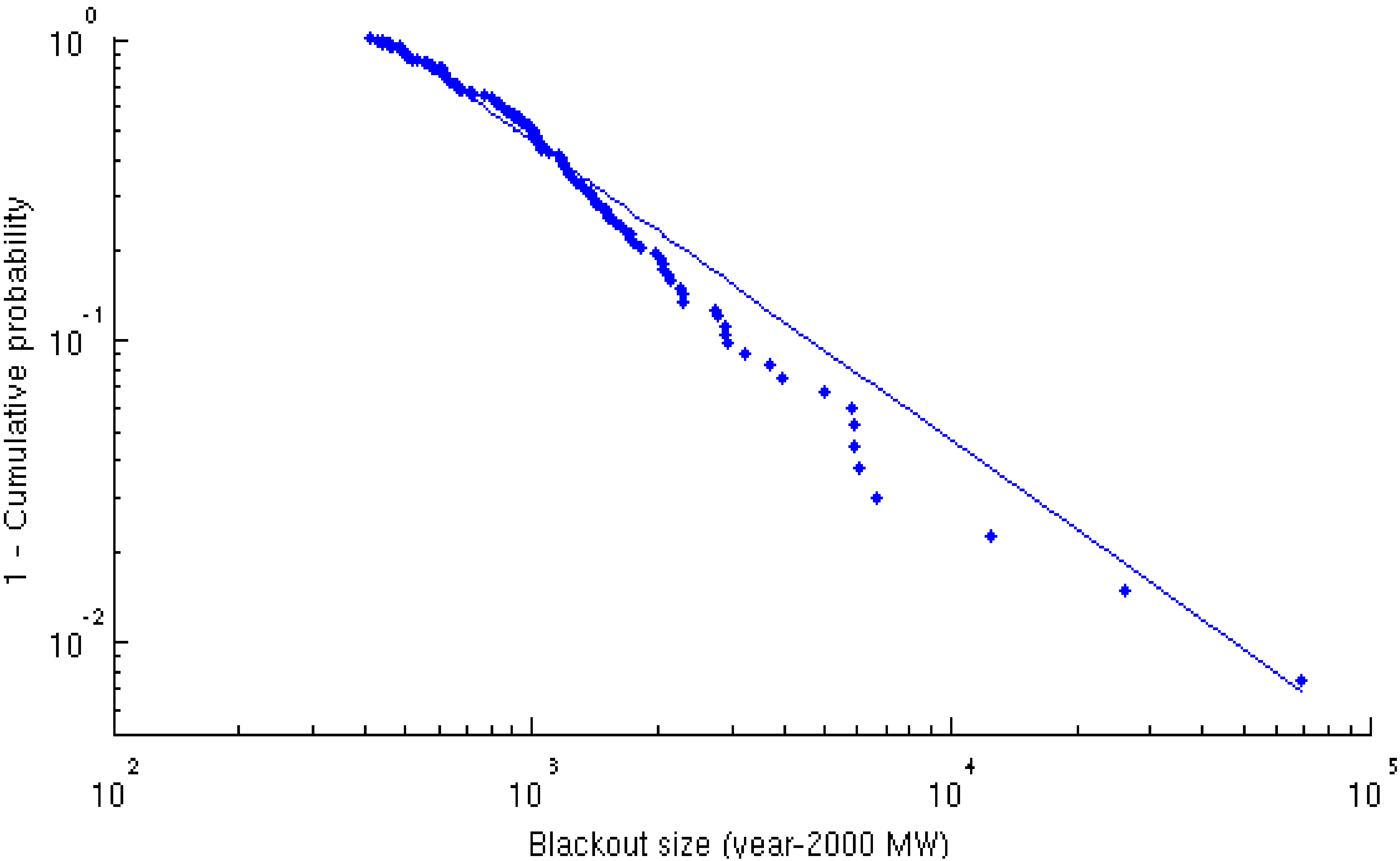
- Motivation and Concepts
  - Cascading Failures in the US
  - Teams and Electricity Networks
  - Optimum Operations
- Toward Optimal Operations via Distributed MPC
  - Method overview
  - Agent problem formulation
  - Cooperation
- Simulation method and results
- Ongoing Work and Conclusions

Motivation:
Large Blackouts &
Cascading Failures
in the United States

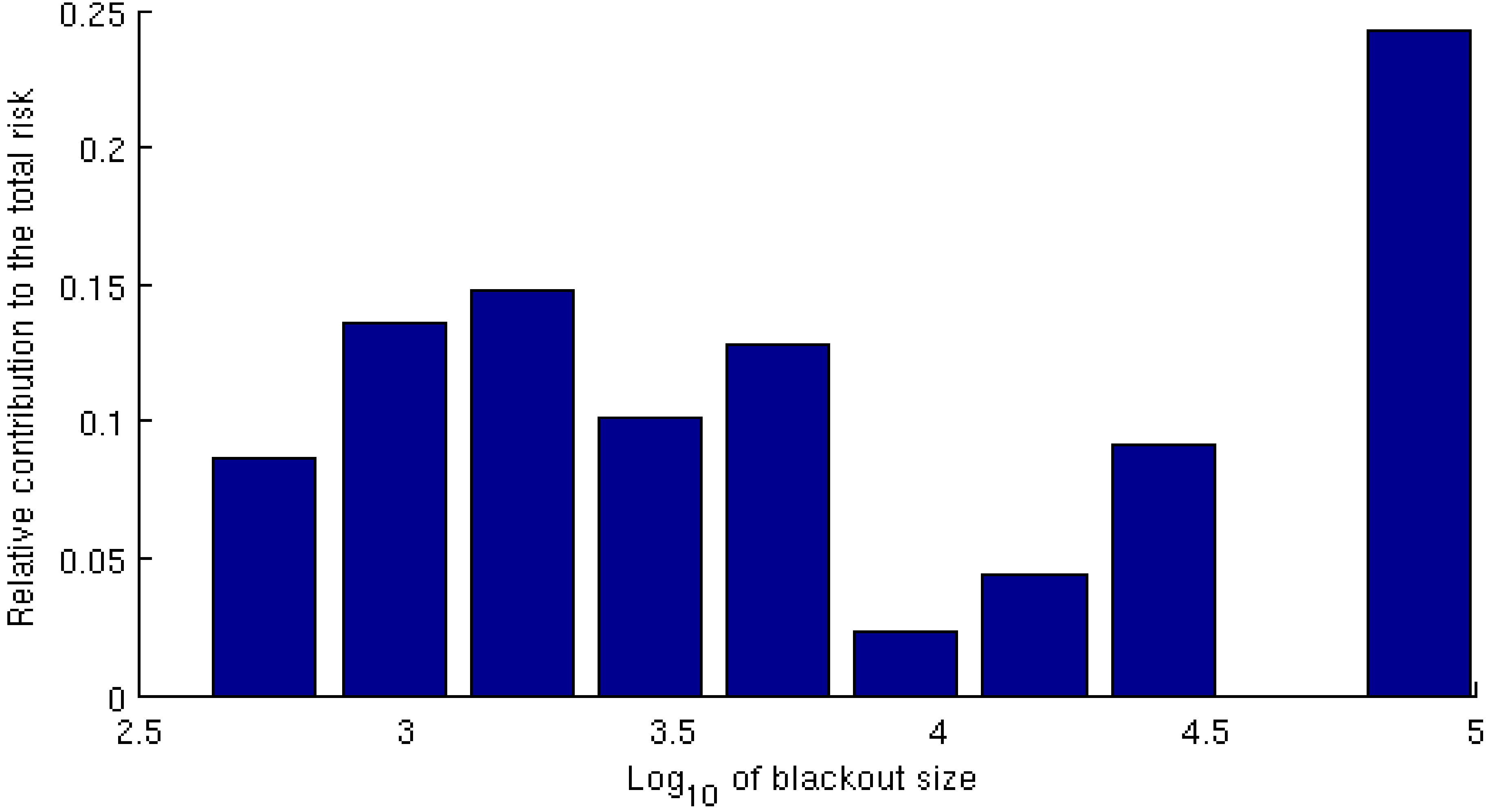
System stress is not decreasing



Contribution of Large Blackouts to Overall Risk



Contribution of Large Blackouts to Overall Risk



The Top 25 US Blackouts on Record

	Date	MW	Location	Notes
1	Aug 14, 2003	70,000	Northeast	**Cascading Failure**
2	Aug 20, 2004	22,700	NPCC	**Major Transmission Line Tripped due to Lightning Strike**
3	Mar 13, 1989	19,400	NPCC	**Solar flare, XFMR fails, 5 lines trip, cascade**
4	Apr 18, 1988	18,500	NPCC	Ice Storm
5	Jul 8, 2003	11,000	ECAR	**Severe Thunderstorms**
6	Oct 23, 2005	10,000	FRCC	Hurricane Wilma
7	Feb 29, 1984	7,901	WSCC	**One Pacific AC intertie circuit tripped due to relay misoperation**
8	Dec 4, 2002	7,200	SERC	Snow/ice storm.
9	Sep 18, 2003	6,512	SERC	Hurricane Isabel
10	Sep 18, 2003	6,512	SERC	Hurricane Isabel
11	Sep 4, 2004	6,000	FRCC	Hurricane Frances
12	Aug 29, 2005	5,120	SERC	Hurricane Katrina
13	Dec 14, 1994	5,020	WSCC	**Cascading failure**
14	Feb 28, 1995	4,500	NPCC	**Line faults, overload, gen loss, cascade**
15	Aug 19, 1991	4,400	NPCC	Hurricane Bob
16	May 17, 1985	4,300	SERC	**Fire near substation**
17	Jan 17, 1994	4,235	WSCC	Earthquake, 6.6 magnitude
18	Nov 16, 1988	4,200	NPCC	**Circuit breaker fault, cascade**
19	Sep 19, 1990	4,000	NPCC	**Deliberate transformer failure by employee, 7 735 lines lost**
20	Oct 2, 1984	3,868	WSCC	**Mis-operation of a phase comparison relay**
21	Aug 5, 1997	3,525	WSCC	**Plane hit line, demand tripped on low voltage,**
22	Dec 15, 2005	3,500	SERC	Ice Storm
23	Mar 12, 1996	3,440	SERC	**Transmission problems, cascade**
24	Dec 23, 1989	3,100	SERC	Supply shortage due to unexpected high demand
25	Sep 18, 2003	3,085	MAAC	Hurricane Isabel

Data from the US Dept. of Energy (EIA 417) and NERC (DAWG)

Observations

- Blackouts are costly
  - Large blackouts contribute more than their share to overall risk
- If we look at a given cascading event it is possible to calculate a small set of control actions that greatly reduce the social costs of the disturbance
  - Aug. 14 – Shed load in Cleveland
  - WSCC/WECC events – Shed load/generation along the Intertie

Is it possible to have
optimal operations,
under stressed conditions,
in real time?

Teams

Power systems are run by autonomous agents: human operators, energy traders, IPP's, customers, thousands of mechanical controllers, ...

These agents can be divided into teams, such that the agents in a team have common goals. That is, each team works on its own problem: unit commitment or dispatch or protection or energy trading or the reaction to cascading failures or...

Teams can have as few as one agent or as many as thousands of agents. Some agents can belong to several teams.

Optimum Operations

By "operations" we mean the streams of decisions made by the teams in real-time.

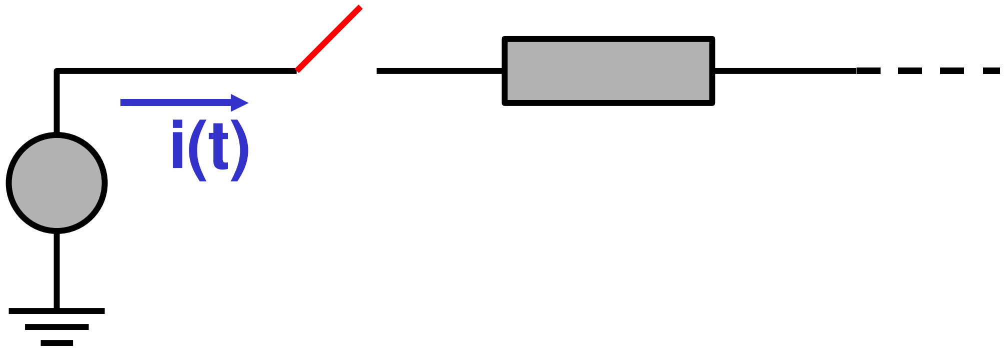
By "optimum operations" we mean the stream-of-decisions that, in hindsight, are the best possible decisions the team could have made.

It is not enough to base decisions on a snapshot of the system, nor to examine each decision separately. Rather, it is the interactions of the elements of the stream, and their effects, both near and far, that are important.

As everybody knows....

A power system is a dynamic hybrid system.

Its variables change with time.
Some change continuously.
Others change discontinuously.



Decision space

The decision-space of a power system (the set of all the decisions—changes-- that agents can make) is large and rich. It includes thousands of continuous and discrete variables.

- **Breaker positions**
- **Tap changer positions**
- **Generator excitation**
- **Prices of energy offers**
- **FACTS device set points**
- **Reactive power resources**
-

Bigger decision spaces contain better decisions

For instance:

$$\min_{X,\,Y} f(X, Y) \leq \min_{X} f(X, Y)$$

Each team of agents searches for its decisions through a sub-space of the system's decision-space.

→ To find the very best decisions, each team of agents must use as large a sub-space as it can.

Summary: Necessary conditions for a team of autonomous agents to make optimum decisions

1. The problem must be well posed:
   - clear, precise and comprehensive goals over
   - a time horizon long enough to allow for dynamics

3. A decision-space large enough to contain the best decisions.

5. A decomposition of the problem into sub-problems, one for each agent.

7. A coordination scheme to keep the agents working coherently, not at cross-purposes.

Our approach to meeting the necessary conditions

1. MPC (Model Predictive Control) to provide a (rolling) time-horizon in the problem formulation
2. Mixed integer formulations to allow for continuous and discrete decision variables
3. A problem-decomposition with some unusual properties
4. Cooperation (exchange of information) among neighboring agents that allows agents to work at their own speeds, so humans can cooperate with much faster computers.

Preliminary results for the curtailment of cascading failures demonstrate some, but not all, the features of our approach.

Method:

Model Predictive Control
Problem Decomposition
Cooperation

Model Predictive Control

- Take a control problem

$$u_1 = Control(x_0, u_0)$$

- Extend the time horizon (prediction)

$$t_0 \ldots t_k \ldots t_K$$

- Explicitly specify objective and constraints
  - Costs, discrete variables, hard/soft limits
- Solve iteratively (feedback) using optimization tools

Global MPC Formulation

- Given the state of the network find a set of control actions that result in minimal social costs

$$
\begin{array}{ll}
Given: & \text{A time horizon: } t_0 \ldots t_k \ldots t_K, \\
 & \text{and state measurements: } x_0 \\
Find: & \text{An optimal control plan } u_0 \ldots u_K \text{ according to} \\
Minimize: & Cost\left(u_{0.} .. u_K, x_{0.} .. x_K\right) \\
s.t.: & Predictor\left(u_k, x_k, x_{k+1}\right) = 0 \\
 & x_{min} \leq x_K \leq x_{max}
\end{array}
$$

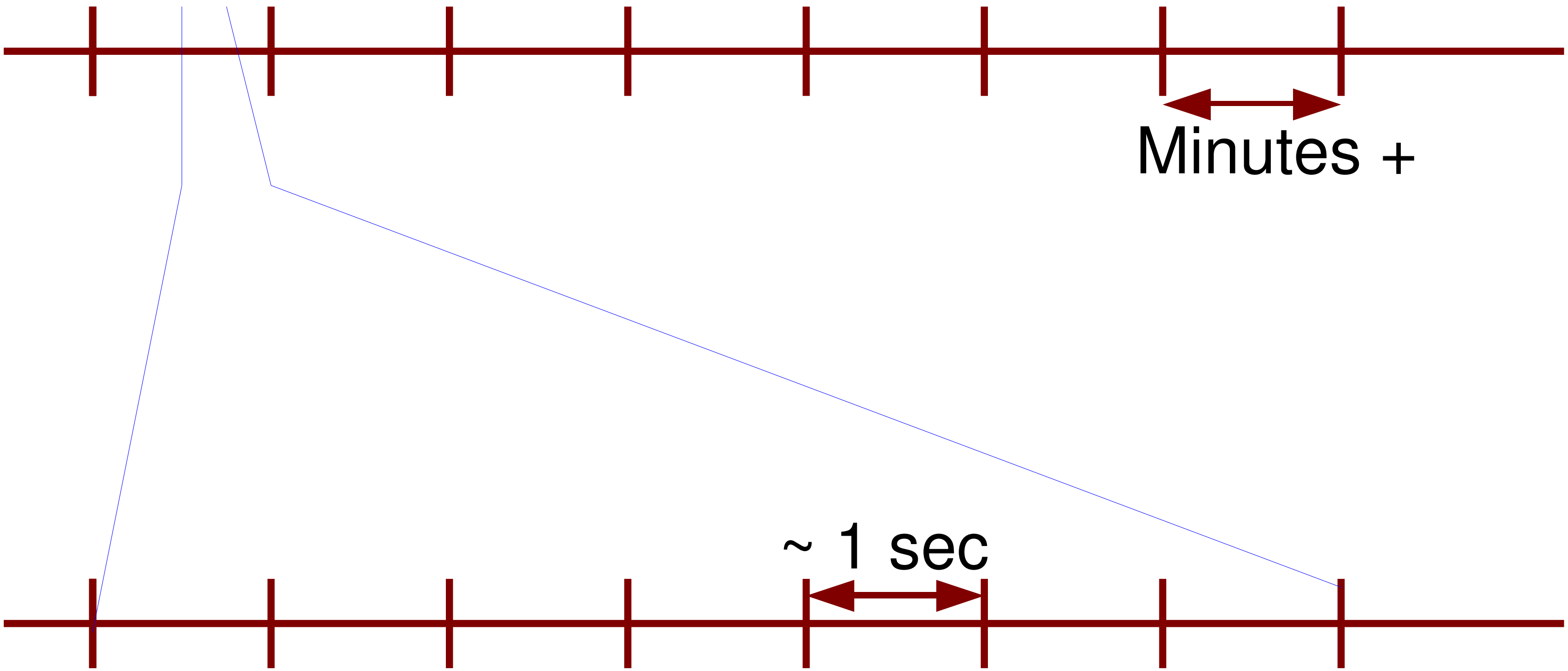
A mixed integer MPC optimization problem

- This problem is far too large to solve in real time.

- How close can we get with existing technology?

Multiple Horizons and Teams

Operators repeatedly solve a large MINLP MPC problem to manage long-range plans



Software agents distributed throughout the grid solve extreme problems with shorter time-horizons

A feasibility test case

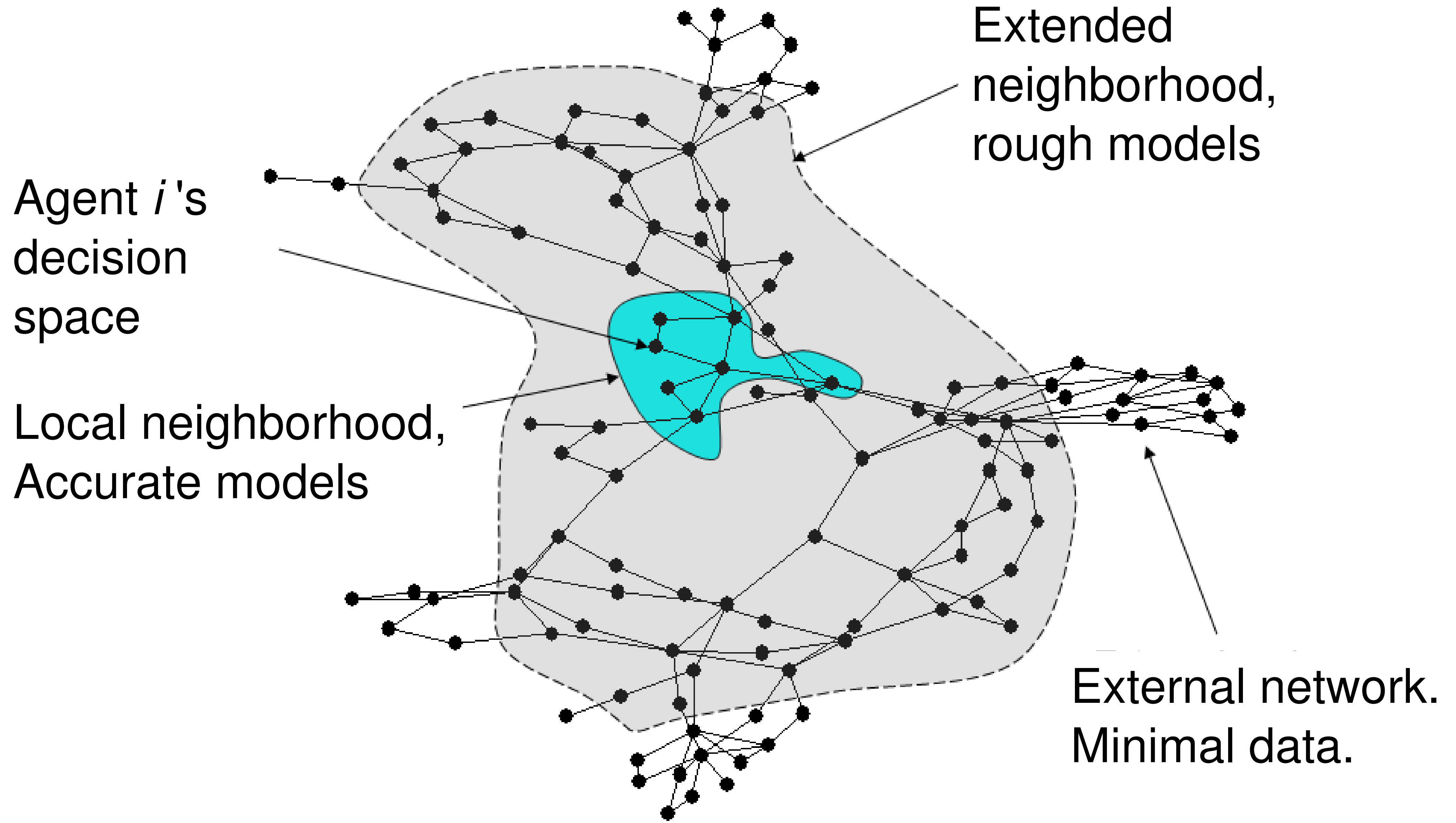
- Can a network of software agents control load and generation such that stress from excessive branch currents do not initiate cascading failures?

Method

- Problem decomposition
  - Assign the calculation and implementation tasks to agents distributed through the network
- Cooperation
  - Allow agents to exchange useful information
- Feedback
  - Formulate the problem to prefer incremental actions, thus compensating for model inaccuracies

Problem decomposition

- Our method
  - Decompose the decision vector disjointly to one agent per node
  - Allow agents to work with overlapping network models, maintaining the models with only as much data as it can collect from its neighbors (truncate the problem at the edges).
  - Allow the agents to use linearized network models (approximate 1^{st} order Taylor series)
    - Actual system constraints are kept intact, though distributed to many overlapping models


Extended neighborhood, rough models
Agent *i* 's decision space
Local neighborhood, Accurate models
External network. Minimal data.

Agent Tasks

- Maintain network model(s)
  - Collect local data from equipment
  - Share local variables with local neighbors (1x / ~0.1 sec)
  - Request data infrequently from extended neighbors (~daily) to maintain a rough network model (prediction/forecast?)
  - Respond to data requests
- Make local control decisions
  - 1x at the given time interval (0.5-1.0 sec), according to the agreed goals.
  - Cooperate with neighbors to improve solutions
  - Implement actions on the fixed schedule

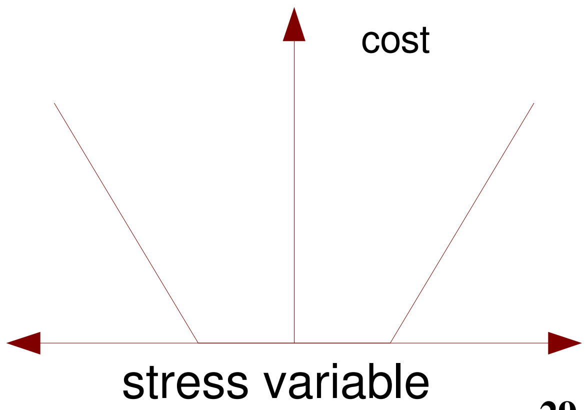
Operator tasks

- Operate a longer time scale (minutes) MPC problem(s) to manage system
  - Mixed integer formulation to calculate switching actions
  - Coordinate with neighbor operators
- Choose and assign variable weights to agents
  - How costly are control actions (load shedding, fast valving, etc)?
  - How agressively should agents react to stress (voltages, currents)?
  - How quickly should agents respond to stress events?

Agent MPC Problem

$$
\begin{aligned}
&\min_{u_0 \cdots u_{K-1}} \quad \sum_{k=1}^{K} \rho^k \left(c_u^T u_k + c_y^T E_k(x_k) \right) && \\
&x_{k+1} = x_k + B u_k && k = 0, \ldots, K-1 \\
&x_{min} \leq x_k \leq x_{max} && k = 0, \ldots, K \\
&u_{min} \leq u_k \leq u_{max} && k = 0, \ldots, K
\end{aligned}
$$

where *E* is a function that approximates the cost of stress for the state.



Eliminating the non-linearities of E

$$
\begin{aligned}
\min_{u_0 \cdots u_{K-1}} \quad & \sum_{k=1}^{K} \rho^k \left(c_u^T u_k + c_y^T (y_k^+ + y_k^-)\right) \\
& x_{k+1} = x_k + B u_k && k = 0, \ldots, K-1 \\
& y_k + y_k^+ - y_k^- = C x_k && k = 0, \ldots, K \\
& y_k^+ \geq 0, \quad y_k^- \geq 0 && k = 0, \ldots, K \\
& y_{min} - \alpha_k \leq y_k \leq y_{max} + \alpha_k && k = 0, \ldots, K \\
& x_{min} \leq x_k \leq x_{max} && k = 0, \ldots, K \\
& u_{min} \leq u_k \leq u_{max} && k = 0, \ldots, K
\end{aligned}
$$

Properties of this formulation

- Guaranteed feasibility
  - u = 0 (no action) is always feasible
- Flexibility
  - Preferences between eliminating stress and minimizing control actions can be adjusted
- Interesting LP properties
  - complimentary slackness: $y_k^+ * y_k^- = 0$

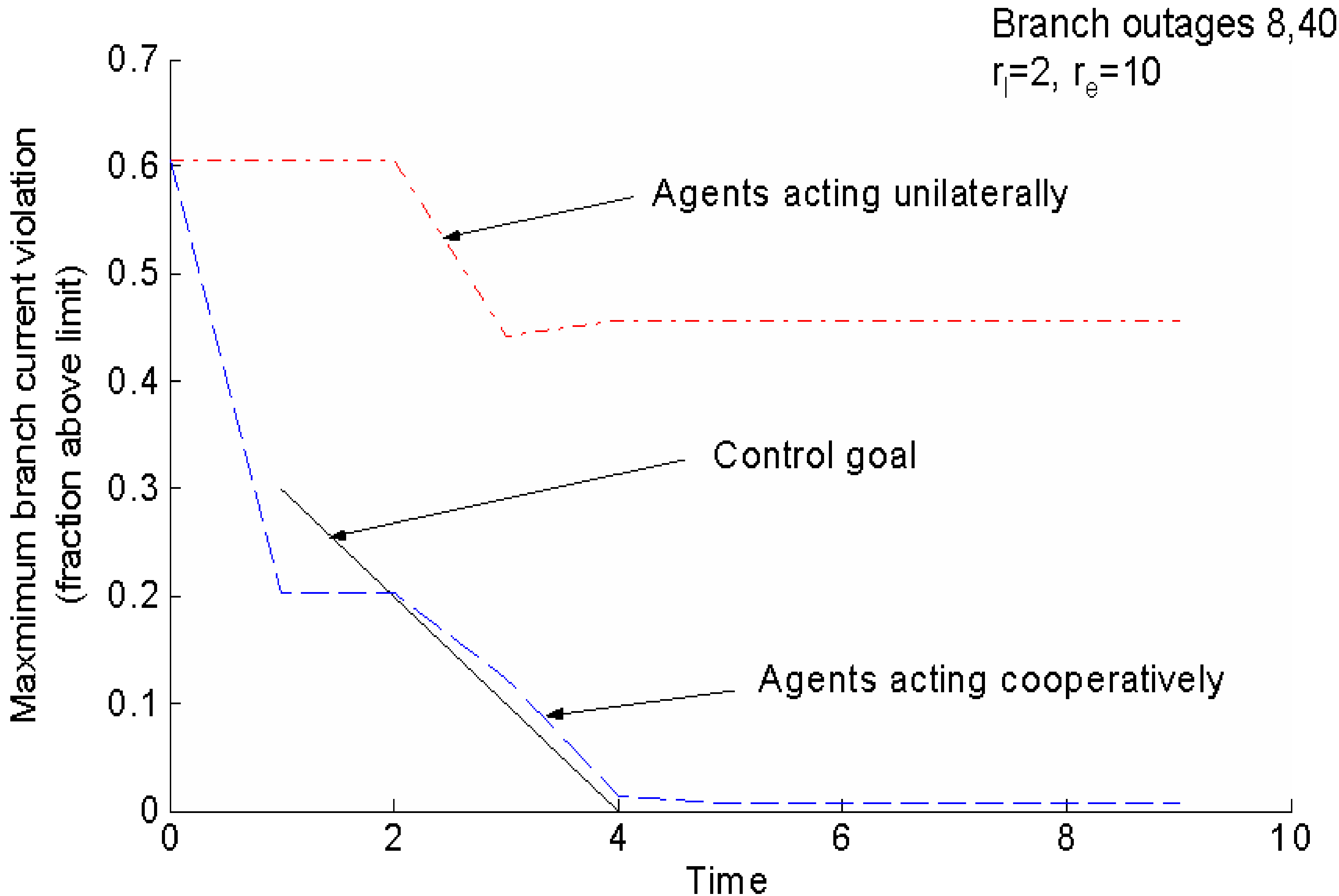
Cooperation scheme

- Several schemes are under investigation. Our current scheme is as follows:
  - Each agent calculation results in a (very sparse) control vector for the entire network: $u^{[n]}$
  - After calculating a control vector, agent *n* sends the vector to a set of its neighbors, along with the time at which the action will be taken.
  - Agent *m* obtains the vector and compares it with its locally calculated action set: $\|u_t^{[n]} - u_t^{[m]}\| < \epsilon$
  - When significant differences exist, agent *m* chooses a sub-set of its measurements that could be important to agent n's solution and sends them to *n*.

Previous Simulation Method

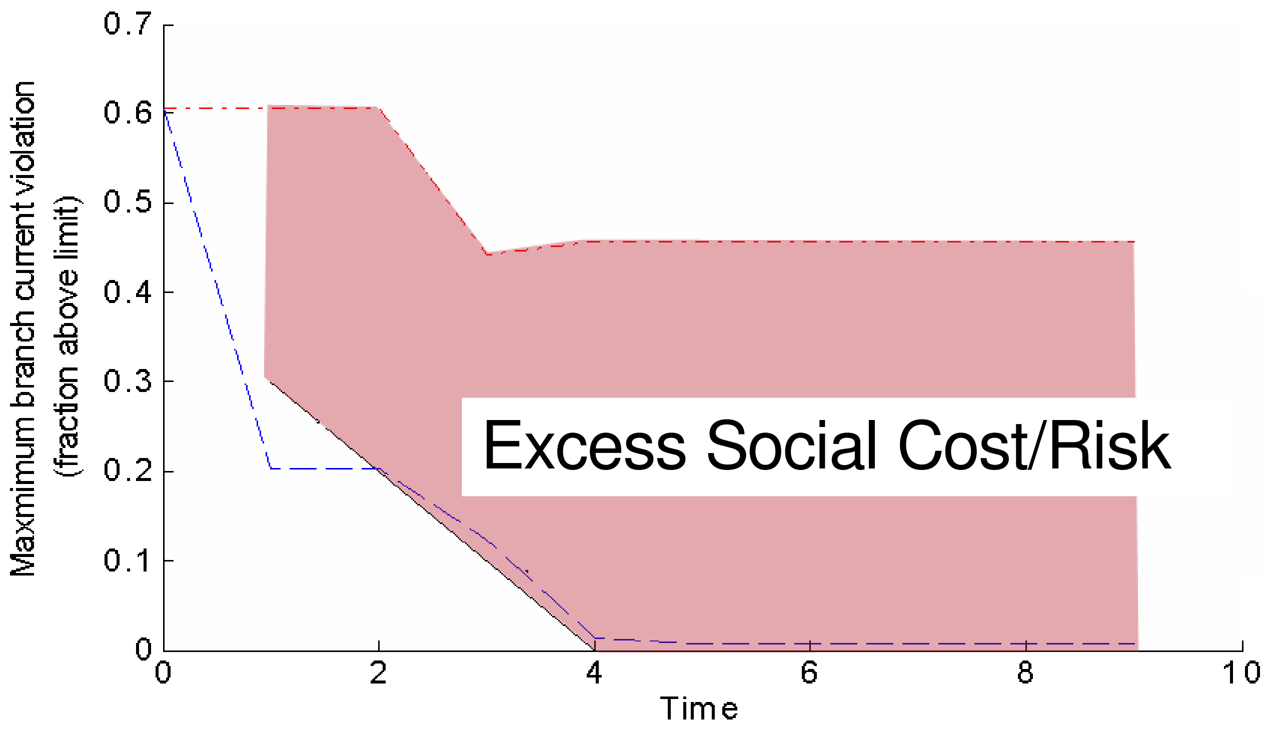
- Agents simulated in MATLAB, operating in a synchronous loop
- Agents interact with an AC load flow model of the IEEE 118 bus network
- Randomly chosen double branch outages are injected into the system
- Agent reactions are recorded

Typical result

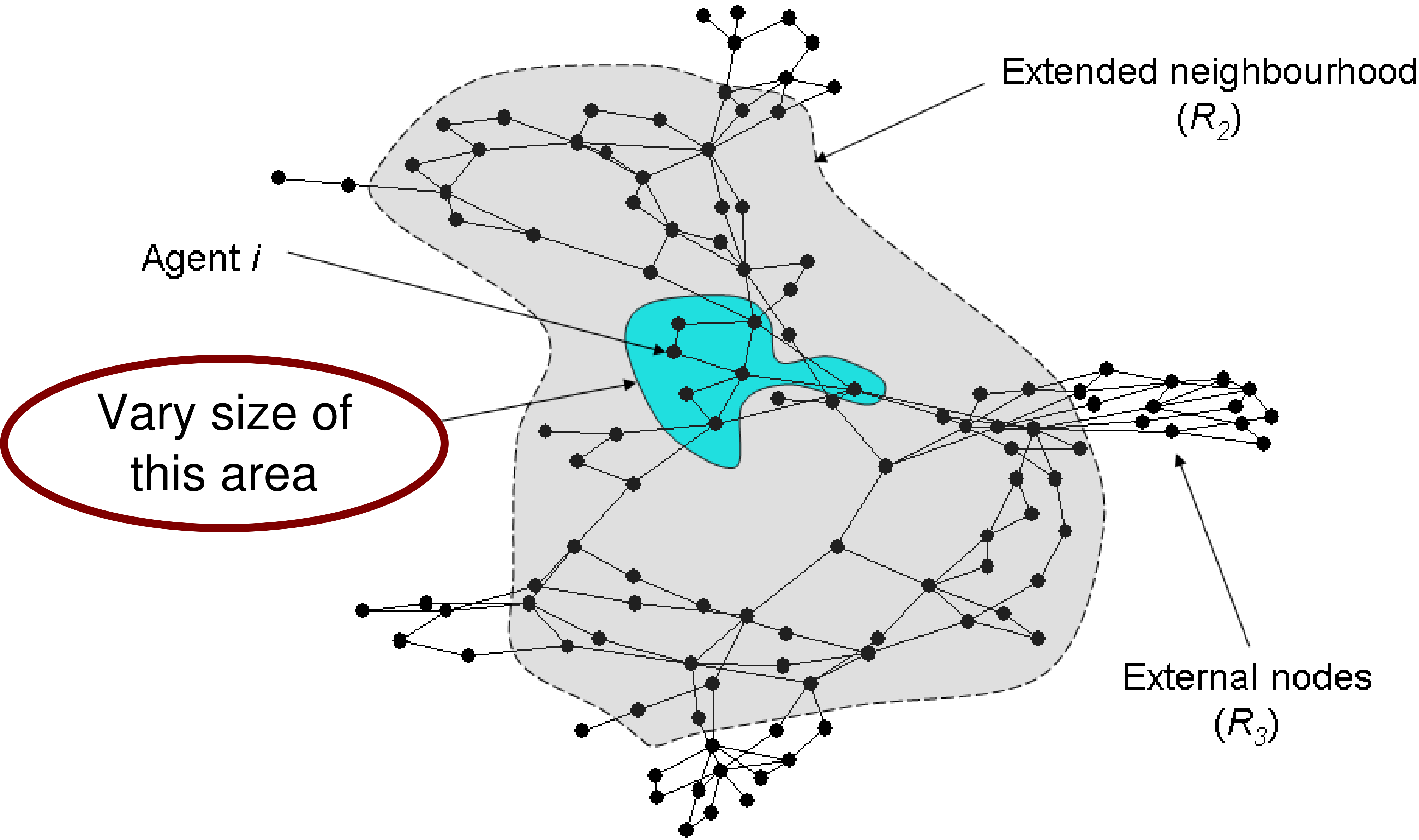


Social cost vs. Communication capital cost

- Choose a measure of the social cost

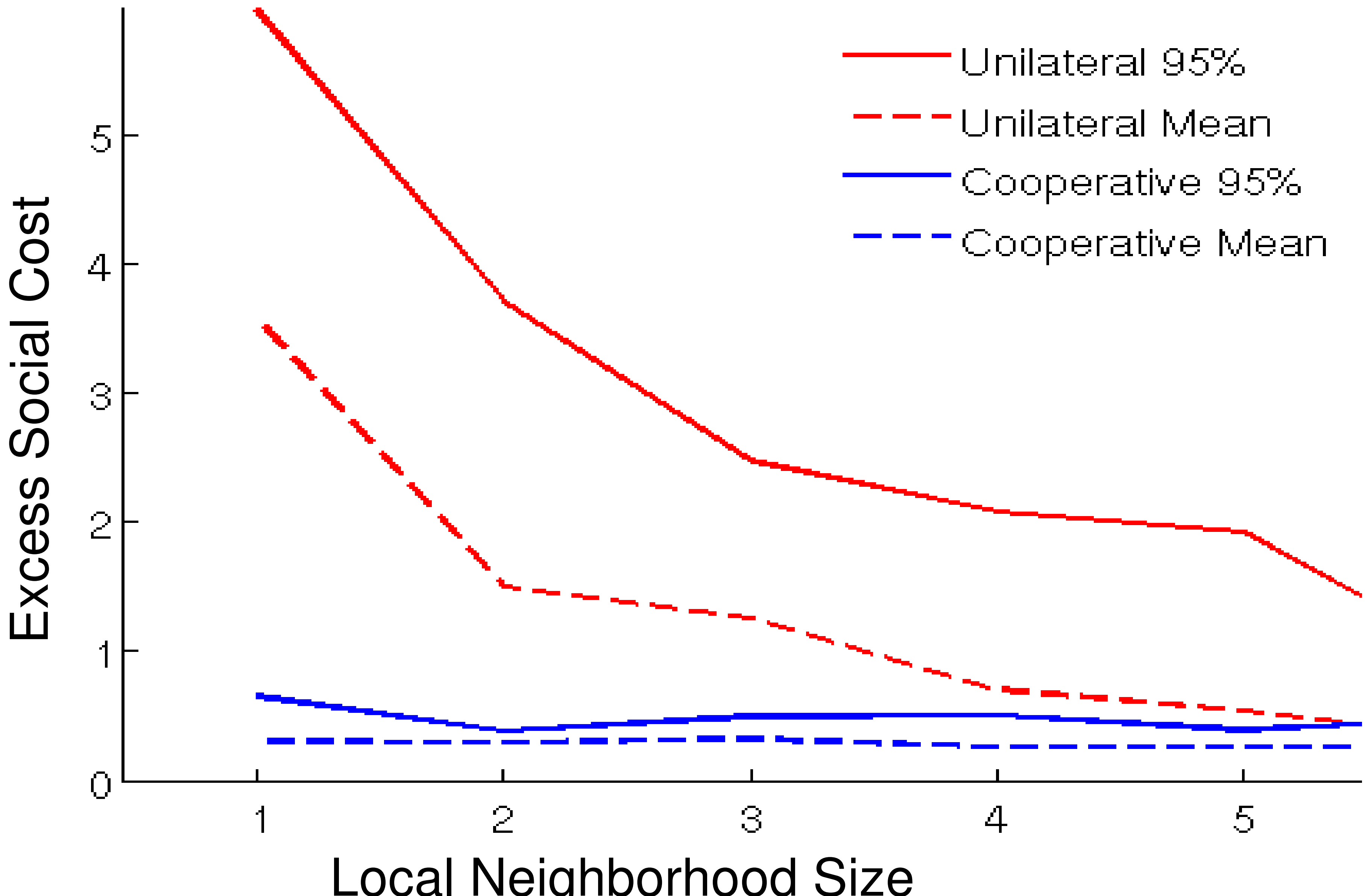


- Run many simulations varied disturbances
- Vary the size of the internal neighborhood



Extended neighbourhood
(R_2)
Agent i
Vary size of this area
External nodes
(R_3)

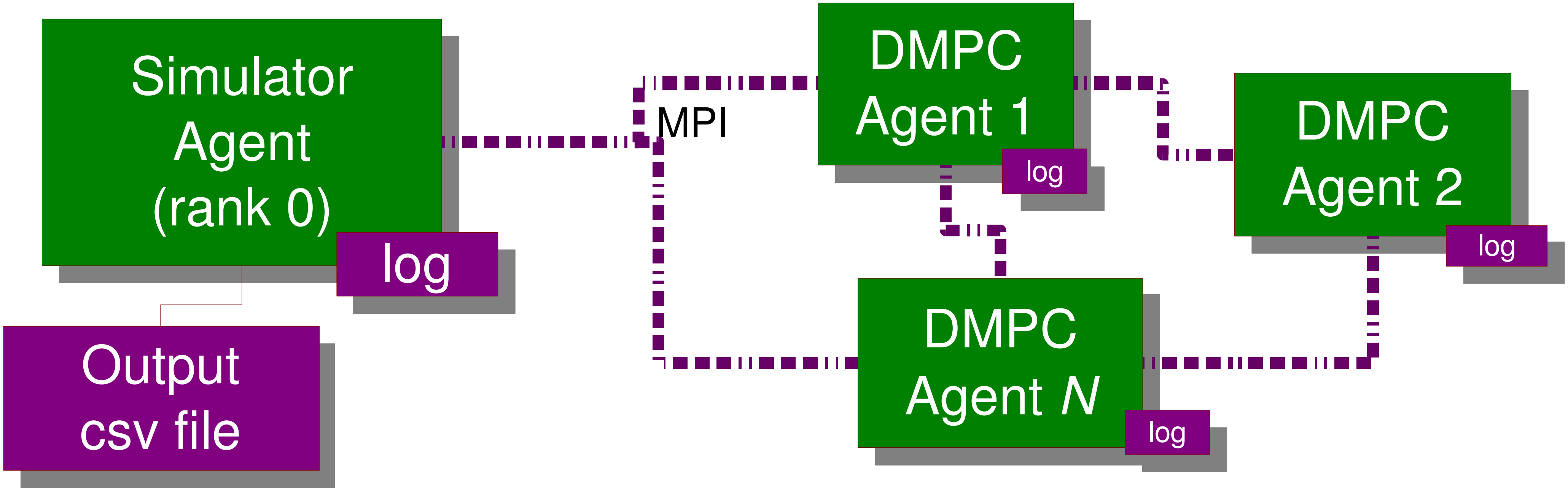
Social cost vs. Communications cost



Simulating Communications

- Electronic communications can be slow.
- Is this approach feasible given reasonable comm. constraints?
- A more accurate simulation method
  - Agents run in separate processes on a (linux/beowulf) computer cluster
  - One agent acts as the operator, maintains an AC load flow network model
  - Agents pass messages via MPI

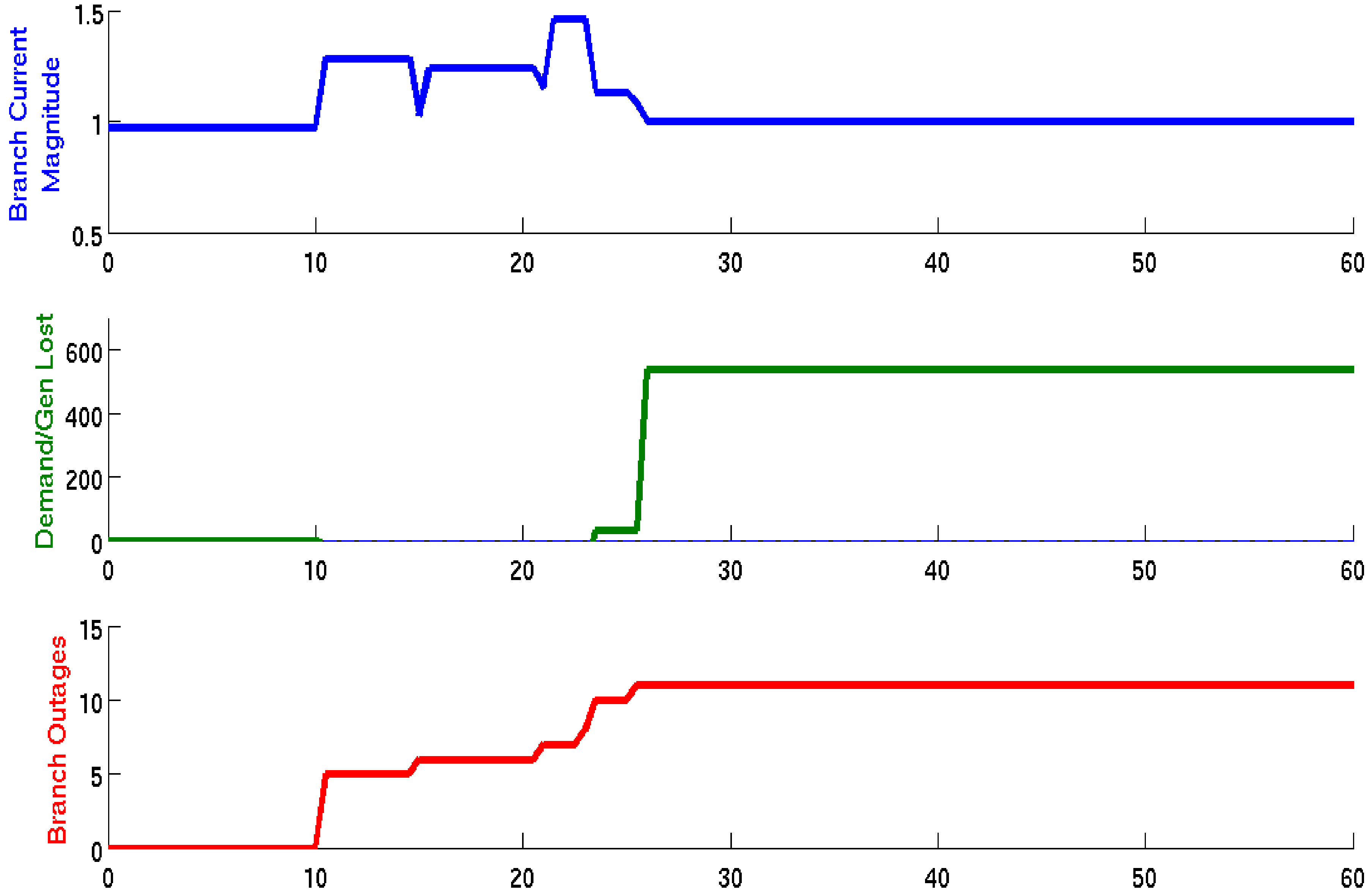
Design/Program Flow



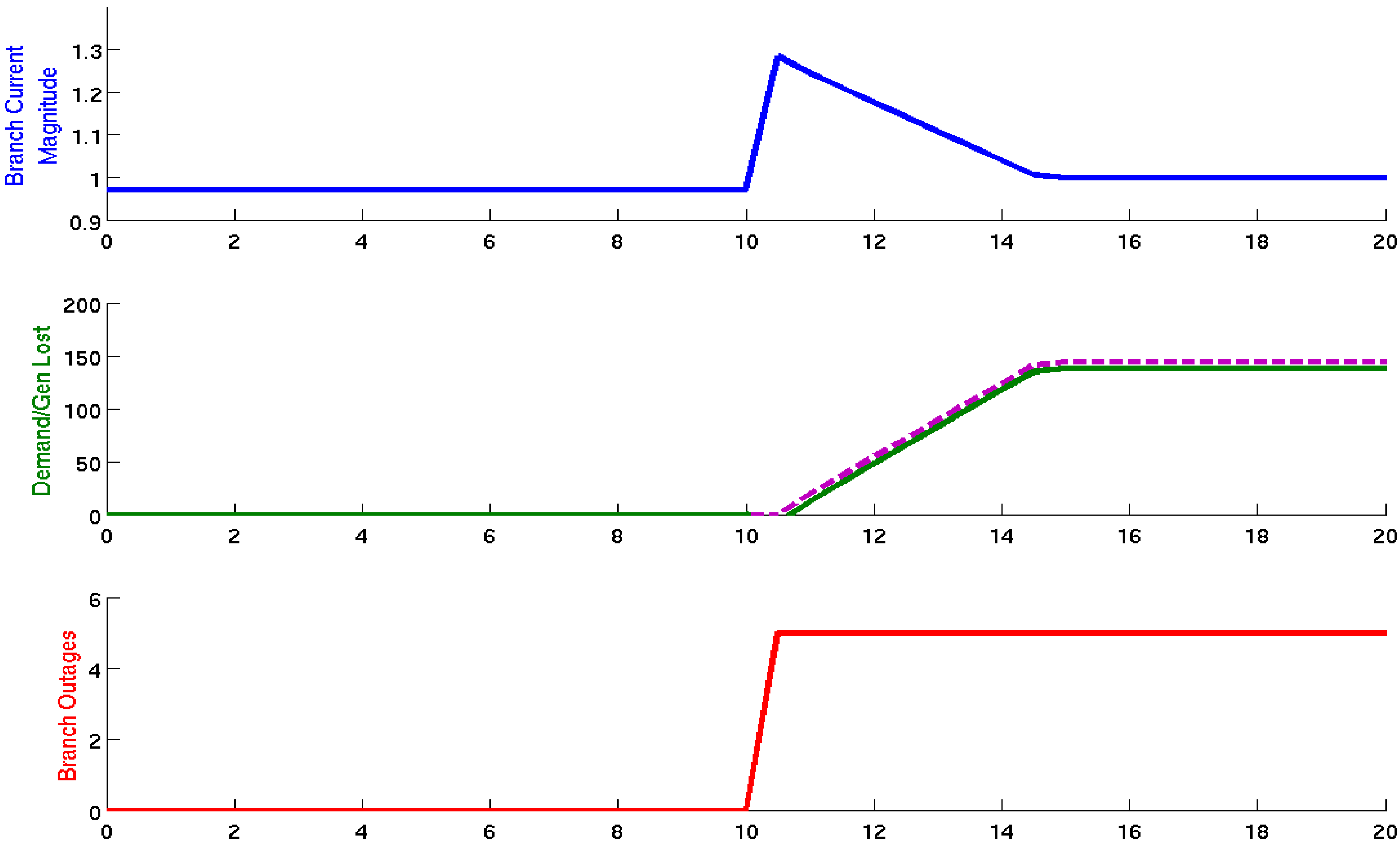
Test case

- 39 bus system
  - 4 branch outages
- Simple AC load flow based cascading failure simulation

Result without control (sub-optimal)



Results with MPC control



Observations on communications

- Time between control steps ~ 0.5 – 1.0 sec to allow for communications
- Agent communication burden is about 10 kB / sec.
  - Message sizes are small
  - Latency more important than bandwidth
- About 3 cooperation iterations are possible in 0.5 second time span

Ongoing work

- Refine and test mixed integer (hybrid) versions of our problem for centralized application
- Compare cooperation methods
  - Existing method (based on data exchange top correct for model errors)
  - Peer pressure (assign a penalty to non-conforming actions)
  - Obedience (do what my neighbor tells me to do)
- Study a sparse implementation of the agent problems

Conclusions

- Large blackouts are too costly
  - The system reacts (is operated) sub-optimally
- Optimum Operations
  - Good solutions are likely to include:
    - Decentralization - Problem too large / complicated for centralized solutions
    - Cooperation – Agents often perform better when cooperating
    - Complete problem formulations -- Include more variables
- Experimental results indicate that it is possible to decompose the operations problem in time and space, with vastly reduced social costs.