

Can cascading failures be eliminated?

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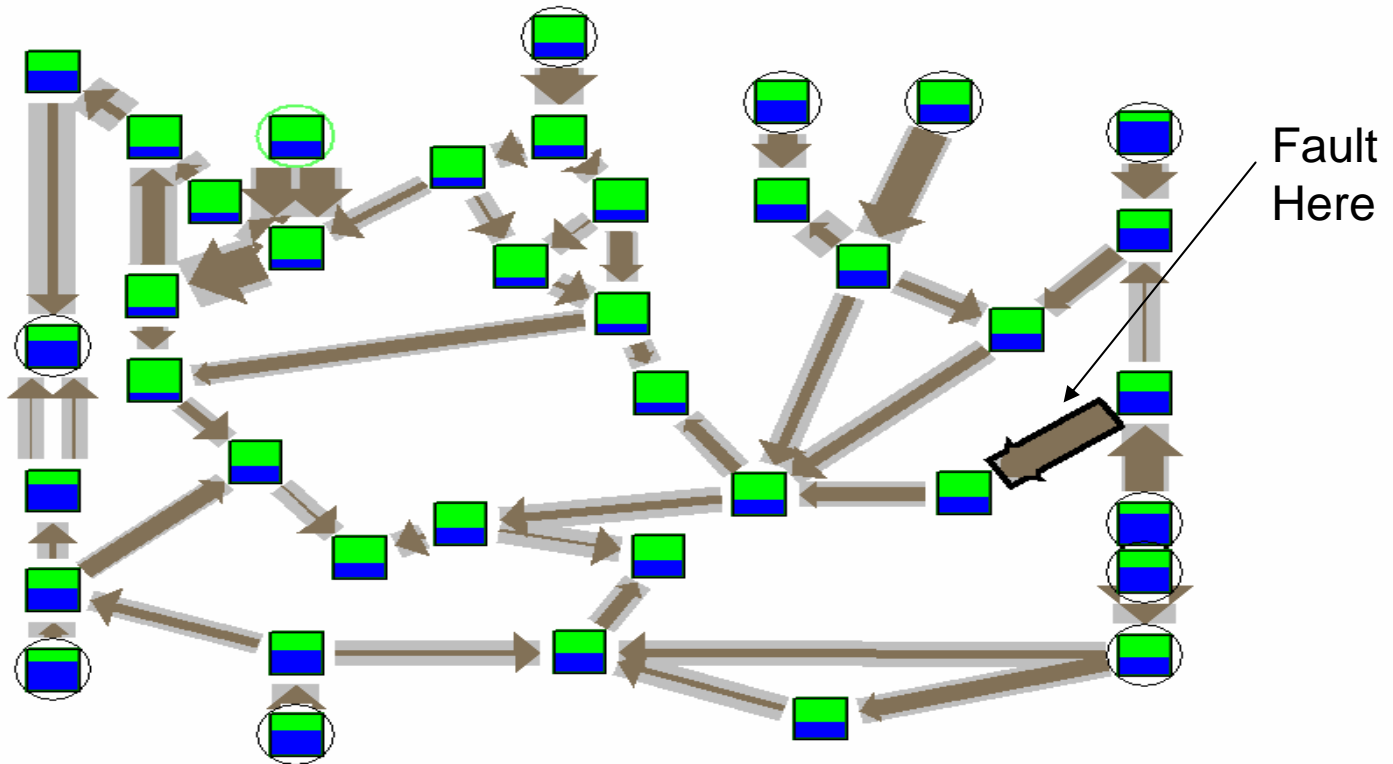
What is a cascading failure?

A cascading failure is a succession of automatic switching operations

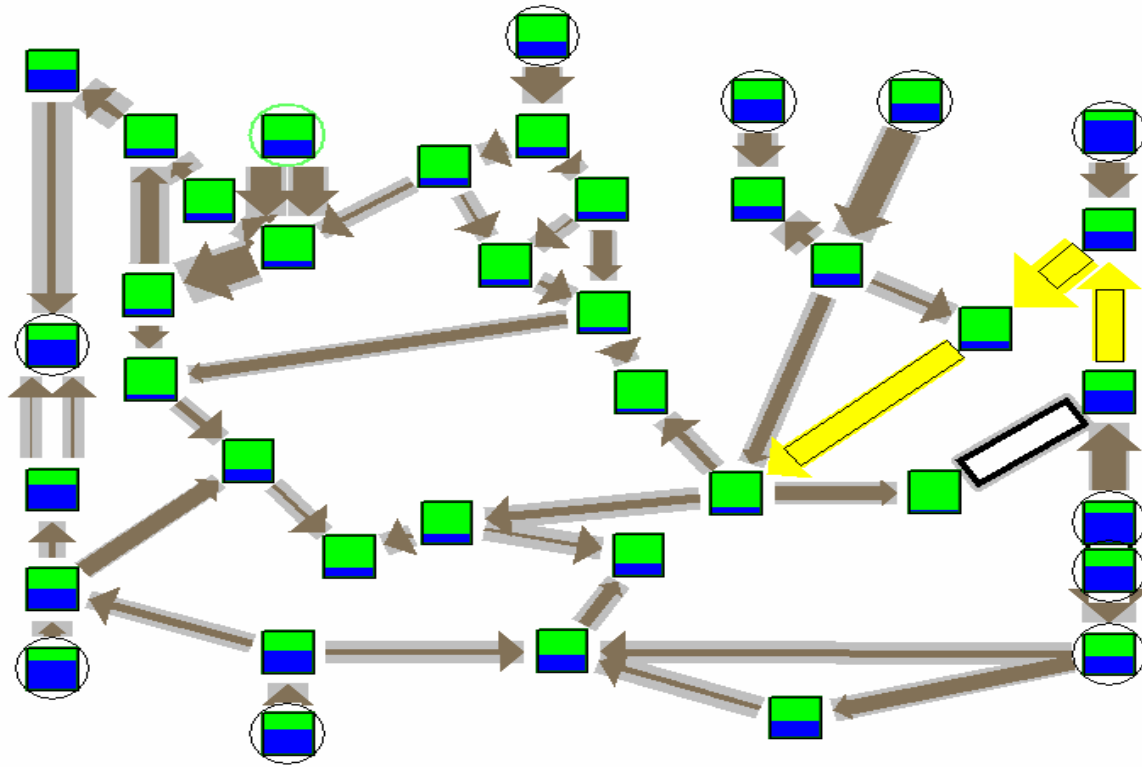
These switching operations are the responses of the equipment-protection-network to certain random disturbances.

Each switching operation de-energizes some equipment (causes failures)

A much simplified illustration...

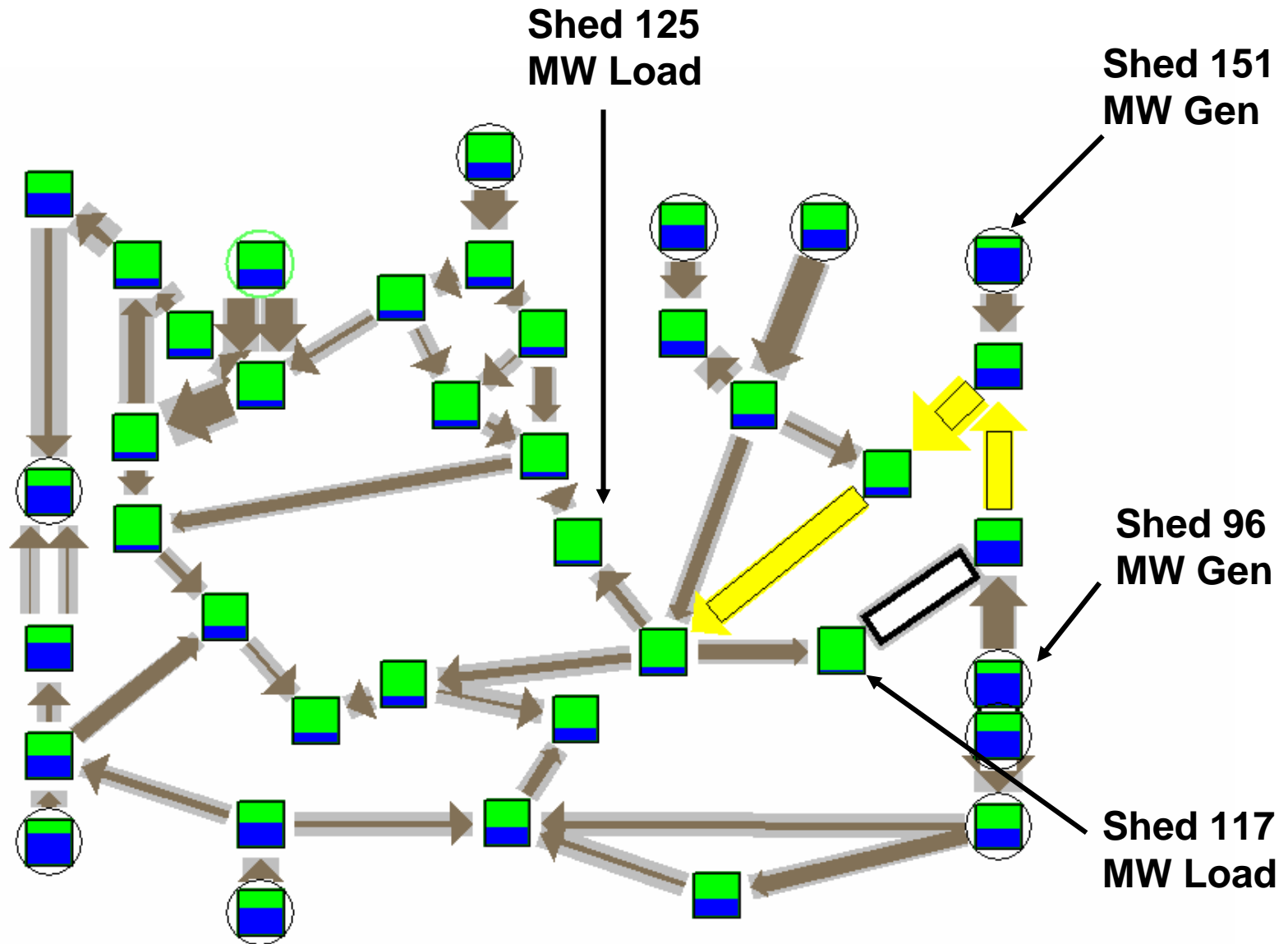


The protection network de-energizes the faulted line



**The first outage is followed by a second set of outages.
The second set is followed by a third set, and so on.**

A way to protect equipment and interrupt the sequence of failures:



The N-1 Criterion

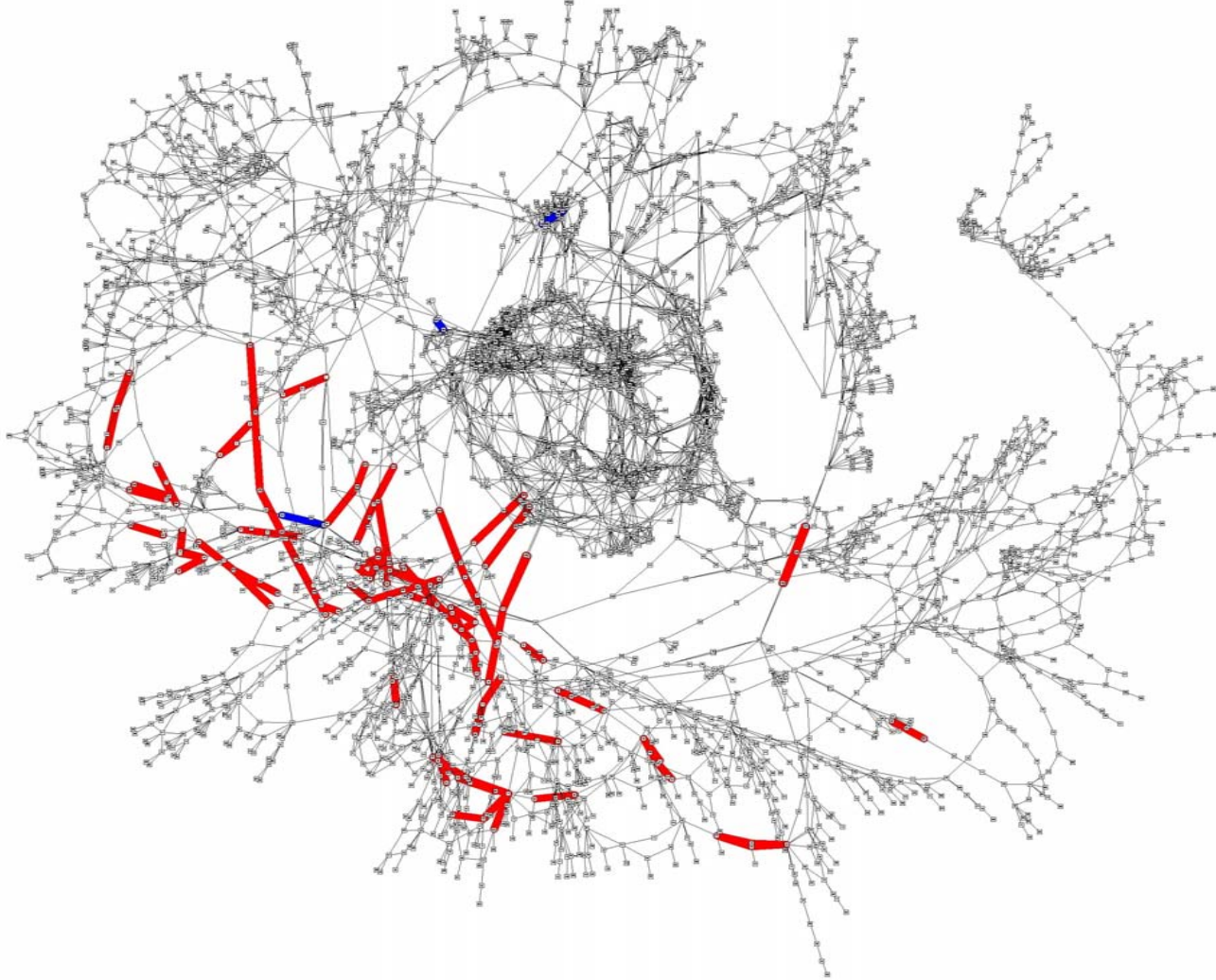
NERC recommends that power systems be operated so that no single transmission or generation failure can compromise the quality of service to any customer.

Consequence: cascading failures are caused by bizarre (multiple) failures

- a succession of failures that happens too fast for human intervention to re-establish the N-1 criterion**
- a single failure in the presence of long standing but hidden failures**

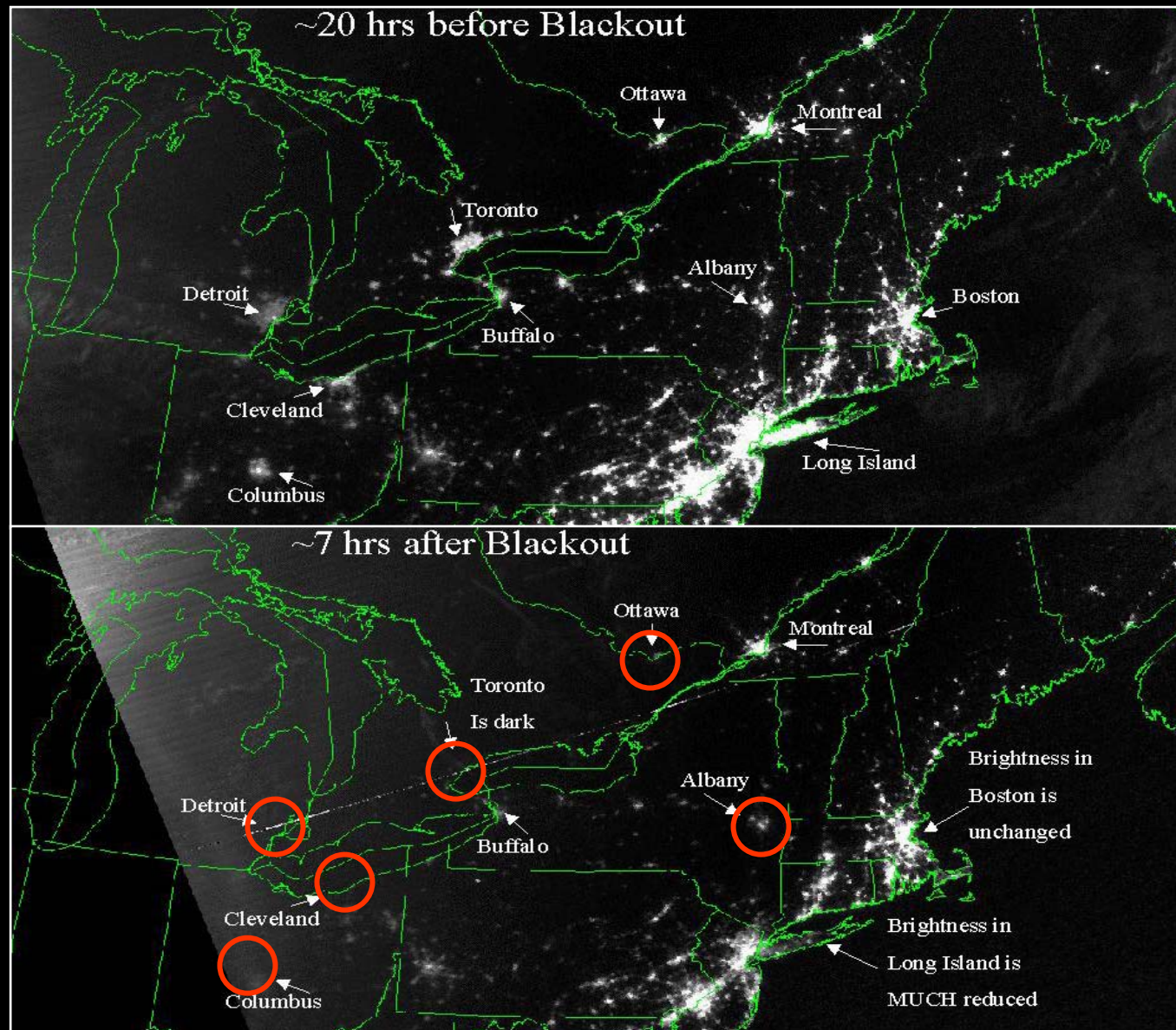
How cascading failures happen in grids with (N-1) security:

A Bizarre Outage → Excessive Stresses → Outages → Excessive Stresses → More Outages → and so on



In the past, human operators have not been effective in limiting the spread of cascading failures.

But cascading failures tend to be self-limiting



Cascading failures are expensive...

Cascading failures cause blackouts that cost from 10 to 50 billion dollars per year.

(The number depends on the measure used)

Besides being large, the societal costs of cascading failures are complex...

“SECURITY OF SUPPLY IS TOP GLOBAL CONCERN FOR UTILITIES

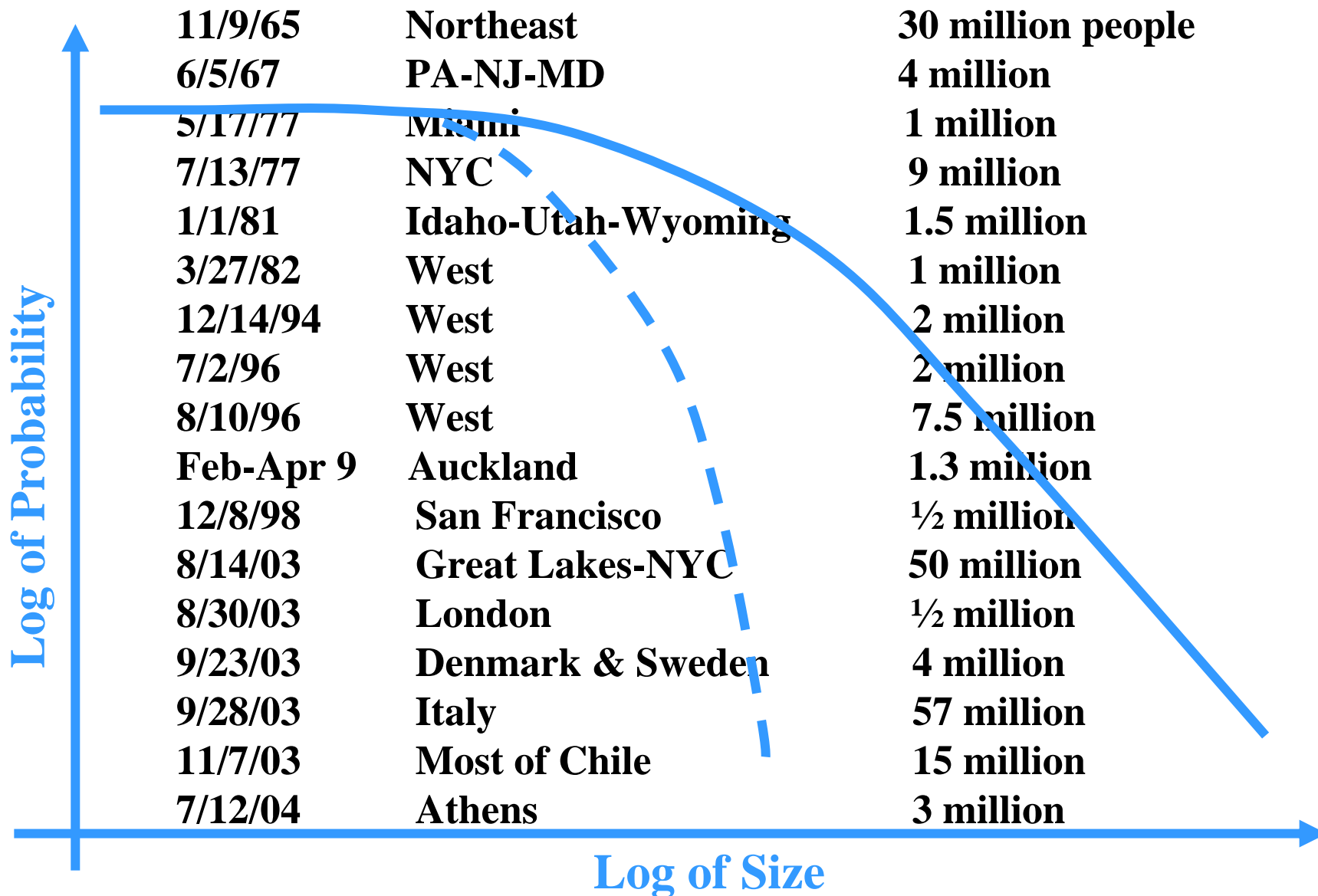
Blackouts on both sides of the Atlantic have propelled security of energy supply to become the top concern for utilities companies across the world, according to the sixth annual PricewaterhouseCoopers report 'Supply Essentials: Utilities Global Survey 2004'. The report, which presents the views of 148 leading companies across 47 countries throughout Europe, the Americas, Asia Pacific, Africa and the Middle East, indicates that securing power supply has risen from the fourth concern only twelve months ago to the highest ranking issue of 2004.”

Failure Statistics 1984-2000

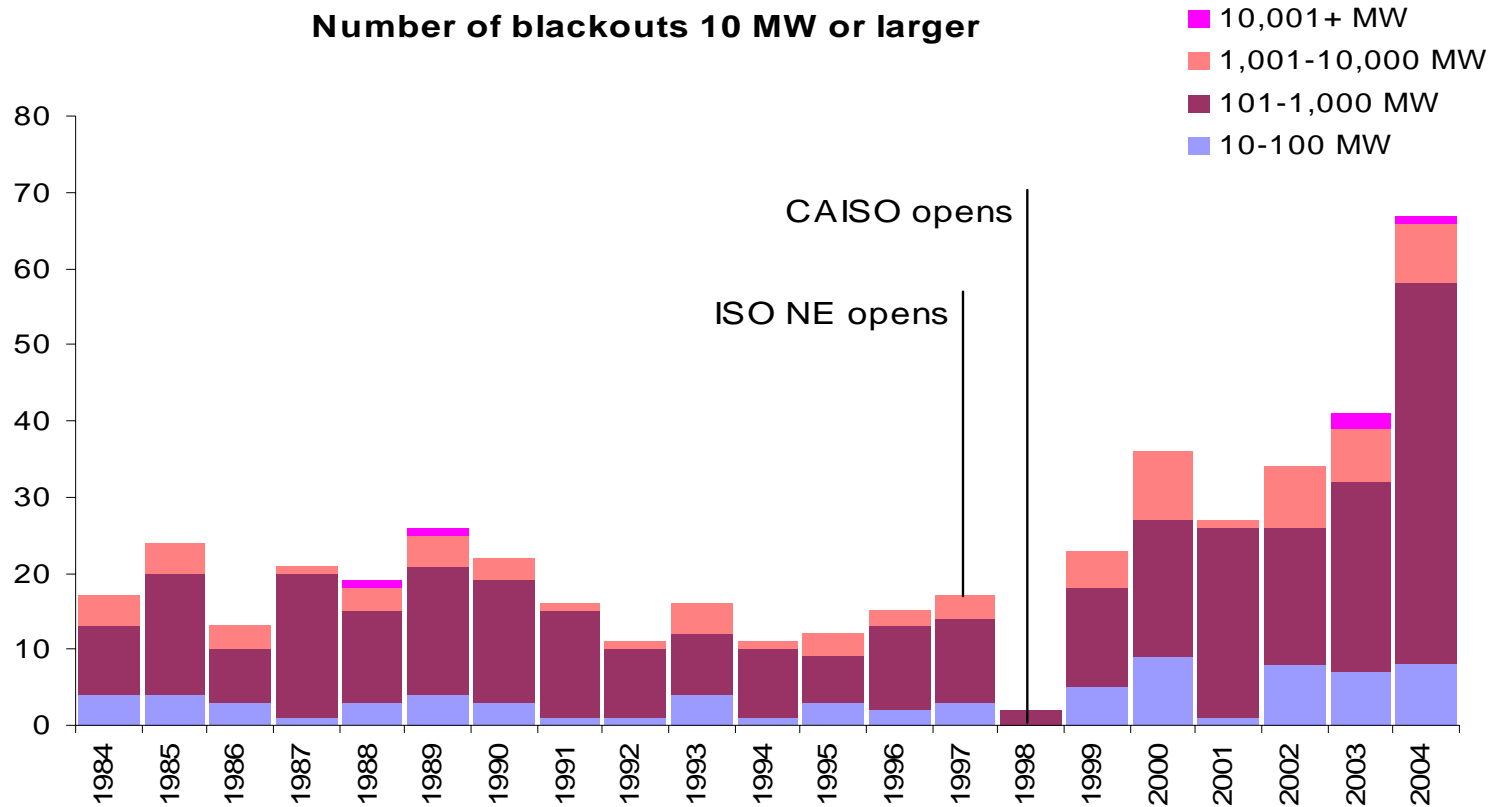
Compiled by the North American Electric Reliability Council

- **533 transmission or generation events**
- **324 (1 every 19 days) had power losses ≥ 1 MW**
- **46 of these (3 per year) were ≥ 1000 MW**

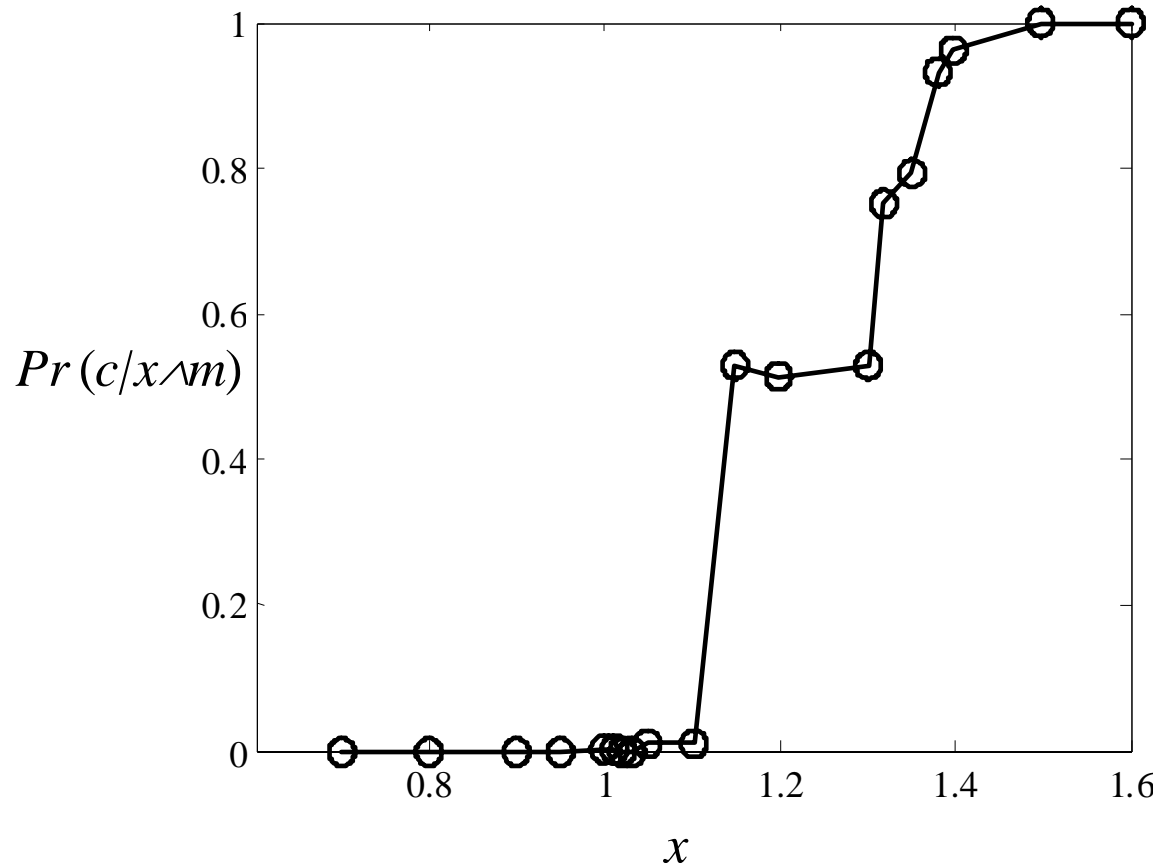
Cascading failures happen often enough to give the distribution of blackouts a fat tail:



We are not winning the battle against cascading failures



Blackout probability seems to be critically dependent on network stress—at a critical stress there is a sharp increase in blackout-probability. Is the underlying mechanism a phase transition? a relaxation? ...?



The probability, Pr , of a cascading failure plotted against a measure of stress, x . c is a cascading failure of 20 or more transmission lines; m is a random multiple contingency. Each point on the plot is the result of 10,000 simulations of a network with 3357 nodes. The points were generated by Huaiwei Liao.

Critical phenomena

- **Cascading failures in electric grids happen quite frequently**
- **Their distribution has a fat tail**
- **They appear to be difficult to control, and have resisted elimination**
- **There are other phenomena with fat-tailed distributions that are difficult to control--forest fires, for instance.**



Why are cascading failures difficult to control?

Some of the events that initiate forest fires --lightning strokes, for instance--are beyond human control. Therefore, as long as there are inflammable forests, there will be forest fires.

Some of the events that initiate cascading failures are difficult, if not impossible, to control:

- lightning strokes and other random, natural events**
- hidden failures**
- deliberate attacks**

Many solutions to the problem of cascading failures have been proposed. Some have been implemented. Examples:

- 1. add transmission capacity**
- 2. improve regulations**
- 3. improve coordination**
- 4. better training for human operators**
- 5. better automatic control systems**
- 6. more data collection**
- 7. more data processing**
- 8. load management**
- 9. more conservation**
- 10. more chainsaws**
- 11. RAS's (Remedial Action Schemes)**
- 12. SPS's (Special Protection Schemes)**

But what exactly is the problem?

Of course, it is critical to get the problem right.

After all, the best possible solution to the wrong problem is still the wrong solution

Notation

Let:

- X** be a space of control schemes and strategies, such as
- use PMU's to collect data
 - shed load at bus-37 if the voltage drops 10%
- C** be the space of all possible operating conditions of the system, such as
- a short circuit on line-25 while it is carrying 1000 MW
 - a short circuit on line-25 while it is carrying 1003 MW, and the state-estimator is down
- $g_k(\mathbf{x}, \mathbf{c})$ be the stress on device-k as a result of condition-c and strategy-x
- $f(\mathbf{x}, \mathbf{c})$ be the societal cost of condition-c and strategy-x

At present, P (protection) is treated as a constraint satisfaction problem...

Find a strategy, \mathbf{x} , such that:

$$\mathbf{g}_k(\mathbf{x}, \mathbf{c}) \leq \mathbf{T}_k \quad \text{for all } k \text{ and all } \mathbf{c} \in \mathbf{C}$$

**Stress-Threshold beyond
which device-k could be
damaged**



The existing strategy is to de-energize each and every device that approaches its threshold.

The beauty of this strategy is that it is unaffected by \mathbf{C} , except for hidden failures and controller mis-operations.

The disadvantage is that makes no attempt to limit the number of devices that are de-energized

P+CFC (protection + cascading failure control), can be formulated as a constraint satisfaction or optimization problem. The constraint satisfaction formulation is:

Find a strategy, x , such that:

Societal cost

$$f(x, c) \leq \$$$

Maximum allowable cost per incident

Stress on device-k

$$g_k(x, c) \leq T_k$$

Stress-threshold

for all k and all $c \in C$

C is so large that finding solutions to this problem is difficult, and verifying solutions is impossible.

Verification

The solution to a problem is only as good as the tests by which it is verified.

For P+CFC, the tests can never be complete or absolute. (At least, not until there is a breakthrough in testing technology.)

At best, one can verify only a small sub-set of the possible operating conditions, say (N-2) or (N-3).

The Aug. 14, 2003 blackout was an (N-k) event, where k was about 25. (See Fig 6.1 in the Final Report On The August 14, 2003 Blackout In The United States And Canada.)

The complete verification problem:

Given a control strategy, \mathbf{x}^* , show that

$$f(\mathbf{x}^*, \mathbf{c}) \leq \$$$

$$\mathbf{g}_k(\mathbf{x}^*, \mathbf{c}) \leq \mathbf{T}_k$$

for all k and all $\mathbf{c} \in \mathbf{C}(\mathbf{x}^*)$

This problem is impossible to solve because \mathbf{C} , the space of all possible operating conditions, is very large. And \mathbf{C} depends on \mathbf{x}^* , the control strategy to be verified. \mathbf{C} grows dramatically with the complexity of \mathbf{x}^* .

At best, one can verify only a small sub-set of the operating conditions, C , and with only approximations to stress and cost.

A partial verification problem:

Given x^* , a control strategy, show that

$$\mathbf{F}(x^*, c) \leq \$$$

$$\mathbf{G}_k(x^*, c) \leq \mathbf{T}_k$$

for all k , and all $c \in C'$

where F and G_k are approximations to f and g_k , and C' is a small sub-set of C

The dangers of partial verification

- 1. Untested conditions can, and invariably will, occur**
- 2. There is an unavoidable tendency to optimize the system for the conditions to be tested. This could make the system more vulnerable to the untested conditions.**

A measure of solution-quality with partial verification

Solution-x1 is better than solution-x2 if x1 is less costly than x2, that is, if:

$$\sum_{\mathbf{c}} F(\mathbf{x1}, \mathbf{c}) < \sum_{\mathbf{c}} F(\mathbf{x2}, \mathbf{c})$$

$$G_{\mathbf{k}}(\mathbf{x1}, \mathbf{c}) \leq T_{\mathbf{k}}, \quad G_{\mathbf{k}}(\mathbf{x2}, \mathbf{c}) \leq T_{\mathbf{k}}$$

for $\mathbf{c} \in C'$

Our approach to solving the P+CFC problem

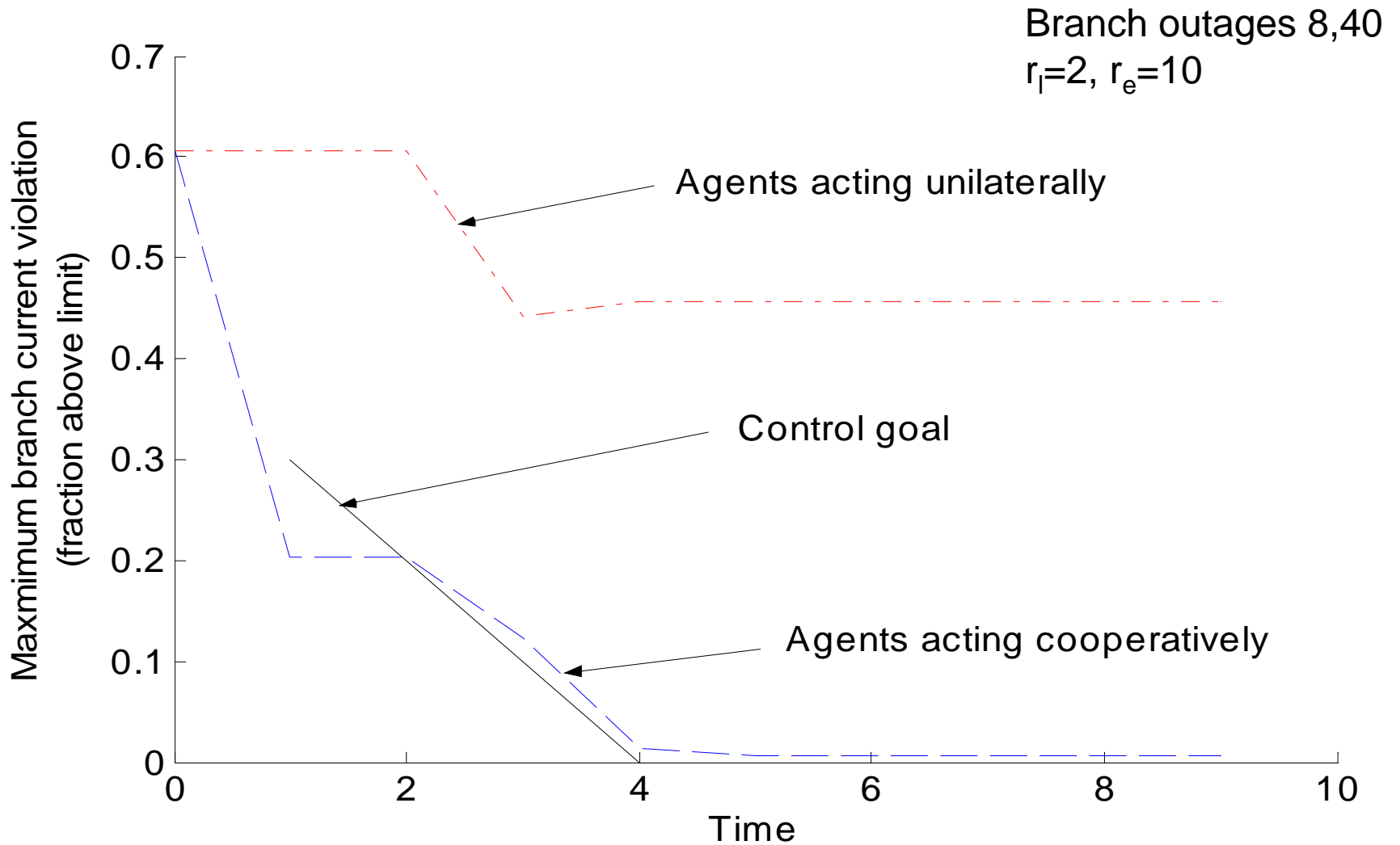
Cascading failures are the sub-optimal reactions of relays to bizarre conditions. (These reactions are good solutions to problem-P, but poor solutions to problem-P+CFC.)

Existing relays are autonomous agents of very limited intelligence.

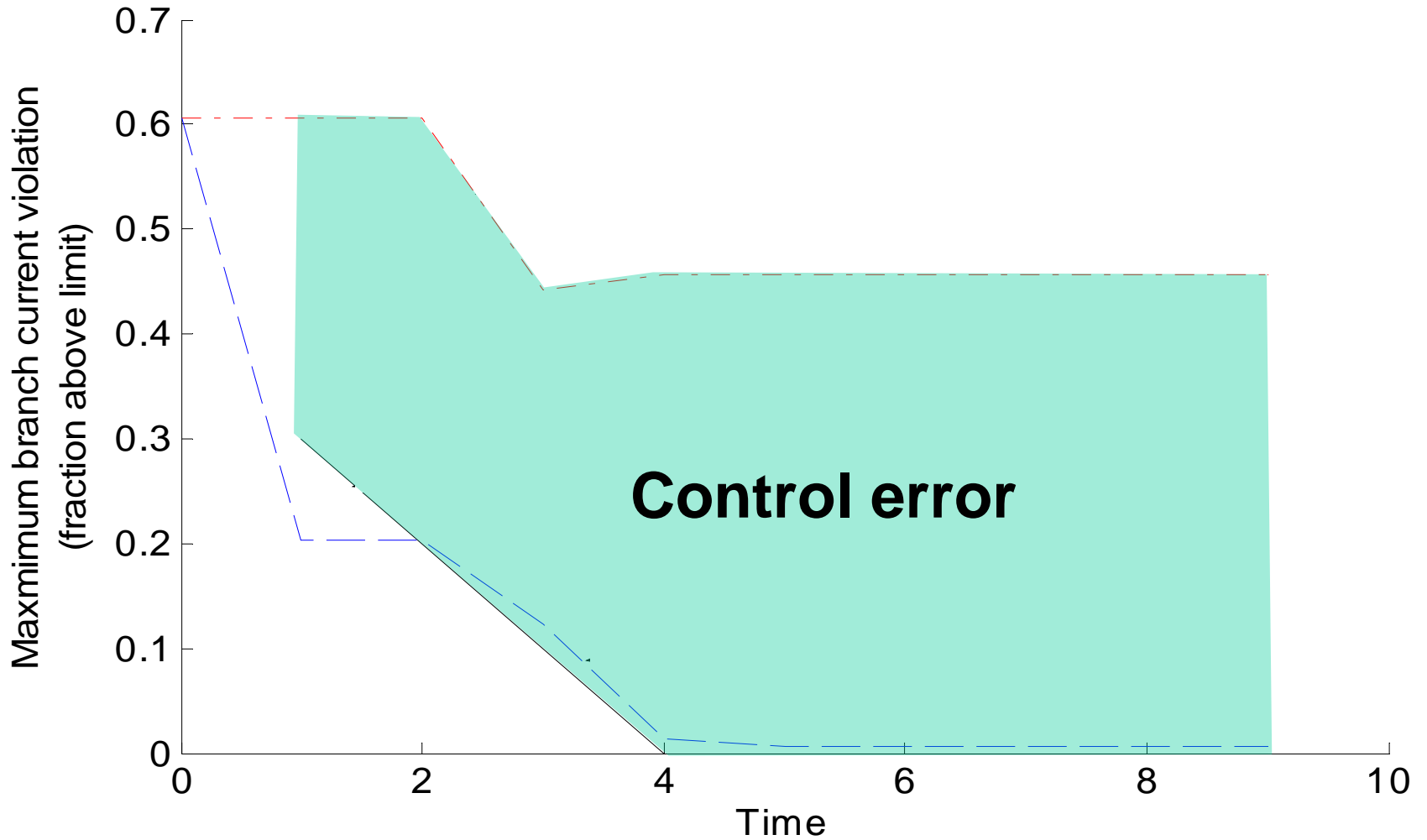
Our approach is to give the relays additional intelligence, and make them use:

- distributed model predictive control,**
 - cooperation (each relay with its neighbors),**
 - and eventually, learning**
- to better solve the P+CFC problem**

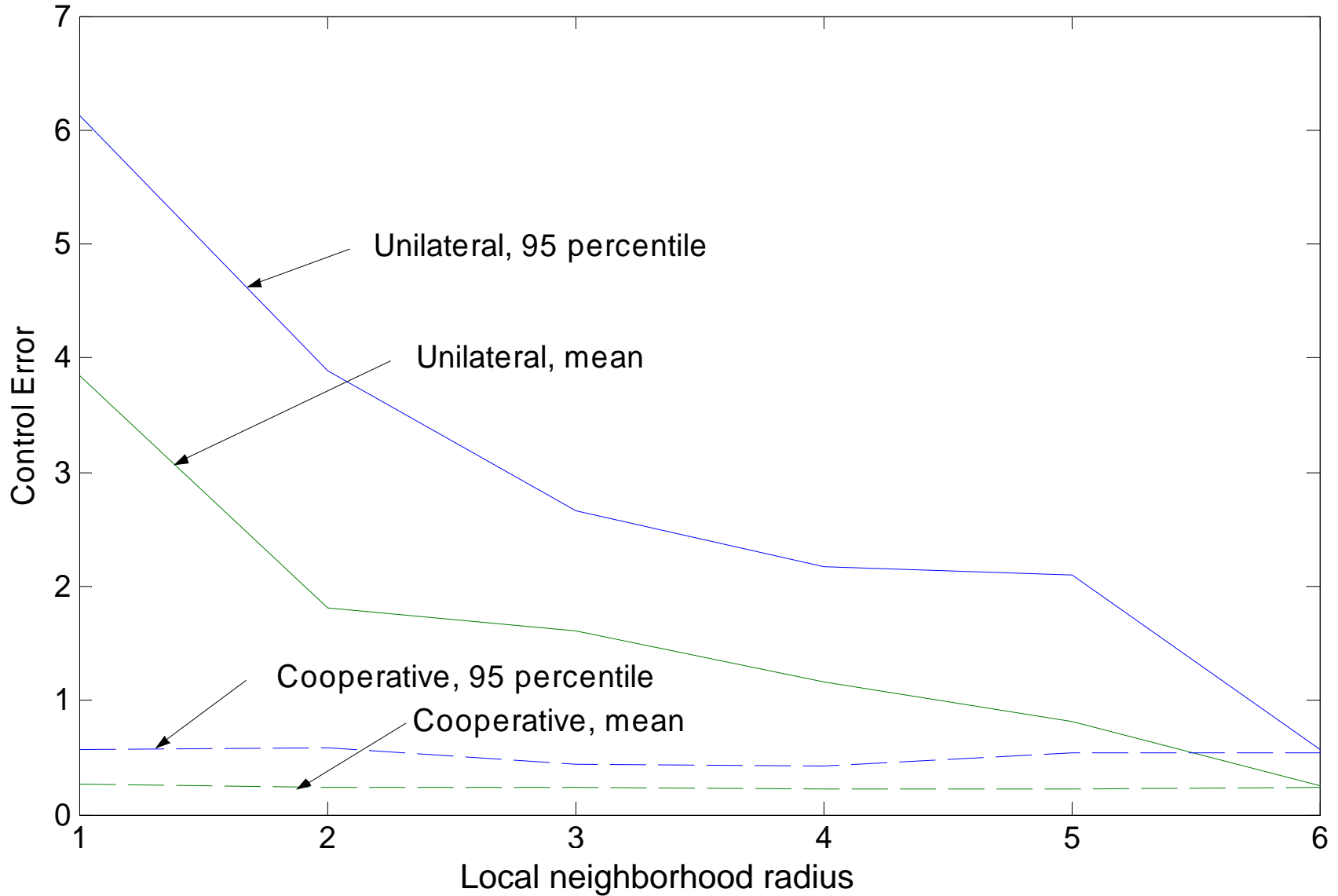
Typical results



Control error...



Control error vs. communication



Conclusions

- 1. Cascading failures are the sub-optimal reactions of relays to bizarre conditions. (The reactions are optimal for problem-P, but sub-optimal for P+CFC.)**
- 2. We can design new and better solutions to P+CFC**
- 3. But a solution is only as good as the tests (and conditions) by which it is verified.**
- 4. We can only test a small sub-set of the possible conditions.**
- 5. Until a breakthrough in verification technology occurs, most conditions will remain untested. These untested conditions will inevitably be a source of cascading failures.**