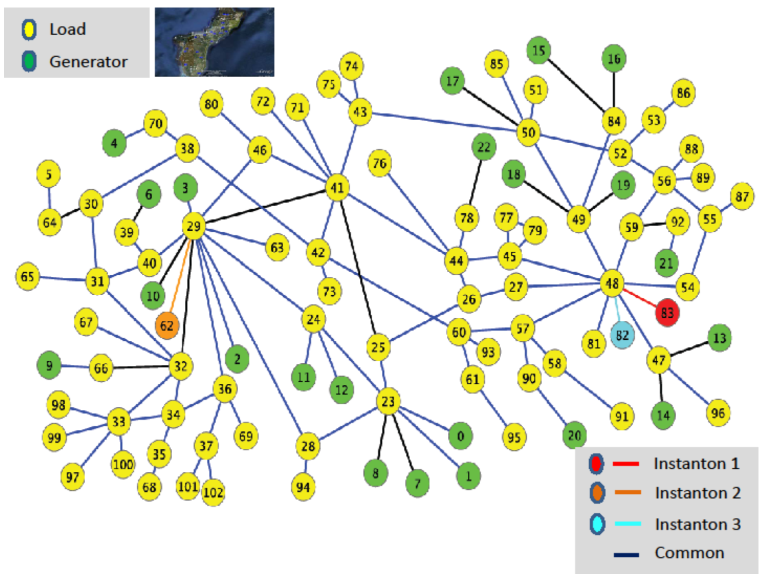
Distance to Failure in Power Grids [Chertkov,Pan,Stepanov]



Example: The power grid of Guam

- Normally the grid is SATisfiable
- Sometimes failures happen
- How to estimate probability of a failure?
- How to predict and prevent a failure?
- Phase space of possibilities is huge

(finding the needle in the haystack)

Optimization & Control Theory for Smart Grids

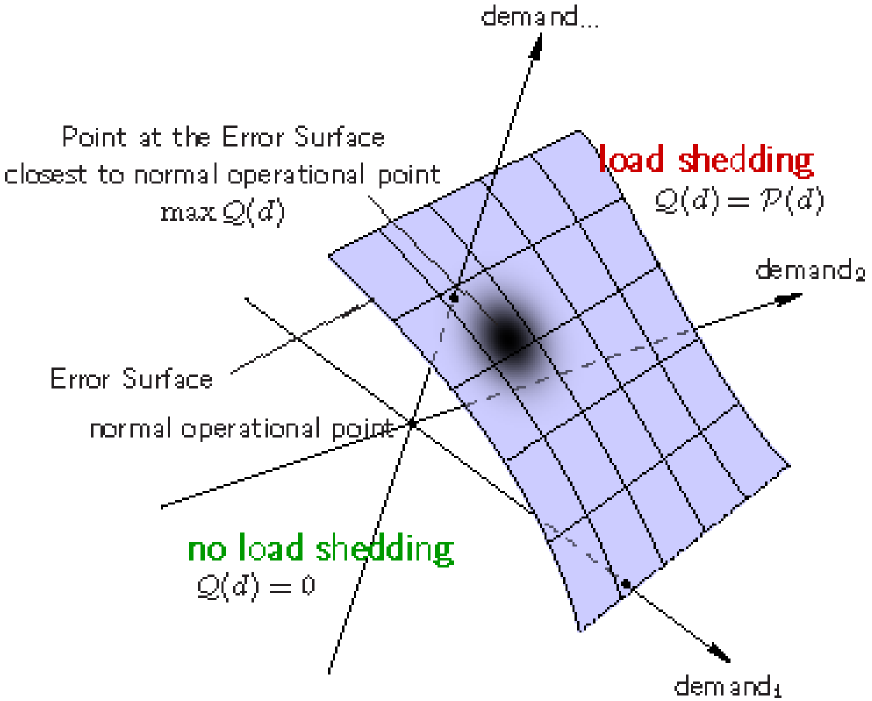
Technique to tackle the problem is borrowed from our (LANL) previous Physics & Error-Correction studies: Instanton Search Algorithm

- For any configuration of demand, construct a function Q(d)=0 if no load shedding is required and Q(d)=P(d) [configuration probability] when shedding is unavoidable

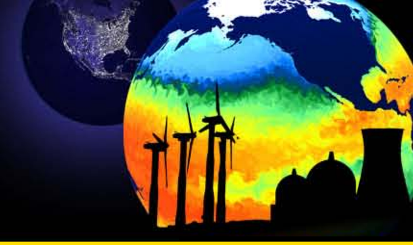
- Generate a simplex (N+1) of UNSAT points

- Use Amoeba-Simplex [Numerical Recipes] to maximize Q(d)

- Repeat multiple times (sampling the space of instantons)



Optimization & Control Theory for Smart Grids



Minimize Load Shedding = Linear Programming for DC

$$LP_{DC}(\mathbf{d}|\mathcal{G};\mathbf{x};\mathbf{u};\mathbf{P}) = \min_{\mathbf{f},\varphi,\mathbf{p},\mathbf{s}} \left(\sum_{a\in\mathcal{G}_d} s_a \right)_{COND(\mathbf{f},\varphi,\mathbf{p},\mathbf{d},\mathbf{s}|\mathcal{G};\mathbf{x};\mathbf{u};\mathbf{P})}$$

$$COND = COND_{flow} \cup COND_{DC} \cup COND_{edge} \cup COND_{power} \cup COND_{over}$$

$$COND_{flow} = \left(\forall a: \quad \sum_{b\sim a} f_{ab} = \begin{cases} p_a, & a \in \mathcal{G}_p \\ -d_a + s_a, & a \in \mathcal{G}_d \\ 0, & a \in \mathcal{G}_0 \setminus (\mathcal{G}_p \cup \mathcal{G}_d) \end{cases} \right)$$

$$COND_{DC} = \left(\forall \{a,b\}: \varphi_a - \varphi_b + x_{ab} f_{ab} = 0 \right), \quad COND_{edge} = \left(\forall \{a,b\}: -u_{ab} \le f_{ab} \le u_{ab} \right)$$

$$COND_{power} = \left(\forall a: \quad 0 \le p_a \le P_a \right), \quad COND_{over} = \left(\forall a: \quad 0 \le s_a \le d_a \right)$$

φ -phases; f -power flows through edges; x - inductances of edges

- no load shedding $\Leftrightarrow LP_{DC}(d) = 0$

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SAT/UNSAT & Error Surface

Statistics of Loads

$$\mathcal{P}(\mathbf{d}|\mathbf{D};c) \propto \exp\left(-\frac{1}{2c}\sum_i \frac{(d_i - D_i)^2}{D_i^2}\right)$$

D is the normal operational position in the space of demands

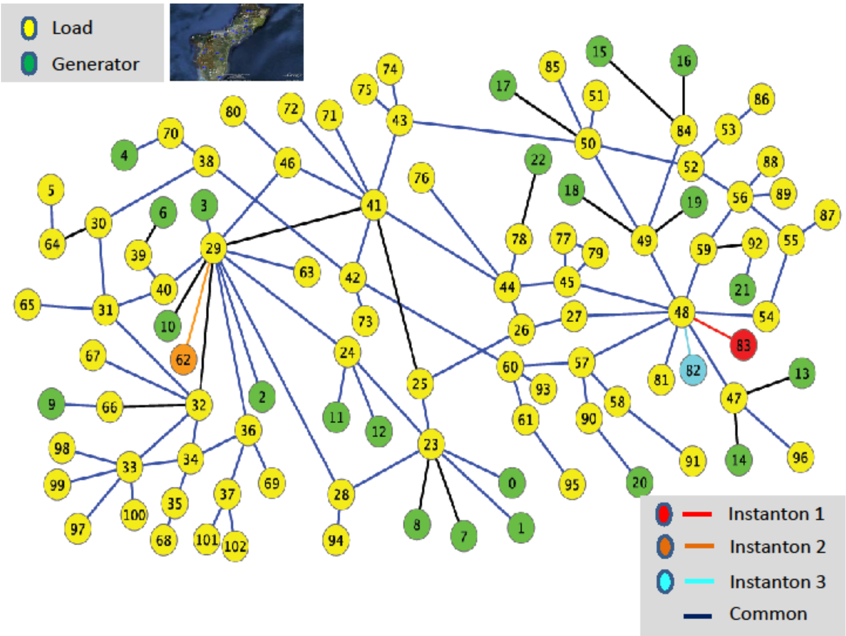
Instantons (special instances of demands from the error surface)

- Points on the error-surface maximizing $\mathcal{P}(\mathbf{d}|\mathbf{D};c)$ - locally!
- $\arg\max_{\mathbf{d}} \mathcal{P}(\mathbf{d})|_{LP_{DC}(\mathbf{d})>0}$ - most probable instanton
- The maximization is not concave (multiple instantons)

No Shedding (SAT) - Boundary - Shedding (UNSAT) = Error Surface

The task: to find the most probable failure modes [instantons]

Example of Guam:



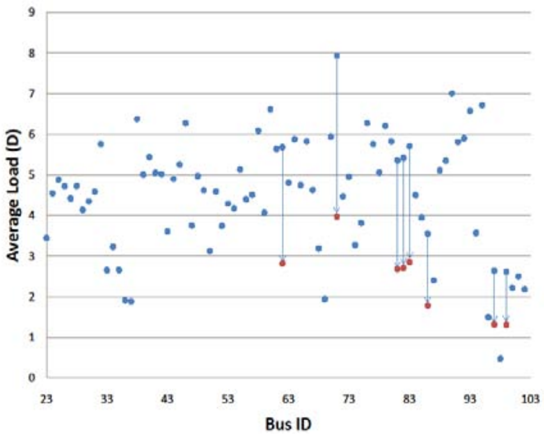
- Data is taken from LANL/ D-division (infrastructure) data-base for a typical day

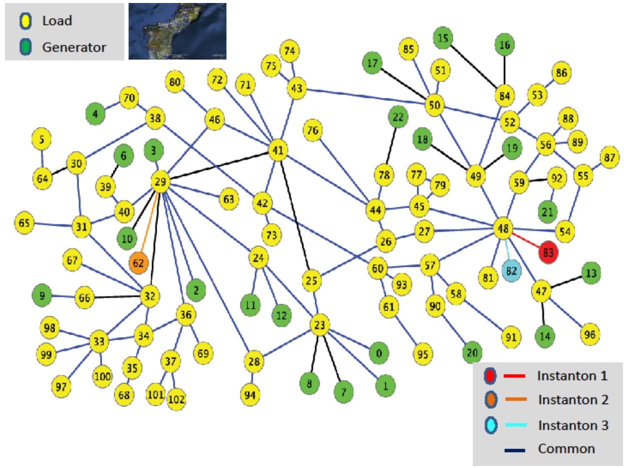
- The instantons (ranked according to their prob. of occurrence) are sparse (localized on nodes connected to highly stressed lines)

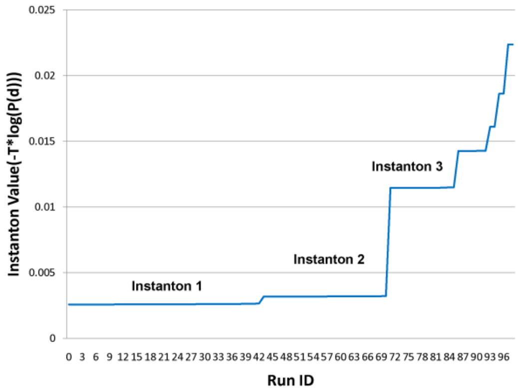
- The analysis reveals weak points of the grid: unserved nodes, stressed links and generators. Normally, there exists only a handful of the weak points calling for attention.

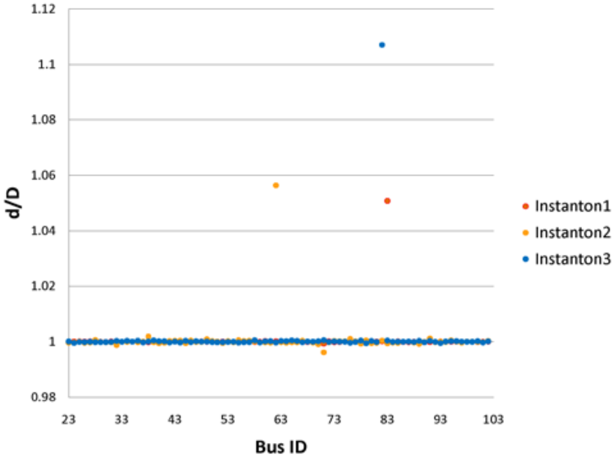
- *other examples were also tested*

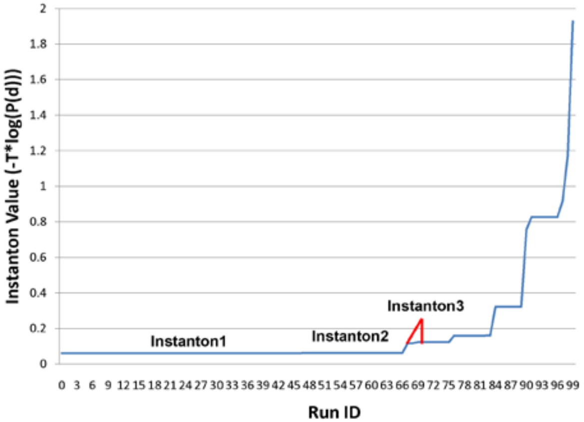
Example of Guam (more details):



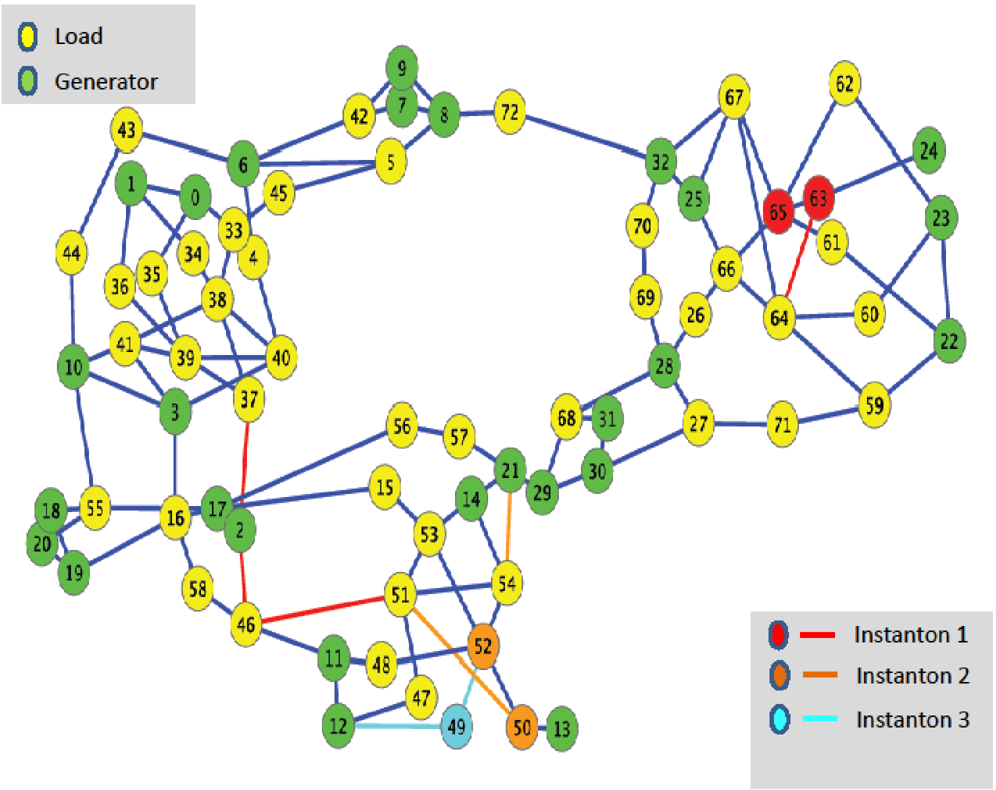






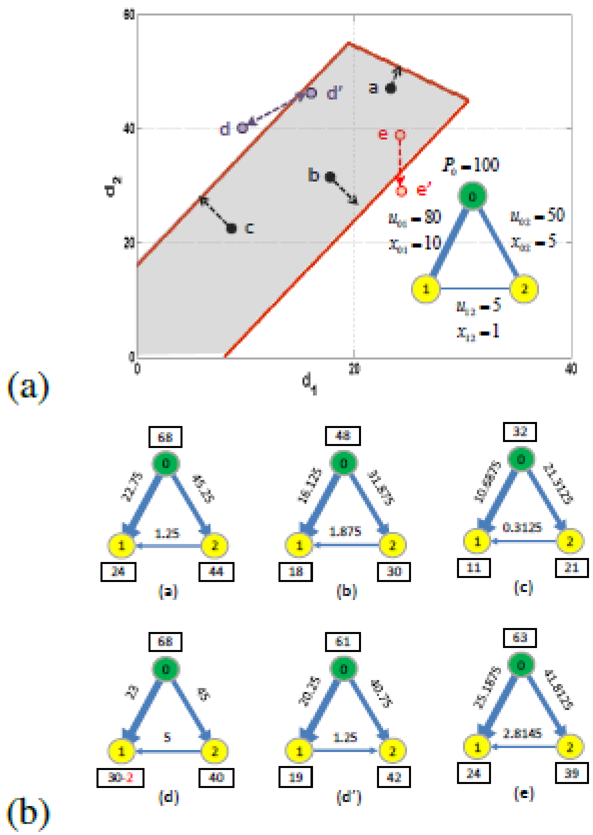


Example of IEEE RTS 96:



- Instantons are localized but not sparse
- Hot spots are not necessarily neigbors, may be far from each other (on the graph)
- Weaker demand may also be bad (``paradox"/triangular example)

Triangular Example [illustrating the ``paradox”]:



- lowering demand may be troublesome [SAT -> UNSAT]
- develops when a cycle contains a weak link
- similar observation was made in other contexts before, e.g. by S. Oren and co-authors
- the problem is typical in real examples
- consider ``fixing” it with extra storage [Scott’s idea]

Conclusions and Path Forward (for the Distance to Failure subproject)

- Formulated Load Shedding (SAT/UNSAT) condition as a Linear Programming task based on DC power flow approximation
- Analyzed power-grid failure using Error-Surfaces and an instanton description
- Instanton-amoeba algorithm was adapted and tested on examples. Good to test, identify (and eventually resolve) hidden problems.

- Incorporate other, more realistic measures of network stability, i.e. voltage stability (via AC power flow) and transient stability (via dynamical models, accounting for voltage collapse, e.g. synthesis with the SOS techniques discussed by Marian)
- Accelerate the instanton-search by utilizing LP-structure of the model. Apply to larger scale problems [e.g. ERCOT driven by renewables – collaboration with R. Baldick]
- Reach beyond our first step to explore cutting-edge topics, e.g. fluctuations in renewables, interdiction, optimal switching, cascading events, and avoidance of extreme outages

Collaborations & Program Development

- LANL has unique combination of theory (T-,CCS-) and application (D-) expertise to tackle the challenging problems
- The ultimate goal is to lead efforts within the DOE complex

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- Multiple collaborations (students, joint grants, exploration) with MIT, Berkeley, U of Michigan, U of Texas, UCSB, PNNL and others
- Actively involved in (NEW) community Building (new confs, journals,etc)

- New DTRA funding (1.2M over 3 years) – Cascading Failures
- New OE funding (350K for FY10 with possible growth in future FY's) -Control of PV with NEDO & LA county
- Wait for (a) DOE FOA 68 (renewable energy integration) - 4M over 3 years
  (b) DOE FOA 313 (distribution automation, heavy involvement with Industry)
- Multiple other submissions/calls, mainly from DOE & DHS

Build a Smartgrid Program at LANL:

- Field is new and growing
  - A lot of interesting power grid problems for CS/IT/Physics
  - Timely research (blackouts, renewable, stimulus)

- Challenges:
  - Pool of interested researchers and students currently small (but growing).

  - We need to encourage students in CS/IT/Physics to work on these problems through the development of joint graduate programs with top schools such as MIT, Berkeley, Stanford, etc.