Practical Reliability and Uncertainty Quantification in Complex Systems

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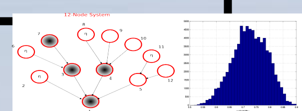
Purpose, Goals and Approach

- Modernize NW system reliability estimation: More complex models of system, system variables and analysis objectives, such as experiment design.
- Estimate epistemic reliability of complex, time-dependent hierarchical systems using Bayes Networks, function analytic probability, and modern computational probability methods.

Significance of Results

- Novel use of varied analytical tools to provide general density estimation based on test data accommodating time-dependent epistemic uncertainty
- Provides well-defined strategy for choosing optimal test suite
- Readily extensible to other network-class problems



Network reliability as Epistemic quantity

Key Accomplishments

- Developed procedure to compute probability distributions for system reliability estimates
- Extended procedure to time-dependent case to assess effects of aging
- Developed Bayesian decision analysis approach to predict optimal test strategies

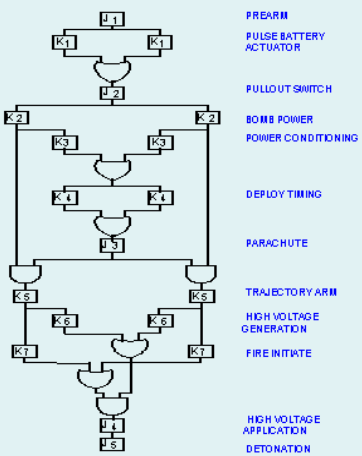
What's Next

- Leverage experience in seeking out new business based on network analysis: E.g. electrical power grids, cyber security, water distribution, evolving biological systems, and complex interacting systems
- Time frame for full-scale implementation of technology: 5-10 years

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Sandia National Laboratories

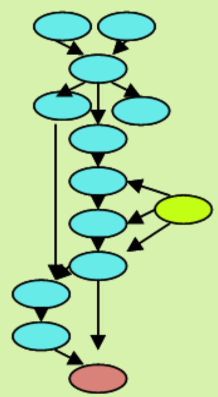
Project Overview



Current NW reliability models are series/parallel approximations with conditionally-independent components

- Conditional only on upstream component providing required inputs
- The probability of each event is based on the results of pass/fail tests
- Generally do not include continuous variables, complex interactions, and associated uncertainties

LDRD to develop new methods and tools for application to NW



New models are more realistic:

- Continuous variables
- Accommodates complex interactions
- Uncertainty models: Non-Gaussian random variables and random fields
- Account for epistemic uncertainties: Data and model form
- More complex aging models

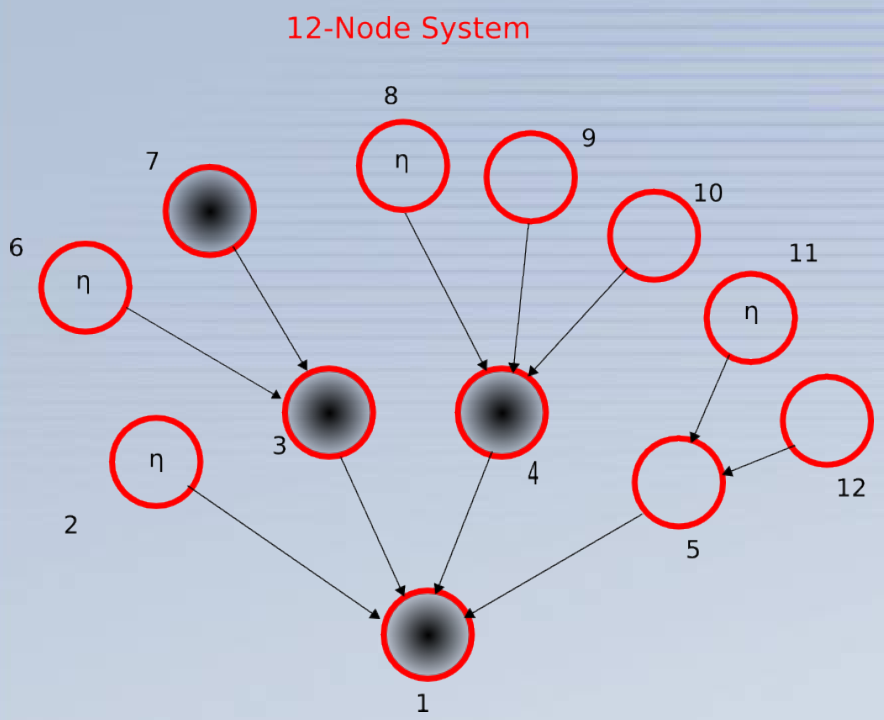
Key Technical Constituents

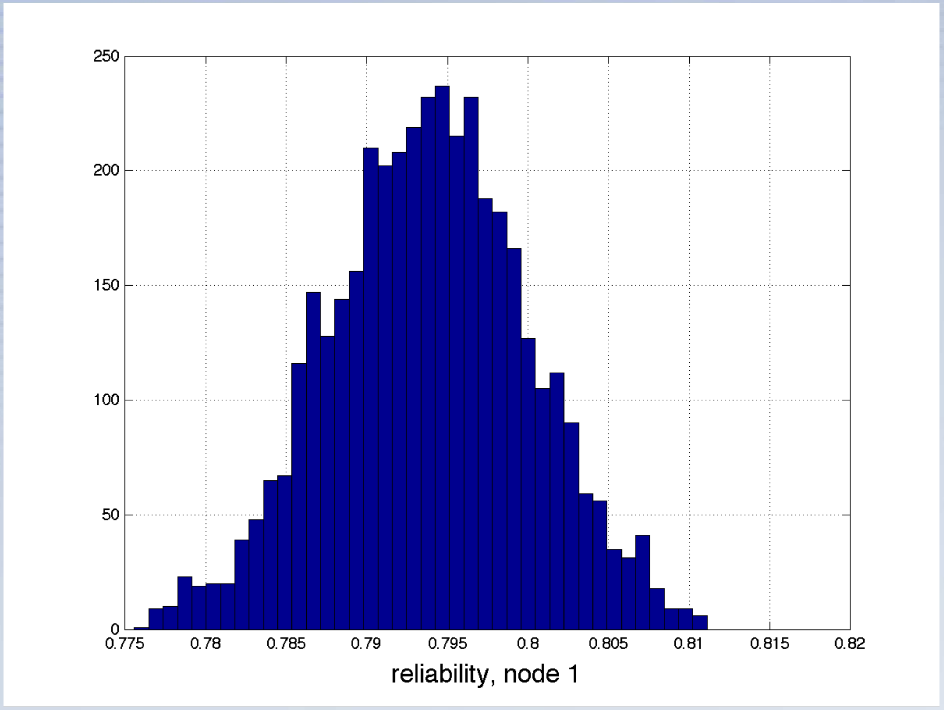
- **Systems Modeled as Networks of Components**
  - Leaf nodes represent random fields over time
    - Approximated by Polynomial Chaos Expansions (PCEs) with time-indexed random fields as coefficients – Allows general (non-Gaussian), time-dependent distributions
    - Accounts for epistemic uncertainty
  - System nodes represent nonlinear operators
- **System is tested at a subset of the nodes**
- **Bayesian Methods**
  - Bayes Theorem to propagate test results through system
  - Bayes Network to factor the system-level likelihood function

Key Technical Constituents

- **Markov Chain Monte Carlo**
  - Sample Bayes posterior distribution
  - Stochastic dimension reduction and fast polynomial solves to speed calculation of likelihood function
- **Bayesian Decision Analysis to optimize the testing strategies**
  - Where does one test next to minimize the risk of making the wrong decision?
  - Involves approximate integration over high-dimensional spaces

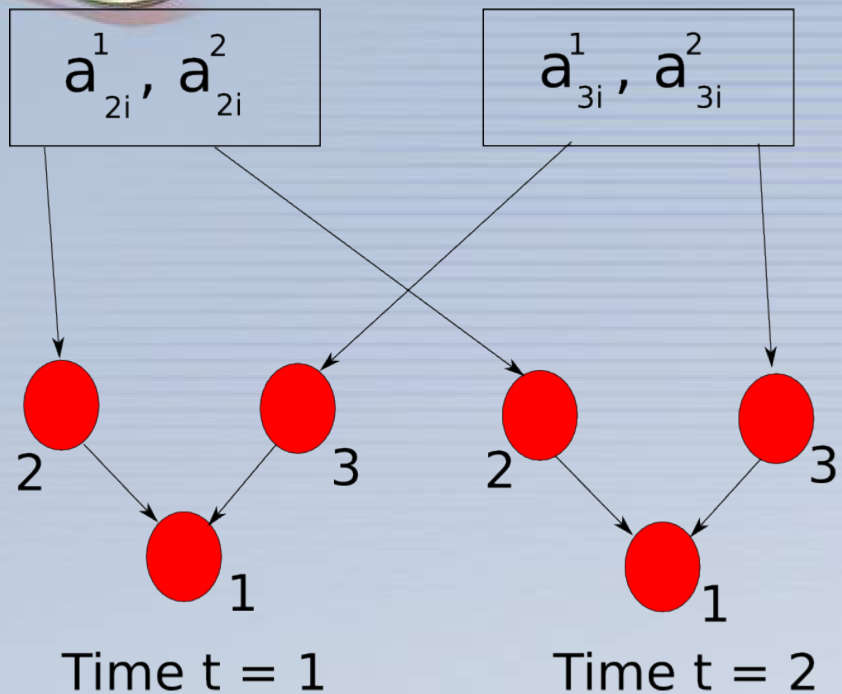
12-Node Network System and its reliability distribution

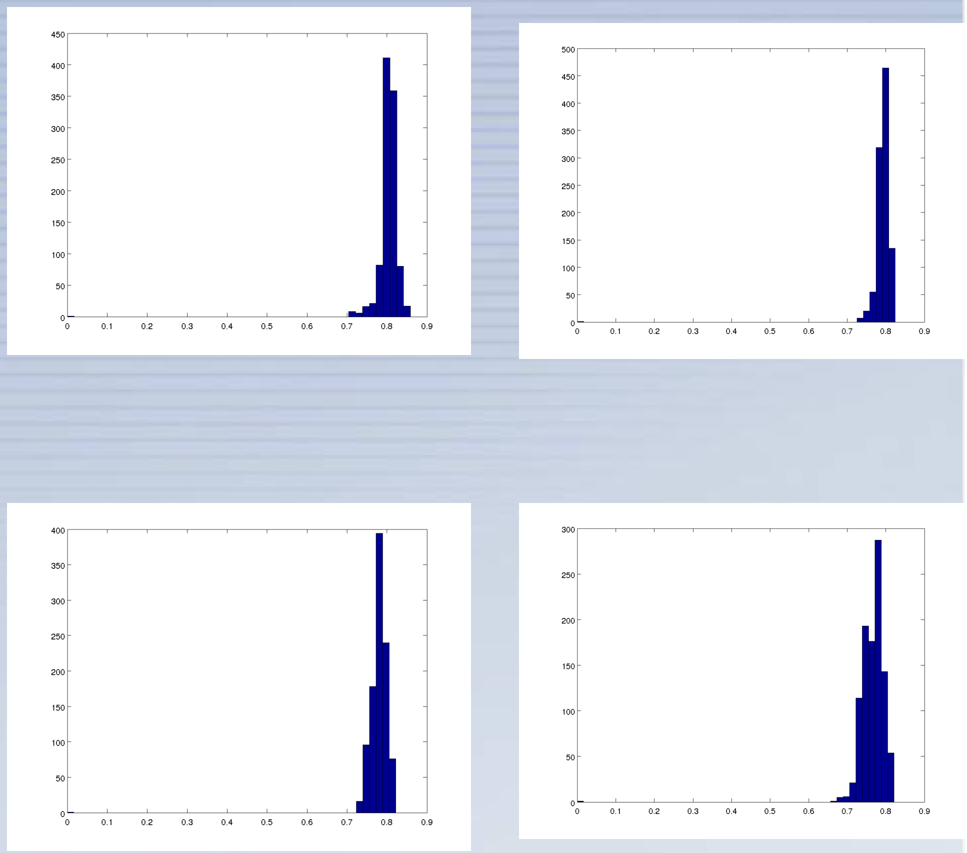




Data taken at nodes 1, 3, 4, and 7

3 Node Time Dependent System





Data taken at t=0, 1, 2

Reliability is accurately estimated at times t = 1, and 2 and accurately predicted at t = 3 (.80, .77, .75, .73)