Distributed Sensor Coordination for Advanced Energy Systems

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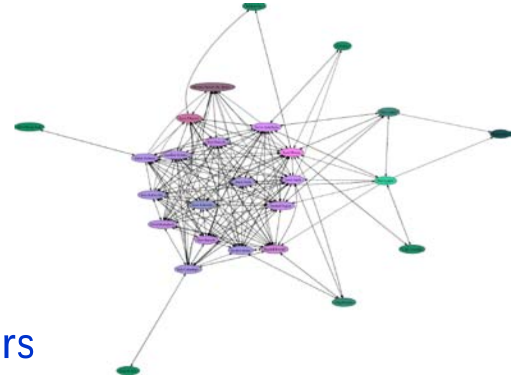
Motivation

- Where are we?
  - Advanced energy systems are becoming more interconnected
    - o More complex, more distributed, more stochastic
  - Computation pushed further down the pipe
    - o More powerful, cheaper, smaller devices



- Where are we going?
  - Smart "sensor" networks
    - o Tens of thousands of tiny, simple, unreliable sensors
  - Intelligent system health management
    - o Sense, decide, act -- repeat 1000s of times

Motivation

2010

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    - o More [illegible] tributed, more stochastic
  - Comput [illegible] ed further down the pipe
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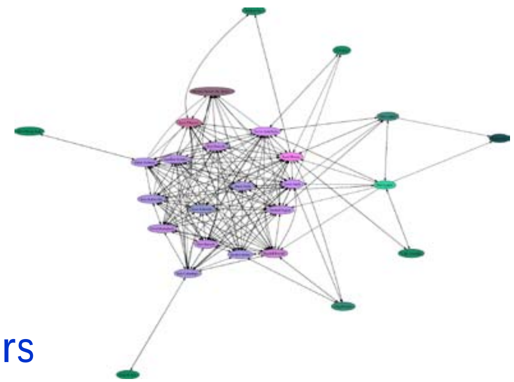

- Where are we going?
  - Smart “sensor” networks
    - o Tens of thousands of tiny, simple, unreliable sensors
  - Intelligent system health management
    - o Sense, decide, act -- repeat 1000s of times
- What do we need:
  - The coordination of thousands of “sensors” ✓
  - Reconfiguration of system to address failing sensors, changing goals ✓
  - Efficient operation in dynamic and stochastic environments

Key Contribution

How to coordinate a very large number of sensors and actuators so that they collectively optimize a system level objective function ?

Where Should Focus Be ?

- *New optimization algorithms ?*

  Not really

- *New control algorithms ?*

  Perhaps

- *Focus on*
  - *What to control ?*
  - *What to optimize ?*
  - *What are "good" system properties ?*

Outline

- Motivation
- Project Milestones and Tasks
- Results to date
  - System properties and agent objectives
  - Sensor Coordination and teams of sensors
  - Sensors in Energy Systems

Task Descriptions

Task	Description	Milestone
1.0	Project management and planning	
2.0	Determine impact of sensor configurations on system performance	0 ✓
2.1	Quantify effectiveness of sensor configuration	1 ✓
2.2	Form sensor teams to improve sensor effectiveness	2 ✓
3.0	Determine sensor objectives and demonstrate sensor reconfigurability	
3.1	Derive Sensor objective functions	3 ✓
3.2	Demonstrate system reconfigurability in simulation	4 (✓)
3.3	Demonstrate system reconfigurability in testbed	5

System Level Objectives to Agent Objectives

Sensor Networks

Design	*High level description*	Control
Sensor Selection *Sensor Placement*	*Sensor Research*	*Mobile Sensors* *Failing Sensors*
Optimization *Agent Objectives*	*Tools*	*Intelligent Control* *Agent Objectives*
Efficiency *Coverage* *Robustness*	*Benefits*	*Responsiveness* *Reconfigurability* *Robustness*
(task 2)		*(task 3)*

Desirable System Properties

- Factoredness:
  - Alignment
  - Modularization
  - Self-organization

$$\mathcal{F}_{g_i} = \frac{\sum_{z'} u[((g_i(z) - g_i(z'))(G(z) - G(z'))]}{\sum_{z'} 1}$$

$$(z'_{-i} = z_{-i})$$

Is what's good for me good for the full system ?

- Sensitivity
  - Signal to noise
  - Locality

$$L(g_i, z, z') = \frac{\|g_i(z) - g_i(z - z_i + z'_i)\|}{\|g_i(z) - g_i(z' - z'_i + z_i)\|}$$

$$L(g_i, z) = \frac{\sum_{z'} L(g_i, z, z')}{\sum_{z'} 1}$$

Can I extract what's good for me from signal I receive?

General Solution

- To get agent objective with high factoredness and sensitivity, start with:

$$g_i(\mathrm{z}) = G(\mathrm{z}) - G(\mathrm{z}_{-i} + c_i)$$

g_i is aligned with G
$G(z_{-i}+c_i)$ is independent of i
g_i has cleaner signal than G
$G(z_{-i}+c_i)$ removes noise

- If g, G differentiable, then:

$$\frac{\partial G(\mathrm{z}_{-i} + c_i)}{\partial \mathrm{z}_i} = 0$$

$$\frac{\partial g_i(\mathrm{z})}{\partial \mathrm{z}_i} = \frac{\partial G(\mathrm{z})}{\partial \mathrm{z}_i}$$

- To get agent objective with high factoredness and sensitivity, start with:

$$g_i(z) = G(z) - G(z_{-i} + c_i)$$

Major impact on system performance and robustness

Outline

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Two sets of results

- Sensor coordination and teams of sensors
  - Basic efficiency
  - Response to failures
  - Scaling to very large systems

- Sensor coordination in Energy Systems
  - Basic optimization
  - Response to changes in system
  - Response to failures

Sensor Coordination: Defect Combination Problem

- Sensors have varying attenuations due to manufacturing defects
- How to select a subset to optimize aggregated attenuation

$$G = \frac{\left|\sum_{i=1}^{N} n_i a_i\right|}{\sum_{i=1}^{N} n_i}$$

- How to coordinate hundreds or thousands of sensors?

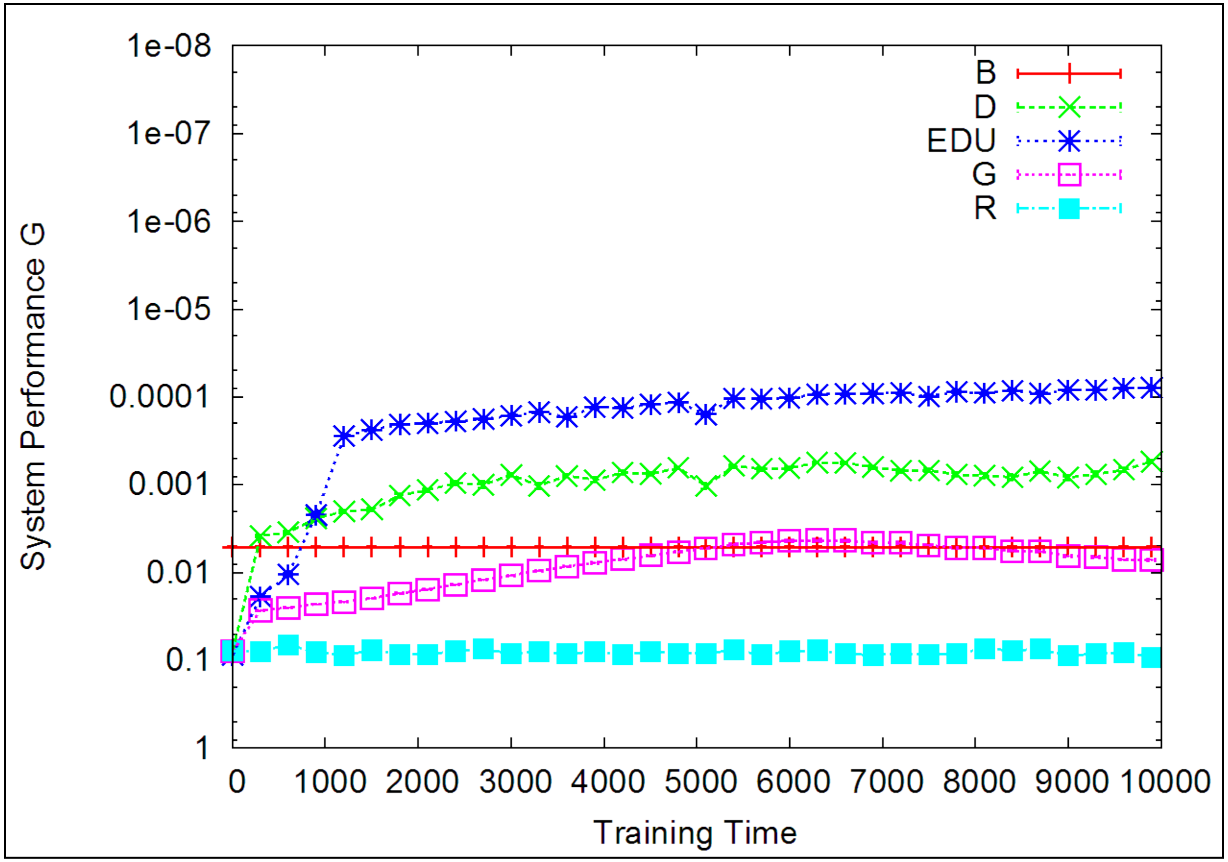
Sensors make decisions: they choose to be on or off

The Defect Combination Problem

- Three agent objectives:
  - **Global (G):** Total system reward (objective)
  - **Difference (D):** System objective minus “system objective without me”
  - **Estimated Difference (EDU):** System objective minus “system with average me”
- Compare to:
  - **Select Best Single Sensor (B):** Centralized global search, Selects the best single sensor
  - **Random:** Randomly select actions

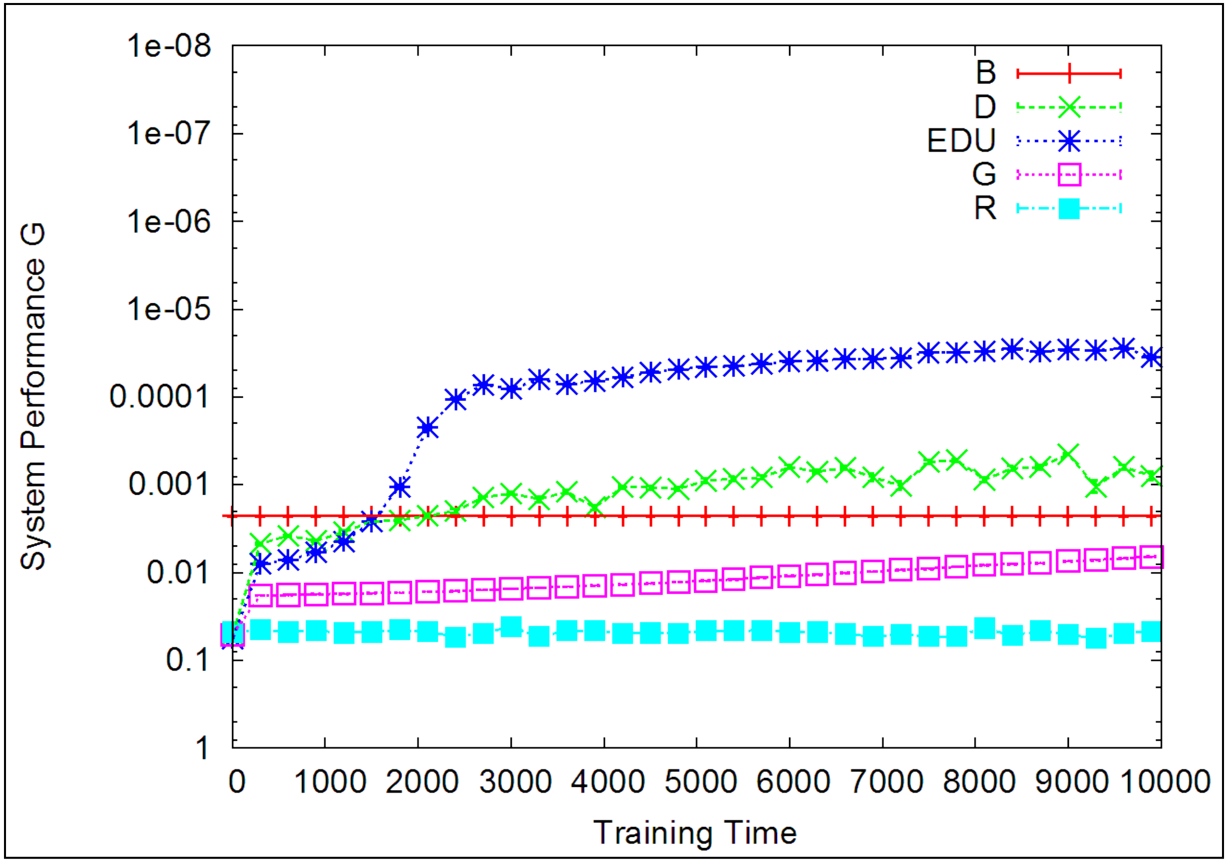
The Defect Combination Problem

200 Sensors



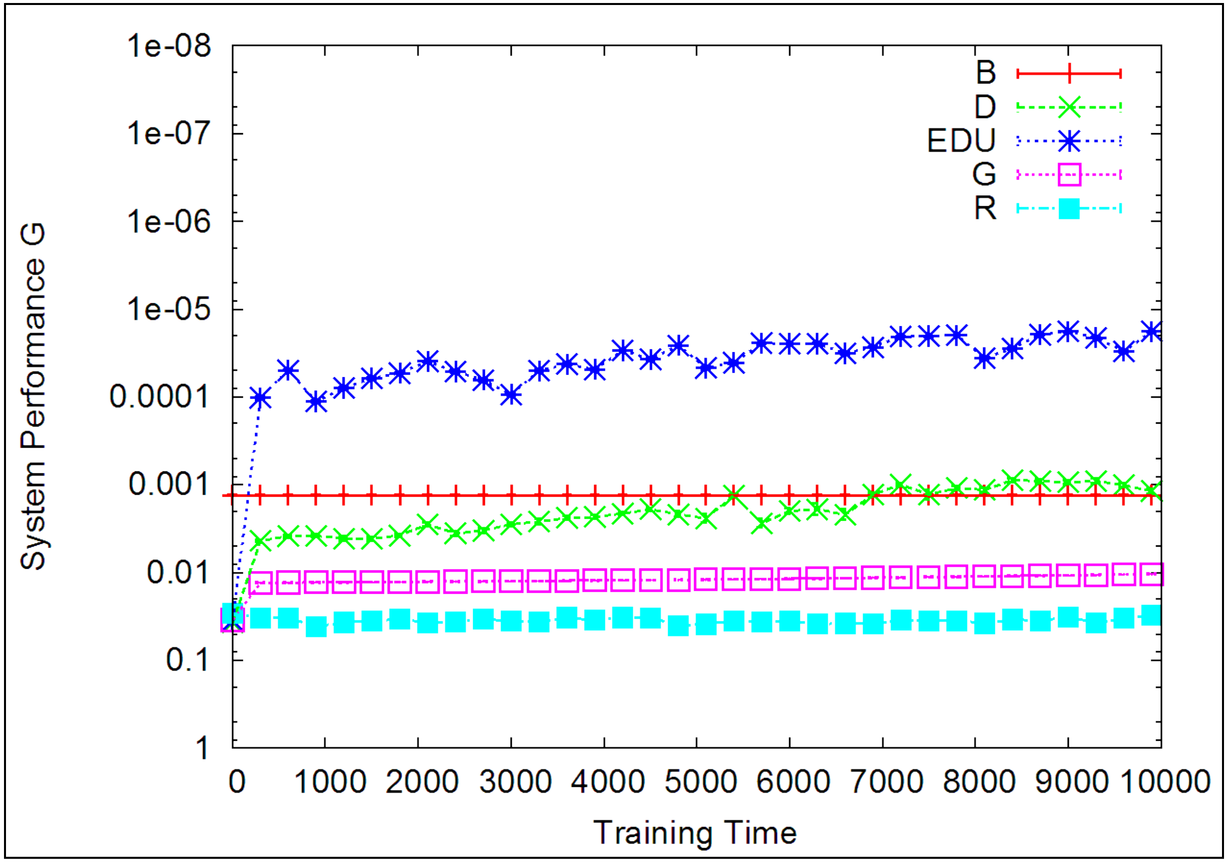
Problem 1: The Defect Combination Problem

500 Sensors, Defect Combination Problem



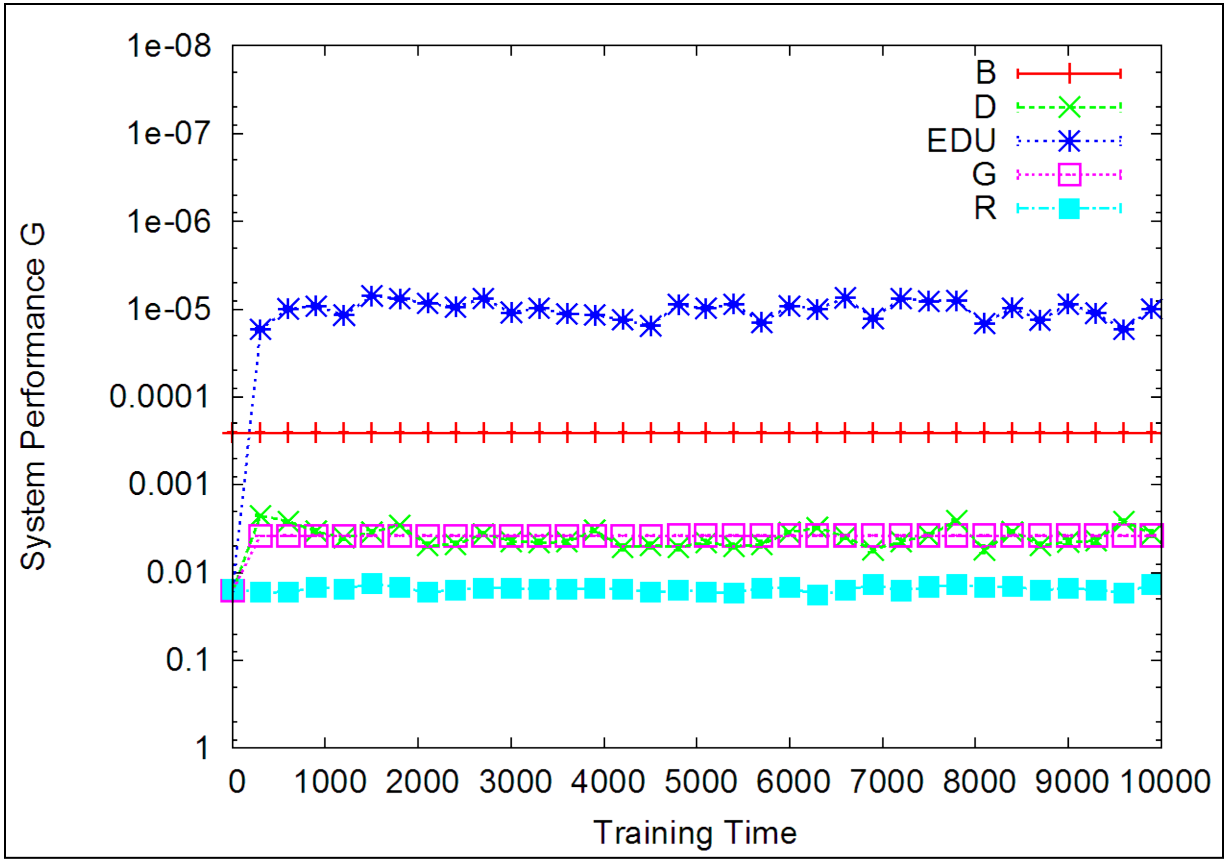
The Defect Combination Problem

1000 Sensors



The Defect Combination Problem

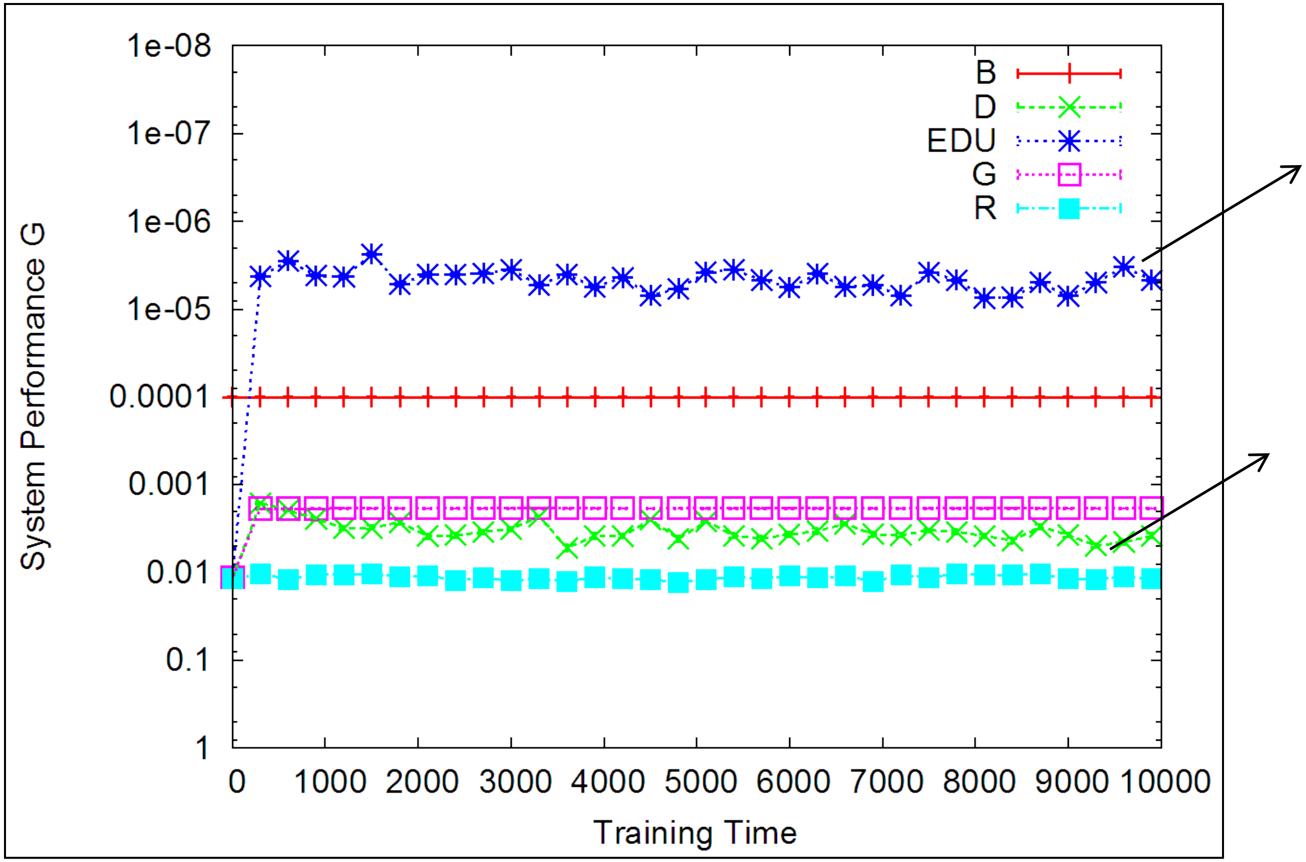
5000 Sensors



The Defect Combination Problem

10000 Sensors

$$g_i(z) = G(z) - G(z_{-i} + c_i)$$



DCP with hierarchical organization

No Hierarchies (Left)

- Agents coordinate directly

Hierarchical Organization (right)

- Agents form teams
- Teams coordinate internally
- Control agents coordinate teams

DCP: Team coordination

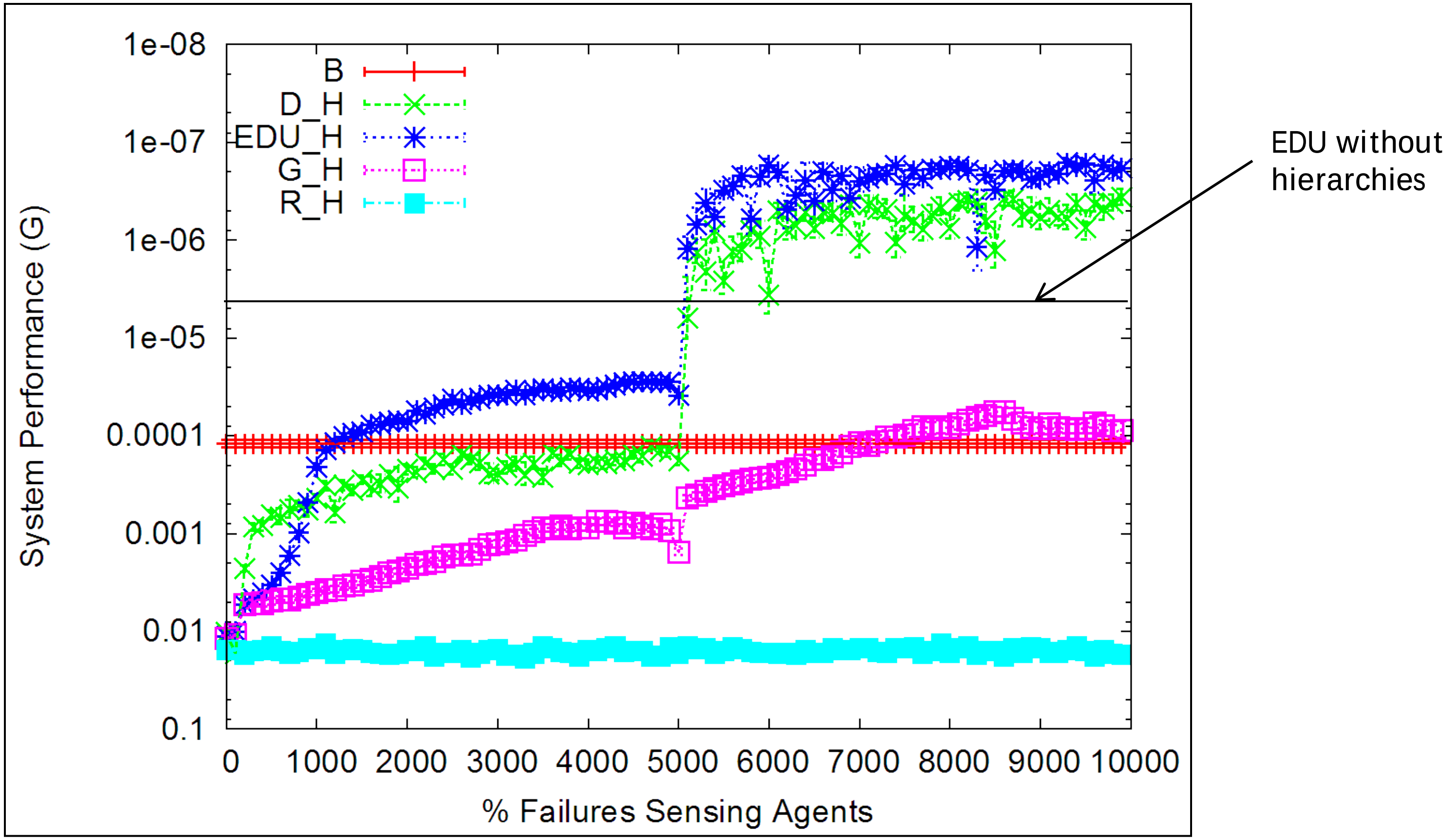
10,000 Sensors with Hierarchical Organization

- Sensing agents randomly divided into teams of 100
- One control agent per team
- Control agents coordinate the actions of teams

- Time step 0 to 5000: Sensing agents learn, control agents are on
- Time step 5000 to 10000: Control agents learn, sensing agents fixed

DCP: Hierarchical Teams

10000 Sensors with Hierarchical Organization



DCP: Hierarchical Teams and Robustness

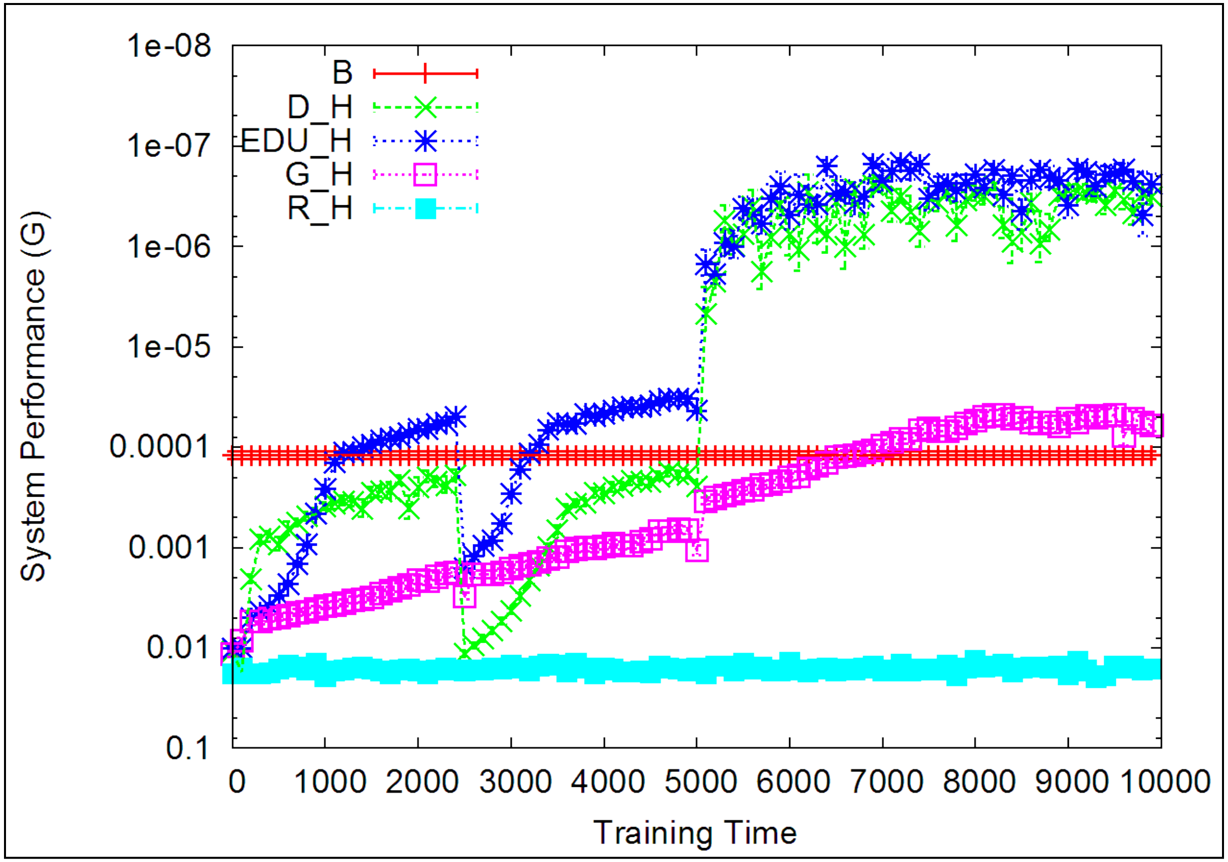
- How does this approach handle sensor agent failures?

- Failure experiments:
  - 10,000 agents
  - 0 to 100% sensor failures
  - Sensing agents learn from time step 0 to 2500
  - Some fail
  - System Reconfiguration: agents learn again, time step 2500 to 5000

  - Control agents learn using the teams with failures present: After step 5000

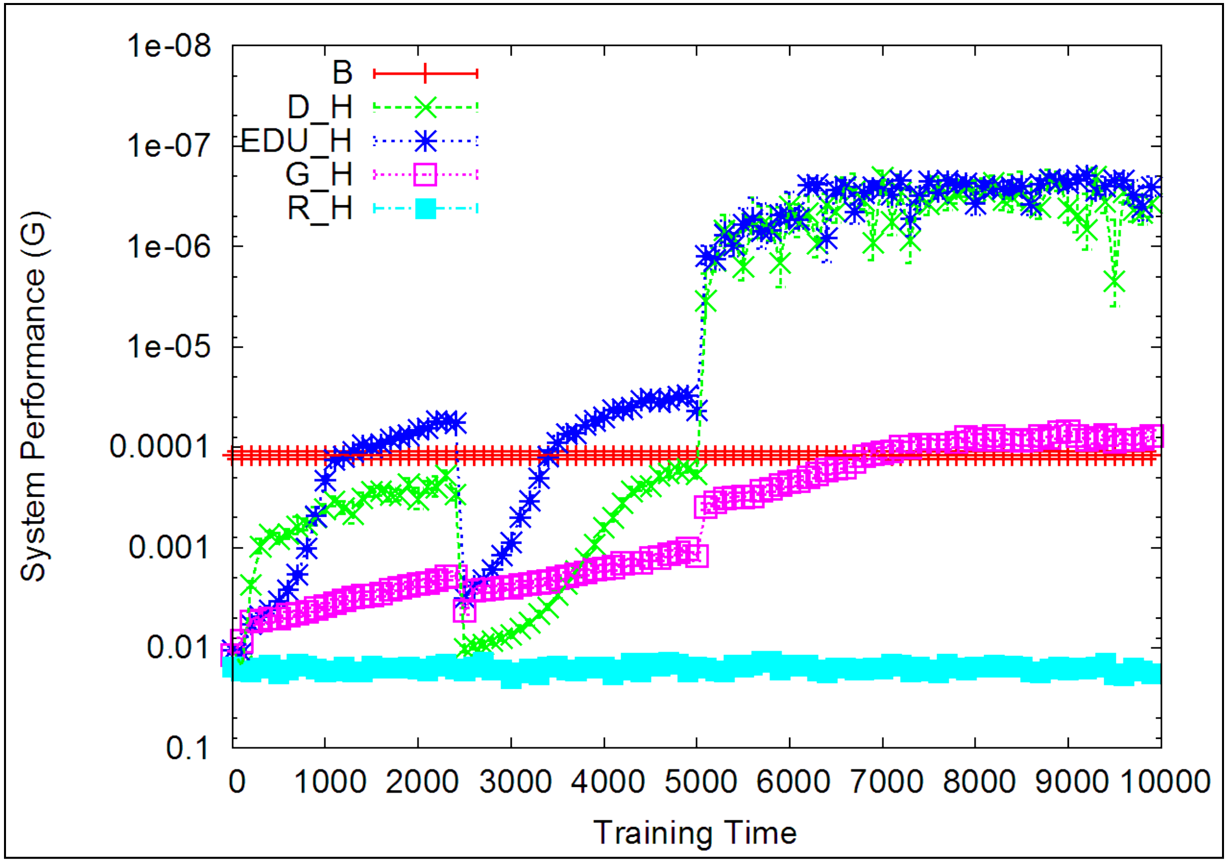
DCP: Hierarchical Teams and Robustness

10000 Sensors with Hierarchical Organization, 10% Sensing Agent Failures



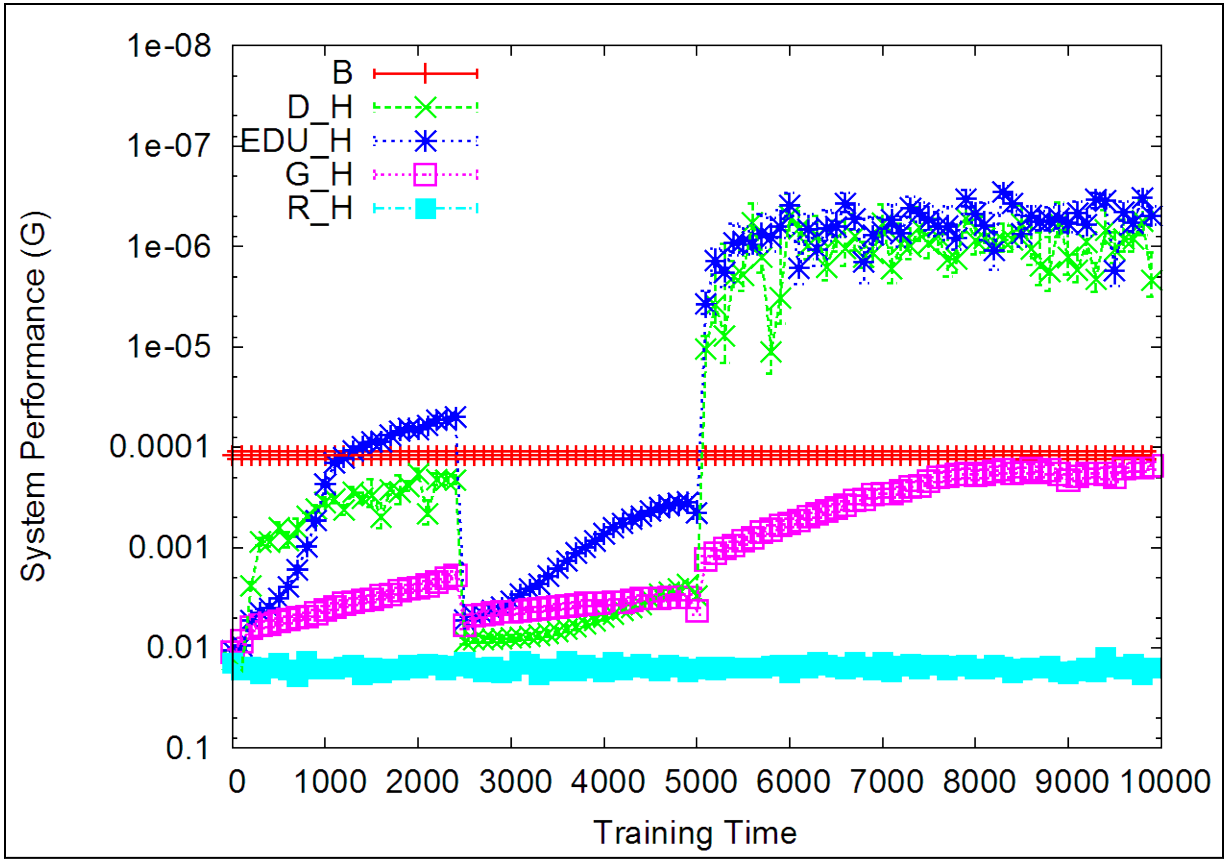
DCP: Hierarchical Teams and Robustness

10000 Sensors with Hierarchical Organization, 20% Sensing Agent Failures



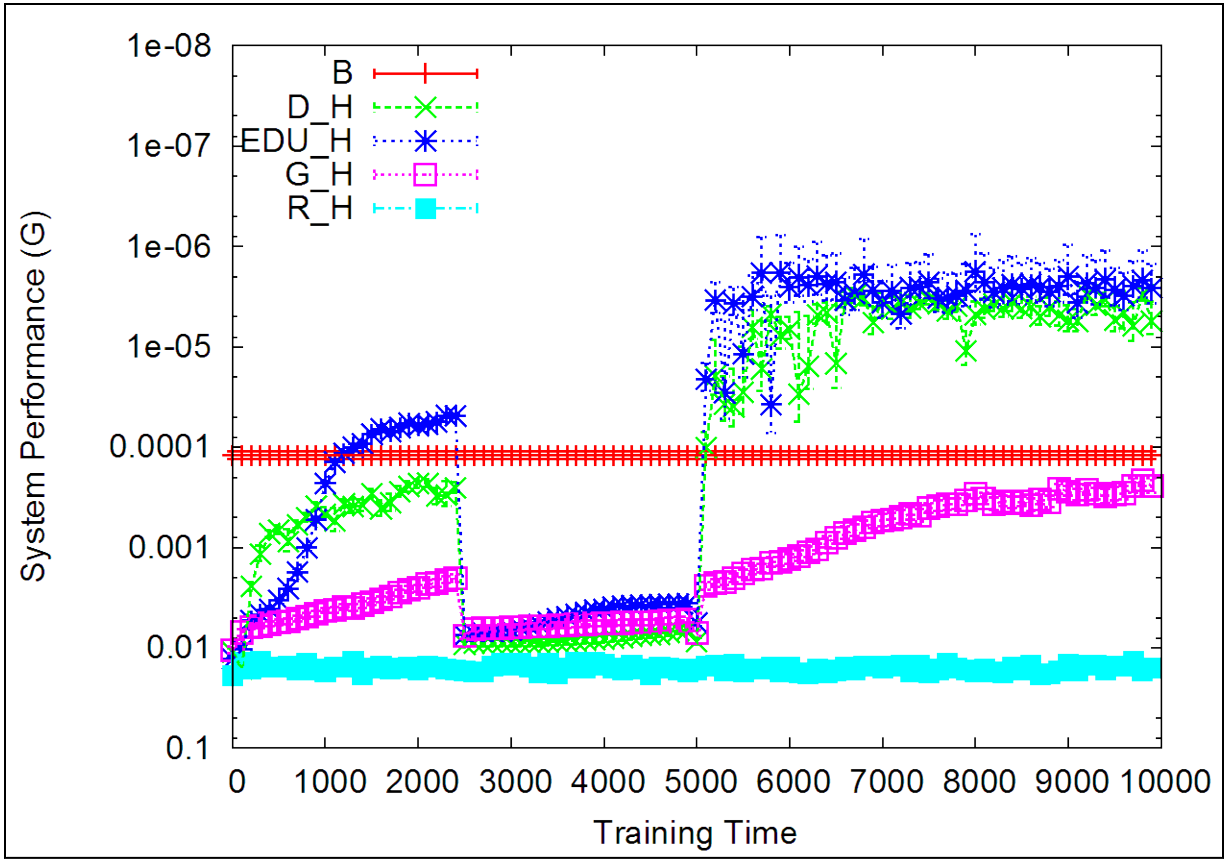
DCP: Hierarchical Teams and Robustness

10000 Sensors with Hierarchical Organization, 50% Sensing Agent Failures



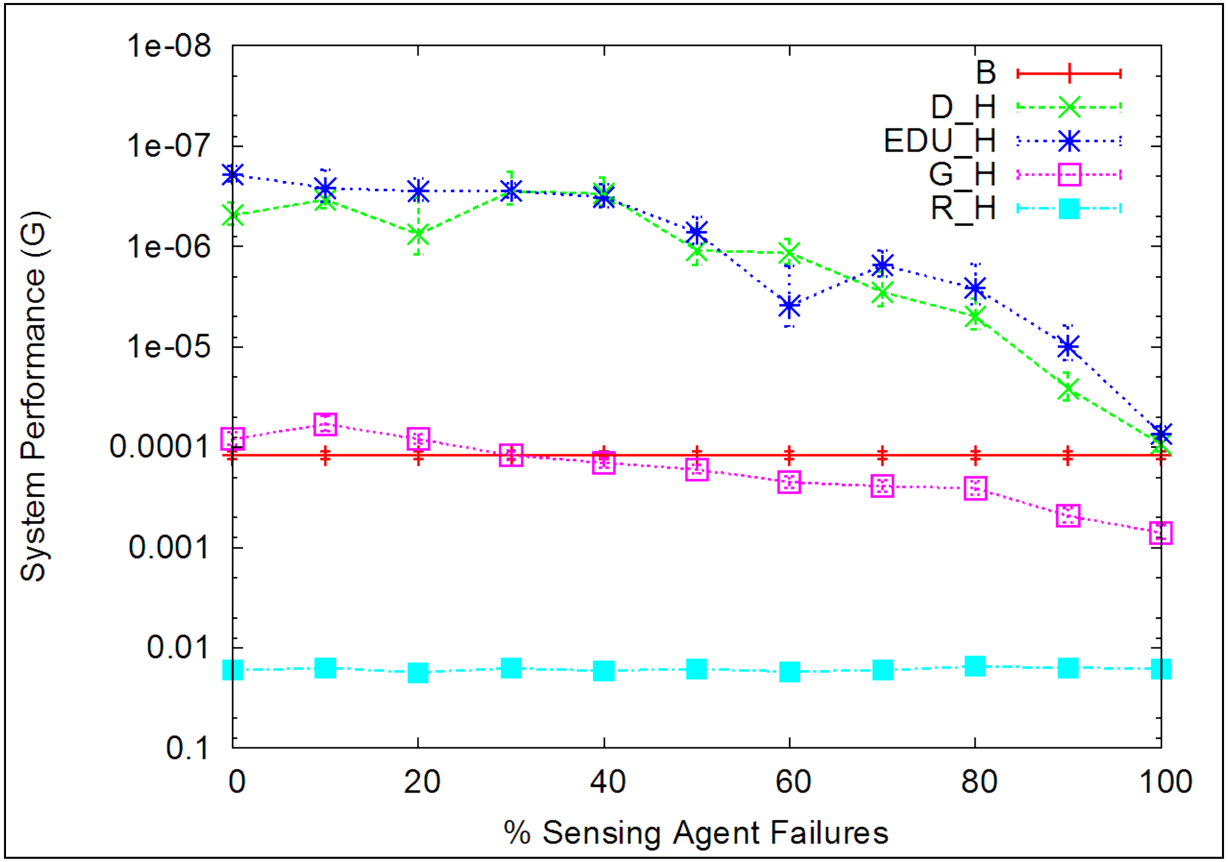
DCP: Hierarchical Teams and Robustness

10000 Sensors with Hierarchical Organization, 80% Sensing Agent Failures



DCP: Hierarchical Teams and Robustness

10000 Sensors with Hierarchical Organization versus Failure Rate



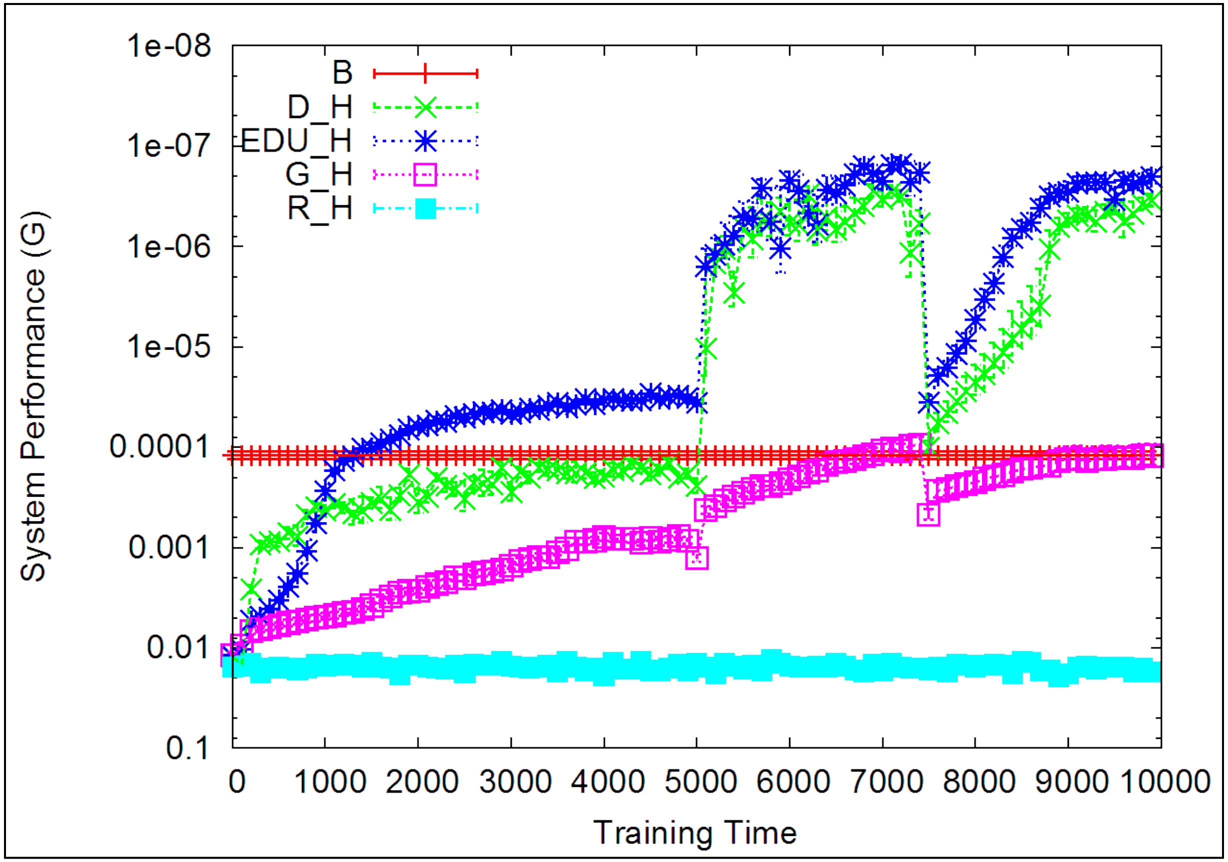
DCP: Hierarchical Teams and Robustness

- How does this approach handle control agent failures?

- Failure experiments:
  - 10,000 agents
  - 0 to 100% control agent failures
  - Sensing agents learn from time step 0 to 5000
  - Control agents learn from step 5000 to 7500
  - Some fail
  - System reconfiguration: control agents learn from 7500 to 10,000

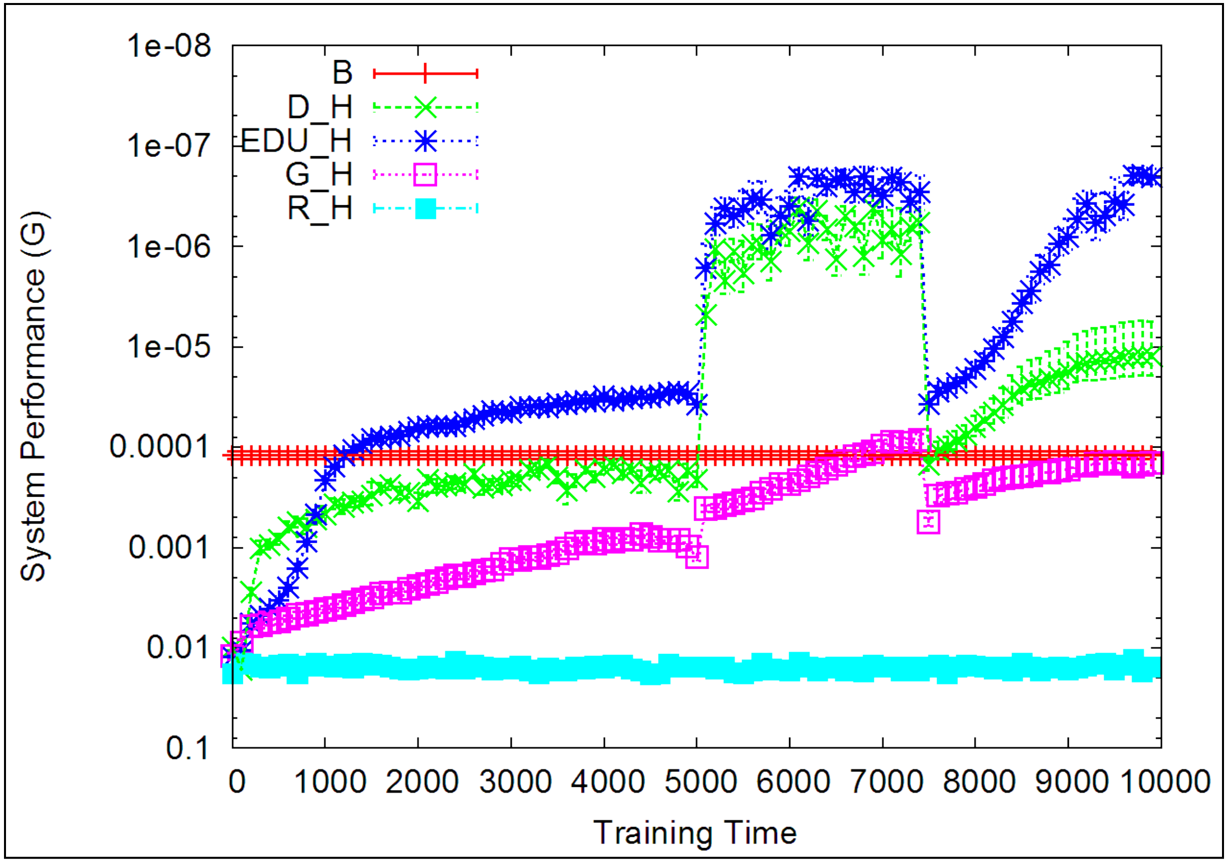
DCP: Hierarchical Teams and Robustness

10000 Sensors with Hierarchical Organization, 10% Control Agent Failures



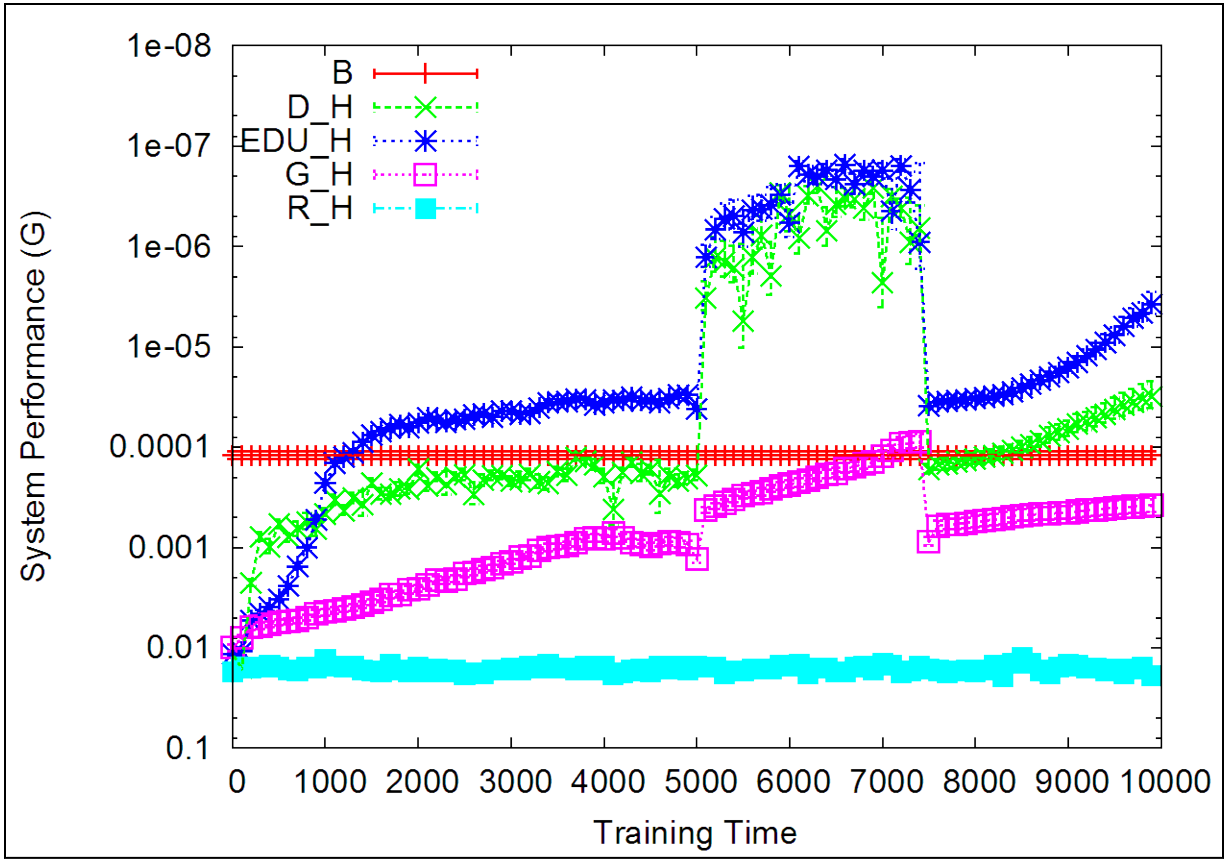
DCP: Hierarchical Teams and Robustness

10000 Sensors with Hierarchical Organization, 20% Control Agent Failures

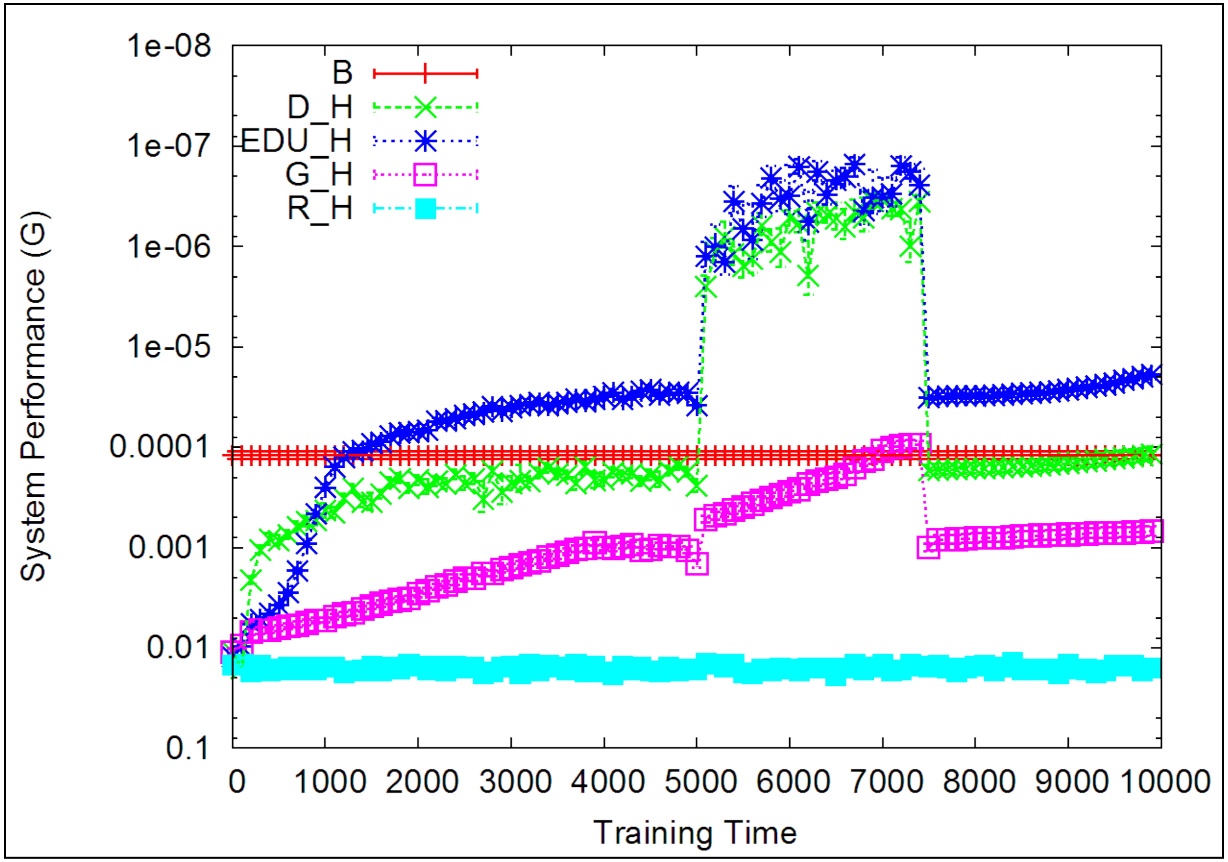


DCP: Hierarchical Teams and Robustness

10000 Sensors with Hierarchical Organization, 50% Control Agent Failures

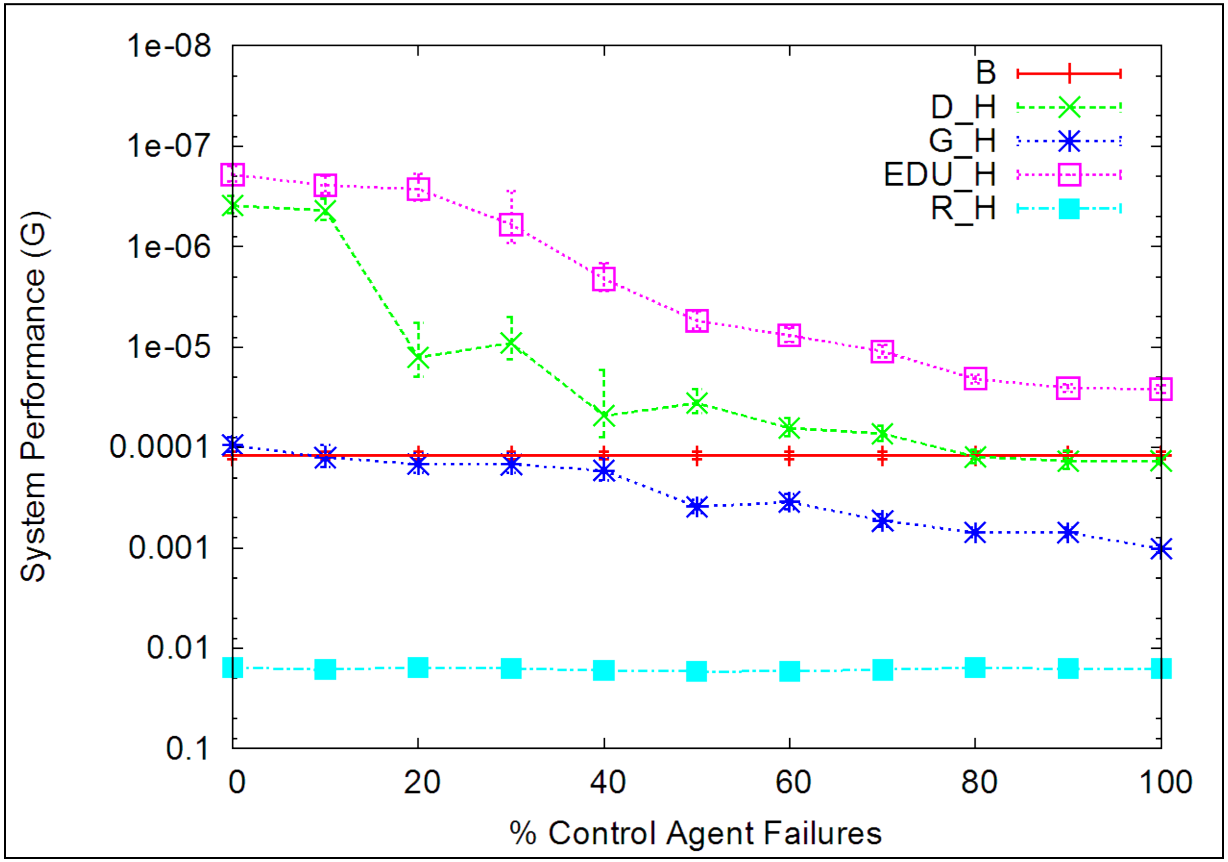


10000 Sensors with Hierarchical Organization, 80% Control Agent Failures



DCP: Hierarchical Teams and Robustness

10000 Sensors with Hierarchical Organization versus Control Agent Failures



Sensors in Power Plants

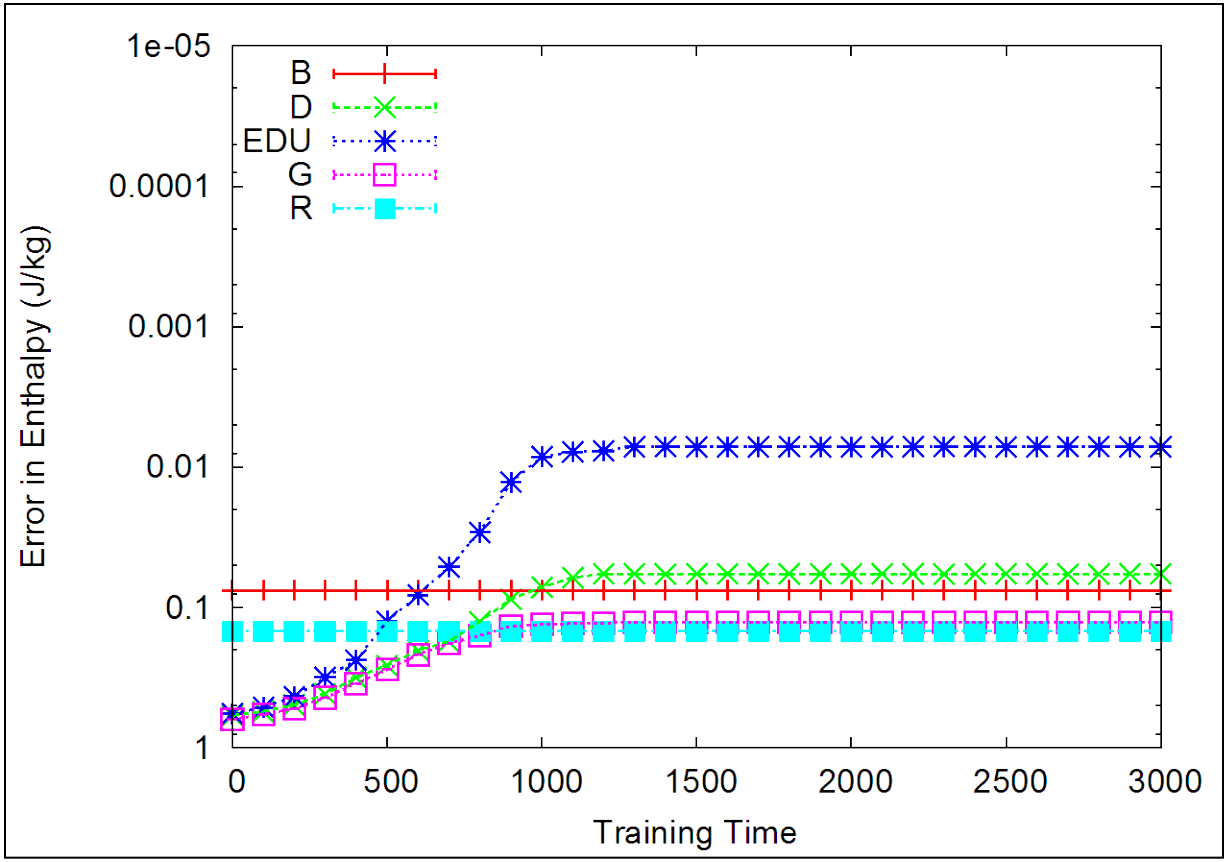
- What’s the difference between DCP problem and Power Plant sensor problem?
  - DCP:
    - Sensors have attenuation on value being measured
    - Aggregate attenuation is the system reward
  - Power Plant:
    - Sensors have temperature and pressure attenuations
    - T and P used to estimate enthalpy
    - Error in enthalpy is the system reward
      - Reward is thus one step removed from actions, unlike DCP

Power Plant Sensor Network

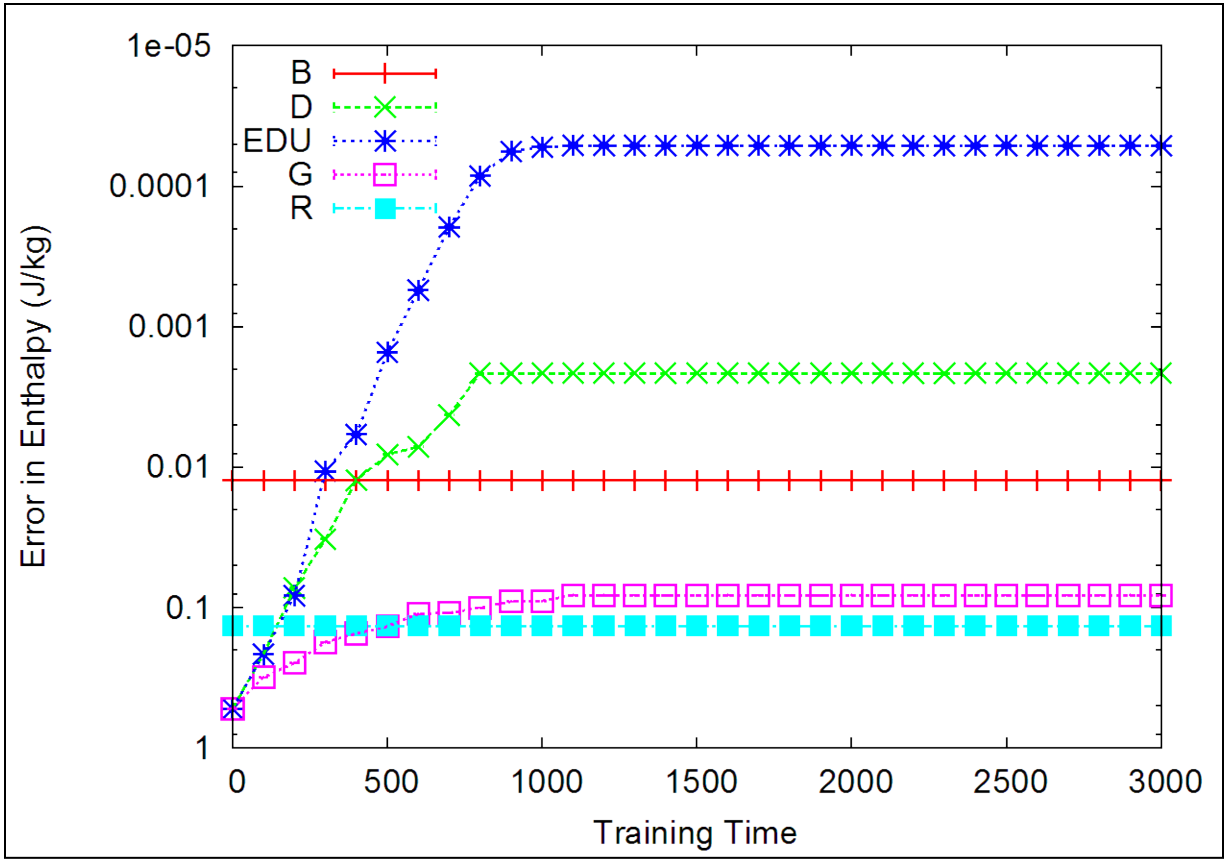
- Sensors choose between actions:
  - Turn off
  - Measure T
  - Measure P
  - Measure T and P

- Enthalpy estimated based on sensed T and P values
- Error in enthalpy used as G(z)
- Minimizing G(z) leads to minimizing P and T sensing error

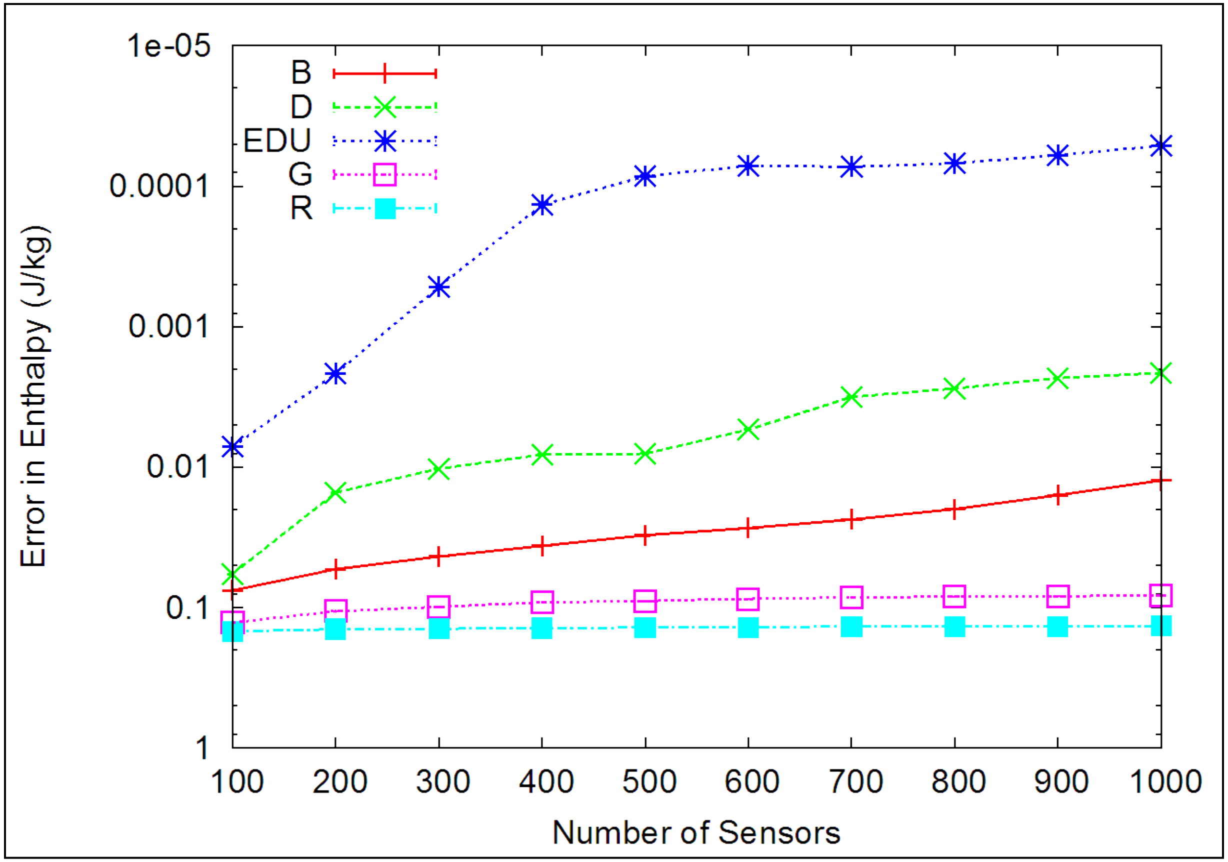
Power Plant: 100 Sensors



Power Plant: 1000 Sensors

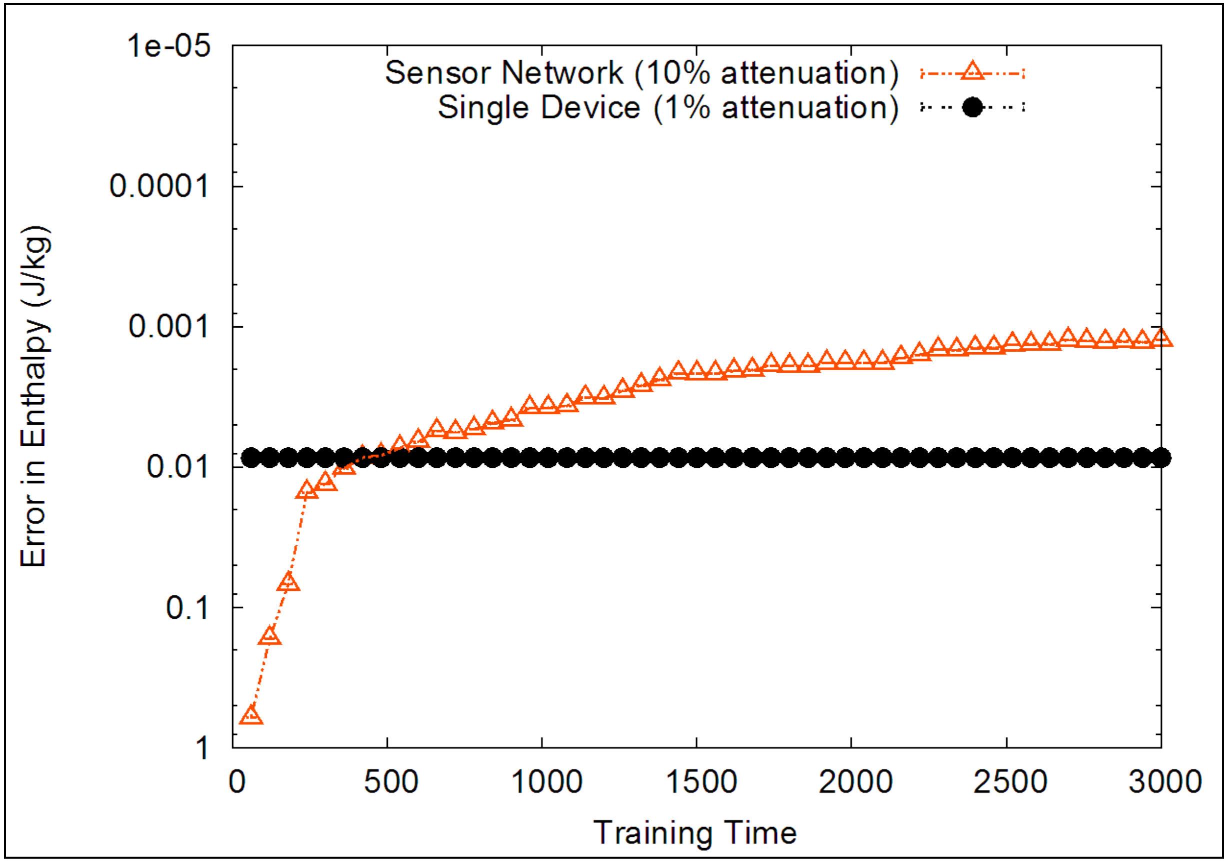


Minimize Enthalpy Error versus Scaling Number of Sensors



Network vs Single Sensor

Network versus Single Sensor (1% error), 200 Sensors (10% error)

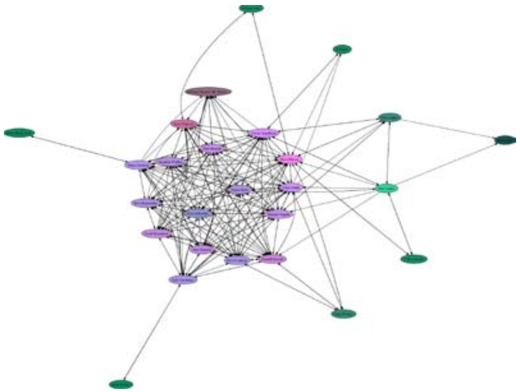


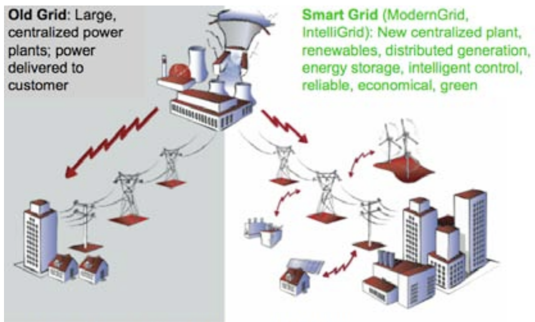
Summary of Results

- Adaptive sensors cover system efficiently
- Sensor objective functions have significant impact on performance
  - Determine what agents should do
  - Ensure sensor objectives have high factoredness (alignedness)
  - Ensure sensor objectives have high sensitivity (signal to noise)
- Sensors adapt to new environmental conditions
- Hierarchical decision making improves performance
- Sensors reconfigure themselves if some fail

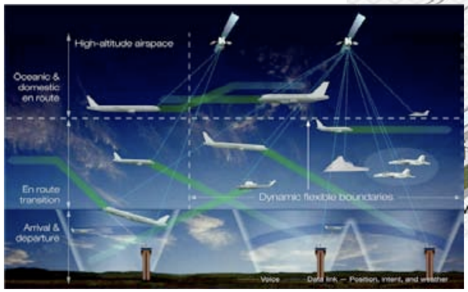
Long Term Benefits

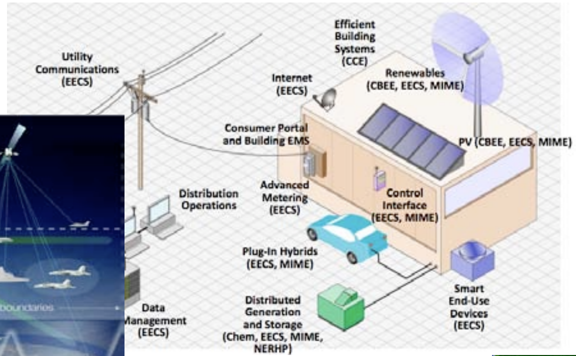
- Directly to advanced energy systems
  - More efficient information collection
  - Quick response to sudden developments
  - Autonomous system reconfiguration
- To the Department of Energy and US Govt
  - Smart power grid
  - Emergency response
  - Self-organizing nano/micro devices
- To American Public
  - Smart house
  - Smart airports

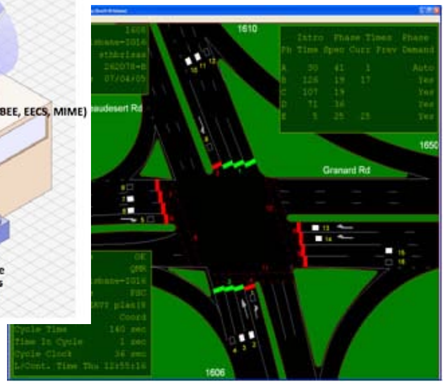




National Energy Technology Laboratory (NETL), 2007







Questions?

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