HMM and Auction-based Formulations of ISR Coordination Mechanisms for the Expeditionary Strike Group Missions

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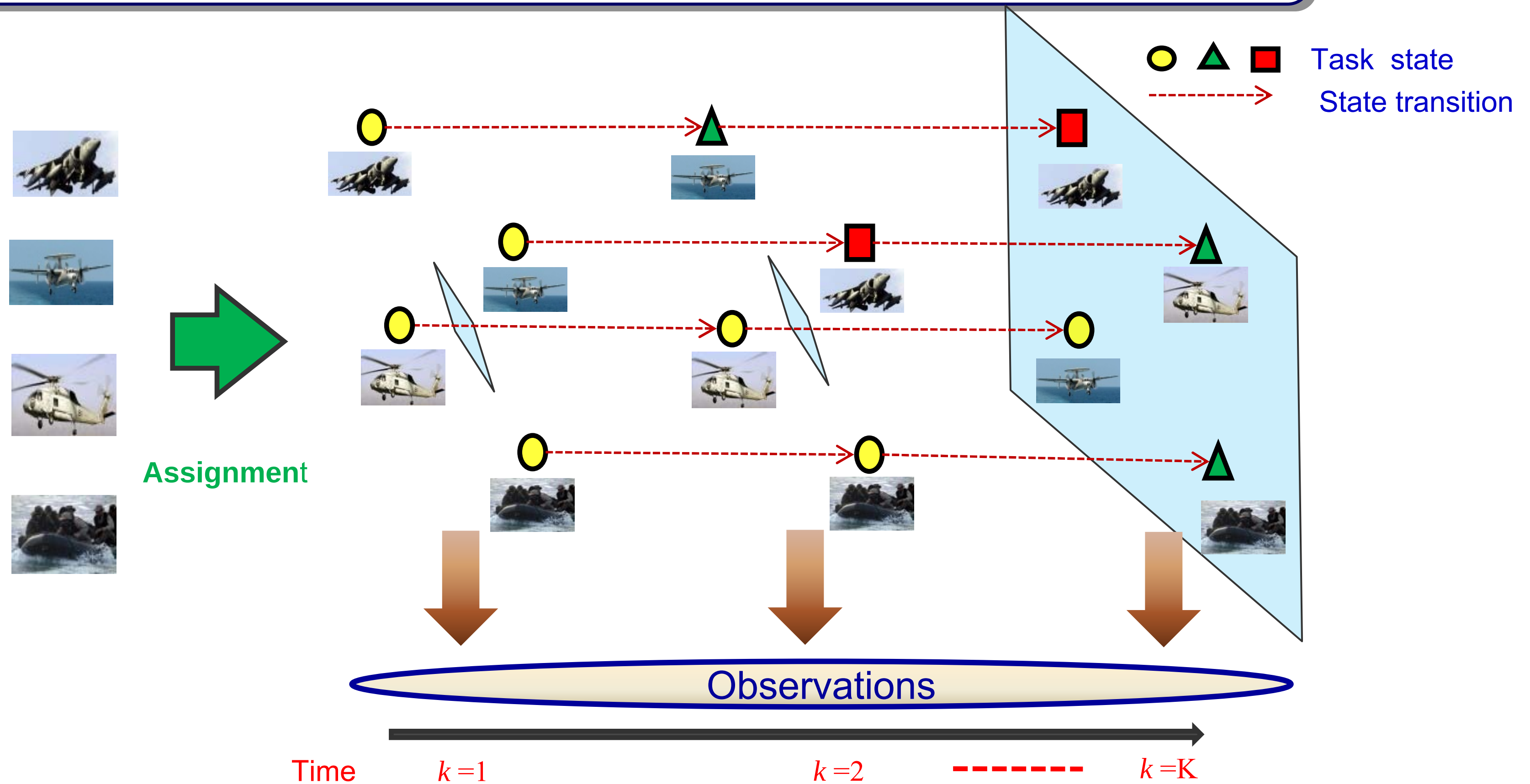
Outline

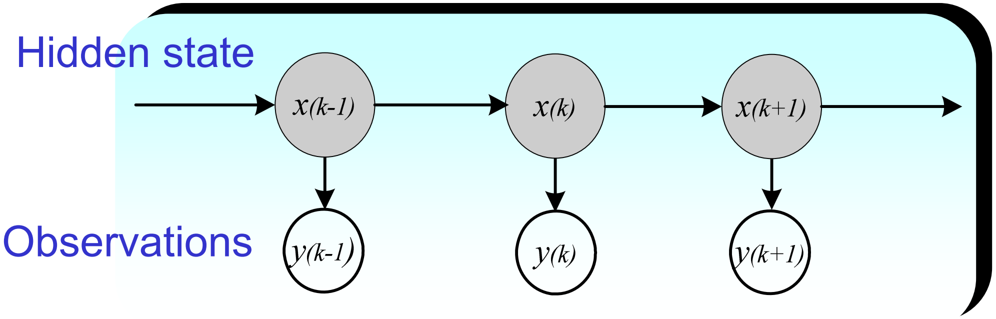
- Dynamic Sensor Scheduling Problem
  - Problem definition and objective of dynamic sensor scheduling
- Hidden Markov Models
  - Model parameters and factorial HMM (FHMM)
- Factorial HMM-based ISR Coordination
  - Sensor scheduling approach by IG policy
  - Many-to-one assignment problem and a 3 phase approach
- Evaluation of Alternative ISR Coordination Structures
  - Auction-based ISR Coordination Mechanisms
  - ISR delay model
- Simulation Results
- Summary

Dynamic Sensor Scheduling Problem



- Complex applications with heterogeneous sensors
  - Trade off performance (e.g., detection, identification, and tracking accuracies) versus sensor usage cost (e.g., power and bandwidth consumption, distance traveled, risk of exposure, deployment requirements)
- Objective
  - Allocate sensing resources to exploit the individual sensor's capabilities to maximize task state estimation accuracy, while minimizing sensor usage cost

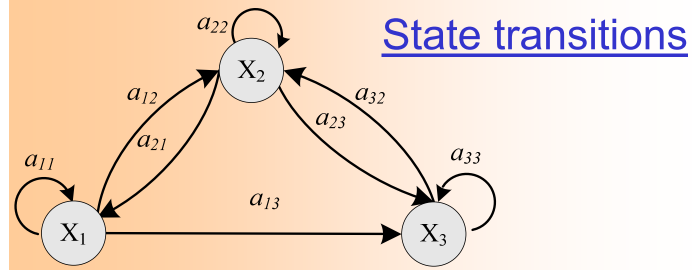
Hidden Markov Models



- Models for analyzing sequential data, where the true states of the system are hidden (e.g., adversary's activities)
- True state can be inferred only via uncertain observations (intelligence and sensor data)
- Solves three problems:
  - Evaluate the probability of a sequence of observed events given a specific model
  - Determine the most likely evolution of an abnormal activity (state sequence) represented by the HMM
  - Estimate HMM parameters that produce the best representation of the most likely state sequence based on observed data

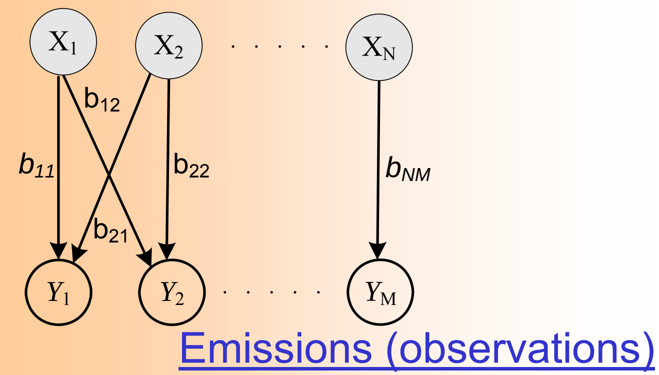
Prior probability vector

$$\underline{\pi} = [\pi_i] = P(x(1) = S_i)$$



Transition matrix

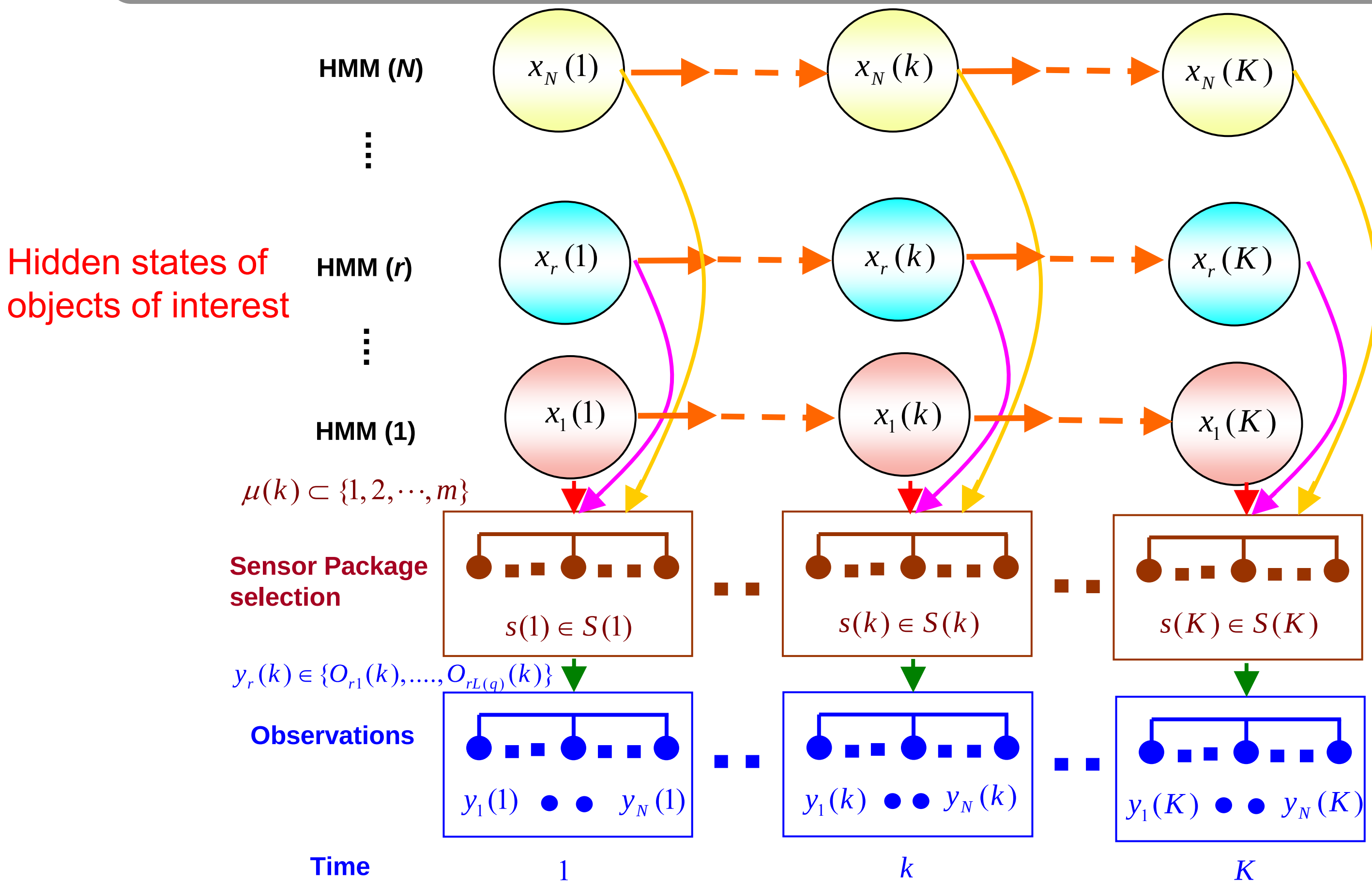
$$A = \left[a_{ij}\right] = \left[P(x(k+1) = X_j) \middle| P(x(k) = X_i)\right]$$



Emission matrix

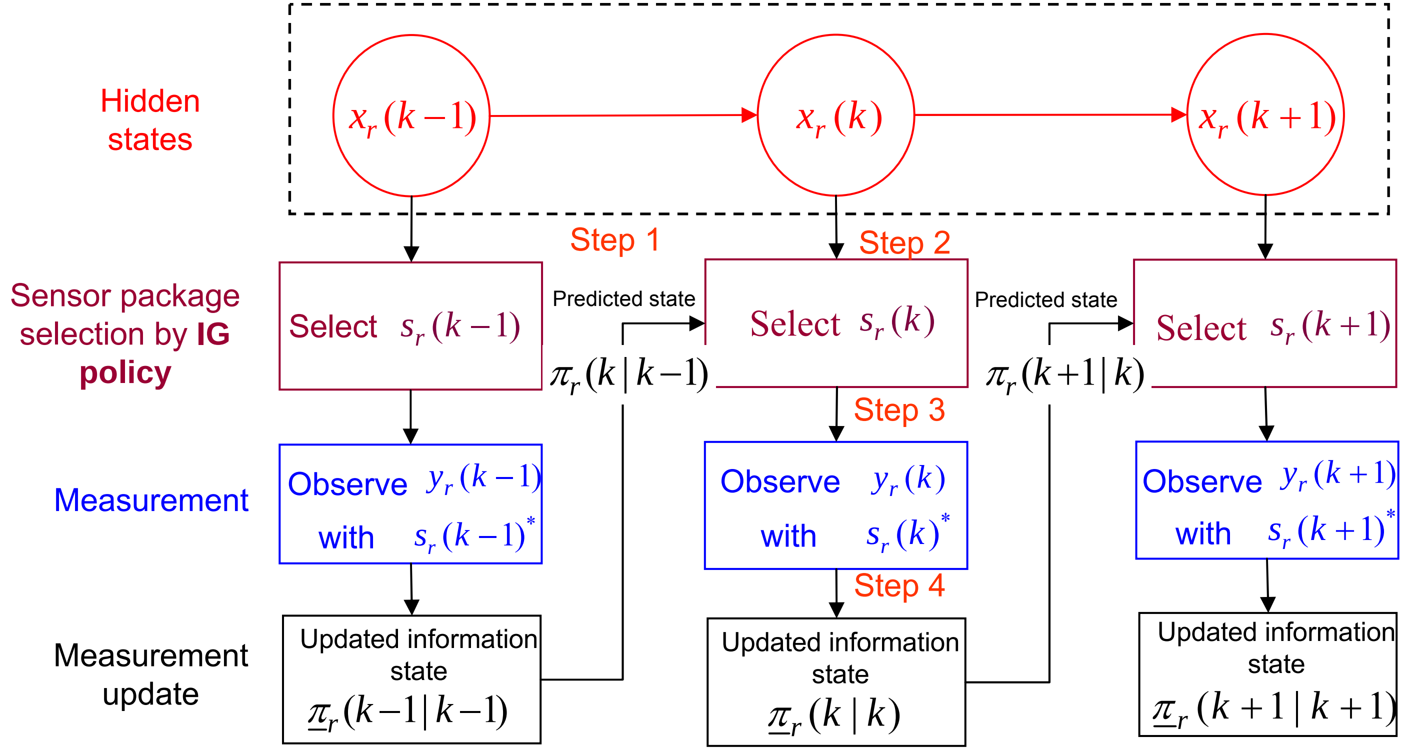
$$B = \left[b_{il}\right] = \left[P(y(k) = Y_l) \middle| P(x(k) = X_i)\right]$$

FHMM-based ISR Coordination



- Simultaneous monitoring of multiple activities dispersed in a region
- M sensors, N surveillance tasks → modeled using N parallel HMMs
  - Assignment constraints (e.g., many to one)
- Objective function – minimize sum of sensor usage and estimation error costs over time

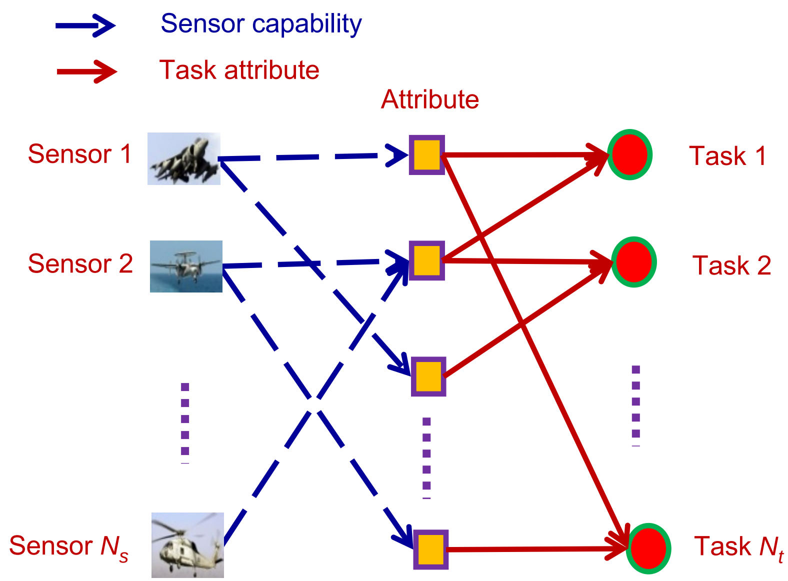
HMM Sensor Scheduling via IG Policy



- Scheduling process consists of four steps:
  - predicted state ⟹ select sensor package ⟹ observe ⟹ update state
- Select the best sensor assignment that maximizes the sum of information gains overall task-sensor package pairs subject to the assignment constraints

Hidden Markov Model (HMM)-based ISR Asset Coordination

- Many-to-one Assignment

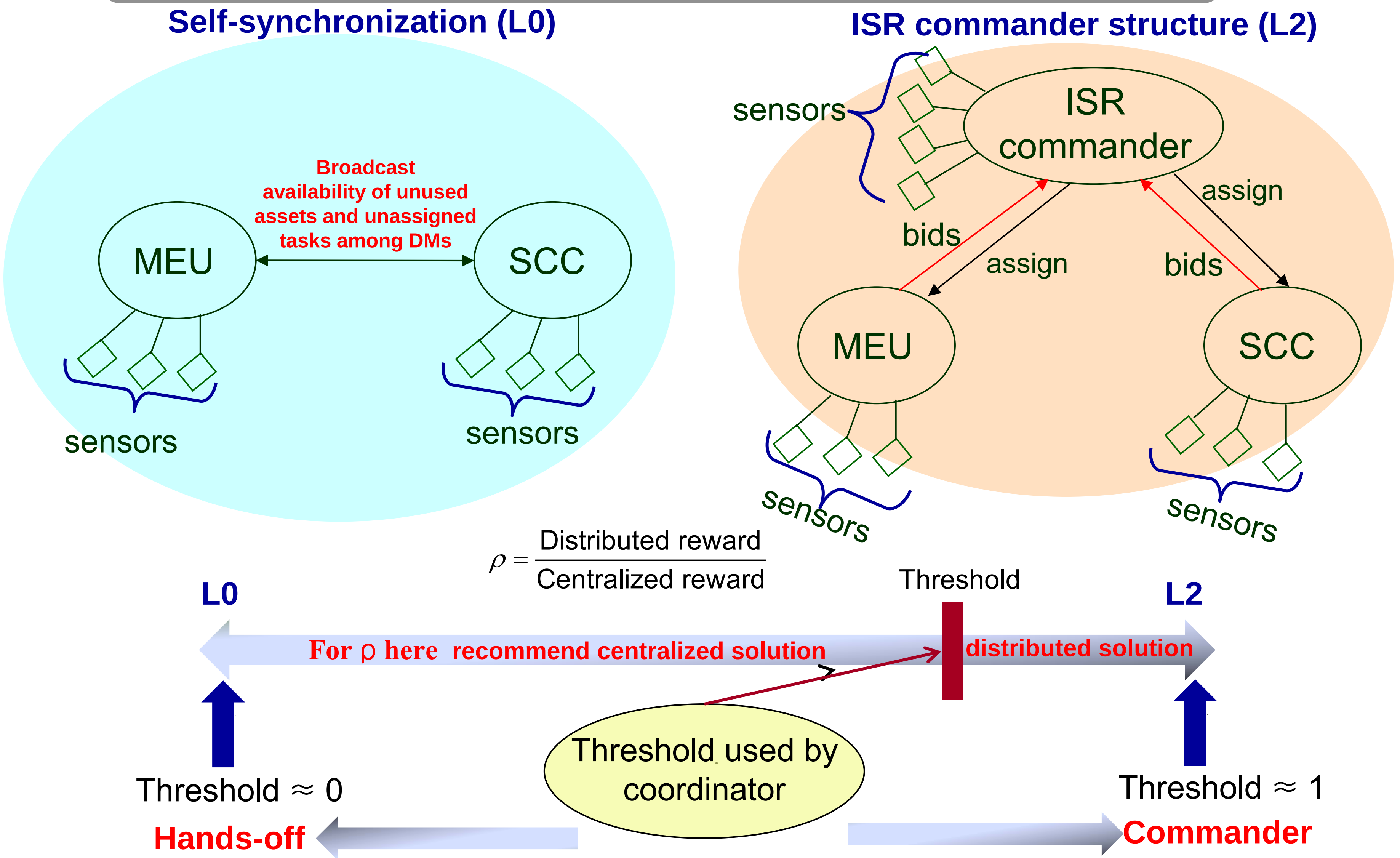


- Many-to-one assignment problem is computationally intractable

  → Decompose many-to-one assignment problem into *three sequential phases*
  - *N*-best sensor packages for each task
  - Multiple disjoint sensor sets from sensor packages
  - Sensor package assignment

- *Phase* 1: Formulated as a binary programming problem(BPP)
  - Generate sensor packages of minimal cardinality
  - *M*-best sensor packages for each task via a branch-and-bound algorithm
- *Phase* 2: Sensor packages may have overlaps when viewed across tasks
  - Disjoint sensor sets with maximum number of sensors → Set-packing problem
  - *L*-best disjoint sensor set generation via a branch-and-bound algorithm
- *Phase* 3: *L* one-to-one (2-D) assignment problems of allocating disjoint sensor packages to tasks
  - Jonker-Volgenant-Castaňon (JVC) assignment algorithm
  - Choose the disjoint sensor set that maximizes the sum of information gains

Auction-based ISR Coordination Mechanisms



MEU: Marine Expeditionary Unit
SCC: Sea Combatant Commander

Evaluation of ISR COORD structures

- ISR delay model
  - Assignment delay, $\Delta_C(k)$ depends on the ISR sensor package allocation process
  - Travel (logistic) delay, $\Delta(s_r(k))$ is the time it takes for an ISR sensor package to reach task location
  - Waiting delay, $\Delta_r(k)$ is the time a task needs to wait until sensor package becomes available.
  - Delay time, $\Delta_C(s_r(k))$ is the sum of three constituent delays

$$\Delta_C(s_r(k)) = \Delta_C(k) + \Delta(s_r(k)) + \Delta_r(k)$$

- Delays impact HMM state probabilities ("information state")

$$\pi_{ri}(k + \Delta_C(s_{lr}(k) \mid k + \Delta_C(s_{lr}(k)) = \frac{b_{rhil}(k + \Delta_C(s_{lr}(k))\pi_{ri}(k + \Delta_C(s_{lr}(k)) \mid k)}{\sum_{i=1}^{n_r} b_{rhil}(k + \Delta_C(s_{lr}(k))\pi_{ri}(k + \Delta_C(s_{lr}(k)) \mid k)}$$

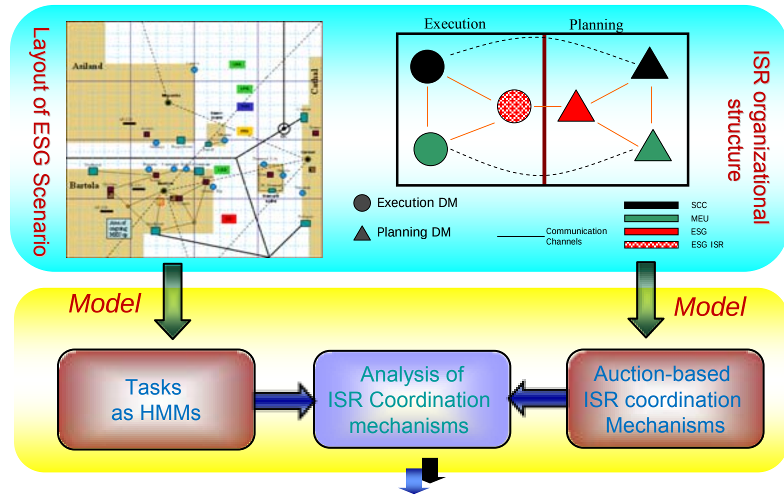
- Cost function ≡ average estimation accuracy of completed tasks

$$J(\mathbf{\Pi}(k \mid k)) = \frac{1}{\text{Completed tasks}} \sum_{r=1}^{N} \sum_{k=1}^{K} [1 - \underline{\pi}_r(k / k)^T \underline{\pi}_r(k / k)]$$

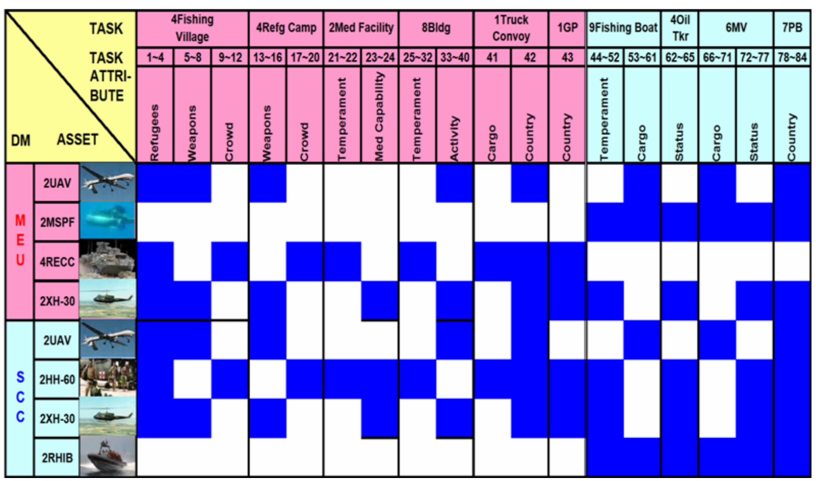
Model-based Pre-experiment Analysis

- **Objective:** The dynamic sensor scheduling model was used as a guide in the design of a mission scenario and asset composition for A2C2 team-in-the-loop experiment 11 at NPS
- We assume that each asset can measure a single attribute
  - 84 attributes → 84 HMMs
  - Scenarios considered different asset package (S_0 ~ S_6)

HMM-based ISR asset coordination



Task-asset capability table

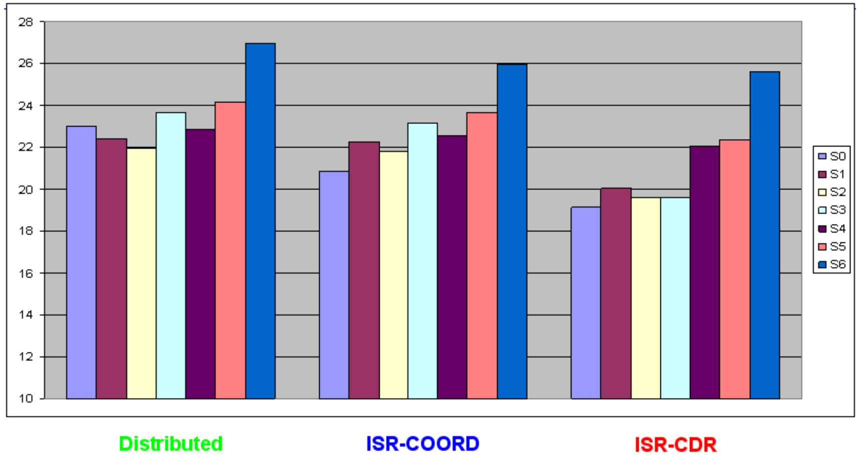


Asset availability scenario

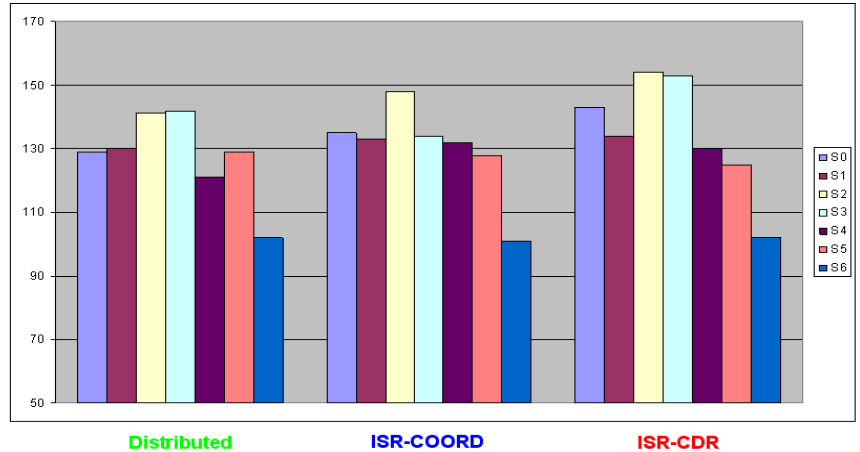
Scenario (Assets)	Assets
S0 (18)	4UAV, 2MSPF, 4RECC, 2RHIB, 4XH30, 2SH60
S1 (17)	3UAV(-1)*, 2MSPF, 4RECC, 2RHIB, 4XH30, 2SH60
S2 (16)	3UAV(-1)*, 2MSPF, 3RECC(-1), 2RHIB, 4XH30, 2SH60
S3 (15)	3UAV(-1)*, 2MSPF, 2RECC(-2), 2RHIB, 4XH30, 2SH60
S4 (14)	3UAV(-1)*, 2MSPF, 2RECC(-2), 2RHIB, 3XH30(-1)**, 2SH60
S5 (13)	3UAV(-1)*, 2MSPF, 2RECC(-2), 1RHIB(-1), 3XH30(-1) **, 2SH60
S6 (11)	2UAV(-2)*,**, 2MSPF(-1), 2RECC(-2), 1RHIB(-1), 3XH30(-1) **, 2SH60

Model-based Pre-experiment Analysis (Cont)

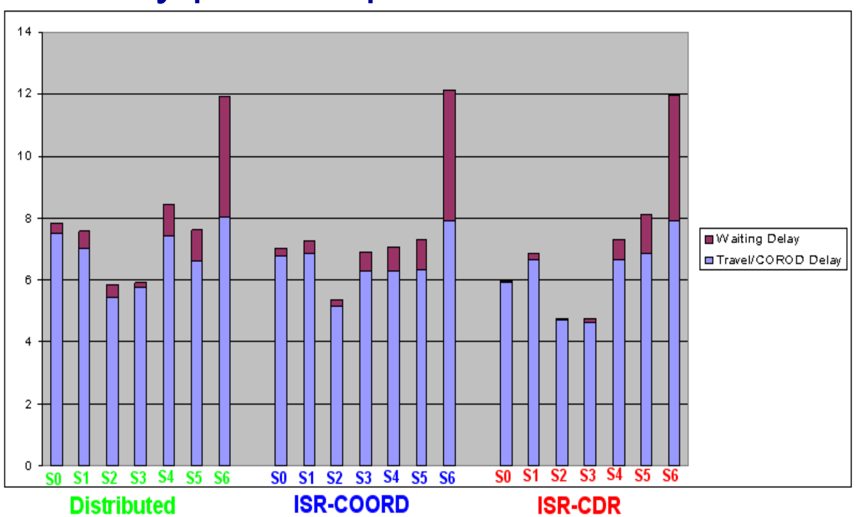
- Estimation error per completed task



- Cumulative complete tasks

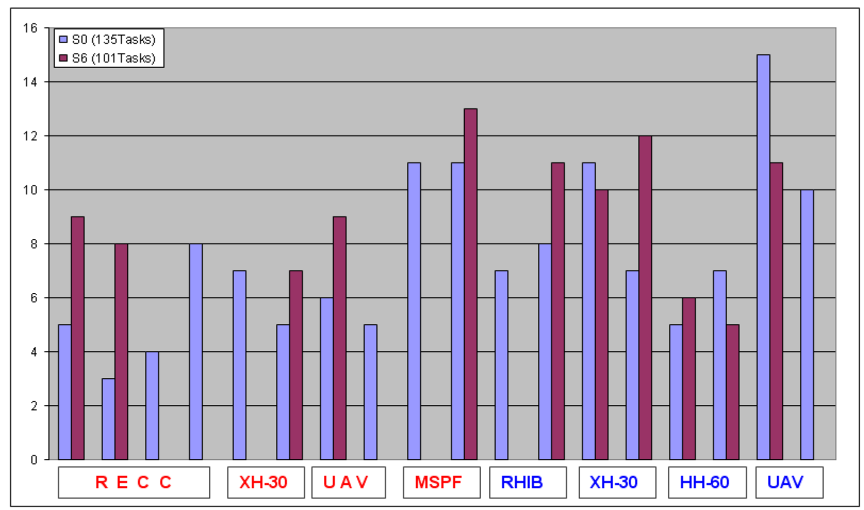


- Delay per completed task



- As the number of assets increase, delay per completed task tends to decrease

- Asset utilization (ISR-Coordinator)



- Estimation error is lowest for CDR structure
- Scenario 5 was implemented at NPS

Summary

- Sensor scheduling problem using factorial HMM for various ISR coordination structures
  - Three-phase solution to a novel many-to-one assignment problem arising in ISR coordination
  - Application to a realistic ESG mission scenario to analyze different asset availability scenarios
  - Evaluation of various ISR coordination mechanisms (self-synchronization, ISR coordinator, ISR commander)
- Evaluation of alternative ISR coordination structures
  - The ISR commander structure has better performance than the other two ISR structures
  - As the number of assets decreases, the state estimation error per task and the delay per task in all ISR structures tend to increase
  - Team performance under asset package scenario S_6 degrades significantly compared to the other scenarios

    → This shows that UAV and MSPF are bottleneck resources