Multi-level Operational C² Holonic Reference Architecture Modeling for MHQ with MOC

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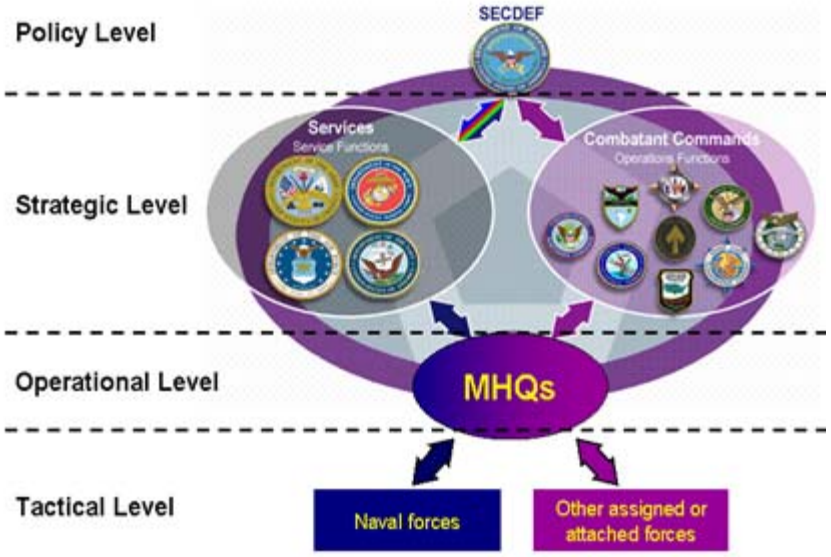
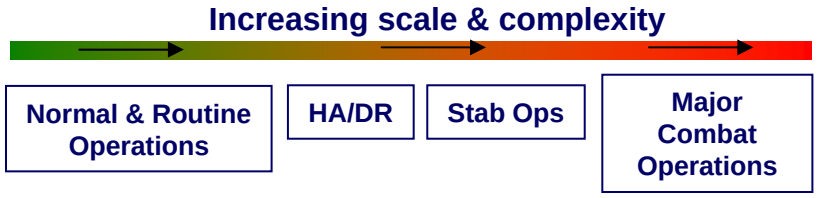
Introduction

- **Motivation**
  - **Maritime Headquarters with Maritime Operations Center** (**MHQ/MOC**) motivated by identified C^2 gaps in recent national-level crises, e.g., September 11, operation Iraqi freedom (OIF), and humanitarian assistance and disaster relief (HA/DR) during Katrina
  - **MHQ/MOC*** is the Navy's new concept at the **operational level** with the capability to ***assess***, ***plan***, and ***execute*** multiple missions
- **Objectives**: provides multi-level adaptive C^2 organizational solution **linking *tactical*, *operational*** and ***strategic levels*** of MHQ/MOC for ***assessing*, *planning* and *executing*** multiple missions

* MHQ/MOC

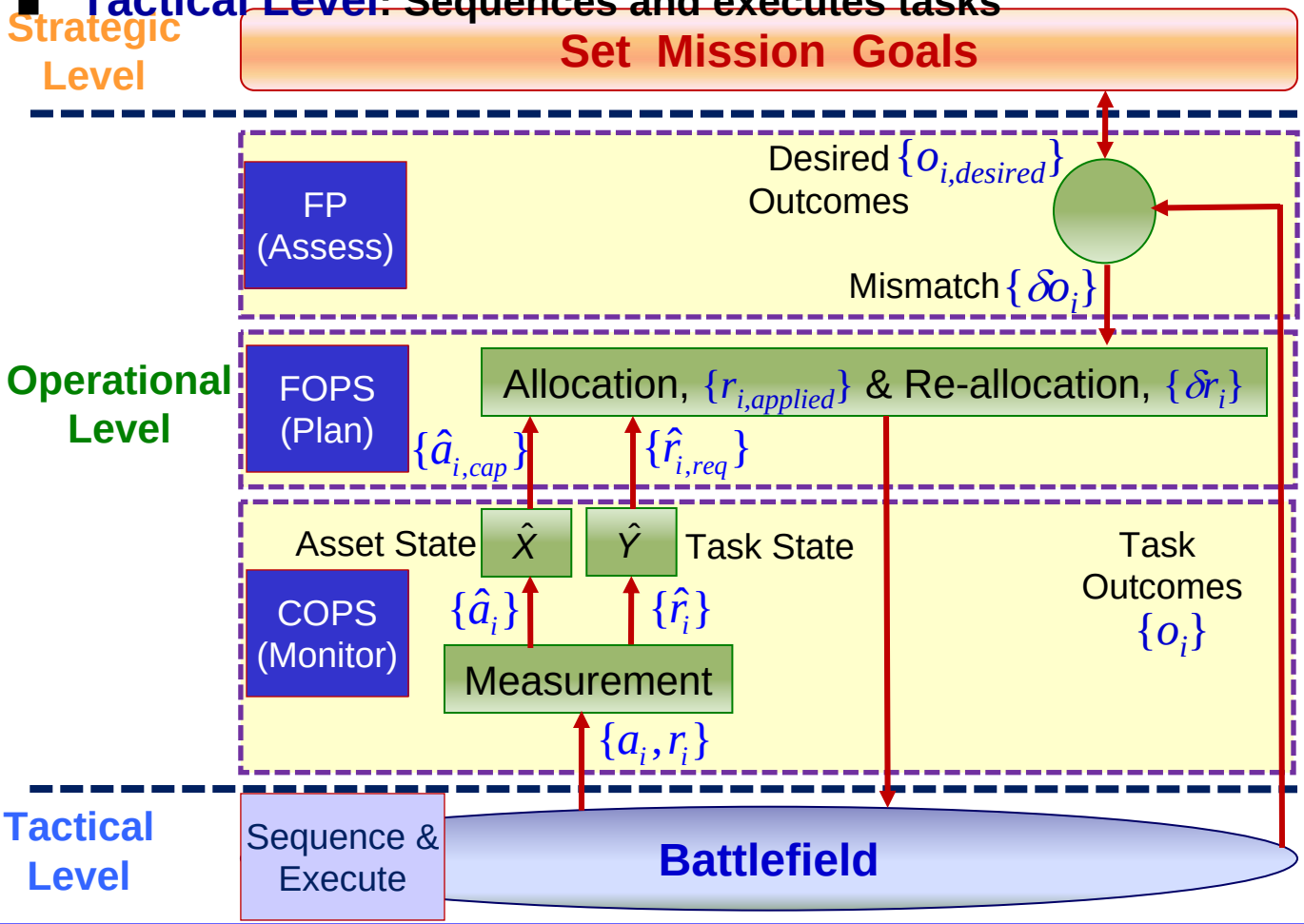


** Range of military operations



Multi-level C² Coordination Modeling Framework

- **Strategic Level**: Decides on the goals of overall mission (***commander's intent***)
- **Operational Level**: Estimates the task-resource requirements, allocates assets to tasks under strategic guidance, and monitors mission progress
- **Tactical Level**: Sequences and executes tasks



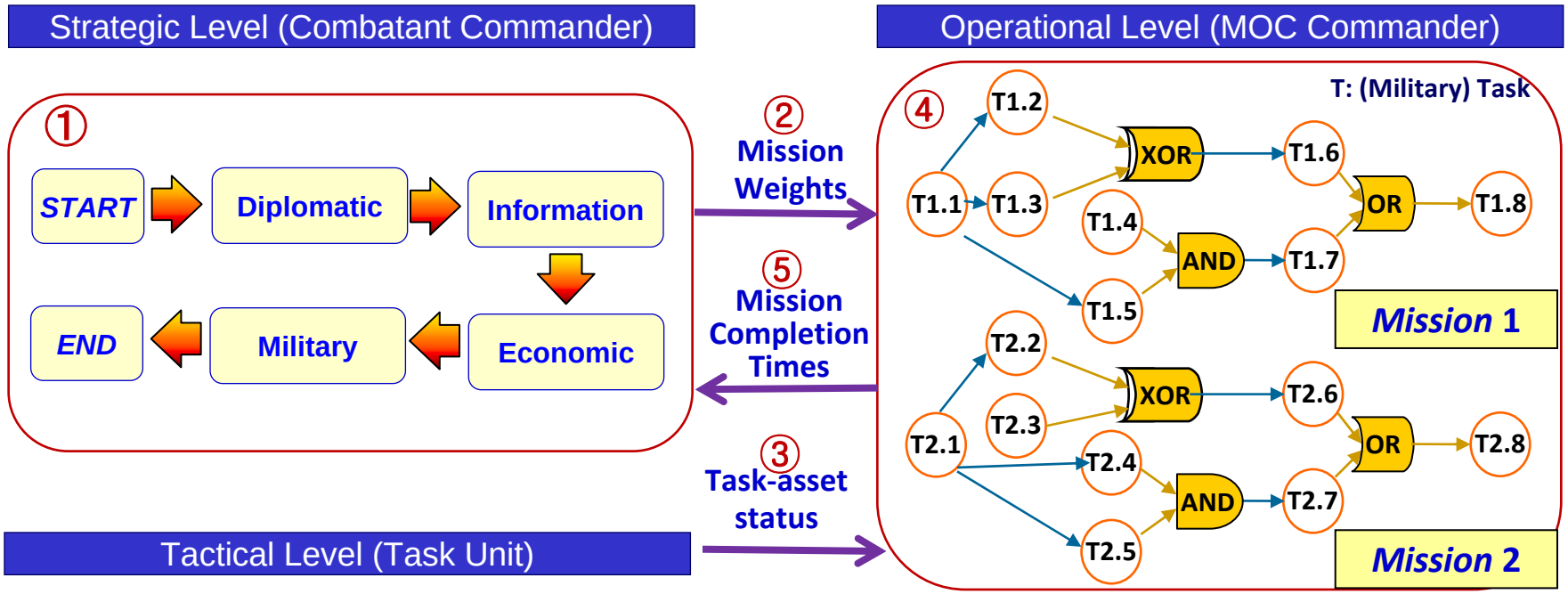
Key question addressed: How to solve multi-level coordination problem in a distributed way?

Multi-level C² Coordination Process

Two coordination layers

- **SLC-OLC layer**: Selects DIME (diplomatic, information, military and economic) action strategies by solving a semi-Markov decision problem (SMDP)
- **OLC-TLC layer**: Plans courses of action for individual missions by solving mission-specific SMDPs

- **Coordination Process**: **1)** Mission weights are transmitted by the SLC-OLC layer to the OLC-TLC layer as the commander's intent → **2)** Each mission planner at the OLC-TLC layer **decides on state-dependent action path** in the mission graph → **3)** The minimum mission completion time is transmitted to the SLC-OLC layer, which specifies the decision epoch of SMDP at the SLC-OLC layer



SMDP: SLC – OLC Layer

- **Key Issue:** DIME action sequencing to achieve the desired effects
- **Approach:** Formulated as a semi-Markov decision problem (SMDP)
  - **State:** Combination of missions

State	HA/DR	Stability Ops.	Major combat Ops.
x_1			
x_2			
x_3			
x_4			
x_5			
x_6			
x_7			
x_8			

  - **Action**: State-based DIME action-paths
  - **Policy**: Best action to take in each state at each decision epoch

- **Overall Transition probability**: The probability of mission completion over the holding (state occupancy) time $T(k)$

$$P(x(k+1),T(k)\mid x(k),u_j(k)) = P(x(k+1)\mid T(k),x(k),u_j(k))F(T(k)\mid x(k),u_j(k))$$

- **Reward Structure**: DIME action cost and reward for mission completion over the holding time $T(k)$

$$R(T(k)\mid x(k),u_j(k)) = \sum_{i=1}^{N} R(z_i(k),u_j(k)) + \mathbf{V}^{\pi}(x)$$

$\mathbf{V}^{\pi}(x)$: the expected total reward of an option (path) at the OLC - TLC layer

- **The expected reward of policy starting at an initial state $x(0)$:**

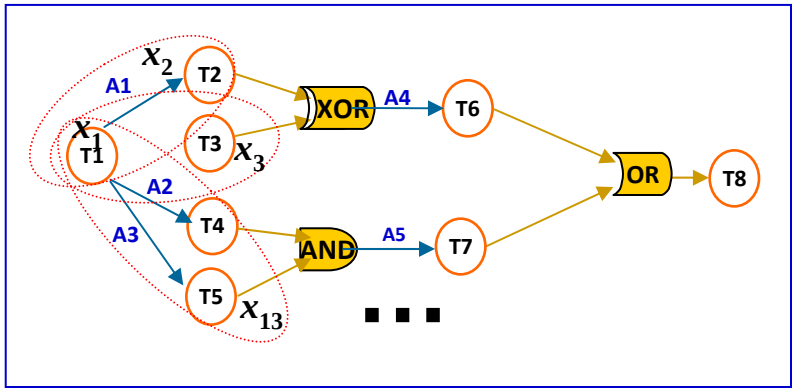
$$V^{\pi}(x(0)) = E^{\pi}\Big[\sum_{k=0}^{K-1}\beta^k R(T(k)\mid x(k),u_j(k)) + \beta^k R(T(K)\mid x(K))\Big]$$

K: the number of decision epochs

β: discount rate

SMDP: OLC – TLC Layer

- **Key Issue:** Find optimal path in a mission graph to complete the mission
- **Approach:** Formulated as distributed semi-Markov decision problem using an mission graph (Meirina *et al.* IEEE T-SMCA, 2008)
  - **State:** Combination of sub-goal (task) states



  - **Action**: State-based goal (task) actions (options)
  - **Policy**: Best action to take in each state at each decision epoch

- **Transition probability**: Probability of completing a mission via a path in the mission graph over the holding time $\mathbf{T}(k)$

$$\mathrm{P}\,(x(k+1),\mathrm{T}\,(k)\,|\,x(k),u_j(k)) = \mathrm{P}\,(x(k+1)\,|\,\mathrm{T}\,(k),x(k),u_j(k))\mathrm{F}\,(\mathrm{T}\,(k)\,|\,x(k),u_j(k))$$

- **Reward Structure**: Function of mission difficulty and task accuracy for the assigned resources

$$\mathrm{R}\,(\mathrm{T}\,(k)\,|\,x(k),u_j(k)) = \mathrm{R}\,(x(k),u_j(k)) + r(\mathrm{T}\,(k)).$$

$r(\mathrm{T}\,(k))$: the reward over the holding time $\mathrm{T}\,(k)$

- **Expected reward of a policy starting at initial state $x(0)$:**

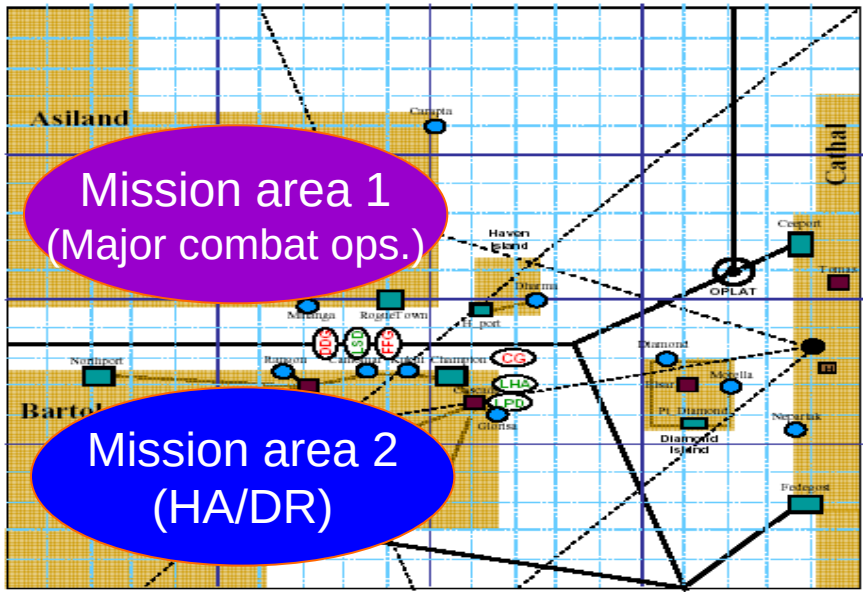
$$\mathrm{V}^{\pi}(x(0)) = E^{\pi}[\sum_{k=0}^{\mathrm{K}-1}\beta^k \mathrm{R}\,(\mathrm{T}\,(k)\,|\,x(k),u_j(k)) + \beta^k \mathrm{R}\,(\mathrm{T}\,(K)\,|\,x(K))]$$

K: the number of decision epochs

β: discount rate

Application to Multi-mission Scenario - 1

Mission Space



- Mission 1: capture a seaport to allow the introduction of follow-on forces (major combat operation)
- Mission 2: rescue activity after a hurricane in the homeland (HA/DR)

State 3

Mission 1

Mission 2

SLC-OLC Layer

- **Solve the SMDP** problem at the SLC-OLC layer ⇒ DIME action policy.
- **Transmit mission weights** to the **OLC-TLC** layer

Diplomatic
Appeal for diplomatic/material cooperation

→

Political
Political reform or yield

→

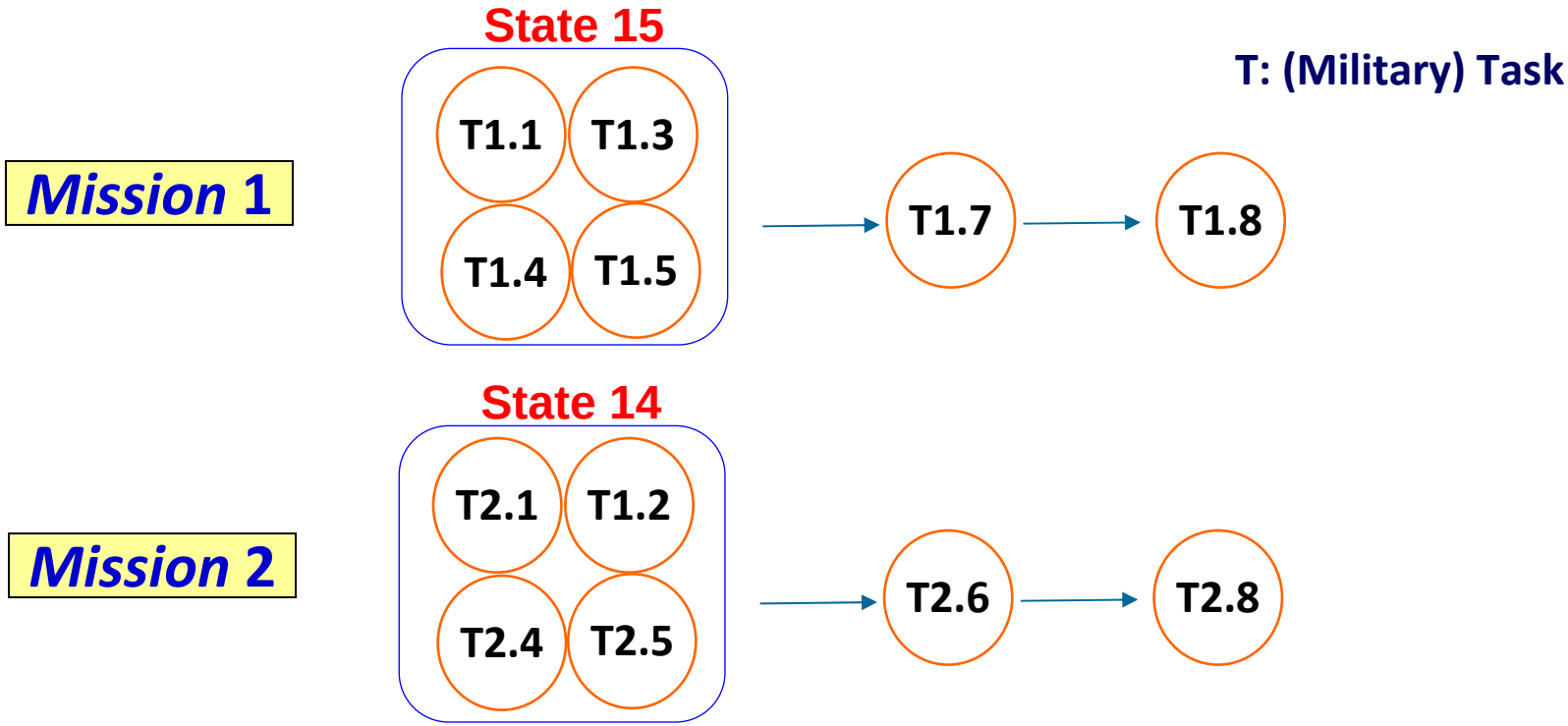
Military
Provide military aid

→

Military
Use conventional military force

Application to Multi-mission Scenario - 2

- The OLC-TLC layer
  - The **take-asset assignment** results provided to the SMDPs at the OLC-TLC layer from TLC.
  - Each OLC-TLC layer mission planner **decides on state-dependent action path** in the mission graph
  - **Transmit the mission completion time** to the **SLC-OLC** layer.



Summary and Future Work

Multi-level Operational C^2 Holonic Reference Architecture

- It can be applied to the Navy's new MHQ with MOC linking tactical, operational and strategic level controls
  - Strategic Level Control (SLC): centralized assessment
  - Operational Level Control (OLC): networked distributed planning
  - Tactical level control (TLC): decentralized execution
- C^2 coordination issues at the three levels, associated with DIME actions (future plans), and mission planning (future operations and current operations) can be modeled using SMDP formalisms within the proposed holonic architecture
- The two layers share the outcomes of SMDP solutions at each layer (e.g., missions to be planned from SLC-OLC → OLC-TLC, mission completion times from OLC-TLC → SLC-OLC) to reach consensus

Future Work

- Game-theoretic incentive mechanisms to induce collaborative behavior
- Distributed auction algorithms with partial information to decide on the best organizational structures

Holding Time Distribution Function

$$F(T(k)\,|\,x(k),u_j(k)) = 1 - \prod_{i=1}^{N}(1-\omega_i(x(k+1),T(k))z_i(k))$$

where

N : Number of missions

ω_i : mission termination condition

z_i : Status of mission i, z_i =1 denotes the presence of a mission