Coordination Challenges and Issues in Stability, Security, Transition and Reconstruction and Cooperative Unmanned Aerial Vehicle Scenarios

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Outline

- **Problem Motivation – SSTR and UAV problem domain**
- **Key Concepts in Multi-agent Coordination**
- **Coordination Challenges and Issues**
  - SSTR
  - UAV
- **Overall Challenges and Gaps in problem domains**
- **Towards Adaptive Multi-agent Systems Coordination**
- **Conclusion**

Problem Motivation – Stability Security Transition and Reconstruction (SSTR) – (1)

- **The United States has been involved as part of multinational coalitions**
  - Afghanistan (e.g., JTF Afghanistan)
  - Iraq (http://www.mnf-iraq.com/)


- **It has also provided humanitarian assistance & disaster relief (HADR) in response to devastating natural disasters around the world.**
  - Indian Ocean tsunami (2004)
  - Kashmir earthquake (2005)


- **Increasingly, the scale and scope of such events involve both civilian and military components, as resources are stretched thin to support multiple ongoing crises**

Problem Motivation – SSTR (2)

Doctrinal Changes

- **Baseline DoD Directive 3000.05 Task: Ensure effective information exchange and communications among the DoD components, US Departments and Agencies, foreign governments and security forces, IOs, NGOs, and members of the Private Sector (para 5.7.1).**
  - This now affords Combatant Commanders around the world an opportunity to provide a basic ICT capacity and leave it behind.

Problem Motivation – SSTR (3)

- **SSTR operations (e.g., HADR)**
  - Stability Operations
    - Military and civilian activities conducted across the spectrum from peace to conflict to establish or maintain order in States and regions.
  - Military support to Stability, Security, Transition and Reconstruction (SSTR).
    - Department of Defense activities that support U.S. Government plans for stabilization, security, reconstruction and transition operations, which lead to sustainable peace while advancing U.S. interests.

- **SSTR becoming a core mission of DoD through the emergence of new doctrine.**
  - Short term goals are to restore security, essential services and meet humanitarian needs
  - Long term goal is to develop indigenous capacity for security and basic necessities.

- **These operations are being given the same priority as combat operations**

- **Without the means to effectively coordinate the activities of the SSTR community, overall response may severely impeded.**

Problem Motivation – UAVs

- **The use of Unmanned Aerial Vehicles (UAVs) to support Intelligence, Surveillance and Reconnaissance (ISR) is becoming increasingly important.**

- **These assets can enable the collection of needed information for the execution of a given set of tasks.**

- **In large scale operations, however, the ability for the UAVs to self-coordinate may be needed as it will be difficult for human operators to effectively control large teams of UAVs**

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Key Concepts in Multi-agent Coordination-1

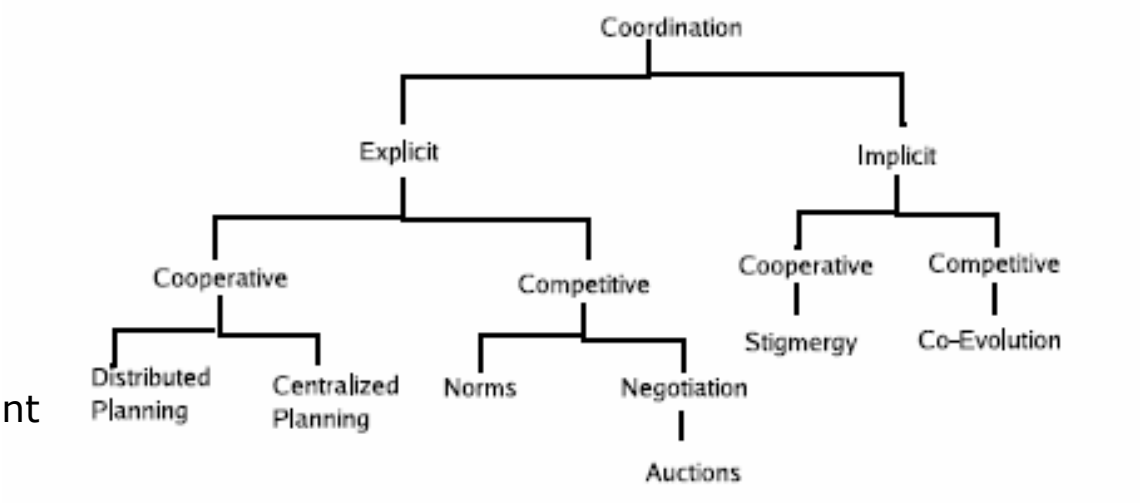
- **Coordination is the cornerstone of multi-agent systems**
- **According to** *Malone and Crowstone*
  - Coordination is defined as the act of managing / mediating *interdependencies* between activities
  - A dependency is a relation among activities mediated by producing or consuming resources
    - Flow dependencies
    - Sharing dependencies
    - Fit dependencies
- **Many other models for Coordination exist**

Thomas W. Malone and Kevin Crowston, “What is Coordination Theory and How Can it Help Design Cooperative Work Systems”, In Readings in Groupware and Computer-Supported Cooperative Work, Assisting Human-Human Collaboration, Ed. Ronald M. Baecker, Morgan Kaufmann Publishers, Inc., SF, California, 1993.

Key Concepts in Multi-agent Coordination-2

Coordination Taxonomy (*based on Storms and Grant*)

- **Explicit**
  - Communicate to mediate interactions
- **Implicit**
  - Social Laws / conventions based on predefined agreements
  - Local sensing / multi-level Pattern recognition (e.g., intent / plan) and local environment changes (i.e., markers)
- **Cooperative**
  - Shared Goals
- **Competitive**
  - Individual Goals



P.P.A. Storms and T.J. Grant. Agent coordination mechanisms for multi-national network enabled capabilities. In Proceedings of the 11th International Command and Control Research and Technology Symposium (ICCRTS) on Coalition Command and Control in the Networked Era, Cambridge, UK, Sept 2006.

Key Concepts in Multi-agent Coordination-3

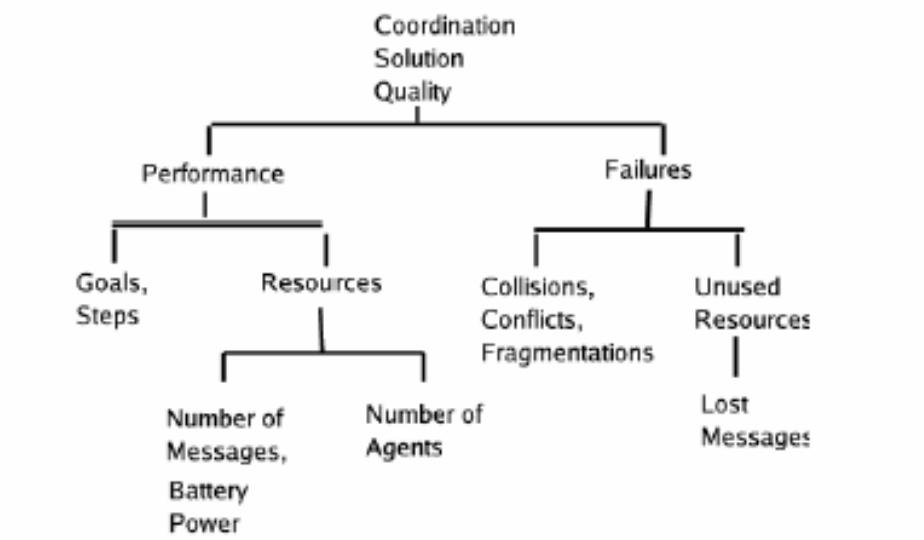
Coordination Metaphors and Mechanisms

- **Organizational**
  - Authority Structure, roles – Cooperative
- **Biological**
  - Living Systems, Colony, Swarms, Stigmergy – Cooperative
- **Market**
  - Negotiation, Auction, Mechanism Design, Contract Net – Competitive
- **Despite all proposed frameworks, a unified approach for coordination remains elusive**
- **No single best way to coordinate due to**
  - Problem space properties
  - Domain
  - System and state characteristic dependencies
  - Required frequency of interaction and
  - Respective intrinsic strengths and weaknesses ofvarious approaches

Key Concepts in Multi-agent Coordination-4

Coordination Metrics

- **Example shows Solution quality in pursuit games in MANET environments**
- **A coordination metric can be obtained using**
  - Harmonic mean of appropriately weighted goals achieved, resource expanded, and conflicts
  - Linear weighting combination of resource expanded and conflicts to evaluate coordination costs alone.
- **To show the scalability of a solution, the evaluation must linearly increase with the complexity of the task**



M. Abramson, W. Chao, and R. Mittu, Design and Evaluation of Distributed Role Allocation Algorithms in Open Environments, International Conference on Artificial Intelligence, Las Vegas, NV, 2005.

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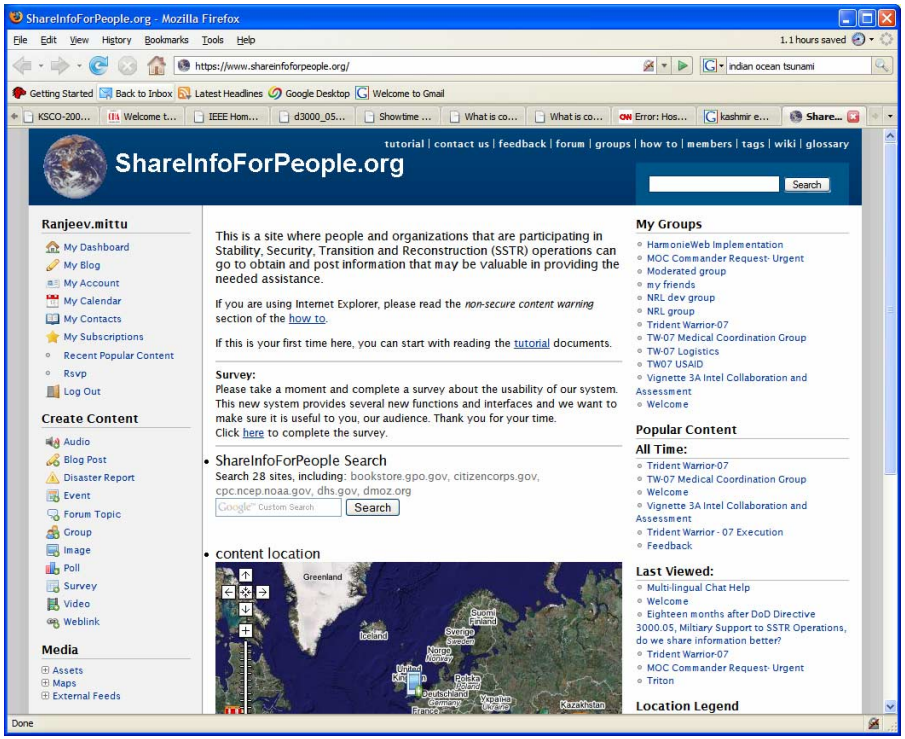
SSTR (1): ShareInfoForPeople.org

- Browser-based set of tools to enable real time collaboration and information sharing based on open standards and frameworks
- Application of web 2.0 technologies to enable real-time collaboration and information sharing for SSTR operations
- Content is indexed based on user-specified meta-data tags to enable searching of local content
- Utilization of GeoRSS technology to integrate latest content from TRITON and Veterans For America [future versions to include content from JPEG Meta-Data Tagging (JMDT) initiative]
- Blogs, wiki, polls and forums within a group-based structure
- Create or upload content such as events, video, audio, images, disaster reports and web links in a group-based structure.
- Fotonotes annotation capability (i.e., image annotation / markup)
- Geo-tagged content; displayed on a map.
- All subscribed-to content generates email alerts.
- Subject Matter Expert (SME) registry



Management, Development and Integration Team

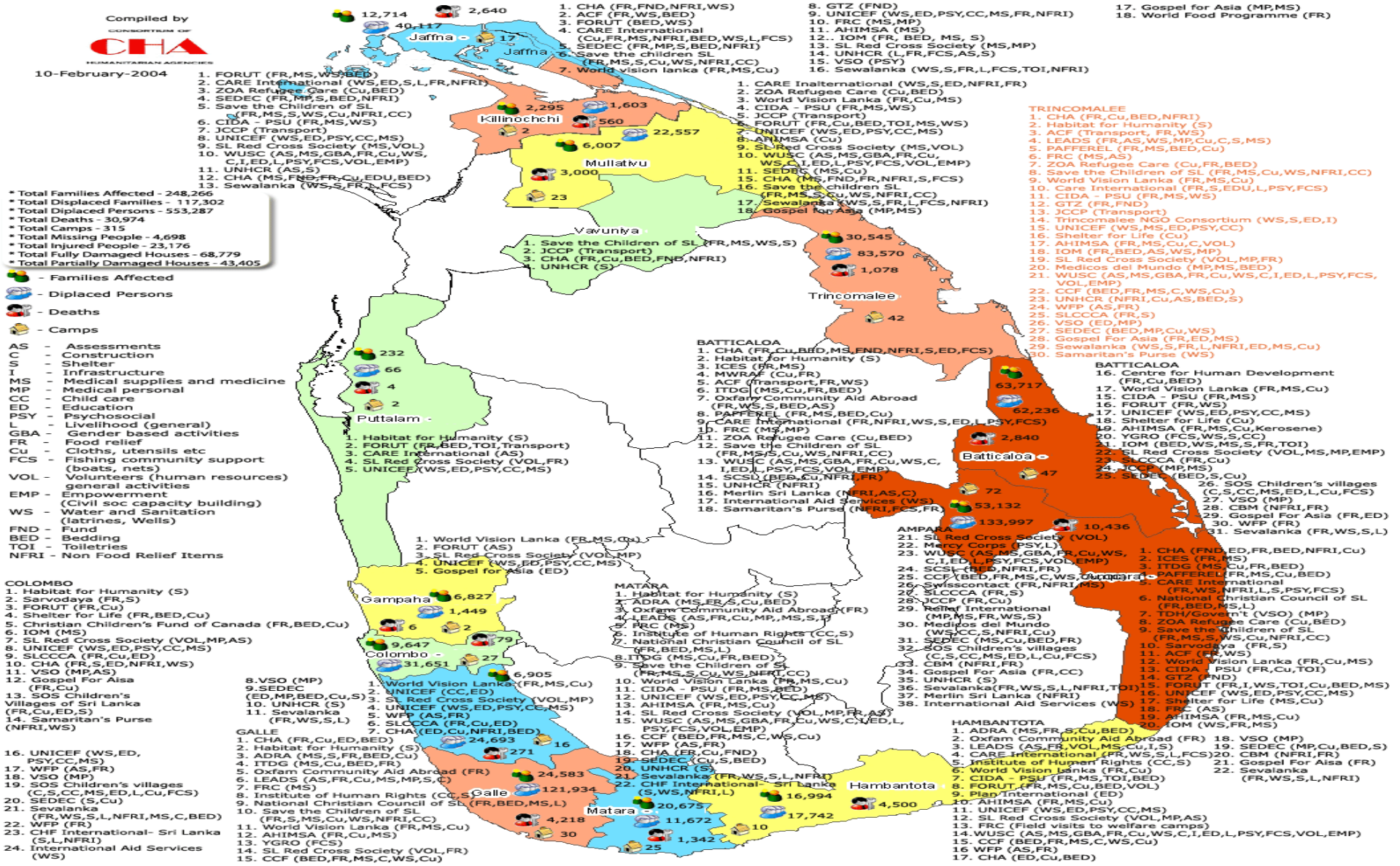
SYNEXXUS
ITT
SPAWAR
NAVSEA
CERDEC
VIGNETTE CORPORATION
INNOVATIVE SOLUTIONS INC.

Operational Challenges in SSTR Coordination – (2)

- **Usually coordination is a result of voluntary efforts**
  - Coordination as "directing" is rarely effective
- **Relief agencies partly function within a framework of self-interest**
  - Assist their targeted beneficiaries
  - Assist their beneficiaries in such a way that their good works are seen and valued by donor community and the "profile" of their agency is enhanced.
  - Farther down on the list is the goal of recognizing the contribution of others or admitting someone else can do the job better
- **Coordination is not necessarily an agency's first priority**
- **Coordination between highly structured organization (military) and loosely structure organizations (civil).**
  - Former tends to be hierarchical, structured, and command-oriented
  - Latter tend to be less formal
  - Functional divisions can be confusing for military commanders
  - In interest of security, military may withhold information; at the same time this does not stop military from wanting information

Operational Challenges in SSTR: Sri Lanka (3)

Groups Active in Tsunami Relief Activities



Coordination Challenges and Issues in SSTR Scenarios — (4)

- **Finding a unified approach to coordination is a key problem that is particularly acute**

- **Cooperative approach in the preparedness phase has to be complemented with a competitive approach in the response phase due to life-threatening situations.**

Coordination Challenges and Issues in SSTR Scenarios —(5)

A Few Challenges

- **Understanding emerging social networks and which groups should be involved and their role(s)**

- **Lack of automated coordination tools; there are processes in place but most coordination is manual; likely benefits from coordination tool(s).**

- **Conflicting goals each of which may be equally important to the respective contributing organizations.**
  - How should a coordination tool allow the users to negotiate roles and understand the consequences / trade-offs?

- **Lack of a common taxonomy / definitions encompassing NGO's, IGO's, Civil and military authorities.**

- **Possible lack of communications infrastructure in which coordination must take place; leading to possible information disadvantage and suboptimal resource allocation.**

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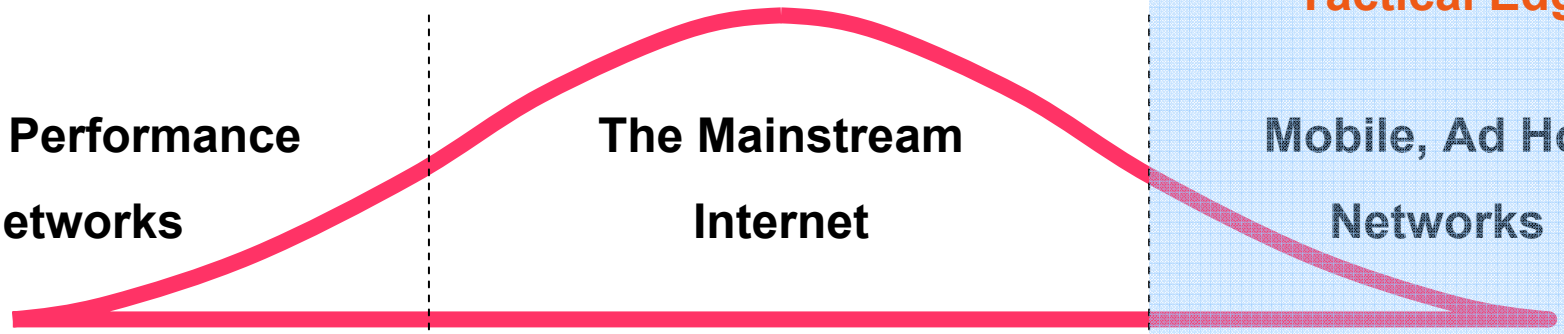
Coordination Challenges and Issues in UAV Scenarios—1

- **Network centric battle-space will contain heterogeneous "sensors" such as UAVs**
- **Variety of mission profiles in dynamic, dense, uncertain environments with known / unknown (mobile) targets and threats**
- **These "sensor" assets much cooperate**
  - Information Gathering & Exploration
  - Target Search
    - Detect, Locate, Track,
    - Identify, classify/confirm, assess outcome, monitor,
    - track and move, engage, destroy
  - These tasks may be naturally determined or dynamically adjusted
- **Some tasks may be highly interdependent**
  - Picture compilation and Exploitation
- **In these problems, resources must be allocated and coordinated in a timely manner**
  - Dynamically schedule and visit targets/threats
  - Determine suitable routes among obstacles and manage airspace
  - Utilization and resource sharing.

- **UAV coordination may be framed as a role allocation problem.**
  - Next 4 slides describe experimentation of role allocation algorithms in MANET.

Internet S&T View and Problem Space

(from 80,000 feet)



Some Common Characteristics

- Stable infrastructure
- Fiber optic/High-speed RF/wireless optical
- Highest bandwidth
- Low latency
- Connection-oriented links
- Policy-based QoS

Some Common Characteristics

- Mixed range of assets
- Mixed media
- Tending to higher bandwidth
- Overprovisioned
- Low to high latency
- Table-based routing
- Mixed policies in forwarding and QoS

Some Common Characteristics

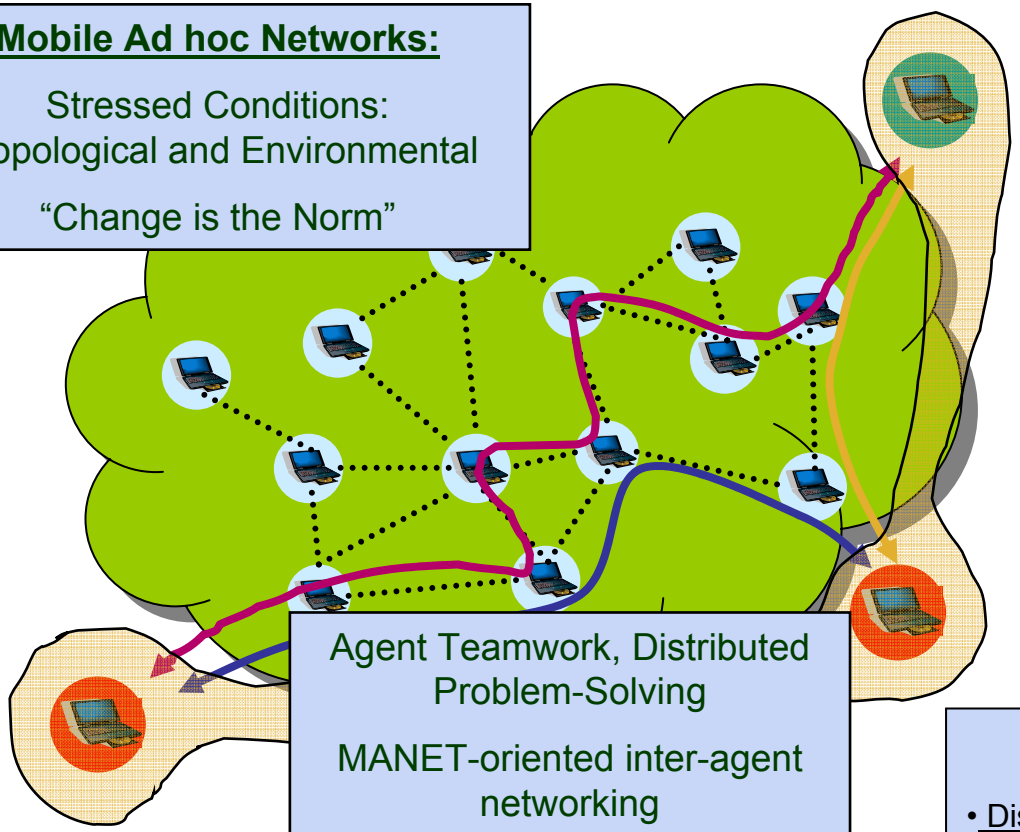
- Ad hoc assets
- Generally wireless
- Design for degraded operation
- Large variability in latency and bandwidth
- Highly dynamic routing
- More distributed network service models required
- Change is the norm

Multi-Agent System (MAS) Operation in Distributed Ad hoc Networks (MODAN)

Mobile Ad hoc Networks:

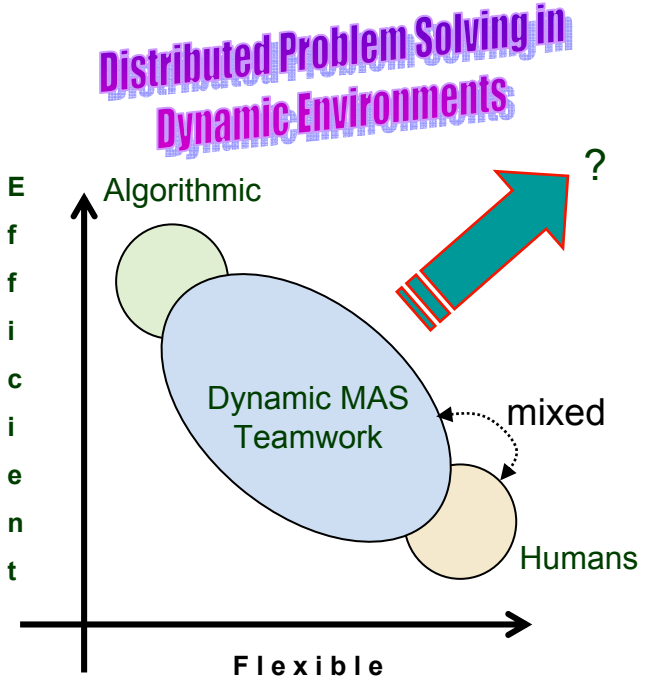
Stressed Conditions:
Topological and Environmental

"Change is the Norm"



Agent Teamwork, Distributed Problem-Solving

MANET-oriented inter-agent networking



Multi-Agent Rationale and Challenge

- Distributed, adaptive solutions to complex problems
- How this works in highly dynamic networks is a largely unexplored problem space?

- **Tactical Network Operations Support**
- **Wireless Communication and Sensor Networks**
- **Distributed Unmanned Vehicle and Robotic Networking**
- **Heterogeneous Combinations of above**

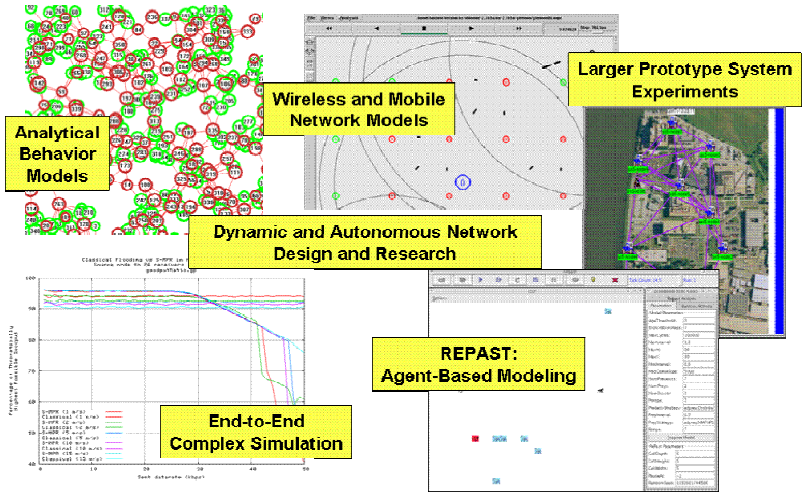
Coordination Challenges and Issues in UAV (2)

Role Allocation Algorithms Studied in MANET

- **The role assignment problem**
  - $\mathcal{M}$ agents, $\mathcal{N}$ roles and $\mathcal{M}=\mathcal{N}$
  - (i,j) ← *Assignment of an agent i to a role j*
  - $a_{i,j}$ ← *Utility of role j to agent i*
  - w_j ← *Priority of role j in the global task*
  - *Maximize* $\sum_{i,j} a_{i,j} w_j$

- **Three classes of algorithms studied**
  - Distributed Stochastic Algorithm (DSA)
  - Simple Distributed Improvement (SDI)
  - Distributed Constraint Optimization (DCO)

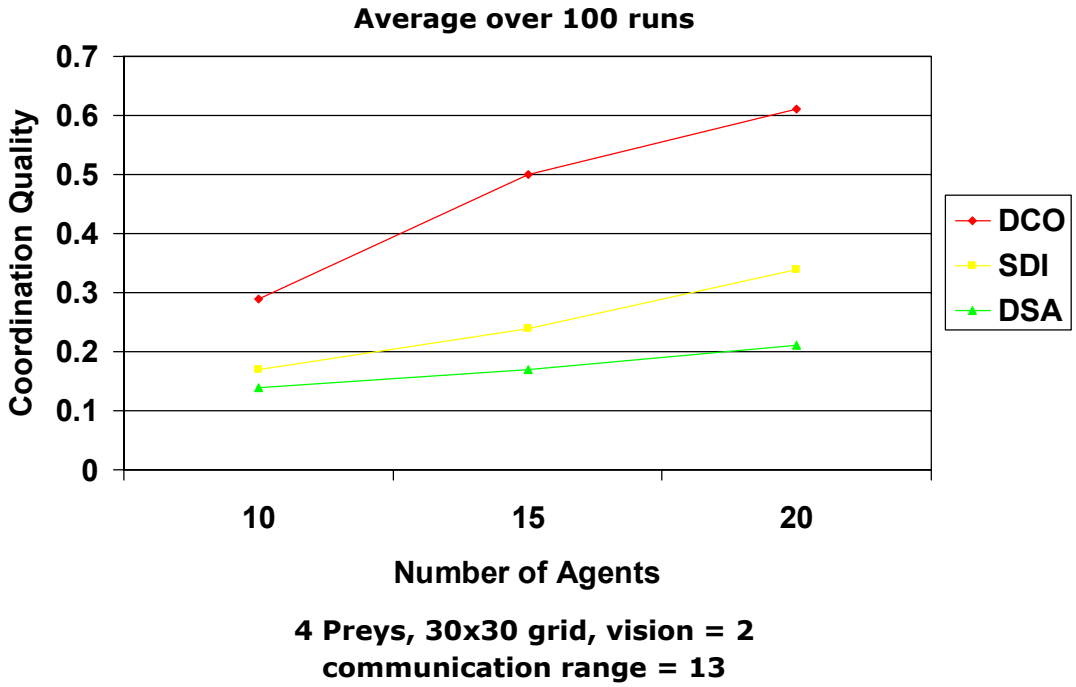
- **Initial implementation and evaluation of assignment algorithms in RePast using coordination solution quality metrics**
  - RePast is an agent-based simulation and modeling tool where agents act concurrently in a decentralized manner.
  - Its powerful scheduling mechanism was used to model the asynchronous behavior of the agents
- **Later experiments conducted in Mobile Network Emulator and NS-2**



Coordination Challenges and Issues in UAV (3)

Role Allocation Algorithms Studied in MANET

- **The comparison of different types of role allocation algorithms shows that DCO works best, but additional experiments are needed.**
- **Each agent solves the role allocation problem in parallel based on state information communicated by their neighbors using the same optimization method.**
- **Hungarian algorithm as optimization method**
  - Variant of the bipartite weighted matching algorithm



Coordination weighs positive and negative interactions

Coordination measure as harmonic mean of goals g, resources r, and failures f:

$$\frac{3grf}{gr + rf + fg}$$

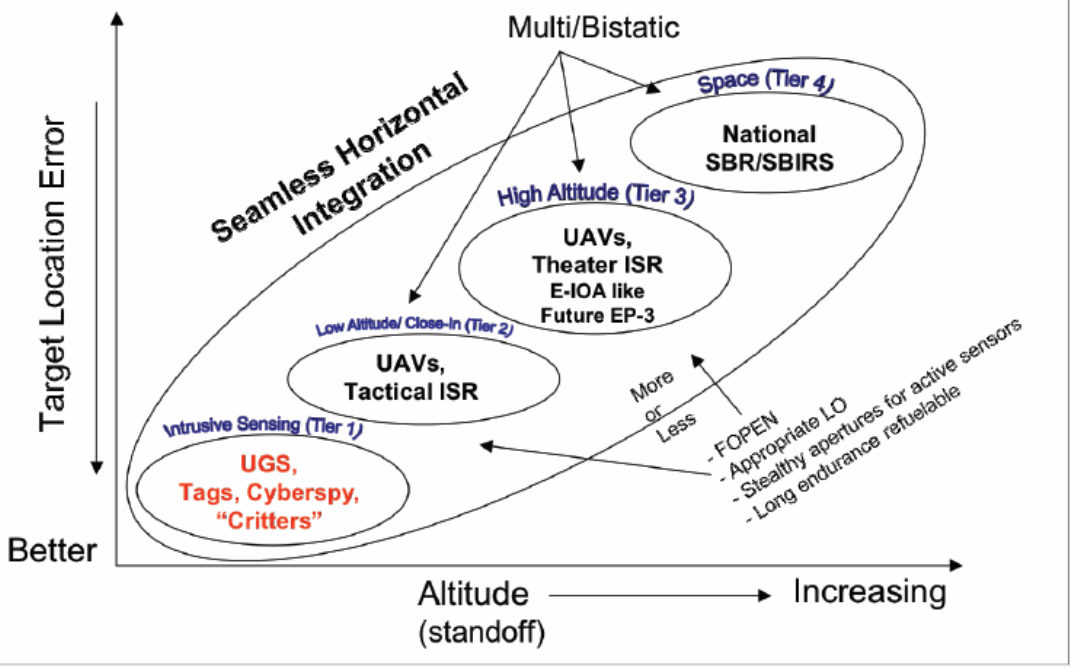
Integrated Emulation Example

Coordination Challenges and Issues in UAV Scenarios—4

Tiered Systems

- **Key enabler of sustainable military force is the notion of a tiered system**
- **Lower Tiers (e.g., UAVs) may serve to provide critical intelligence, and serve as key cueing devices for other sensors.**

From: Report of the DSB on Future Strategic Strike Force (Feb 2004)



{Blair} Figure 3-1: Future tiered ISR systems.

[35 Co-Authors] Developing a Viable Approach for Effective Tiered Systems, NRL Memorandum Report 1001-07-9024, January, 2007.

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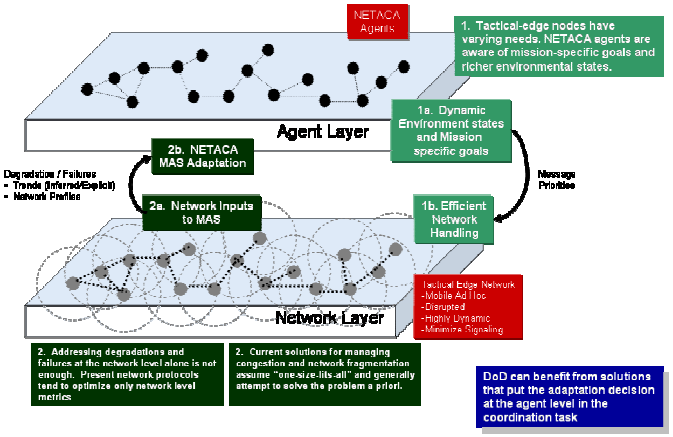
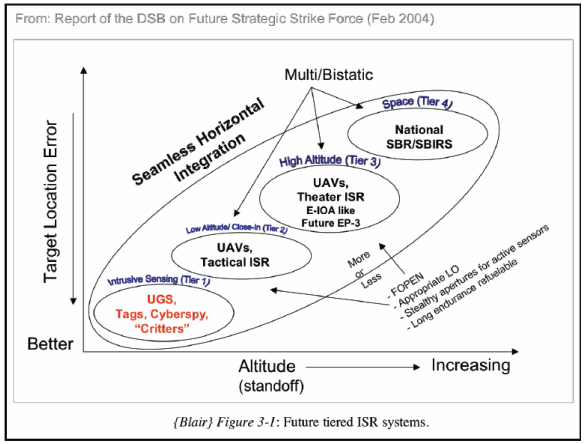
Overall Challenges and Gaps-1

- **Similar challenges in SSTR and UAV coordination**
  - Cooperative information sharing in partially observable dynamic environments
  - UAVs may also support SSTR operations
- **Degraded communications infrastructure in disasters; affect of distance / environment on UAV communications**
  - Mobile ad-hoc Networks (MANET)
  - Message loss and delays; coordination algorithms must be robust in response
  - Network-aware coordination
- **Deficiencies in penetrating foliage, tracking individuals and WMD activities places more requirements on lower sensing tiers**
  - However, need to address camouflage, concealment and deception.
  - May be an area where adversarial reasoning employing game theory could provide value.
- **Given the diversity of the assets, and the fact that coordination must be achieved both in the horizontal and vertical planes, and the environments in which the components of a tiered system will operate; it is not likely that a single coordination approach or even a family of coordination approaches will work well from a static perspective.**
  - It is more reasonable to expect that systems should learn which approaches work well and under which circumstances, and adapt appropriately.





{Blair} Figure 3-1: Future tiered ISR systems.

Overall Challenges and Gaps-2

- **Computational research issues in Coordination**
  - Multiagent planning, replanning and scheduling between heterogeneous coordination entities.
  - Distributed techniques such as automated plan merging and negotiation tools between responders may resolve local conflicts issues without an entire re-planning effort.
  - The degree of interdependence (coupling) in capabilities and resources is a factor in the complexity of the coordination task.
    - While coordination tools have been directed towards assisting human-to-human collaboration, agents can be introduced to reduce interdependence by providing fast and robust solutions bypassing delays in human response such as information gathering tasks.
    - Specifically, coordination support assistant agents can help incident commanders in directing large-scale teams and gather information for situational awareness.
  - Human-computer interactions have also become critical in flexible robot-agent-person teams to smooth out the cognitive demands of such interactions.

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Towards Adaptive Multi-agent Systems Coordination

- **A suitable framework (or multiple frameworks) is required to address current challenges and issues in agent-based coordination.**
- **The proposed multi-agent coordination approach should be flexible enough to adequately address resource constraints**
  - Communication failures / degradation
  - Computational and temporal dimension (should exhibit adaptability in time-constrained environments)
    - Tradeoff between the cost of reasoning versus value of coordination
  - Permit run-time reasoning regarding the selection of particular coordination mechanism/protocol
    - Attempt to dynamically choose between centralized and decentralized mechanisms.

- **The framework should support the investigation of coordination concepts in net-centric problem settings/environments.**
  - It should provide flexibility for problem definition, and allow for studying different concepts, including models, algorithms, or agent-mediated decision support capabilities.
  - The framework should permit basic simulation in order to validate advanced multi-agent coordination concepts in order to asses the value of coordination.

Conclusion

- **Coordination is a key requirement underlying distributed continual planning to satisfactorily improve net-centric decision support components characterizing dynamic planning and execution.**

- **We briefly overviewed the basic elements and aspects of coordination and focused on some of the issues, gaps and challenges lying ahead for the defense research community.**

- **As a result, research areas to be further investigated have been identified in relation to SSTR such as disaster management response and the cooperative UAV problem domains.**

Acknowledgements

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