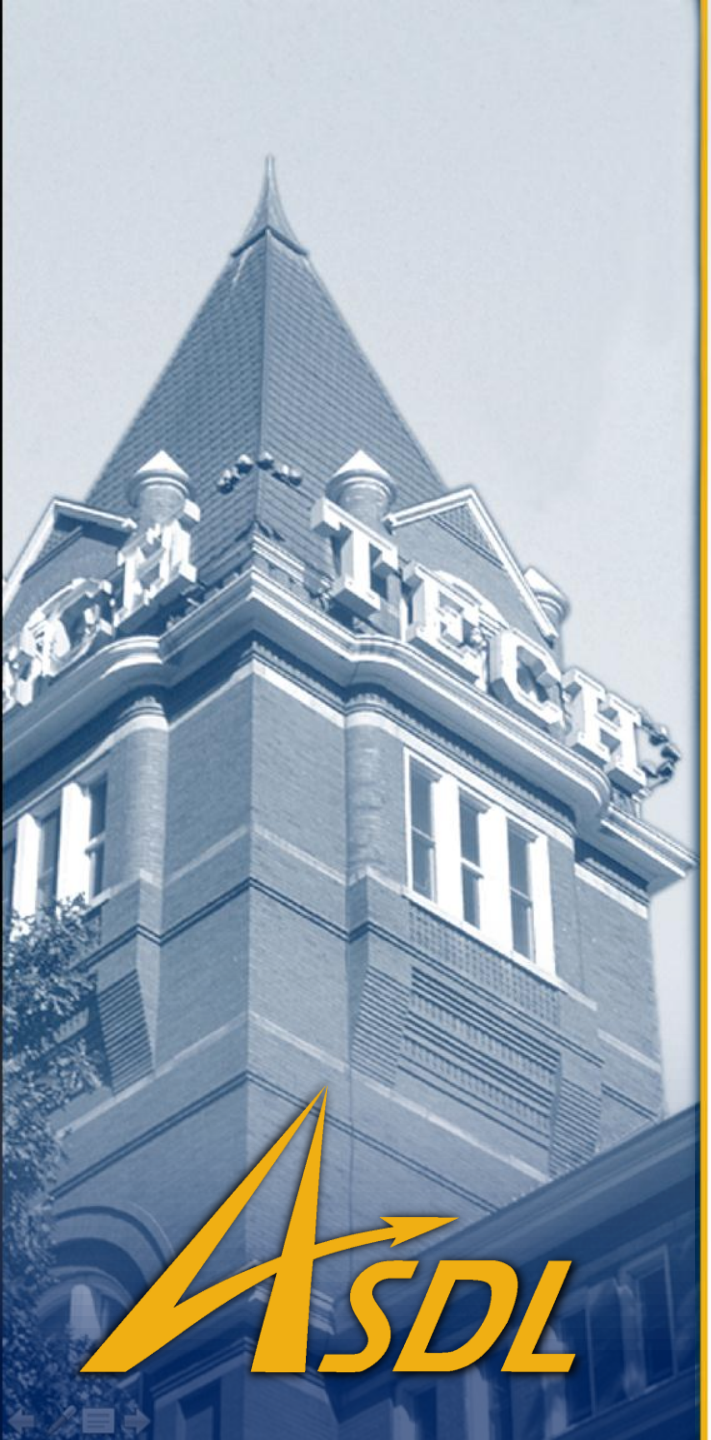

Trade-offs Between Command and Control Architectures and Force Capabilities Using Battlespace Awareness

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19th ICCRTS
6/17/2014

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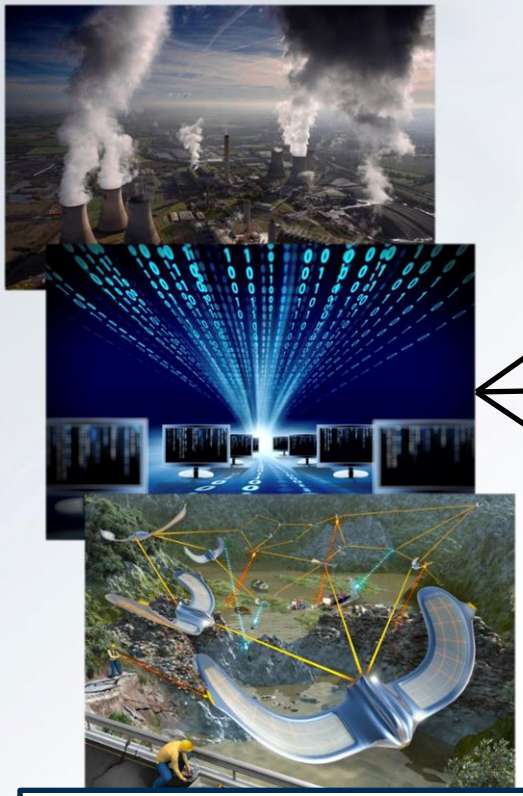
Evolving C2 Approaches



Shift from the Industrial age to an Information age

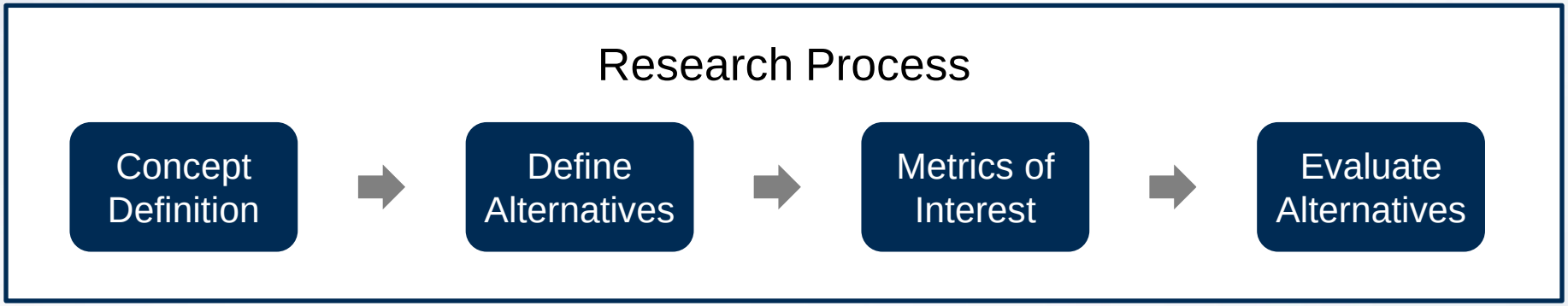
- Increased communications capabilities
- Increased autonomous systems
- Highly networked and complex System-of-Systems

There is a need to investigate novel C2 approaches to improve the agility and effectiveness of Military System-of-Systems (MSoS)

Research Objective

Examine trade-offs between C2 architectures with…

- Varied force capabilities
- Varied operating environments



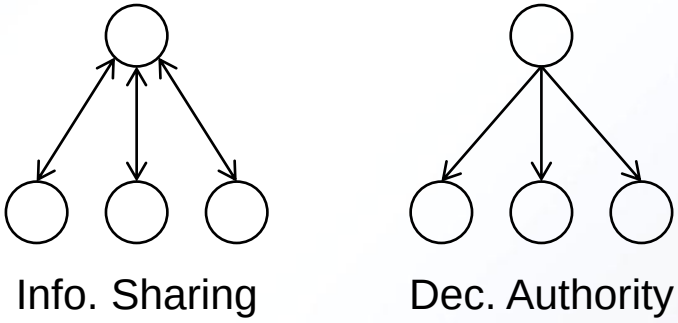
Defining a C2 Architecture

- There are many C2 functions
  - Establishing mission objectives, task assignment…
  - Establishing *communications links*
  - Establishing *decision authority*
- Focus on information sharing and decision authority

C2 architecture: the architecture that defines how *information is shared* and *decision authority allocated* within a collection, or organization, of entities

C2 Architectures as Networks

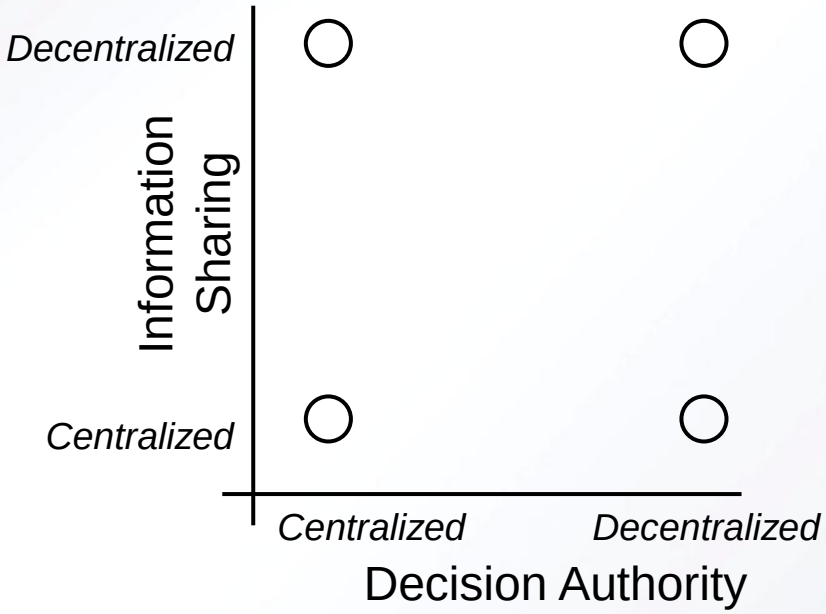
- Model C2 architectures as two networks
  - Information sharing
  - Decision authority
- Nodes represent entities or agents
- Links represent information or decision paths



Example Centralized C2 Architecture

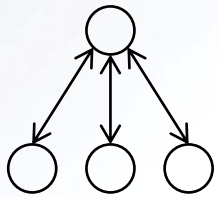
C2 Architecture Design Space

- Design space is defined by the decentralization of information sharing and decision authority
- Focus on extreme corners of the design space

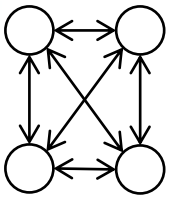


C2 Architectures Considered

- Information sharing networks
  - Centralized – star network
  - Decentralized – complete network (fully connected)
- Decision authority networks
  - Centralized – star network
  - Decentralized – empty network

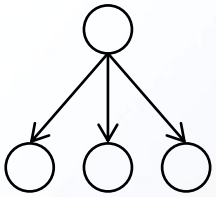


Centralized

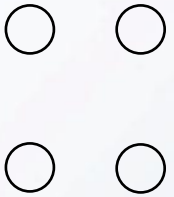


Decentralized

Information Sharing Networks Considered



Centralized



Decentralized

Decision Authority Networks Considered

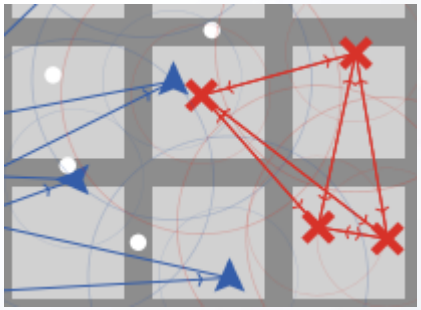
Measuring C2 Effectiveness

- Use information entropy-based battlespace awareness
- Based on Shannon's information entropy

- Discrete state space $X = \{x_i\}$
- Uncertainty $H(X) = -\sum_{i=1}^{n} p(x_i) \log_b p(x_i)$
- Max. uncertainty $U = H(X)_{max} = \log_b n$
- Battlespace awareness $A(t) = 1 - {}^{H(X)}/_{U}$
  - $0 \leq A(t) \leq 1$
  - $A(t) = 0 =$ complete uncertainty

Simulation Environment

- Developed an agent-based model to simulate C2 performance (using NetLogo)
- Modeled a UAV surveillance mission
  - Agents try to develop awareness of others in the battlespace
  - Agent teams
    - Blue (searches for red and white)
    - Red (evades blue)
    - White (randomly moves around battlefield)



Screenshot of NetLogo Simulation Environment

Inputs		Outputs
Operational Environment Agent Capabilities C2 Architectures	→ Simulation Environment →	Battlespace Awareness Mission Performance

Evaluating C2 Effectiveness

- Battlespace awareness
  - Discrete state space $X = \{team, op.level, loc.\}$
  - Battlespace awareness $A(t) = 1 - {}^{H(X)}/_{U}$

- Search efficiency
  - $\eta(t) = 1 - \frac{N_{duplicate}}{|B|-1}$
    - $N_{duplicate}$ = number of blue agents searching a grid already being searched by another agent
    - B = set of all blue agents
  - $0 \leq \eta(t) \leq 1$

Experimental Design

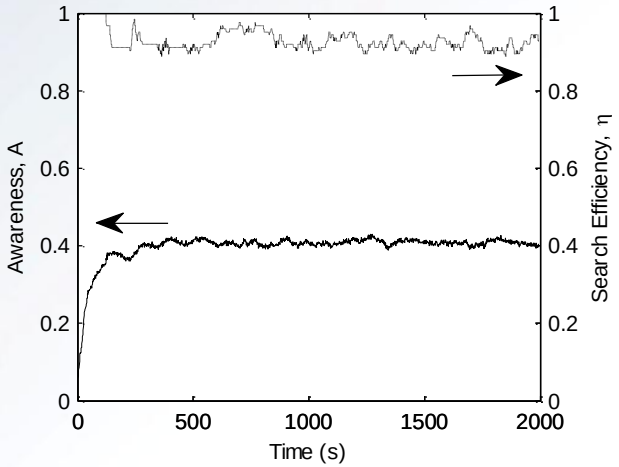
- Experiment 1: test the impact of red team C2 architectures on blue team performance
- Experiment 2: test the impact of blue team sensing capability on blue team performance
- Experiment 3: test the impact of network reliability on blue team performance
- Experiment 4: test the impact of jamming (node removal) on blue team performance

Awareness and Efficiency Time Trajectories

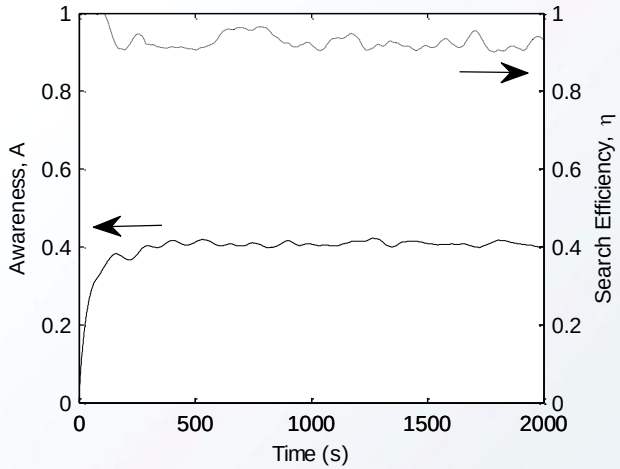
- Awareness and efficiency reached steady-state values after ~500 seconds for all cases
- Remaining results will focus on the steady-state values for smoothed data

Input Parameter	Baseline Setting
Blue C2 architecture	cen/cen*
Red C2 architecture	dec/dec
Sensing radius (m)	350
Network reliability	0.8

**cen/cen = cen. information / cen. decision networks*



(a)

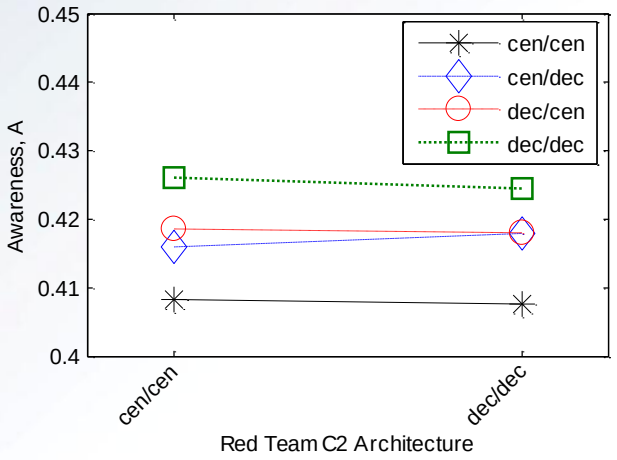


(b)

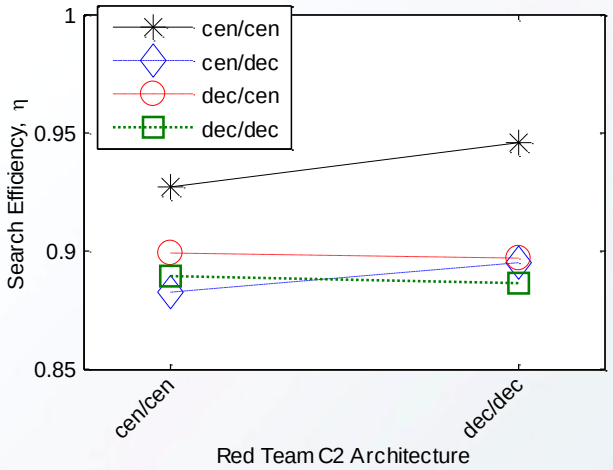
Baseline case (a) raw and (b) smoothed time trajectories of blue team awareness and search efficiency. Trajectories were smoothed using a Savitzky-Golay filter.

Effect of Red C2 Architecture

- Blue team awareness and search efficiency showed small sensitivity to red C2 architecture
- Decentralizing information and decision networks generally improved blue team awareness (more redundancy and faster decision making)
- Centralizing decision authority generally improved search efficiency (more coordinated decision making)



(a)

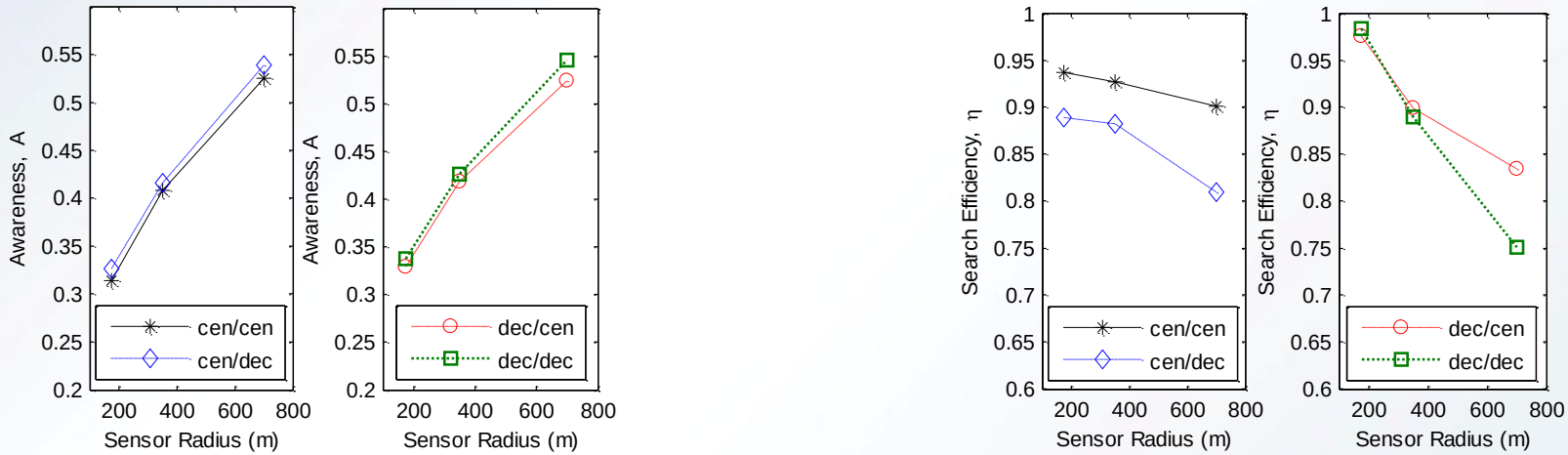


(b)

Effect of red C2 architecture on (a) blue team steady-state awareness and (b) search efficiency

Effect of Sensor Radius

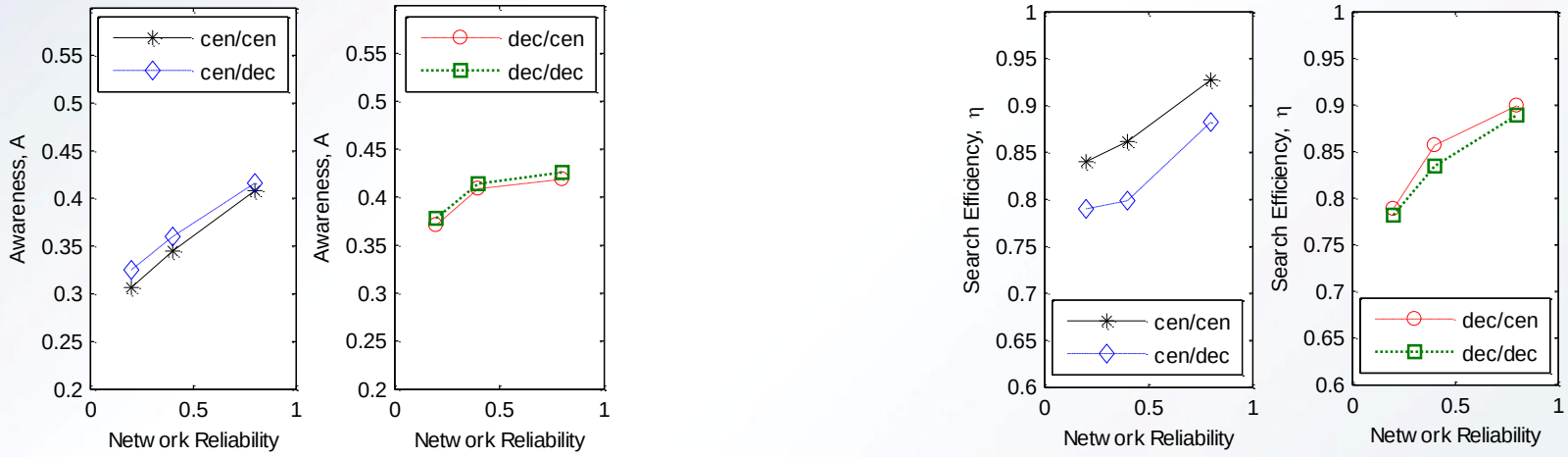
- Increasing sensor radius improved awareness but decreased search efficiency – this is due to information overload
- Centralizing decision authority can reduce the effects of information overload on search efficiency



Effect of blue team sensor radius on (a) blue team steady-state awareness and (b) search efficiency

Effect of Network Reliability

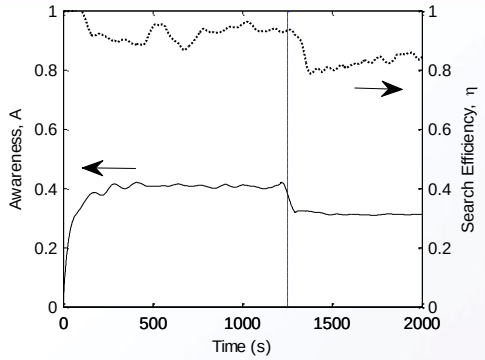
- Decentralizing information sharing resulted in diminishing returns for improving awareness with network reliability
- Fully centralized architectures can maintain higher search efficiency in low reliability environments



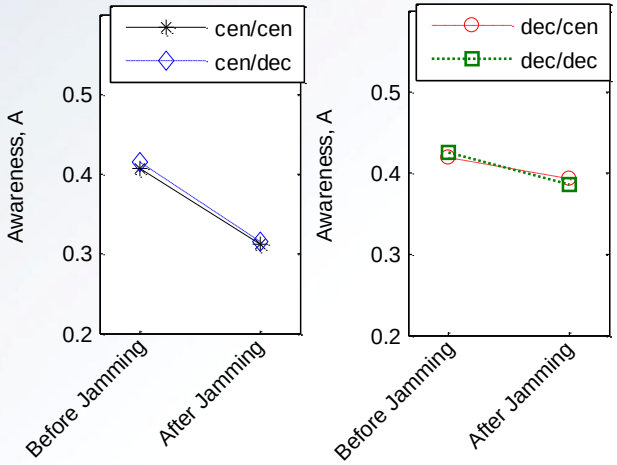
Effect of network reliability on (a) blue team steady-state awareness and (b) search efficiency

Effect of Jamming

- Jamming was modeled by removing the most central agents from their networks at 1250 seconds into the simulation
- Decentralizing information sharing improved C2 robustness to node removal – this is due to the lack of a central agent required to connect agents



(a)



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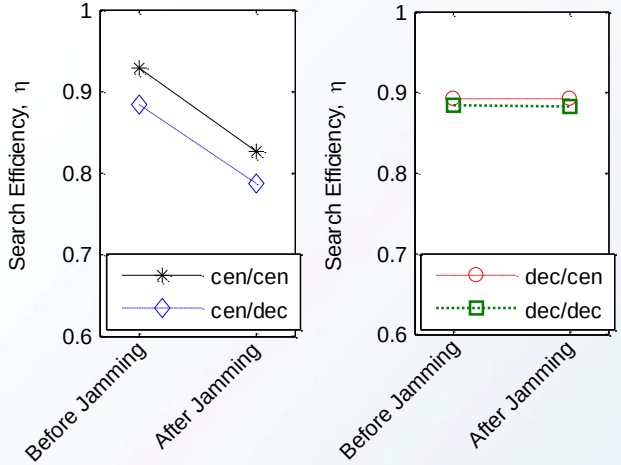
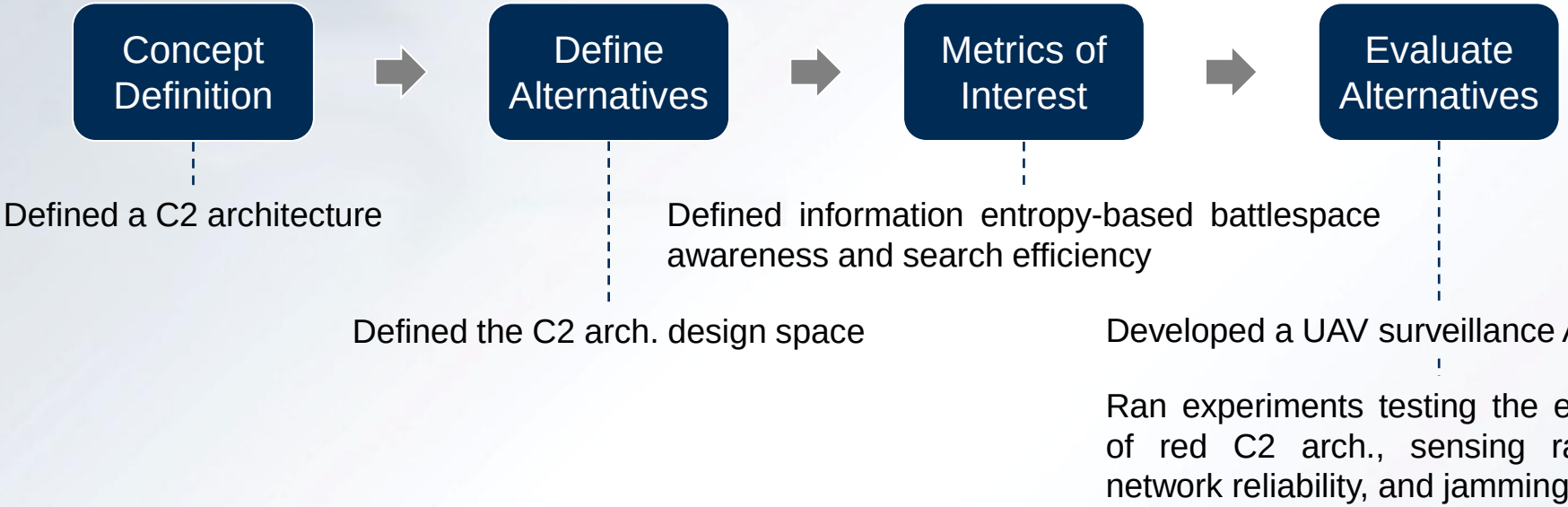


(c)

Effect of jamming the most central agents on (a) blue team awareness and search efficiency time trajectories (b) steady-state awareness and (c) efficiency

Summary



- C2 architectures can be used to study the effects of information sharing and decision authority on C2 processes
- Supplementing traditional mission metrics with information entropy-based battlespace awareness provides additional insights into C2 effectiveness
- Agent-based modeling provides an effective, low fidelity method of evaluating C2 architectures

Future Work

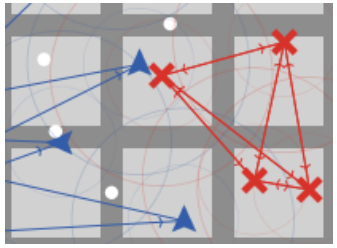
- Consideration of other network topologies
- Focus on network resilience
- Introduction of network reconfiguration

BACKUP SLIDES

Agent-based Model

Agent Teams

- Blue team (search for red and white)
- Red team (evade blue)
- White team (random movements)



Agent Attributes

- Sensing radius
- Sensing resolution
- Latency
- Bandwidth
- Message reliability
- Processing capability
- Decision making capability
- Velocity

Agent Actions

- Sense = identify other agents within search radius
- Send message = send information or decisions to neighboring agents
- Process information = process information received from others
- Make decision = make a search or evasion decision
- Evade = evade enemy agents
- Search grid = search an assigned grid area