19th ICCRTS
C2 Agility: Lessons Learned from Research and Operations

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

Primary Topic
Topic 4: Experimentation, Metrics, and Analysis

Alternate Topics
Topic 5: Modeling and Simulation
Topic 2: Organizational Approaches, Collaboration, Social Media/Networking

Student Paper

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

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Information age organizations must effectively utilize new communications capabilities to gain an advantage over their competition. Command and Control (C2) research has demonstrated the potential for decentralization of C2 to improve mission performance in networked battlefields. However, it is unlikely that all future missions will be best executed with a decentralized C2 architecture. Therefore, it is desirable to understand the trade-offs that exist between adopting various C2 architectures. This work investigated the interplay between C2 architectures employed by friendly and enemy forces with varied force capabilities and mission conditions. C2 architectures were decomposed into information sharing and decision authority networks, where nodes represented assets and directed links represented the flow of information or decisions. The topologies of these networks were varied to compare decentralized and centralized C2 architectures. An agent-based model was developed to simulate mission performance with varied C2 architectures, force capabilities, and mission conditions. Information entropy-based battlespace awareness was used to evaluate the performance of C2 architectures. Results showed trade-offs between C2 architectures depending on force capabilities (sensor radius), missions conditions (network reliability and jamming), and enemy C2 architectures. Results also suggested that future C2 studies consider information entropy-based battlespace awareness as a measure of C2 effectiveness.

I. Introduction

Advances in information technology have led to a shift from the Industrial age to an Information age characterized by highly networked and complex systems.[1] For military organizations, an important aspect of this transition is the need to evolve Command and Control (C2) approaches to ensure that they reflect an increased dependence on network technology.[1,2] Decentralized approaches to C2 are often proposed as a method of leveraging new networking capabilities.[1,3–5] Several studies have evaluated the performance of decentralized, "Edge-like" C2 approaches and shown their potential benefits relative to C2 effectiveness and agility when compared to traditional, centralized C2 in Information age missions.[6–9] C2 agility is defined by Alberts as the "capability to successfully cope with changes in circumstances.[6]" Accordingly, recent observations in the battlefield have shown increased decentralization of information sharing.[10]

C2 agility is not free though. There are costs associated with improving C2 agility, such as the time and effort spent developing enabling technologies, training appropriate skills, and implementing proper procedures. The importance of considering these costs when exploring new C2 approaches is reflected by a push to consider requisite agility, or the agility appropriate for a situation considering costs and circumstances faced.[6,9] A step towards proper consideration of requisite agility is developing an understanding of the trade-offs that exist between methods available for improving C2 agility, such as decentralization of C2, as well as evaluating required capabilities for successfully implementing agile C2 approaches. It is important to understand trade-offs between potential C2 approaches because knowing the limits of when certain approaches can be effectively applied can define capabilities needed from future forces.

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Though there is a clear focus on decentralizing C2 for future missions, it is still important to consider the full space of potential C2 approaches. As shown by the NATO Research Group SAS-085,[9] no single C2 approach is most appropriate for all possible conditions of its operation.[9] This position is supported by contingency theorists such as Burns and Stalker,[11] Woodward,[12] and Lawrence and Lorsch,[13,14] who have shown that effective organization designs are highly contingent upon certain factors, such as their environment and culture. Applying this concept to C2, as is done by Alberts and Nissen,[15,16] this creates a need to understand the conditions best suited to various C2 approaches.

Additionally, while information sharing in the battlefield is trending towards decentralization, decision making has shown the potential to trend in the opposite direction.[10,17,18] Improved networking capabilities have enabled troops to maintain communication with commanding officers throughout engagements, but these capabilities have also given operational commanders the ability to develop situational awareness far from the battlefield and take decision authority away from local leaders at the scene. So while information sharing has become more decentralized, actual decision making may trend towards centralization. Therefore, exploration and analysis of potential C2 approaches should include seemingly contradicting approaches to information sharing and decision authority.

There is a developing body of research investigating approaches to C2 and organizational structures of military entities. As Carley,[19] Levitt,[20] and Nissen[21] note, computational methods to modeling and exploring organizational forms show great promise. Several computational studies focused on C2 took an Organization and Management Theory approach to the problem, comparing novel C2 approaches to classical organizational archetypes.[7,15,16,22,23] Others used a network science or social network analysis approach,[24–26] which in the case of Scheidt and Schultz[26] was complemented with information theory metrics. Agent-based models were used by Friman[27] and Alberts (abELICIT).[6] Experiments were also conducted using the ELICIT multiplayer intelligence game, where subjects were used to simulate the performance of hierarchical and Edge C2 configurations.[8,28] Several NATO research groups have also studied C2 approaches, with a focus on C2 agility.[2,9,29,30] These studies demonstrate the applicability of computational methods to the study of C2 organizational approaches and the need to study novel C2 approaches. However, most of these studies focused on overall mission performance as a measure of effectiveness, had limited consideration of required force capabilities and the effects of an enemy's C2 approach, or had limited consideration of adaptive C2 approaches.

This paper aims to complement this body of work by computationally examining trade-offs between C2 architectures with varied force capabilities and mission conditions. Mission conditions are defined to include enemy C2 architectures. Information sharing and decision making responsibilities are also considered as separate aspects of C2. Information entropy-based battlespace awareness is defined and used as a metric for evaluating C2 effectiveness. A definition of a C2 architecture for the purposes of this paper is given in section II.

This paper also establishes a foundation for a complementary investigation into developing a methodology for the analysis and optimization of resilient, adaptive C2 architectures. Methods and insights gained from this study are being used to guide this effort to consider the effects of implementing adaptive architectures.

II. Defining C2 Architectures

C2 is a term that can be defined in many ways, depending on the context and application. The Department of Defense (DoD) defines C2 as "the exercise of authority and direction by a properly designated command over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission.[31]" This definition focuses on the authority held by a designated commander over subordinate forces and defines C2 functions to include asset selection and the planning and coordination of mission objectives and procedures. Alberts defines a similar list of essential C2 functions.[32] Since this work is inspired by recent developments in communications technologies and their effects on C2, emphasis is placed on the communications and decision making aspects of C2. To differentiate between the encompassing definition of C2 and the focus of this work, the following definition is given for a C2 architecture:

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

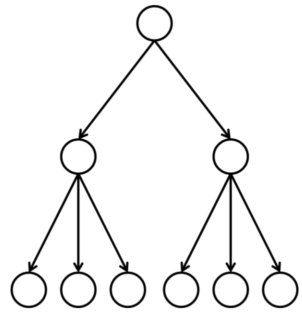


Figure 1: Example decision authority network for a C2 architecture with centralized decision authority.

The entities included in a C2 architecture can range from individual troops or systems to teams of troops or collections of systems. Having defined a C2 architecture, a method is now required to represent C2 architectures as more than general concepts, so they can be differentiated, compared, and modeled. Since a C2 architecture focuses on the information sharing and decision making aspects of C2, C2 architecture are separated into two planes, or networks; one defining the information sharing network and one defining the decision authority network. The information sharing network defines how information is shared between entities, while the decision authority network defines the command relationships between entities. Since information and decisions flow from one asset to another, these networks are represented as directed graphs. The nodes of the graphs represent entities while the directed links represent the flow of information or decisions made. Figure 1 shows an example of the decision authority network of a C2 architecture with centralized decision authority.

Exploring potential C2 architectures can be viewed as exploring a C2 architecture design space. Two proposed design spaces from the literature are the CAR model from Pigeau and McCann[33] and the C2 approach space from the NATO Research Group SAS-050.[2] The CAR model defines the three primary dimensions of C2 as competency, authority, and responsibility. The C2 approach space defines the three primary dimensions of C2 approaches as the allocation of decision rights, patterns of interactions, and distribution of information. Since this study defines C2 architectures to focus on information sharing and decision authority, the C2 approach space is used as a starting point for the C2 architecture design space. However, the C2 approach space is reduced to a two-dimensional space to simplify its implementation and adaptation to C2 architectures. One axis of the C2 architecture design space is defined to be the amount of decentralization of information sharing, ranging from fully centralized to fully decentralized. The other axis is defined to be the amount of decentralization of decision authority, also ranging from fully centralized to fully decentralized. A notional diagram of the extreme corners of the C2 architecture design space is shown in Fig. 2. This design space is not necessarily a discrete space, as hybrid designs allow C2 architectures that fill in the gaps between fully centralized and decentralized designs. However, representing this space as a continuous design space requires the definition of a continuous metric that captures the level of decentralization of information sharing or decision authority. Only the four corners of the space were considered in this study. Developing a basic understanding of the trends and characteristics of the corners of the C2 architecture design space provides a foundation for extending this work to consider the full, continuous design space.

III. Evaluating C2 Archictecture Effectiveness

Evaluating the performance of C2 architectures requires consideration of metrics beyond those typically associated with mission success. As noted by the NATO Research Group SAS-085,[9] "Measures of C2 Quality are based upon the degree to which the functions associated with C2 are accomplished, not whether the mission succeeded or not." Since this work focuses on the ability of a C2 architecture to share information and provide awareness to those with the authority to make decisions, battlespace awareness is used as the primary metric for evaluating C2 architecture effectiveness. The use of battlespace awareness is further supported by Vice Admiral Cebrowski's description of the importance of information superiority in Network-centric warfare.[34] A brief discussion of the implementation of battlespace awareness is given. The method

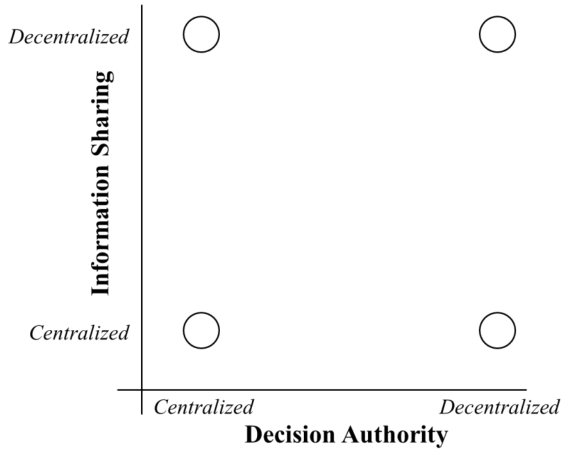


Figure 2: Notional corners of the C2 architecture design space.

used to determine battlespace awareness is based on the TABS framework.[35]

Endsley describes a three level approach to situational awareness: perception, comprehension, and projection.[36] Perry defines situational awareness to be a function of information quality and the ability of a decision maker to process or comprehend that information.[37] This work focuses on the perception and comprehension aspects of Endsley's situational awareness, while considering both aspects of Perry's definition. The result is a definition of battlespace awareness based on the knowledge of state properties of other agents in the battlefield. Shannon's information entropy[38] is used to represent battlespace awareness as a quantitative metric. The following steps summarize the method used to calculate information entropy-based battlespace awareness for this study:

1. Define battlespace awareness as the composite knowledge of discrete state properties (team, operational level, and location) of other agents.

2. Model each state property as a discrete probability distribution. The probability distribution agent i has for a given state property of agent j represents the probabilities agent i assigns to the possible states of agent j. Probability estimations are determined by an agent's sensing and processing actions.

3. Use information entropy to determine the maximum entropy/uncertainty (U) of a state property based on the maximum number of possible states/outcomes (see Equation 1)

4. Use information entropy to determine the amount of entropy/uncertainty ($H(X)$) represented by a probability distribution (see Equation 2).

5. Transform H(X) into a measure of battlespace awareness (see Equation 3).

$$U = H(X)_{max} = log_b(n) \tag{1}$$

$$H(X) = -\sum_{i=1}^{n} p(x_i) log_b p(x_i) \tag{2}$$

$$A(t) = 1 - \frac{H(X)}{U} \tag{3}$$

where

$X =$ probability distribution for a state property

$n =$ number of possible states/outcomes for a state property

$0 \leq A(t) \leq 1$

Table 1: Example Battlespace Awareness Calculations for an Enemy Agent's Team State Property

Example Case	Team Probability Distribution (X)			Battlespace Awareness Calculations		
	Blue Team	Red Team	White Team	U(bits)	$H(X)$(bits)	$A(t)$
1 (maximum uncertainty)	1/3	1/3	1/3	1.585	1.585	0
2 (intermediate uncertainty)	0	3/4	1/4	1.585	0.8113	0.4881
3 (no uncertainty)	0	1	0	1.585	0	1

Possible team states were blue, red, or white. Possible operational levels were "not operational" and "fully operational." Possible locations were defined by grid areas in the battlefield. A log base of two was used for all calculations. Table 1 provides examples of battlespace awareness calculations for three possible probability distributions of the team state of an agent. The first case has maximum uncertainty as the agent is estimated to be a blue, red, or white team agent with equal probability. The third case has minimum uncertainty as the agent is estimated to be a red team agent with complete certainty. The second case has intermediate uncertainty.

IV. Simulation Environment

Exploring trade-offs between C2 architectures required a model capable of simulating mission execution with defined C2 architectures for friendly and enemy forces, in a range of mission conditions with varied force capabilities. The following model requirements were established for this study: (a) application to a test mission affected by communications capabilities and enemy C2 architectures, (b) consideration of varied force capabilities, and (c) modeling of information sharing and decision authority networks.

Several modeling methods were considered before developing the model used for this study. Lanchester Equations,[39] System Dynamics models,[40–42] Discrete Event Simulation, and Agent-based models (ABMs) were among those considered before selecting ABM for this study. ABM was selected because Information age military operations are best described as complex systems.[43–45] Complex systems are dynamic systems with many interacting parts, whose interactions can be highly nonlinear in nature. The complexity of these systems typically leads to emergent behavior that may not be obvious upon initial consideration of the system.[6,46,47]

ABMs are models that aim to capture system level effects by modeling individual agent behaviors in a bottom-up approach. The agent behaviors are defined in the model and agents typically interact with each other in a well-defined environment. Defining the behaviors of agents rather than the overall system requires a thorough understanding of the problem at the micro level, rather than the macro level. Though it is not always easy to identify basic rule sets for agents in a complex system, it is generally easier to do that than to predict system level behavior of non-linearly interacting agents. ABMs have gained popularity in the military modeling community in recent years due to their ability to effectively capture complex interactions in warfare scenarios with many interacting components.[43–46,48–51]

NetLogo was selected as the ABM environment for this work. NetLogo is a publicly available environment developed at Northwestern University,[52] with preprogrammed functionality enabling those new to ABMs to quickly become proficient, while including enough complexity to satisfy those with extensive experience using ABMs. NetLogo advances through a simulation in discrete time events, called ticks. NetLogo represents an environment as a collection of discrete patches that appear as squares on the map. For this study, each tick is assumed to represent one second of time and each patch assumed to represent one square meter.

Figure 3 shows a flow diagram of the basic inputs and outputs to the simulation environment created.

IV.A. Test Mission

The test mission selected for this study was an Unmanned Aerial Vehicle (UAV) surveillance mission. The importance of information sharing and decision making in the operation of a team of UAVs made this mission appropriate for a study focused on networked communications. UAVs are also gaining value as a military asset due to their ability to handle dull, dirty, and dangerous missions with limited human vulnerability.

In the simulated mission, UAVs (blue team) are tasked with searching for targets (red team) in a specified

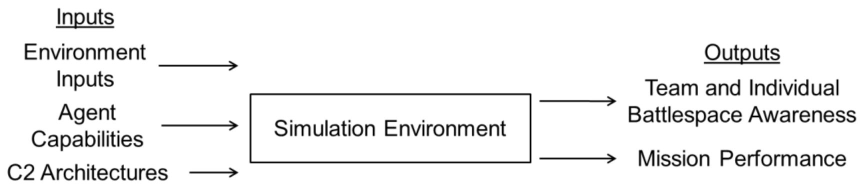


Figure 3: Simulation Environment Inputs and Ouputs.

battlefield. Neutral agents (white team) are also present in the battlefield. The battlefield is divided into grid areas to help UAVs define their search pattern. When a UAV completes searching a grid area, it either makes or requests a decision for what grid area to search next. Targets attempt to evade agents believed to be on the blue team by moving away from their believed locations. This mission was selected because it satisfied established requirements for the model while being simple enough to prevent excessive complication of the problem. Additionally, the simplicity of the mission enables adaptation to other missions that may be of interest in future studies.

IV.B. Agent Actions, Capabilities, and Types

The battlefield is modeled as a two-dimensional space, defined by two parameters, the battlefield area and search grid area:

$$\text{Env} = \text{Env}(\text{Area}_{\text{BF}}, \text{Area}_{\text{GD}}) \tag{4}$$

UAVs, targets, and neutral agents are modeled as agents with assigned capabilities and the ability to perform one or more actions in each time step. Equation 5 shows the capabilities (input parameters) that define an agent, while Table 2 describes those capabilities. Table 3 describes the actions agents can take. The actions modeled were based on the processes described by the Information Superiority Reference Model from Perry, et al.[37] and the agent action and interaction rules used by Jin and Liu.[51]

$$\text{Agent} = \text{Agent}(\text{sens}_{\text{rad}}, \text{sens}_{\text{res}}, \text{lat}, \text{band}, \text{rel}, \text{proc}, \text{dec}, \text{vel}) \tag{5}$$

The *sense* action models an agent sensing its surroundings and attempting to identify agents within its sensing radius. Sensor performance was modeled using a generic sensor performance model from Perry, et al.[37] Up to a defined intermediate sensing range, agents have some probability of detecting others based on their sensing capability. Beyond the intermediate range and up to a defined maximum sensing range, the probability of detection decreases linearly to zero. Agents can also sense their current location within a grid area to determine if they have completed searching a grid. When an agent senses another agent, an awareness message is sent to neighboring agents in the information sharing network. Awareness messages describe the believed team, operational level, and location of an agent. When an agent determines that it has completed searching a grid, a search completed message is sent to neighboring agents in the information

Table 2: Descriptions of Agent Capabilities

Agent Capabilities	Variable Name	Description
Sensing Radius	sens_{rad}	Maximum radius within which other agents can be sensed
Sensing Resolution	sens_{res}	Resolution with which the location of other agents can be sensed
Latency	lat	Time it takes a sent message to be received
Bandwidth	band	Maximum amount of information an agent can receive before needing to process or remove old information
Message Reliability	rel	Likelihood a sent message is received (network reliability)
Processing	proc	Determines the time it takes an agent to process information
Decision	dec	Determines the time it takes an agent to make a decision
Velocity	vel	Agent velocity

Table 3: Descriptions of Possible Agent Actions

Agent Actions	Description
Sense	Identify other agents within search radius and own location within a search grid
Send Message	Send information to neighboring agents in the information sharing network or decisions to neighboring agents in the decision authority network
Process Information	Process (fuse) information received from other agents
Make Decision	Make a search or evasion decision
Evade	Evade enemy agents (move away from nearby enemy agents)
Search a grid area	Move towards or continue searching an assigned grid area

sharing network. Search completed messages describe the grid that an agent has just completed searching. These messages are used to prevent search overlap when agents decide what grid to search next. Search completed messages are followed by a search request message for agents that do not have the authority to make their own decisions.

The *send message* action models an agent sending information to neighboring agents in its information or decision network. The amount of messages an agent can receive from others is limited by its bandwidth. If an agent has received more messages than its bandwidth allows, the agent can no longer receive messages from others until messages are processed or removed.

The *process information* action models an agent fusing information received from others with its own information to develop a cohesive picture of the battlespace. The fusion of information from multiple sources is modeled using a Bayesian updating process used in the TABS framework.[35] The time it takes an agent to process information depends on its processing capability.

The *make decision* action models an agent making a decision for itself or an agent it has decision authority over. Agents without decision authority are required to wait for those with authority (determined by the decision authority network) to make decisions for them. Search decisions are based on the nearest known un-searched grid. Evasion decisions involve selecting a direction and distance to move towards based on nearby enemies. Decision making time depends on an agent's decision capability.

The *evade* action models an agent attempting to evade another agent. Agents move a specified distance and direction determined by an evasion decision. Agents attempting to evade enemies make an evade decision or send an evade decision request message when they determine that there are enemies within their sensor range.

The *search* actions model an agent searching through an assigned grid. Agents perform a simple snake-like search pattern throughout a grid.

IV.C. Modeling C2 Architectures

As discussed in section II, C2 architectures are defined by information sharing and decision authority networks. These networks are defined for each team (blue, red, and white) in the simulation and represented as directed graphs with N nodes, where nodes represent agents within a team. For example, a blue team with N agents would be represented by an information sharing graph $\mathrm{G_{info}}$ and a decision authority graph $\mathrm{G_{dec}}$. $\mathrm{G_{info}}$ would be defined by an adjacency matrix $\mathbf{A_{info}}$ with $N \times N$ elements $\mathbf{A_{info}}_{ij}$, where $\mathbf{A_{info}}_{ij} = 1$ if there exists a directed link from node i to node j (node i sends information to node j) and $\mathbf{A_{info}}_{ij} = 0$ otherwise. $\mathrm{G_{dec}}$ would be defined by an adjacency matrix $\mathbf{A_{dec}}$, where $\mathbf{A_{dec}}_{ij} = 1$ if there exists a directed link from node i to node j (node i has decision authority over node j) and $\mathbf{A_{dec}}_{ij} = 0$ otherwise. The C2 architecture used by a team is then defined by two parameters, the information sharing and decision authority adjacency matrices.

$$\text{C2 Architecture} = \text{C2 Architecture}(\mathbf{A_{info}}, \mathbf{A_{dec}}) \tag{6}$$

Centralized information sharing was represented by having agents share information only with a central processing agent (similar to a central processor), as opposed to sharing information with each other. The central processing agent receives information sent from other agents, processes that information, then sends the processed information back to neighboring agents in the information sharing network. This representation resulted in a tree-like network for centralized information sharing. Decentralized information sharing was represented by having agents share information with all other teammates. This representation resulted in a fully connected network for decentralized information sharing.

Centralized decision authority was represented as a hierarchical command structure where a commander agent had decision authority over all other agents. This representation also resulted in a tree-like network for centralized decision authority. Decentralized decision authority flattened the command structure and resulted in all agents having the authority to make their own decisions throughout a mission. This representation resulted in an empty network for decentralized decision authority.

Blue team central processing and commander agents were modeled to be in a location outside of the battlefield, not actively searching for targets. All other agents stayed in the battlefield. Comparisons between blue C2 architectures maintained an equal number of battlefield (search) agents, with central processing or commander agents added as needed.

Examples of the four C2 architectures considered in this study are described below for teams of six agents.

Figure 4 shows a notional diagram of the information sharing and decision authority networks for a C2 architecture with decentralized information sharing and centralized decision authority (upper left corner of Fig. 2). Since information sharing is decentralized, no central processing agent is used. Since decision authority is centralized, a commander is used for decision making.

Figure 5 shows a notional diagram of the information sharing and decision authority networks for a C2 architecture with decentralized information sharing and decentralized decision authority (upper right corner of Fig. 2). Since information sharing and decision authority are decentralized, no central processing agent or commander are used.

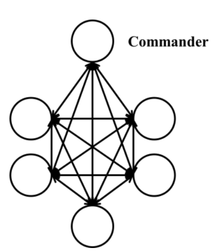
Figure 6 shows a notional diagram of the information sharing and decision authority networks for a C2 architecture with centralized information sharing and centralized decision authority (lower left corner of Fig. 2). Since information sharing and decision authority are centralized, a central processing agent and commander are used.

Figure 7 shows a notional diagram of the information sharing and decision authority networks for a C2 architecture with centralized information sharing and decentralized decision authority (lower right corner of Fig. 2). Since information sharing is centralized, a central processing agent is used. However, since decision authority is decentralized, no commander is used.

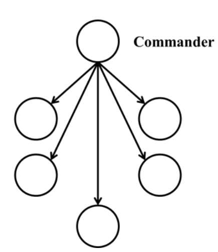
Figure 8 shows a screenshot of a simulation run with the blue team having centralized information sharing and decentralized decision authority and the red team having decentralized information sharing and decentralized decision authority. The light areas represent search grids in the battlefield with dark areas used to designate search grid borders. The triangle-shaped agents are blue team agents. The "X"-shaped agents are red team agents and the circle agents are white agents. The halos surrounding agents represent their respective sensing radii.

V. Experimental Design

For the experiments conducted in this study, blue agents were set to search grid areas in an attempt to gain awareness of other agents, while red agents were set to evade blue agents and avoid detection. White agents were set to randomly move around the battlefield. The baseline case and experimental settings used are shown in Table 5 in the Appendix. A case is defined as a specific combination of inputs for the environment, agent capabilities, and C2 architectures. Four sets of experiments were run, aimed at investigating the effects of changing blue and red team C2 architectures (experiment one), blue team sensing capabilities (experiment



(a) Information Sharing Network

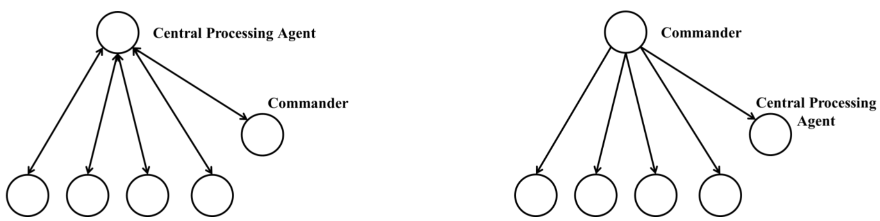


(b) Decision Authority Network

Figure 4: C2 Architecture with Decentralized Information Sharing and Centralized Decision Authority

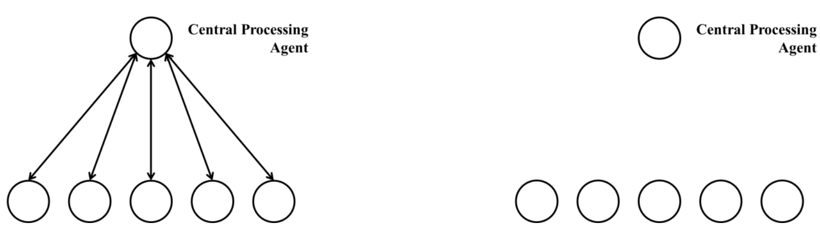
(a) Information Sharing Network (b) Decision Authority Network

Figure 5: C2 Architecture with Decentralized Information Sharing and Decentralized Decision Authority



(a) Information Sharing Network (b) Decision Authority Network

Figure 6: C2 Architecture with Centralized Information Sharing and Centralized Decision Authority



(a) Information Sharing Network (b) Decision Authority Network

Figure 7: C2 Architecture with Centralized Information Sharing and Decentralized Decision Authority

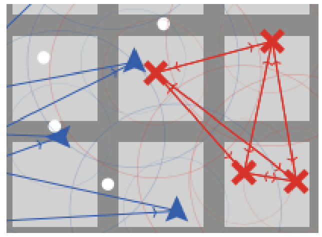


Figure 8: Screenshot of Simulation Run with Information Sharing Links Shown.

two), network reliability (experiment three), and C2 architecture robustness (experiment four) on mission and C2 performance. A summary of the experimental settings is shown in Table 4. 25 repetitions were used for each case.

C2 architecture robustness was investigated by introducing targeted communications jamming halfway through a simulation run. Jamming an agent resulted in the agent losing the ability to send and receive messages from all other agents. For C2 architectures with a central processor and/or commander agent, both those agents were jammed. For C2 architectures without either a central processor or commander agent, one of the battlefield agents was jammed. When agents without decision authority lose their connection to a commander agent, they enter a lost-link procedure in which they are temporarily given the authority to make their own decisions.

Table 4: Summary of Experimental Settings

Experiment	Simulation Parameters Changed from Baseline (Number of Settings)
1	Blue team C2 architecture (4), Red team C2 architecture (2)
2	Blue team sensor radius (3), Blue team C2 architecture (4)
3	Network reliability (3), Blue team C2 architecture (4)
4	Blue team C2 architecture robustness (4)

VI. Results

The results presented focus on mean blue team battlespace awareness ($A_{\text{blue}}(t)$) as a measure of C2 effectiveness and blue team search efficiency ($\eta(t)$) as a measure of mission performance. The mean blue team battlespace awareness was calculated using the mean awareness each blue team agent had for the team, operational level (op), and location (loc) of every other agent in the battlefield (shown in Eq. 7). The blue team search efficiency was calculated using the number of blue agents searching grids already being searched by other teammates, reflecting the wasted effort of blue agents searching the battlefield (shown in Eq. 8). Awareness and search efficiency values shown are taken from the mean values of the 25 repetitions run for each case. Analysis of the variability seen between repetitions indicated that 25 repetitions was sufficient for analysis of general trends between cases. Shorthand designations of cen/cen, cen/dec, dec/cen, and dec/dec are used to define C2 architectures, where the first descriptor defines the information sharing network and the second descriptor defines the decision authority network (e.g. cen/dec = centralized information sharing with decentralized decision authority).

$$A_{\text{blue}}(t) = \frac{1}{|B|} \sum_{i \in B} \sum_{\substack{j=1 \\ j \neq i}}^{N} \frac{1}{3} [A_{\text{team}\,ij}(t) + A_{\text{op}_{ij}}(t) + A_{\text{loc}\,ij}(t)] \tag{7}$$

where

$$B = \text{set of all blue agents}$$
$$N = \text{total number of agents}$$
$$A_{\text{team}ij}(t) = \text{awareness agent } i \text{ has for the team of agent } j \text{ at time } t$$
$$0 \leq A_{\text{blue}}(t) \leq 1$$

$$\eta(t) = 1 - \frac{\text{N}_{\text{duplicate}}}{|B| - 1} \tag{8}$$

where

$\text{N}_{\text{duplicate}}$ = number of blue agents searching a grid already being searched by another blue agent

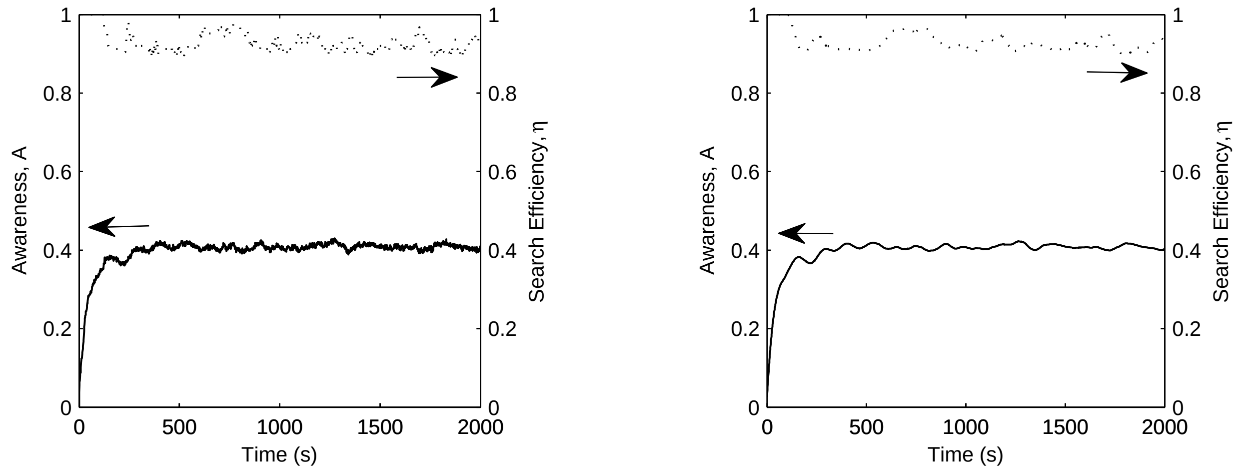
B = set of all blue agents

$0 \leq \eta(t) \leq 1$

Figure 9 shows mean blue team awareness and search efficiency time trajectories for the baseline case of a fully centralized blue (cen/cen) against a fully decentralized red (dec/dec) C2 architecture. Awareness and search efficiency time trajectories were smoothed (using a Savitzky-Golay smoothing filter from the MATLAB Signal Processing Toolbox) to reduce noise in the trajectories and aid in comparisons between cases. The awareness trajectory started at zero and increased as blue agents sensed and gained awareness of others until a steady-state awareness was reached. The search efficiency started at 1 since initial agent grid assignments were coordinated, then decreased as agents started to make search grid decisions based on their awareness of others. The steady-state search efficiency was 0.93. Steady-state values were the same for both raw and smoothed trajectories. The awareness and search efficiency trajectories for all cases displayed the same behavior of reaching a steady-state value, so the remaining results will focus on comparisons of steady-state values between cases.

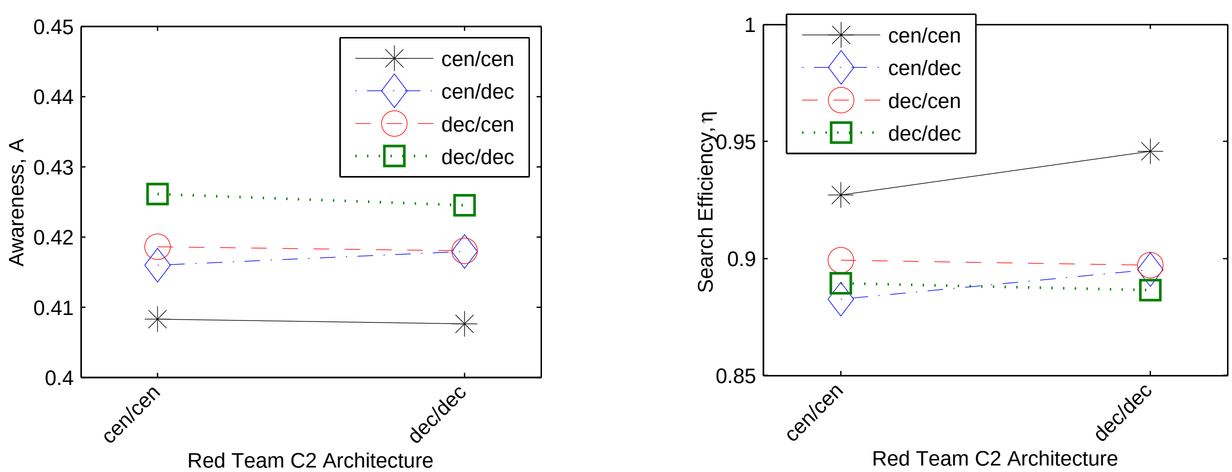
Figure 10 shows the performance of the blue team using the four C2 architectures considered in this study against two different red team C2 architectures (experiment one). Blue team steady-state awareness and search efficiency showed relative insensitivity to the red team C2 architecture used. While this result is surprising, it should be noted this comparison only considers the baseline inputs for the environment and agents. It is likely that the low velocity of the red agents relative to the blue agents resulted in this insensitivity. This difference in velocities outweighed the effects of changing the red team C2 architecture, since blue agents were able to move faster through the battlefield than other agents and maintain awareness of them. Comparing the performance of the blue team C2 architectures shows that decentralized information networks generally provided better mean team awareness than centralized information networks. The redundancy in fully connected information networks improved the probability that awareness messages were received by other agents, increasing the mean team awareness. Decentralized decision authority also showed improved mean team awareness. Faster decision making enabled by distributed decision authority allowed agents to choose a new search grid faster and continue searching for and sensing other agents. However, decentralizing decision authority showed reduced search efficiency, due to the lack of a single decision maker (commander agent) making coordinated decisions for other agents. These general trends regarding the effects of decentralizing C2 on awareness and search efficiency were consistent throughout most cases. These trends support the intuitive view that centralized decision making provides higher quality decisions while decentralized decision making enables faster reactions to events during a mission.

Figure 11 shows the results from experiment two, where the blue team sensor radius and blue team C2 architecture were varied. The red C2 architecture was fixed to be fully decentralized (dec/dec). Blue C2 architectures showed an improvement in awareness as sensor radius was increased due to an increase in the frequency with which other agents were sensed. However, increasing sensor radius showed a decrease in the search efficiency for all architectures. This trend is likely due to information overload, since increasing the frequency of sensing other agents increased the number of awareness messages sent through the information network. As the information network became overloaded with messages, bandwidth limitations prevented agents from receiving some messages. Information overload did not have a negative effect on awareness though. The differing effects information overload had on awareness and search efficiency can be explained by considering the ratio of awareness to search messages being sent over the network. While the number of awareness messages increased, the number of search related messages did not, since the rate at which agents complete searching grids is independent of sensor radius. This increase in the ratio of awareness to



(a) (b)

Figure 9: Baseline case (a) raw and (b) smoothed time trajectories of the mean blue team awareness and search efficiency. Trajectories were smoothed using a Savitzky-Golay smoothing filter with cubic moving average and frame size of 99.

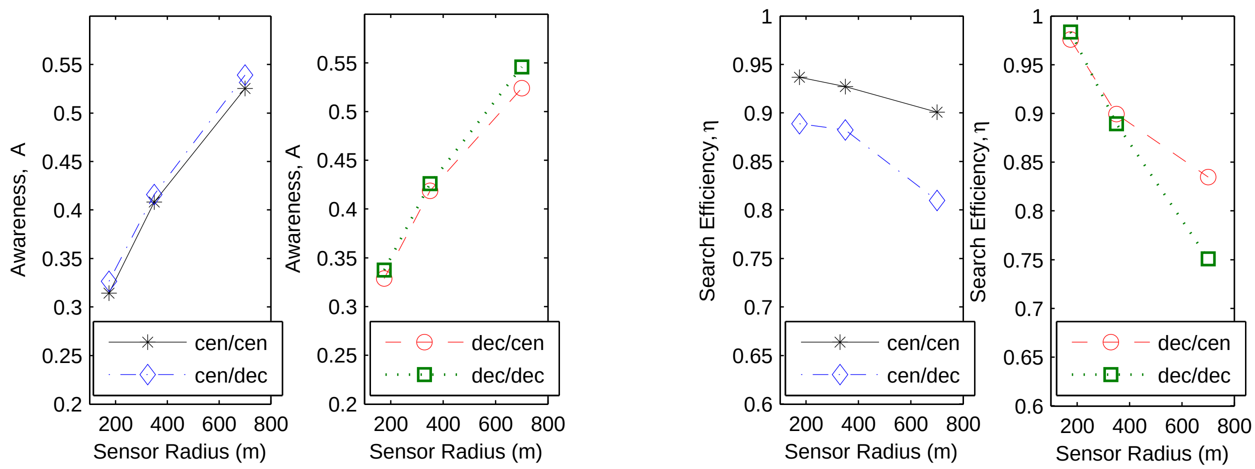


(a) (b)

Figure 10: Effect of red C2 architecture on (a) blue team steady-state awareness and (b) blue team steady-state search efficiency. Both metrics showed relative insensitivity to red C2 architecture.

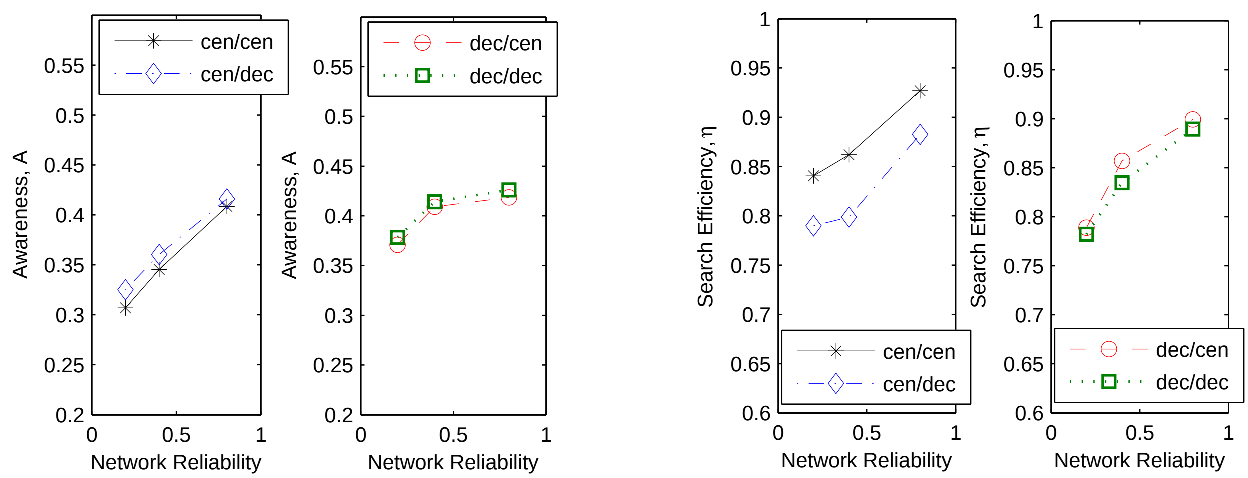
search messages resulted in the information network being flooded with awareness messages, which improved the team awareness but increased the likelihood of search messages being dropped. Since search messages were more likely to be dropped, search grid decisions were more likely to be made using incomplete or inaccurate information. The sensitivity of search efficiency to sensor radius was higher for architectures with decentralized compared to centralized information networks. This higher sensitivity is likely a result of the redundancy in decentralized information networks increasing the likelihood that messages were received and further amplifying the effects of information overload on search efficiency. These results also show that centralizing decision authority can reduce the effects of information overload on search efficiency, due to the inherent coordination of having a central decision maker (comparing cen/cen to cen/dec and dec/cen to dec/dec).

Figure 12 shows the results from experiment three, where the network reliability and blue team C2 architecture were varied. The red C2 architecture was fixed to be fully decentralized (dec/dec). Blue C2 architectures showed an improvement in awareness and search efficiency as network reliability was increased. These trends are due to the increased likelihood that awareness and search messages were received by team-



(a) (b)

Figure 11: Effect of blue team sensing radius on (a) blue team steady-state awareness and (b) blue team steady-state search efficiency. Increasing sensor radius resulted in information overload which negatively affected search efficiency.



(a) (b)

Figure 12: Effect of network reliability on (a) blue team steady-state awareness and (b) blue team steady-state search efficiency. Increasing network reliability generally improved awareness and search efficiency due to a higher likelihood of receiving messages. However, architectures with decentralized information sharing showed a threshold to awareness gains from improved network reliability.

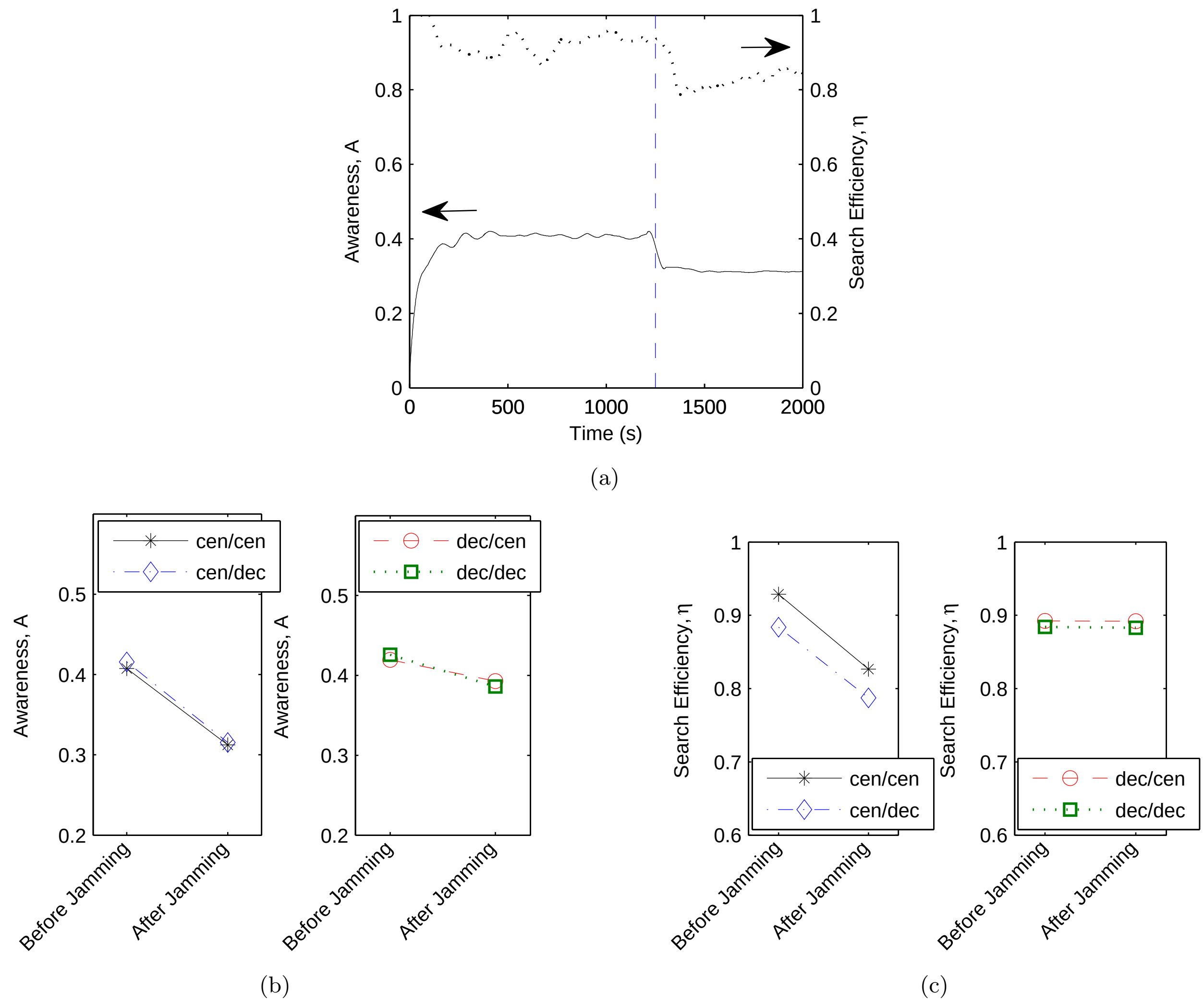


Figure 13: Effect of jamming on (a) smoothed time trajectories for the mean blue team awareness and search efficiency for the baseline case (vertical line represents the jamming event at 1250 seconds). Effect of jamming on (b) blue team steady-state awareness and (c) blue team steady-state search efficiency. C2 architectures with decentralized information sharing showed more robustness to jamming than architectures with centralized information sharing.

mates. However, this experiment appears to show a point of diminishing returns to increases in network reliability for architectures with decentralized information sharing. This threshold indicates that efforts to increase network reliability beyond a certain level will yield limited gains for architectures with decentralized information sharing. This is due to the redundancy in decentralized networks providing similar benefits to those gained by increasing network reliability, since both serve to improve the likelihood that messages are received. Therefore, once a certain level of message reliability is reached, whether it is through improving the network reliability or adding network redundancy, any further gains from increasing reliability are minimal. At that point, the likelihood of messages being received is no longer a significant limitation on awareness. Focusing on the cases with low network reliability, architectures with decentralized information sharing show improved awareness compared to those with centralized information sharing. This result indicates that decentralized information sharing is desired for high awareness in such environments. However, maintaining high search efficiency in low network reliability cases seems to require centralized information networks. Therefore if search efficiency is a primary goal, then it may be beneficial to operate with centralized information networks for missions where network reliability is expected to be low.

Figure 13 shows the smoothed awareness and search efficiency trajectories for the baseline case with a jamming event at 1250 seconds (experiment four). Since the baseline case has centralized information and decision authority networks, the central processing and commander agents were jammed during the event. Jamming continued for the remainder of the simulation for all cases. Both trajectories reached an initial steady-state value, dropped after the jamming event, then stabilized to a new steady-state value. The existence of before and after jamming steady-state values was seen for all other cases, so the remaining discussion of this experiment will focus on steady-state values to compare different blue team C2 architectures.

Figure 13 also shows the remaining results from experiment four, focusing on the effects of jamming on blue team steady-state awareness and search efficiency. The red C2 architecture was fixed to be fully decentralized (dec/dec). The blue architectures with decentralized information sharing showed less awareness and search efficiency sensitivity to the jamming event than those with centralized information sharing. This robustness to jamming is due to the lack of a central agent required to connect other agents. Since agents have multiple paths to share information with each other, the loss of a single agent in the network does not significantly affect the ability to share information.

VII. Conclusions

This paper described a method for evaluating trade-offs between C2 architectures, with consideration of force capabilities (sensor radius), the battlefield environment (network reliability, jamming), and enemy C2 architectures. A C2 architecture was represented as the combination of two networks: one defining the information sharing links between entities and one defining the decision authority relationships between entities. A subset of the C2 architecture design space was investigated to compare the performance of centralized and decentralized C2 architectures in varied operational conditions. Information entropy-based battlespace awareness was used to evaluate C2 effectiveness. This metric provided a way to evaluate C2 architectures based on the accomplishment of C2 functions, rather than simply considering the success or failure of a mission. Battlespace awareness specifically focused on the ability of a C2 architecture to develop awareness of the team, operational level, and location of other agents in the battlefield.

Results showed that blue team mean awareness and search efficiency quickly reached steady-state values during a simulation, enabling comparison of architecture performance using steady-state values, rather than time based trajectories. Blue team C2 architecture performance was shown to be insensitive to the architecture used by the red team, for the baseline case tested. Comparing the performance of blue team architectures with varied sensing capabilities showed that increasing sensor radius improved the awareness developed of another agents in the battlefield but with the potential for information overload to flood communications networks and decrease search efficiency. Improving network reliability showed benefits to awareness and search efficiency due to the increased likelihood of agents successfully sharing information with each other. However, architectures with decentralized information sharing showed a limit to the benefits possible with improved network reliability, as a region of diminishing returns was reached above a reliability threshold. Introducing a jamming event into the simulation enabled a study of the robustness of C2 architectures to targeted agent removal. Architectures with decentralized information sharing showed more robustness to jamming events due to the existence of multiple paths for information sharing.

This study has shown the ability to evaluate C2 architectures using information entropy-based battlespace awareness, comparing the effects of force capabilities and mission parameters on architecture performance. The consideration of battlespace awareness as a measure of C2 effectiveness provided additional insights into the behaviors of various C2 architectures that may not have been gained if the analysis only focused on traditional mission measures of performance. The results discussed suggest that future C2 studies should consider battlespace awareness when performing trade-offs between potential C2 architectures.

VIII. Future Work

While this study provided new insights and methods for evaluating trade-offs between C2 architectures, there are limitations to its applicability. The most notable limitation is a lack of model validation. Without proper data to compare simulation results to, insights gained from this study are restricted to analysis of trends and general behavior rather than point estimates of C2 performance. The simulation environment also used relatively simple models of agent actions. While ABMs are designed to reduce the complexity of agent behaviors to simplistic actions, there is still room to incorporate more descriptive agent models. The ABM developed would especially benefit from improvements to the information processing and decision making models, due to the importance of these processes in C2.

The authors also recognize that there are many other ways to represent decentralization of C2. This study focused on fully connected networks, but future work will aim to consider the full design space of networks that can be applied to potential C2 architectures. Another limitation is the lack of network reconfiguration, which would have enabled consideration of adaptive C2 architectures. Though network nodes (agents) were effectively removed from a network when when jamming events occurred, agents were unable to rewire their links to respond to jamming. This limitation is the focus of ongoing work seeking to extend this study by taking a complex networks approach to study resilient, adaptive complex systems.

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Appendix

Table 5: Experimental Design

Input Type	Parameter	Baseline	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Environment	$Area_{BF}$ (m^2)	31500	31500	31500	31500	31500
	$Area_{GD}$ (m^2)	3500	3500	3500	3500	3500
Blue Agents	$sens_{rad}$ (m)	350	350	**175, 350, 700**	350	350
	$sens_{res}$ (m^2)	35	35	35	35	35
	lat (s)	2	2	2	2	2
	$band_{battlefield}$ (items)	50	50	50	50	50
	$band_{non-battlefield}$ (items)	100	100	100	100	100
	rel	0.8	0.8	0.8	**0.2, 0.4, 0.8**	0.8
	proc (s)	2	2	2	2	2
	dec (s)	6	6	6	6	6
	vel (m/s)	35	35	35	35	35
Red Agents	$sens_{rad}$ (m)	350	350	350	350	350
	$sens_{res}$ (m^2)	35	35	35	35	35
	lat (s)	2	2	2	2	2
	$band_{battlefield}$ (items)	50	50	50	50	50
	$band_{non-battlefield}$ (items)	100	100	100	100	100
	rel	0.8	0.8	0.8	**0.2, 0.4, 0.8**	0.8
	proc (s)	2	2	2	2	2
	dec (s)	6	6	6	6	6
	vel (m/s)	35	35	35	35	35
Blue C2 Arch.	Info. Sharing	centralized	**centralized, decentralized**	**centralized, decentralized**	**centralized, decentralized**	**centralized, decentralized**
	Dec. Authority	centralized	**centralized, decentralized**	**centralized, decentralized**	**centralized, decentralized**	**centralized, decentralized**
Red C2 Arch.	Info. Sharing	decentralized	**centralized, decentralized**	decentralized	decentralized	decentralized
	Dec. Authority	decentralized	**centralized, decentralized**	decentralized	decentralized	decentralized
Team Size	blue (battlefield agents)	4	4	4	4	4
	red (battlefield agents)	4	4	4	4	4
	white (battlefield agents)	4	4	4	4	4