A Methodology for Analyzing Complex Military Command & Control (C2) Networks

For 10th ICCRTS, Track 4 (Assessment, Tools, and Metrics)
Tysons Corner, Virginia
June 14th, 2005

By: David A. Jarvis

Originally prepared under contract for Navy Warfare Development Command (NWDC)

©2005 Alidade Incorporated. All Rights Reserved
Purpose of Presentation

• Discuss the application of complex network theory principles to military C2 networks
• Present results of CJTFEX 04-2 analysis
• Summarize validity and potential applications of C2 Network Analysis (C2NA) method
Introduction

- Problem / Issue: Warfighter is faced with increasingly complex C2 networks
  - Increasing number of IP networks, communication networks, and applications all creating a complex information environment
  - Warfighter’s capability and effectiveness of new applications and networks are difficult to analyze
  - Traditional C2 analyses limited to IT performance and human interface

- Possible Solution
  - New analysis techniques can now be applied to define the structure, dynamics and evolution of collaboration in command and control networks
    - A “network” is any collection of interacting elements arranged for purpose, not necessarily an IT network
  - Techniques enable the analysis of how warfighters actually use networks, as opposed to how engineers tell us how to build them
  - Metrics can be used in defining and measuring new information architectures
Trial of Network Analysis Method

- Introduction of analysis method within CJTFEX 04-2 (12-day joint US/UK exercise)
  - Existing Cross Domain Solution (CDS) Limited Objective Experiment data collection used to validate method
  - Performed in addition to traditional NWDC Analysis effort

- Analysis Focus - Email
  - The analysis is applicable to a wide range of networks, email used as a stepping stone
  - Email is the primary method of asynchronous electronic communication in the Information Age
  - Indicates structures of collaboration and command and control
Analysis Assumptions & Scope

• Analysis Assumptions
  – A node is an email address
  – A link exists if at least one email has been exchanged between two nodes, TO: and CC: are treated identically
  – Structural analysis only, the content or intent of messages not considered
  – Artifacts exist in the raw data (e.g. record message traffic), corrected where possible

• Analytical Scope
  – Overview Analysis of six hour timeframes (based on battle rhythm), analyzing each independently
  – Detailed Analysis on two selected timeframes, demonstrating structure and dynamics of C2 network
Questions for Analysis

1. Does the email cross domain solution change previously established operating procedures?

2. Who are the key nodes for email traffic flow?

3. How robust is the email network in light of the removal of nodes and/or links?

4. How does the structure of the email network evolve over the course of the experiment?

5. What are the internal dynamics of select sub-networks and how do the sub-networks interact with each other?

These are the questions... what metrics provide the answers?
Network Metrics (Example)

Link/node ratio = 1.33 (8 links, 6 nodes)

Degree distribution (histogram)

Characteristic path length (CPL)

CPL = 1.5 (median of the averages)
Network Metrics (Example)

Clustering coefficient

\[ C = \frac{3 \times \# \text{ of triangles}}{\text{Number of connected triples of nodes}} \]

\[ C = \frac{3 \times 3}{34} = \sim 0.26 \]

Betweenness - A measure of network resilience and flow

\[ C_B(n_i) = \sum_{j,k} \frac{g_{jk}(n_i)}{g_{jk}} \]

- \( C_B(n_i) \) = Betweenness centrality for node \( i \)
- \( g_{jk} \) = \# of shortest paths (geodesics) linking the two actors \( j \) and \( k \)
- \( g_{jk}(n_i) \) = \# of shortest paths (geodesics) linking actors \( j \) and \( k \) that contain \( i \)
# Network Metric Thumb Rules

## Experimentation and Analysis

<table>
<thead>
<tr>
<th>Metric</th>
<th>Range</th>
<th>Operational Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes, $n$</td>
<td>$n &gt; \sim 100$</td>
<td>Network effects unlikely to occur with $n &lt; 50$</td>
</tr>
<tr>
<td>Number of links, $l$</td>
<td>$l &lt; \sim 2n$</td>
<td>$l &lt;&lt; 2n$, too brittle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$l &gt;&gt; 2n$, too much overhead</td>
</tr>
<tr>
<td>Degree distribution</td>
<td>Skewed</td>
<td>Adaptivity, modularity</td>
</tr>
<tr>
<td>Largest hub</td>
<td>$&lt; 100$ links</td>
<td>Hub appears, recedes by reconnection 5% of links</td>
</tr>
<tr>
<td>Average path length</td>
<td>$\log(n)$</td>
<td>Short distances even for large networks (e.g., $10^4$ nodes $\Rightarrow$ Average path length $= \sim 4$)</td>
</tr>
<tr>
<td>Clustering</td>
<td>Skewed</td>
<td>Hierarchy, organization</td>
</tr>
<tr>
<td>Betweenness</td>
<td>Skewed</td>
<td>Cascade control</td>
</tr>
<tr>
<td>Path horizon</td>
<td>$\log(n)$</td>
<td>Self-synchronization</td>
</tr>
<tr>
<td>Susceptibility/Robustness</td>
<td>Low (random removal)</td>
<td>Hubs should be kept obscure until needed, damage abatement/repair schemes</td>
</tr>
<tr>
<td></td>
<td>High (focused removal)</td>
<td></td>
</tr>
<tr>
<td>Neutrality</td>
<td>$(0, 2)$</td>
<td>Increased network effects, decreased susceptibility, tipping points, max $= n/2$</td>
</tr>
</tbody>
</table>

Metrics measure how people interact in a military context

©2005 Alidade Incorporated. All Rights Reserved
A Methodology for Analyzing Complex Military Command & Control (C2) Networks

10th ICCRTS
June 14th, 2005

Question #1

Does the email cross domain solution (CDS) change previously established operating procedures?

• We found:
  – CDS increased integration between US and UK networks
  – Additional baseline information required to fully define cross domain email need and use

• Method supports:
  – Defining role for individual liaison officers
A Methodology for Analyzing Complex Military Command & Control (C2) Networks

CDS Interactions
Aggregate Network of UK Interactions

Multiple conduits between domains

Question #1

$\Delta = \text{UK}$

$\bullet = \text{US}$
A Methodology for Analyzing Complex Military Command & Control (C2) Networks

10th ICCRTS
June 14th, 2005

Question #2
Who are the key nodes for email traffic flow?

• Based on multiple metrics, we found:
  – J2 ACOS
  – Information Operations
  – Asst. JOC Watch

• Method supports:
  – Developing network defense for most important nodes
  – Providing input to plans for graceful degradation of capability
  – Examining use of method to exploit adversary networks and C2 structure
Question #2

Collaboration Measures

<table>
<thead>
<tr>
<th>Timeframe</th>
<th>Receive Only</th>
<th>Xmit Only</th>
<th>Xmit &amp; Receive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 6 1200-1800</td>
<td>684 (56%)</td>
<td>91 (7%)</td>
<td>441 (36%)</td>
</tr>
<tr>
<td>Day 8 1200-1800</td>
<td>894 (58%)</td>
<td>146 (10%)</td>
<td>504 (33%)</td>
</tr>
</tbody>
</table>
Question #3

How robust is the email network in light of the removal of nodes and/or links?

• We found:
  – Resilient to random node removal
  – Vulnerable to targeted node removal
  – Network structure makes rapid recovery possible

• Method supports:
  – Critical node placement in distribution of staff
  – Development of alternate C2 paths
  – Improving node counter-targeting
Robustness Measurement
Detailed Timeframe – Day 8 1200-1800

In targeted case ~2% of nodes removed, ~25% of network lost
Skewed distribution is evidence of a scale-free network.
• We found:
  – Network structure follows staff daily battle rhythm, significant events did not alter the network structure
  – Distance to get information from one person to another remained roughly constant

• Method supports:
  – Re-engineering networks based on user behaviors to assist in meeting warfighter requirements
Question #4

- Network size cycles with daily battle rhythm
- Link activity cycles with daily battle rhythm
- Clustering coefficient has no obvious pattern
• Ratio approximates thumb rule
• Link activity grows linearly with addition of nodes
## Network Progression
### Day 5

<table>
<thead>
<tr>
<th>Time (EDT)</th>
<th>$n$</th>
<th>$k$</th>
<th>$k_d$</th>
<th>$k/n$</th>
<th>$k_d/n$</th>
<th>CPL</th>
<th>log($n$)</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000-0600</td>
<td>557</td>
<td>2636</td>
<td>984</td>
<td>4.73</td>
<td>1.77</td>
<td>5.02</td>
<td>2.99</td>
<td>0.08</td>
</tr>
<tr>
<td>0600-1200</td>
<td>2069</td>
<td>16,700</td>
<td>5558</td>
<td>8.07</td>
<td>2.69</td>
<td>4.78</td>
<td>3.74</td>
<td>0.05</td>
</tr>
<tr>
<td>1200-1800</td>
<td>1449</td>
<td>13,209</td>
<td>4329</td>
<td>9.12</td>
<td>2.99</td>
<td>4.52</td>
<td>3.64</td>
<td>0.12</td>
</tr>
<tr>
<td>1800-2400</td>
<td>1183</td>
<td>8867</td>
<td>2928</td>
<td>7.50</td>
<td>2.48</td>
<td>4.83</td>
<td>3.47</td>
<td>0.20</td>
</tr>
</tbody>
</table>
What are the internal dynamics of select sub-networks and how to the sub-networks interact with each other?

- **We found:**
  - Structures of the sub-networks were very different from entire CJTFEX email network, the CJTFEX was scale-free, the staff sub-networks were not
  - Identifiable nucleus of communications in each staff
  - The two nuclei of Staff #1 and Staff #2 were well-connected
  - Using different link definitions (reciprocal, threshold) can provide additional information about the network

- **Method supports:**
  - Development of techniques to split staffs between assets
Network Diagram
Staff #2 Sub-Network Interactions – Entire Exp.
(Reciprocal Link Definition)

= nucleus node
Future Applications

• Information Operations / Information Assurance
  – Focus network defense on most important nodes
  – Improve node counter-targeting
  – Examine use of method to exploit adversary networks and C2 structure

• C2 Structure and Information Flow
  – Support decision of critical nodes placement in distribution of staff
  – Develop alternate C2 paths
  – Measure and understand key command and staff relationships to more effectively use Collaborative Information Environment

• Network and Information Management
  – Assist warfighter in defining requirements and providing feedback on engineering design parameters
  – Provides metrics for evaluation and design of information management practices
  – Provide input to plans for graceful degradation of capability
Next Steps

- Next experiment to use methodology CDS LOE II (JTFEX 05-2)
- Multi-level C2 analysis, combining multiple C2 systems
  - Email
  - Chat
  - Voice Over IP
- Content analysis
- Incorporation of lessons learned from CDS LOE I (JTFEX 04-2)
Questions?