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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)

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

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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 to the sub-networks interact with each other?

These are the questions…
what metrics provide the answers?

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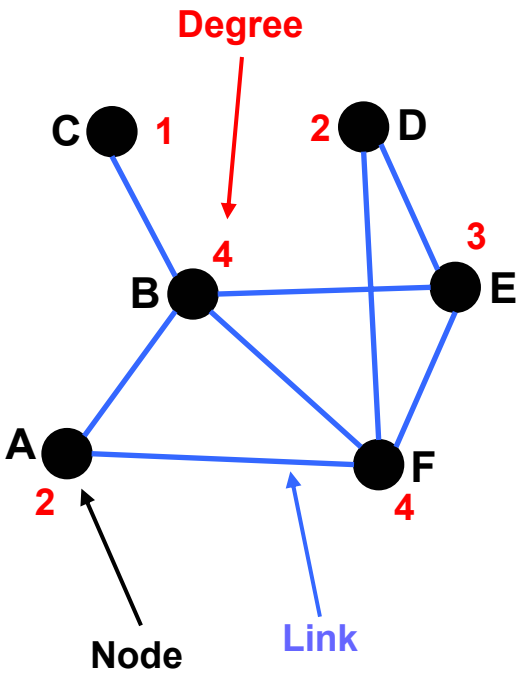
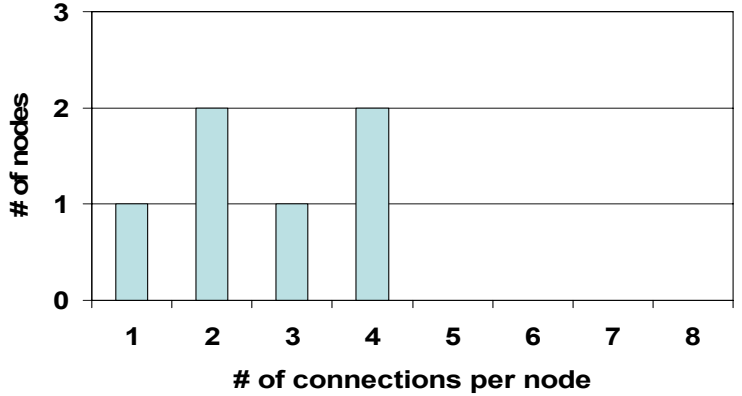
Network Metrics (Example)



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

Degree distribution (histogram)

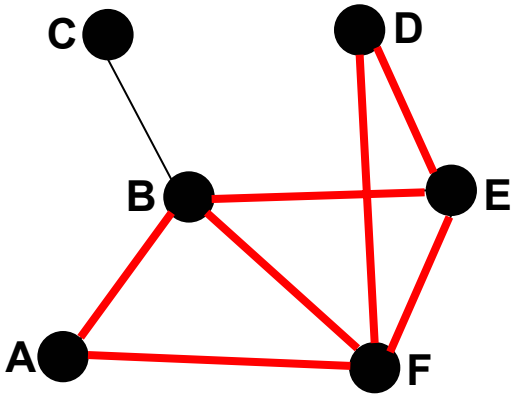


Characteristic path length (CPL)

	A	B	C	D	E	F	Avg
A	0	1	2	2	2	1	1.6
B	1	0	1	2	1	1	1.2
C	2	1	0	3	2	2	2.0
D	2	2	3	0	1	1	1.8
E	2	1	2	1	0	1	1.4
F	1	1	2	1	1	0	1.2

CPL = **1.5** (median of the averages)

Network Metrics (Example)



Clustering coefficient

$$C = \frac{3 \text{ x } \# \text{ of triangles}}{\text{Number of connected triples of nodes}}$$

$C = 3 \text{ x } 3 / 34 = \sim\mathbf{0.26}$

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

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Network Metric Thumb Rules

Experimentation and Analysis

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

Metrics measure how people interact in a military context

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

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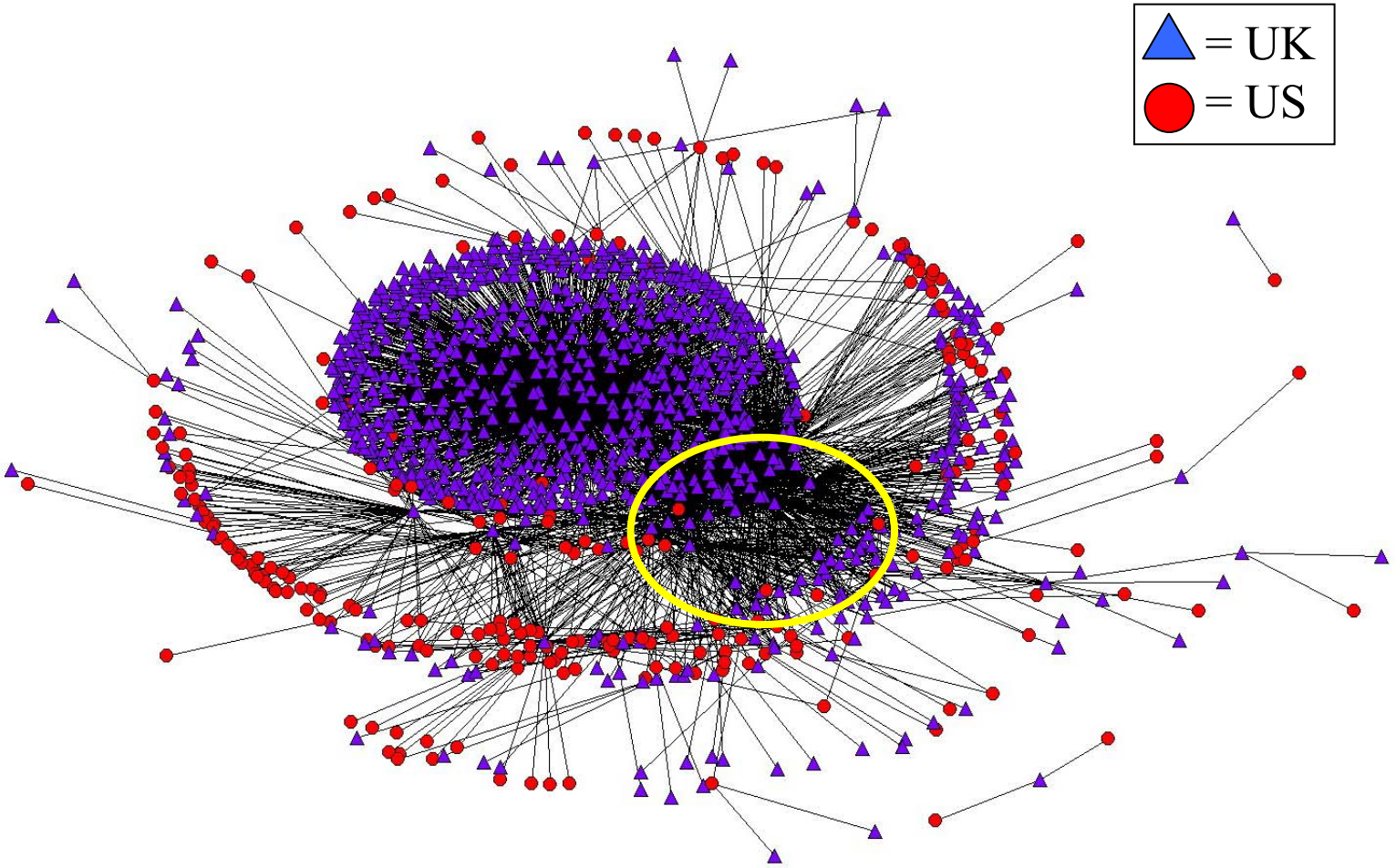
Question #1

CDS Interactions

Aggregate Network of UK Interactions



Multiple conduits between domains

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

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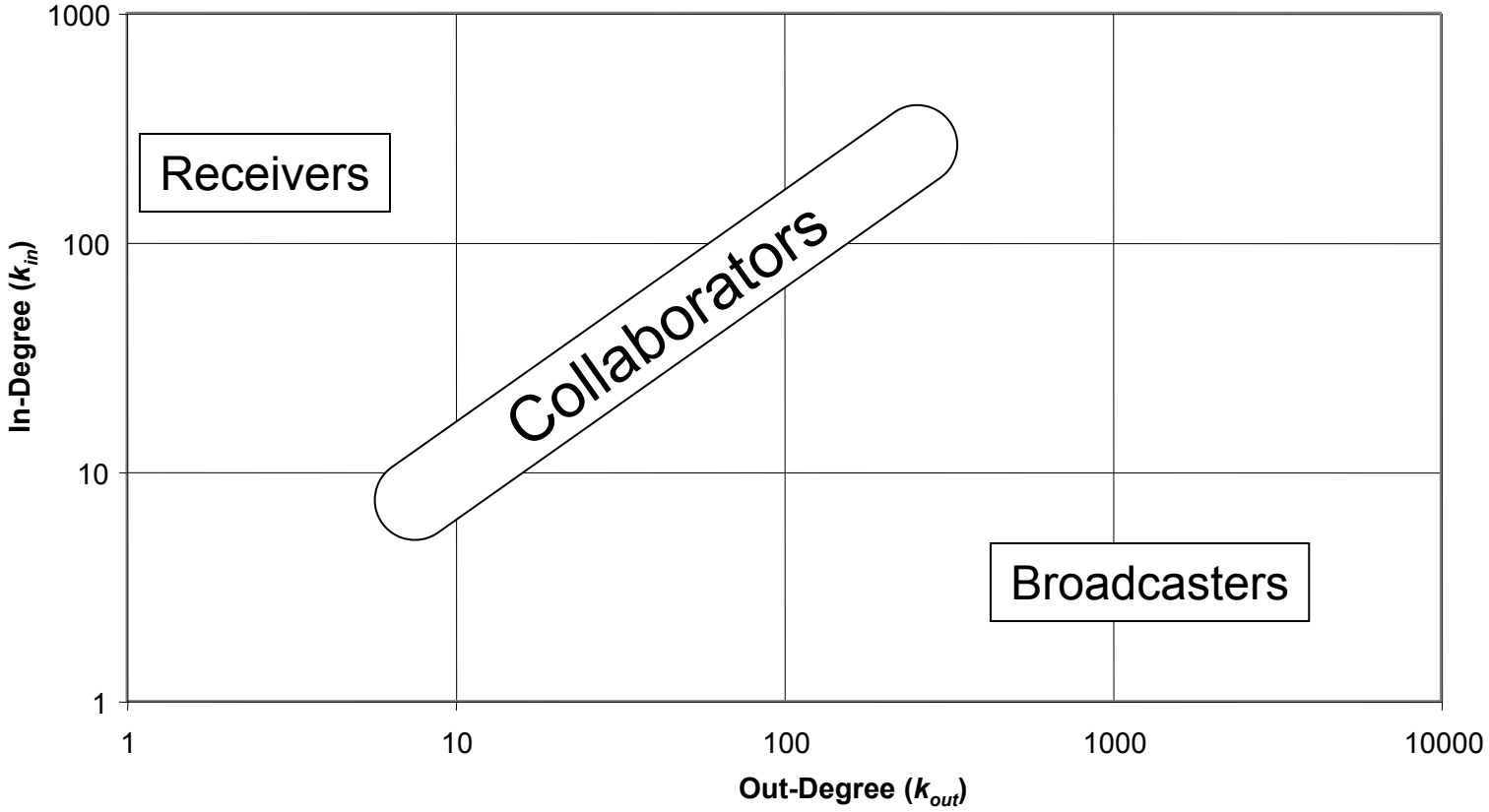
Question #2

Collaboration Measures



Timeframe	Receive Only	Xmit Only	Xmit & Receive
Day 6 1200-1800	684 (56%)	91 (7%)	441 (36%)
Day 8 1200-1800	894 (58%)	146 (10%)	504 (33%)

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

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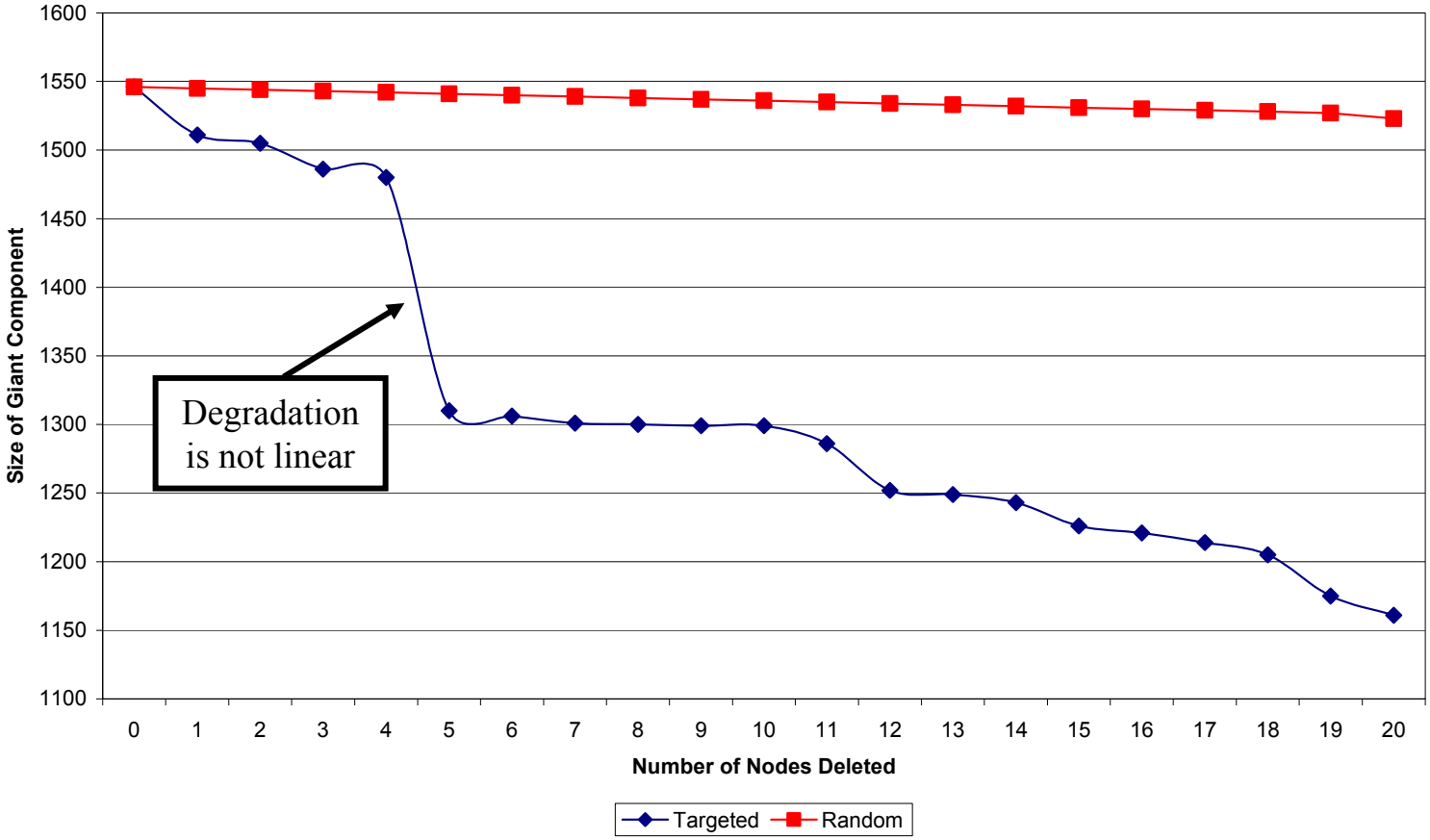
Question #3

Robustness Measurement

Detailed Timeframe – Day 8 1200-1800



In targeted case ~2% of nodes removed, ~25% of network lost

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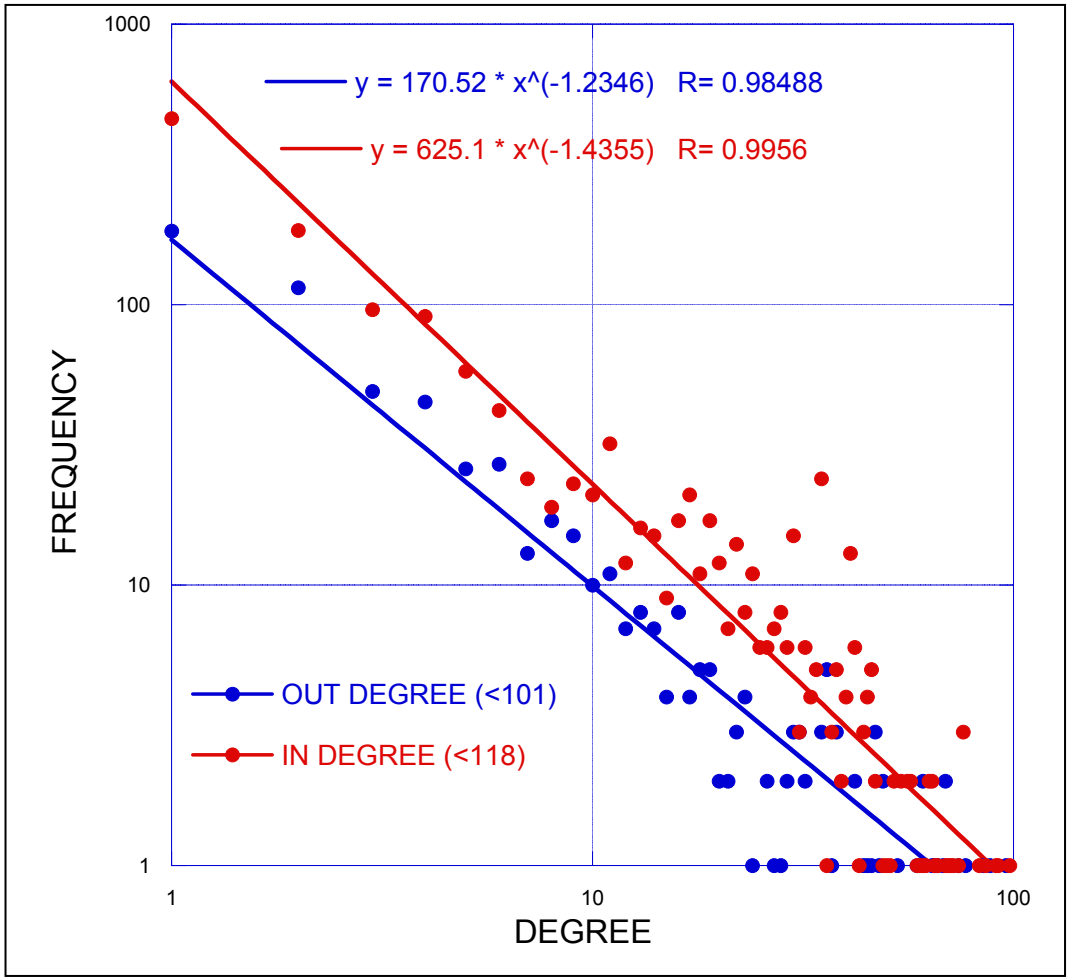
Question #3

Degree Distribution

Detailed Timeframe - Day 8 1200-1800



Skewed distribution is evidence of a scale-free network

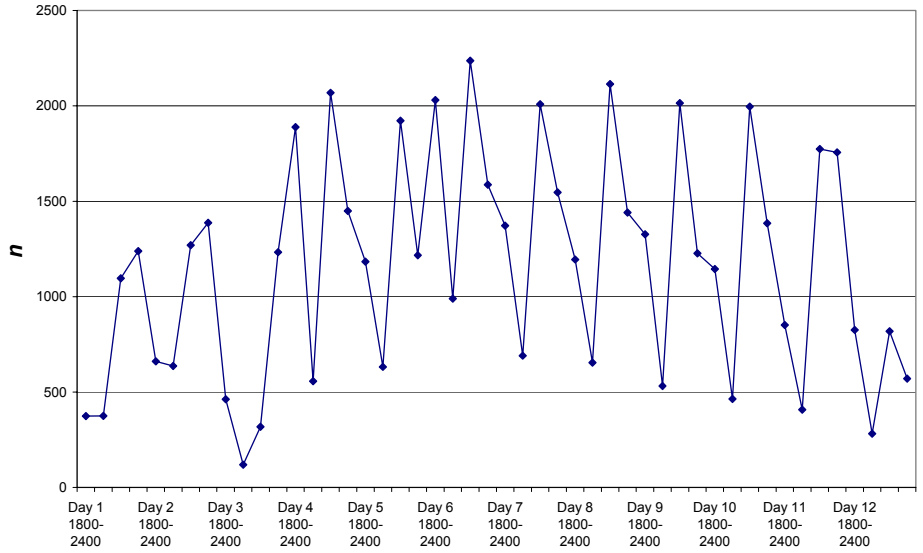
Question #4

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

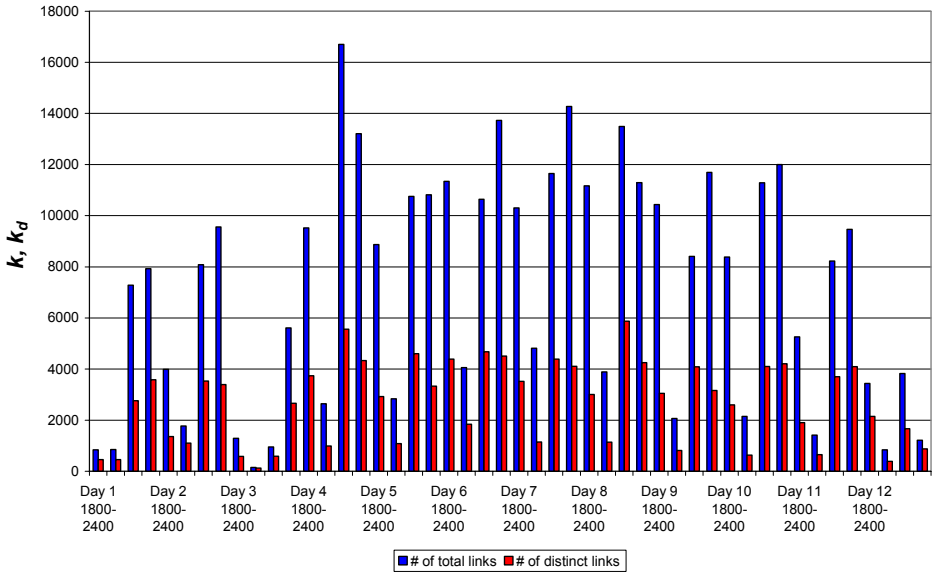
- We found:
  - Network structure follows staff daily battle rhythm, significant events did not alter the network structure
  - Distance to get information from one person to another remained roughly constant
- Method supports:
  - Re-engineering networks based on user behaviors to assist in meeting warfighter requirements

Question #4

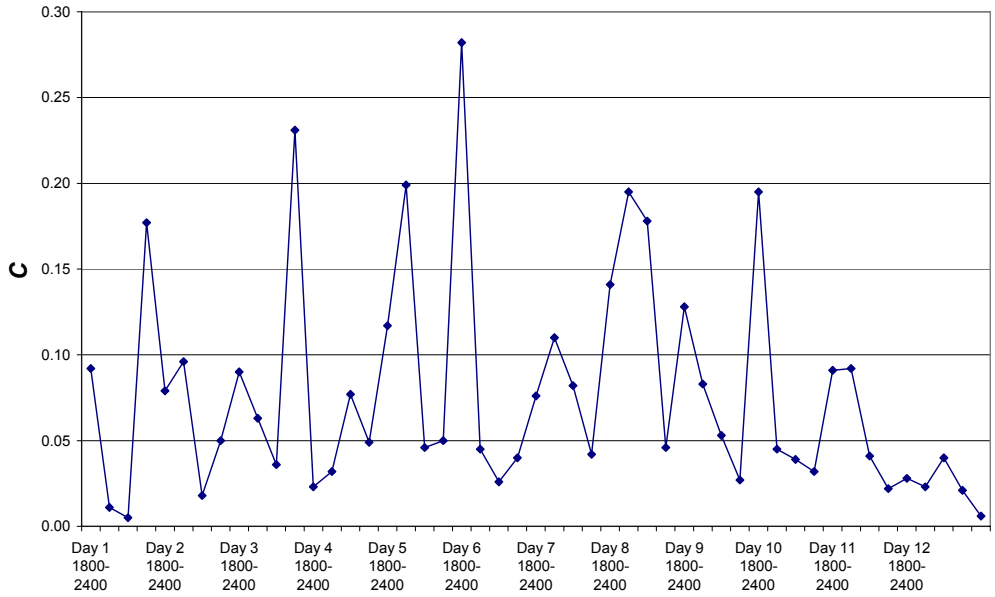
Number of Nodes



Number of Links



Clustering Coefficient



- Network size cycles with daily battle rhythm
- Link activity cycles with daily battle rhythm
- Clustering coefficient has no obvious pattern

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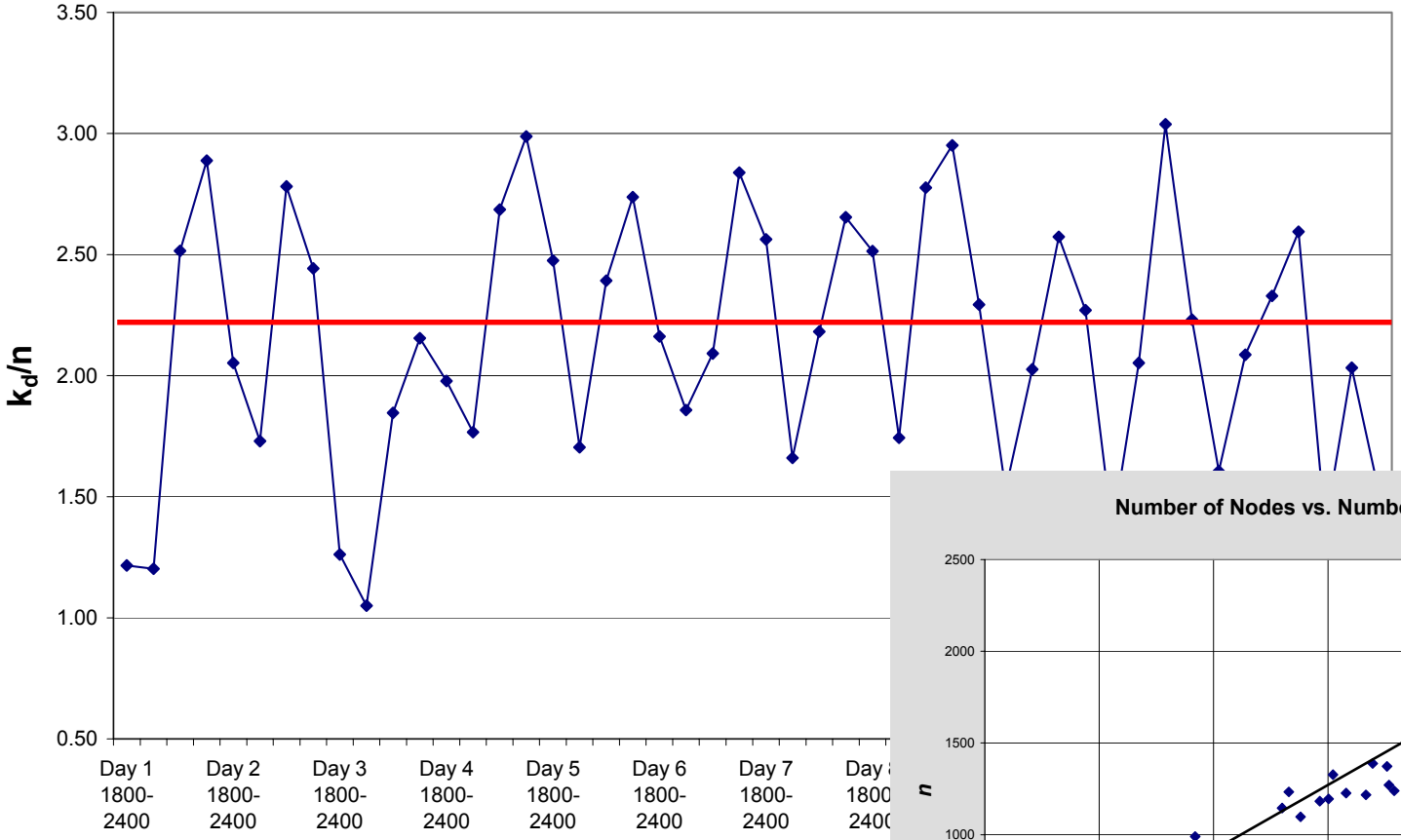
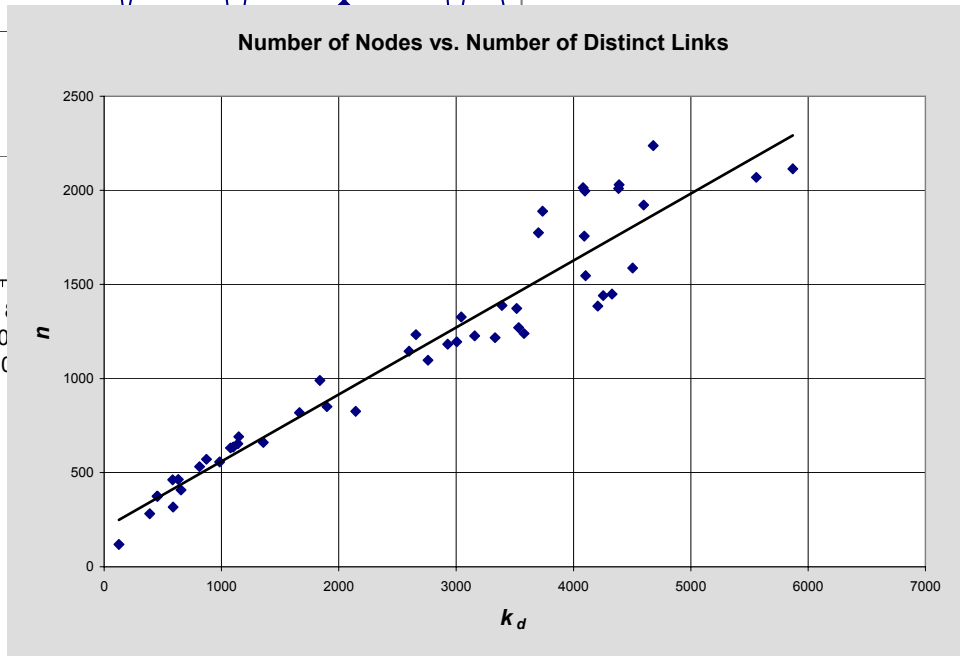
Question #4

Link to Node Ratio (Distinct)





- Ratio approximates thumb rule
- Link activity grows linearly with addition of nodes

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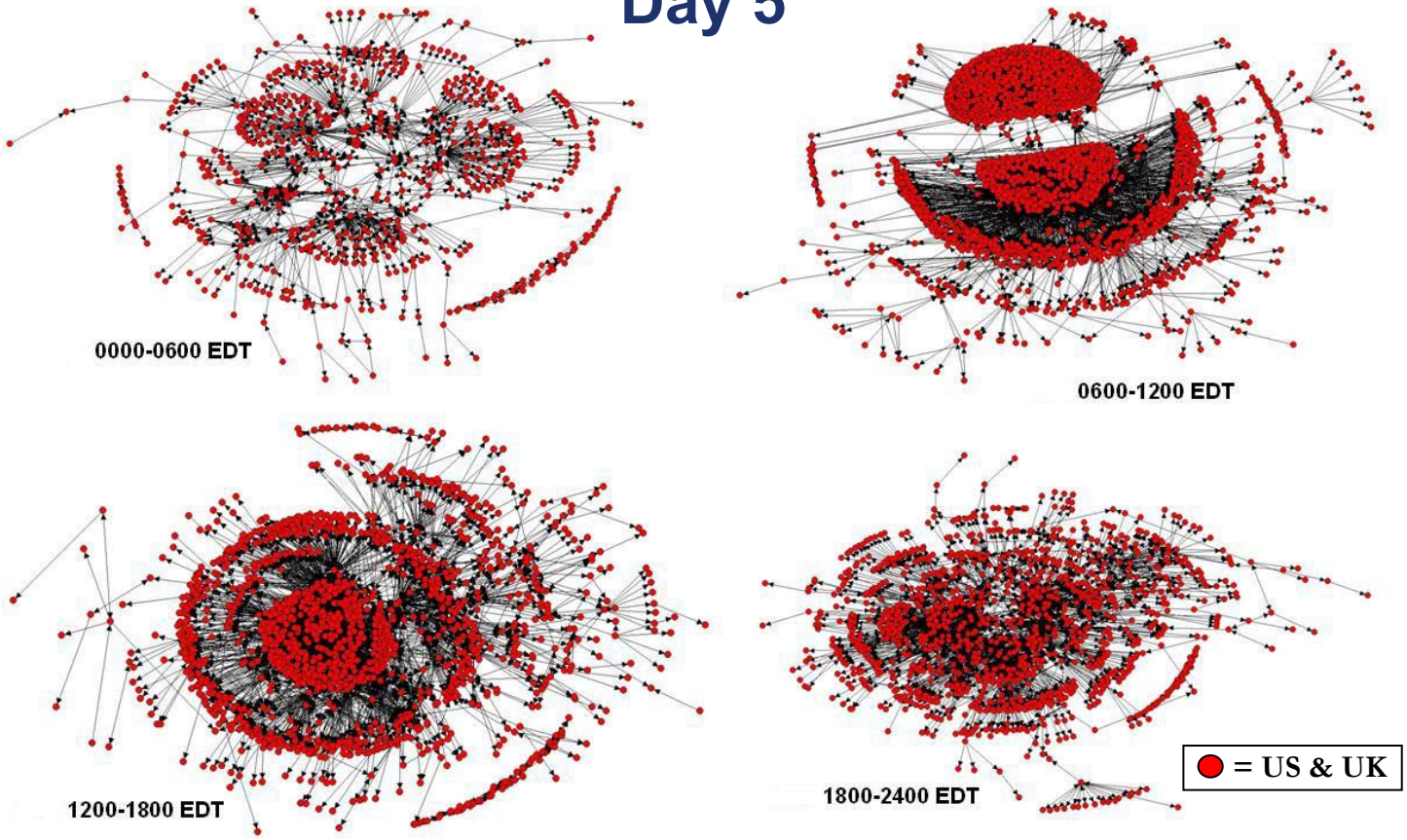
Question #4

Network Progression

Day 5



Time (EDT)	n	k	k_d	k/n	k_d/n	CPL	log(n)	C
0000-0600	557	2636	984	4.73	1.77	5.02	2.99	0.08
0600-1200	2069	16,700	5558	8.07	2.69	4.78	3.74	0.05
1200-1800	1449	13,209	4329	9.12	2.99	4.52	3.64	0.12
1800-2400	1183	8867	2928	7.50	2.48	4.83	3.47	0.20

Question #5

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

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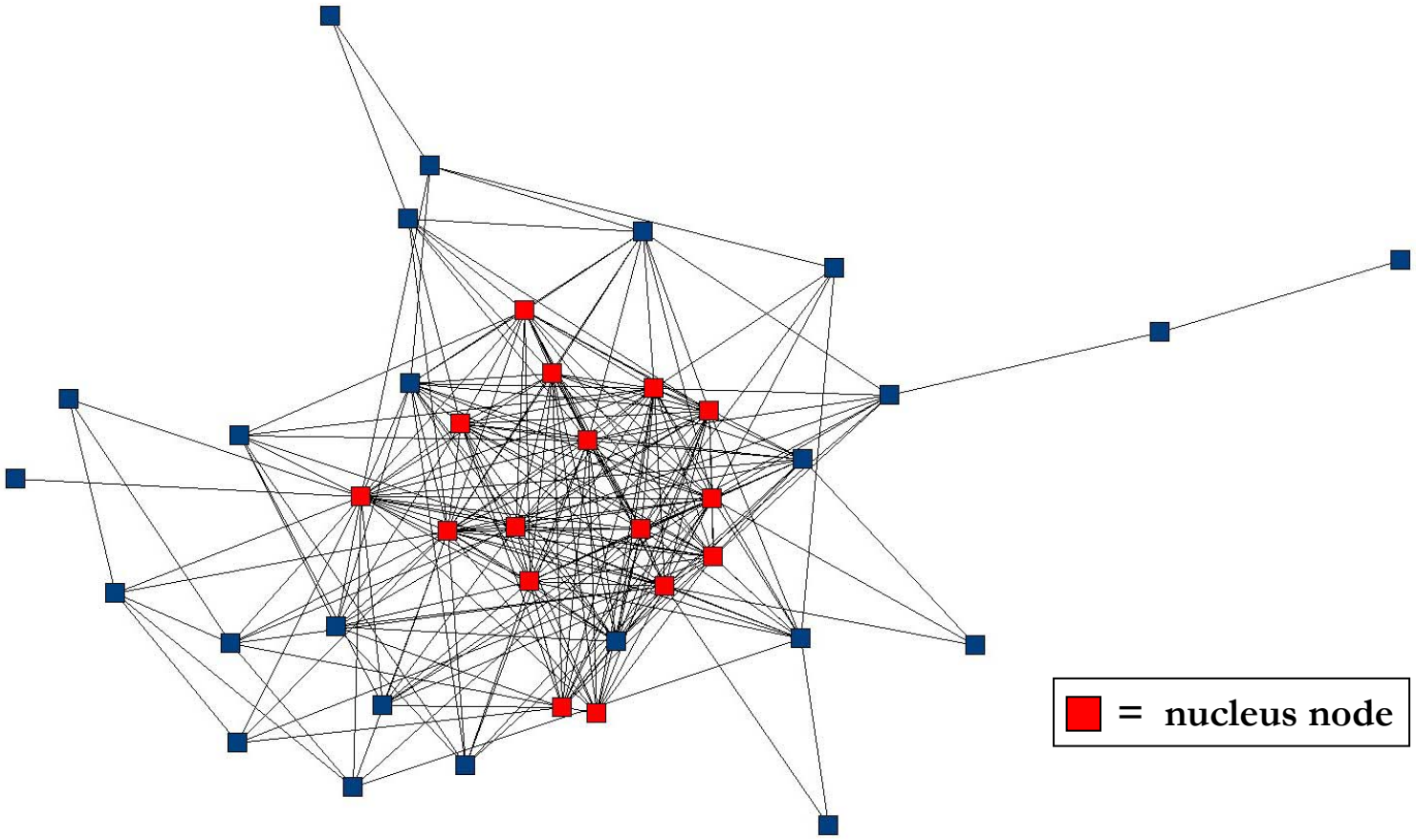
Question #5

Network Diagram

Staff #2 Sub-Network Interactions – Entire Exp.

(Reciprocal Link Definition)



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)

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Questions?