Preferential System Connectivity and its Impact on Performance

System of Systems Engineering Collaborators Information Exchange (SoSECIE)

13 October 2015

David A. Flanigan, Ph.D.

David.Flanigan@jhuapl.edu

Jeffery S. Dixon

Jeffery.Dixon@jhuapl.edu

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Motivation and Objective

- During the initial phase of system development, a series of artifacts describe and document the interfaces between systems, typically with an adjacency matrix
- The shortfall is that this adjacency matrix is designed for an established system organization (e.g. military command and control structure), leaving no analysis of alternate organization structures
- Therefore, we cannot assess if additional capability could be achieved by examining different system-to-system connections
- We are motivated to develop a methodology in which to document and compare the relative mission performance based on the connectivity choices

Literature Review

- Early stage systems engineering activities use models and simulations in order to explore the complex and emergent behaviors as systems interact with each other (US Air Force)
- The Department of Defense (DoD) has a separate Acquisition Modeling and Simulation Group that also identifies the use of models to define the systems scope and understand the system-to-system interactions during initial development.
- The National Air and Space Administration (NASA) also promotes the use of concept studies. NASA uses a directed graphic (digraph) matrix analysis technique that evaluates combinations of systems and subsystems within intentionally successful and unsuccessful scenarios, in order to identify which subsystems interact with other subsystems during the event tree trace of activities
- Buede identifies the use of N2 diagrams to show flow of information between items or nodes, stressing that the importance of these diagrams is to show where there is no interaction between nodes
- Browning uses a similar method called the Design Structure Matrix (DSM) that is similar to an N2 matrix to show relationships between units within an organization, although this effort strives for greater production efficiency, and uses it as a tool to explore changes to the organizational structure

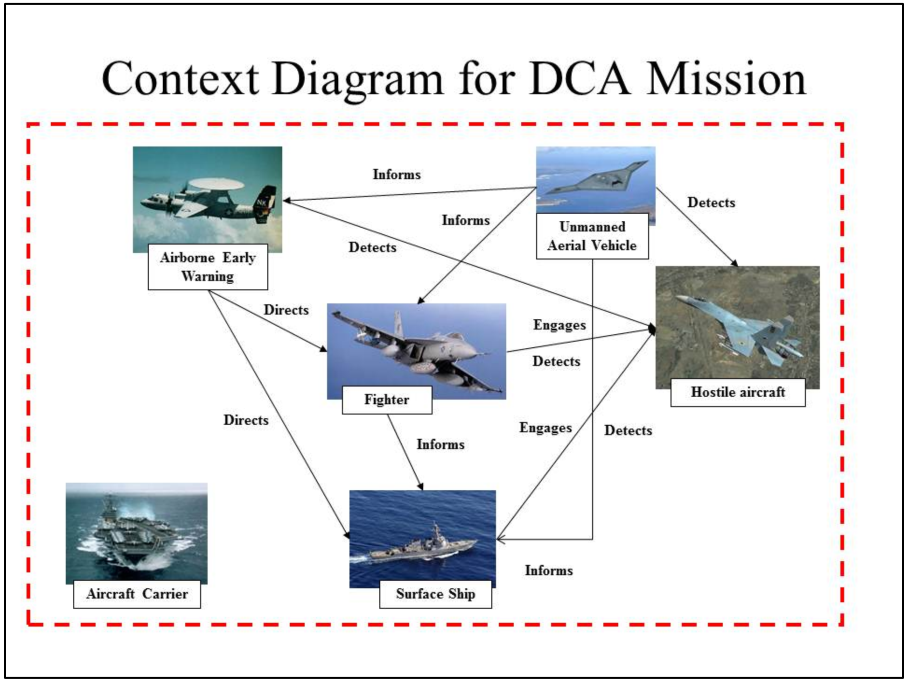
We can use these examples as motivation to pursue exploration of our preferential connectivity concept, as none of the literature reviewed addresses potential connections and their performance difference

Preferential Adjacency Matrix

- **As a result, we introduce a means to evaluate the dissimilar platform pairing and their effect on overall mission performance**
- **A 4 step method to analyze the Preferential Adjacency Matrix is developed:**
  - **Identify relevant systems**
  - **Develop adjacency matrix**
  - **Describe preferential connections between systems**
  - **Rebuild the adjacency matrix**

Identify Relevant Systems

- The first step is to identify the relevant systems that will interact with each other within our system concept
- Requires review of the mission objectives, the operating environment, and adversary forces
- Documented in a system context diagram



Develop Adjacency Matrix

- The second step is to take these relevant systems and place them in an adjacency matrix
- Document whether the node pairings are able to connect with each other, typically yes (one) or no (zero)
- This should align with the context diagram described in the previous phase and directionality
- Note that a self-connection (e.g. ship to ship) may indicate that two different ships may connect to each other

	AEW	Ship	Fighter	UAV
AEW	1	1	1	0
Ship	1	1	1	0
Fighter	1	1	1	0
UAV	1	1	1	1

Initial Adjacency Matrix

Preferential connections

- **The third step is to describe the preferential connections between a system-to-system pairing**
- **We will explore three types of impacts:**
  - **Platform difference**
  - **Operations familiarity**
  - **Potential to collaborate**

Node 1	Node 2	Platform similarity	Operational familiarity	Potential Collaborative Compatibility
AEW	AEW	Yes	Yes	Yes
AEW	Ship	No	Some	Yes
AEW	Fighter	No	More	Yes
AEW	UAV	No	None	Yes
Ship	Ship	Yes	Yes	Yes
Ship	Fighter	No	Some	Yes
Ship	UAV	No	None	Yes
Fighter	Fighter	Yes	Yes	Yes
Fighter	UAV	No	None	No
UAV	UAV	Yes	Yes	Yes

Factors to consider for the adjacency matrix

Rebuild the adjacency matrix

- **The fourth step is to then re-build the adjacency matrix with additional information**

	A1	A2	S1	S2	F1	F2	F3	F4	U1	U2	U3
A1	0 / 0	0 / 1	1 / 0	1 / 1	0 / 0	0 / 0	0 / 1	0 / 1	1 / 1	1 / 1	1 / 1
A2	0 / 1	0 / 0	1 / 1	1 / 0	0 / 1	0 / 1	0 / 0	0 / 0	1 / 1	1 / 1	1 / 1
S1	1 / 0	1 / 1	0 / 0	0 / 1	1 / 0	1 / 0	1 / 1	1 / 1	2 / 1	2 / 1	2 / 1
S2	1 / 1	1 / 0	0 / 1	0 / 0	1 / 1	1 / 1	1 / 0	1 / 0	2 / 1	2 / 1	2 / 1
F1	0 / 0	0 / 1	1 / 0	1 / 1	0 / 0	0 / 0	0 / 1	0 / 1	3 / 1	3 / 1	3 / 1
F2	0 / 0	0 / 1	1 / 0	1 / 1	0 / 0	0 / 0	0 / 1	0 / 1	3 / 1	3 / 1	3 / 1
F3	0 / 1	0 / 0	1 / 1	1 / 0	0 / 1	0 / 1	0 / 0	0 / 0	3 / 1	3 / 1	3 / 1
F4	0 / 1	0 / 0	1 / 1	1 / 0	0 / 1	0 / 1	0 / 0	0 / 0	3 / 1	3 / 1	3 / 1
U1	1 / 1	1 / 1	2 / 1	2 / 1	3 / 1	3 / 1	3 / 1	3 / 1	0 / 0	0 / 0	0 / 0
U2	1 / 1	1 / 1	2 / 1	2 / 1	3 / 1	3 / 1	3 / 1	3 / 1	0 / 0	0 / 0	0 / 0
U3	1 / 1	1 / 1	2 / 1	2 / 1	3 / 1	3 / 1	3 / 1	3 / 1	0 / 0	0 / 0	0 / 0

Complete Adjacency Matrix (platform / operations)

Platform familiarity (0: same platform, 1: low difference, 2: some difference, 3: large difference)
Operational familiarity (0: same organization, 1: different organization).

<table>
<tr><th></th><th>A1</th><th>A2</th><th>S1</th><th>S2</th><th>F1</th><th>F2</th><th>F3</th><th>F4</th><th>U1</th><th>U2</th><th>U3</th></tr>
<tr><td>A1</td><td colspan="2" rowspan="2">Same platform type</td><td colspan="2" rowspan="2">Some familiarity</td><td colspan="4" rowspan="2">More familiarity</td><td colspan="3" rowspan="2">No familiarity, accepting of change</td></tr>
<tr><td>A2</td></tr>
<tr><td>S1</td><td colspan="2" rowspan="2">Some familiarity</td><td colspan="2" rowspan="2">Same platform type</td><td colspan="4" rowspan="2">Some familiarity</td><td colspan="3" rowspan="2">No familiarity, accepting of</td></tr>
<tr><td>S2</td></tr>
<tr><td>F1</td><td colspan="2" rowspan="4">More familiarity</td><td colspan="2" rowspan="4">Some familiarity</td><td colspan="4" rowspan="4">Same platform type</td><td colspan="3" rowspan="4">No familiarity, hostile towards change</td></tr>
<tr><td>F2</td></tr>
<tr><td>F3</td></tr>
<tr><td>F4</td></tr>
<tr><td>U1</td><td colspan="2" rowspan="3">No familiarity, accepting of</td><td colspan="2" rowspan="3">No familiarity, accepting of</td><td colspan="4" rowspan="3">No familiarity, hostile towards change</td><td colspan="3" rowspan="3">Same platform type</td></tr>
<tr><td>U2</td></tr>
<tr><td>U3</td></tr>
</table>

Graphical Summary of Adjacency Matrix
A: Airborne Early Warning aircraft
S: Surface ships
F: Fighter aircraft
U: Unmanned Aerial Vehicles

Illustrative Example

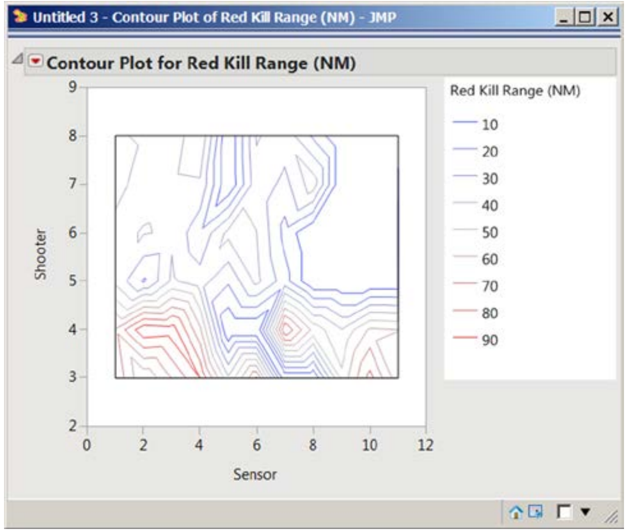
- Two Carrier Strike Groups (CSG) are present to defend their High Value Units (HVU) from airborne red forces, performing the Defensive Counter Air (DCA) mission, which is measured by the percentage of red threats that are successfully neutralized, and the average range from the HVU where red forces are neutralized
- The first MOE indicates a measure of engagement efficiency and capability against the red forces
- The second MOE indicates the available battlespace, or buffer that remains to require an additional layer of defensive capability, normally referred to as "defense in depth"
- Each CSG assigns their own aircraft and ships stations in which to detect, identify, and engage incoming airborne threats.
  - Airborne Early Warning (AEW) aircraft detect targets at long range
  - Surface ships can detect and engage targets at longer ranges
  - Fighters can engage targets at shorter ranges
  - Unmanned Aerial Vehicles (UAV) can detect targets at shorter ranges

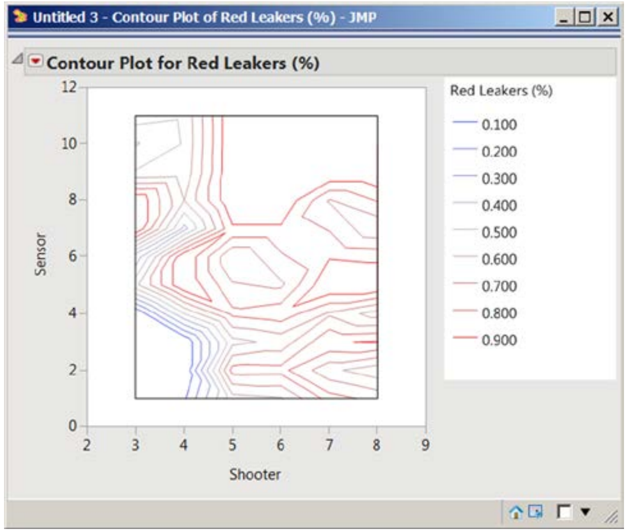
Illustrative Example

- We use a simulation to represent the simple motion and behavior of the red and blue forces to evaluate our preferential adjacency matrix concepts
- At each time increment, the range is checked between the red forces and blue force sensor ranges in order to evaluate if detection and identification of the threat is achieved, through a random draw
- If detection and identification are successful, blue forces may engage the threat based on the range of the blue weapons and the shooter-threat distance
- We modify the detection and engagement proficiency by reducing any platform and operational familiarity factors, as a result of the preferential connection description
- Each run in the simulation will last a total of 30 minutes, or until all red forces are neutralized, whichever occurs first
- Each run was executed for a total of 30 Monte Carlo replications

Summary Metrics

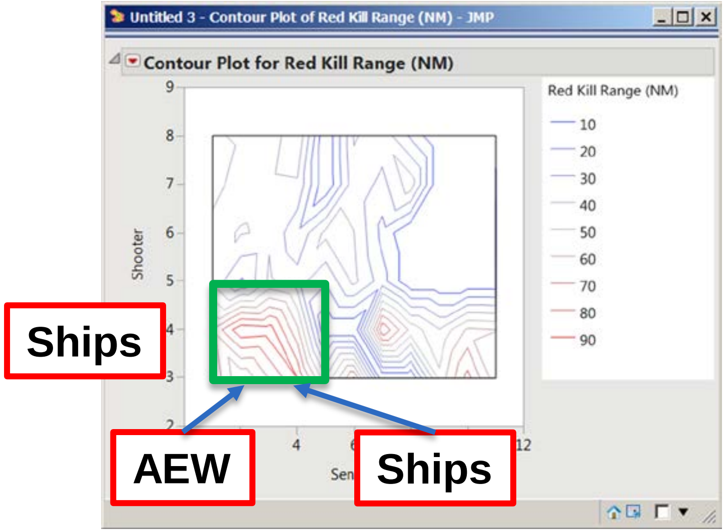
- Shooters 3 and 4 correspond to the surface ships, and shooters 5-8 correspond to fighters. Sensors 1 and 2 correspond to AEW, sensors 3 and 4 correspond to surface ships, sensors 5-8 correspond to fighters, and sensors 9-11 correspond to UAVs.
- Note that longer ranges where red fighters are neutralized are maximized with surface ships as shooters
- Lower leaker rates occur with ships as shooters, and higher leaker rates occur with the fighter and UAV pairings

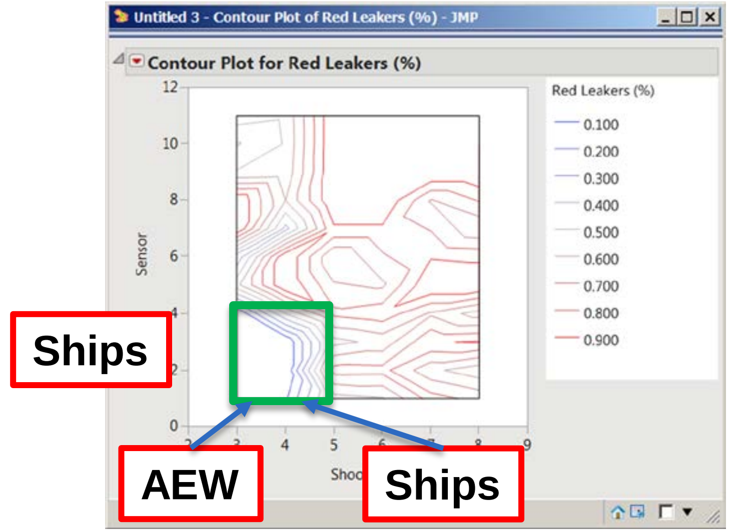




Summary Metrics

- Shooters 3 and 4 correspond to the surface ships, and shooters 5-8 correspond to fighters. Sensors 1 and 2 correspond to AEW, sensors 3 and 4 correspond to surface ships, sensors 5-8 correspond to fighters, and sensors 9-11 correspond to UAVs.
- Note that longer ranges where red fighters are neutralized are maximized with surface ships as shooters
- Lower leaker rates occur with ships as shooters, and higher leaker rates occur with the fighter and UAV pairings





Results

- We arrive at the following conclusions:
- In order to minimize the number of red leakers, and maximize the standoff distance of red kills, the ship performs the best when paired with other ships, AEW, and UAV as sensors that provide earlier detection and engagement opportunities
- The fighters suffer in performance from their relatively shorter-range weapons and lack of compatibility with other systems

<table>
<tr><th></th><th>A1</th><th>A2</th><th>S1</th><th>S2</th><th>F1</th><th>F2</th><th>F3</th><th>F4</th><th>U1</th><th>U2</th><th>U3</th></tr>
<tr><td>A1</td><td colspan="2" rowspan="2">Longer red kill range, lower leaker %</td><td colspan="2" rowspan="2">Longer red kill range, lower leaker %</td><td colspan="4" rowspan="2">Longer red kill range, medium leaker %</td><td colspan="3" rowspan="2">Longer red kill range, medium leaker %</td></tr>
<tr><td>A2</td></tr>
<tr><td>S1</td><td colspan="2" rowspan="2">Longer red kill range, lower leaker %</td><td colspan="2" rowspan="2">Longer red kill range, lower leaker %</td><td colspan="4" rowspan="2">Longer red kill range, medium leaker %</td><td colspan="3" rowspan="2">Longer red kill range, medium leaker %</td></tr>
<tr><td>S2</td></tr>
<tr><td>F1</td><td colspan="2" rowspan="4">Medium red kill range, higher leaker %</td><td colspan="2" rowspan="4">Medium red kill range, higher leaker %</td><td colspan="4" rowspan="4">Shorter red kill range, higher leaker %</td><td colspan="3" rowspan="4">No performance</td></tr>
<tr><td>F2</td></tr>
<tr><td>F3</td></tr>
<tr><td>F4</td></tr>
<tr><td>U1</td><td colspan="2" rowspan="3">Medium red kill range, higher leaker %</td><td colspan="2" rowspan="3">Medium red kill range, higher leaker %</td><td colspan="4" rowspan="3">Shorter red kill range, higher leaker %</td><td colspan="3" rowspan="3">No performance</td></tr>
<tr><td>U2</td></tr>
<tr><td>U3</td></tr>
</table>

Conclusion

- We have created a new methodology to develop a preferential adjacency matrix and identify the resultant performance based on the connections between systems
- We used general assumptions of dissimilar system interoperability and performance assumptions
- We also described a limited scope of functional activities during the scenario execution
- For the notional example, the initial modeling results confirm the hypothesis that dissimilar platform types and organizations (e.g. different CSG) would have a declining performance with increasing platform and operational dissimilarities

Future Work

- Future work could address cultural or social biases and how that would affect performance
- Future work could expand to additional detailed functions that would more specifically calculate the overall mission outcome
- Future work could also be extended to higher fidelity simulations that may lead to greater insight into the actual system performance
- Through the use of this method, we could start to explore the potential trade space of how systems could accomplish the mission based on variable connections, in order to develop performance requirements and expectations for different conditions and collaborators
- Additional work would apply a similar approach to different domains, such as fire departments, police departments, or the Department of Homeland Security that require multiple organizations from different jurisdictions to interoperate

APL

JOHNS HOPKINS

APPLIED PHYSICS LABORATORY