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GUEST EDITOR

Andreas Tolk
Old Dominion University

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Sean Deller
Michael I. Bell
Shannon R. Bowling
Ghaith A. Rabadi
Andreas Tolk

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Applying the Information Age Combat Model: Quantitative Analysis of Network Centric Operations

Sean Deller, Shannon R. Bowling, Ghaith A. Rabadi,
and Andreas Tolk (Old Dominion University, USA)

Michael I. Bell (Alidade Incorpoated, USA)

Abstract

The nature of and the approach to command and control is evolving in order to meet the challenges of Information Age warfare. One of the main tasks of command and control is the arrangement of the assets within a combat force in order to ensure their ability to manage and exploit information. Connectivity between the various assets represents existence, capacity, reliability, and other attributes of links establishing the connectivity. The Information Age Combat Model was introduced by Cares in 2005 to contribute to the development of an understanding of the influence of connectivity on force effectiveness that can lead eventually to quantitative prediction and guidelines for design and employment. This paper describes the model and several extensions to it. It presents an initial attempt to achieve such an understanding through the quantitative analysis of a basic but powerful model of network centric operations to demonstrate the correlation between connectivity and effectiveness. It also documents first prototypical studies showing how these results can be used in current models and can even contribute to a new generation of combat models that are net-centric instead of using the current platform-centric approach.

Introduction

> *"New approaches to accomplishing the functions that are associated with Command and Control are becoming an essential part of an Information Age transformation of military and civilian institutions; such a transformation is required to meet twenty-first century security challenges."* (Alberts, 2007, 2)

While the nature of and the approach to command and control is evolving in order to meet the challenges of Information Age warfare, the essential functions that must be accomplished remain constant. One of those essential functions is the organization, or "arrangement" (from the definition of "Command and Control" in Joint Publication 1-02, 79-80), of the assets within a combat force. Certainly, the many different ways to arrange a given set of assets will have different impacts on the combat effectiveness of the force. Some arrangements will enable self-synchronization, while other arrangements will impede it. How then, should an Information Age combat force be organized in order to optimize its effectiveness?

The concept of Network Centric Operations (NCO) represents a shift from traditional attrition-based approaches to a warfighting style that emphasizes speed of command and self-synchronization. One goal of NCO is to field a force that is capable of achieving information superiority, i.e. "having a dramatically better awareness or understanding of the battlespace rather than simply more raw data" (Cebrowski and Garstka 1998, 32), thus enabling a massing of effects instead of the traditional massing of forces that will disrupt the enemy's strategy and preclude his courses of action. Prior to the introduction of the NCO concept, assessment of the combat potential of a force tended to focus on force composition (the number of platforms or other entities of each type) and individual platform capabilities, with force lay-down (spatial distribution) and employment (tactics) as important but scenario-dependent factors. Network centric operations shift the focus towards the information-based aspects of force employment: information collection, communication, and exploitation. Central to the ability of a force to manage and exploit information is its connectivity: the existence, capacity, reliability, and other attributes of the links that connect its platforms, command and control centers, and other entities. A fundamental problem is to develop an understanding of the influence of connectivity on force effectiveness that can lead eventually to quantitative prediction and guidelines for design and employment.

This paper presents an initial attempt to achieve such an understanding through the quantitative analysis of a basic but powerful model of network centric operations and demonstrate the correlation between connectivity and effectiveness. Furthermore, it shows possible ways to apply implications and results of such simple models to new modeling and simulation approaches in support of legacy models of operations with military participation and introduces prototypical implementations for a potential new generation of combat models.

The Information Age Combat Model (IACM)

The Information Age Combat Model (IACM), recently introduced by Cares (2005), attempts to describe combat (or competition) between distributed, networked forces or organizations. The basic objects of this model are not platforms or other entities capable of independent action, but rather nodes that can perform elementary tasks (sense, decide, or influence) and links that connect these nodes. Information flow between the nodes is generally necessary for any useful activity to occur. This focus on "network-centric" rather than "platform-centric" operations is intended to advance the state of the art in combat modeling "by explicitly representing interdependencies, properly representing complex local behaviors and capturing the skewed distribution of networked performance" (Cares 2005, 34).

The IACM employs four types of nodes defined by the following properties:

- *Sensors* receive signals about observable phenomena from other nodes and send them to Deciders;
- *Deciders* receive information from Sensors and make decisions about the present and future arrangements of other nodes;
- *Influencers* receive directions from Deciders and interact with other nodes to affect the state of those nodes;
- *Targets* are nodes that have military value but are not Sensors, Deciders, or Influencers.

These properties represent the minimum required for each type of node. Other possible characteristics will emerge in the following discussion. Each node belongs to a "side" in the competition, of which there are at least two. We will restrict the present discussion to two sides, conventionally termed BLUE and RED. In principle, any pair of nodes can interact, regardless of side, but some restrictions will be found to occur for both theoretical and practical reasons. It is worth noting that Influencers can act on any type of node, and Sensors can detect any type. The Target type was introduced primarily to reflect the fact that not all military assets fall into one of the other three types. In most situations, however, an Influencer will target an adversary Sensor, Decider, or Influencer.

The basic combat network shown in figure 1 represents the simplest situation in which one side can influence another. The BLUE Sensor (S) detects the RED Target (T) and informs the BLUE Decider (D) of the contact. The Decider then instructs the BLUE influencer (I) to engage the Target. The Influencer initiates effects, such as exerting physical force, psychological or social influence, or other forms of influence on the target. The process may be repeated until the

Decider determines that the desired effect has been achieved. It should be noted that the effect assessment requires sensing, which means that this will be conducted in a new circle.

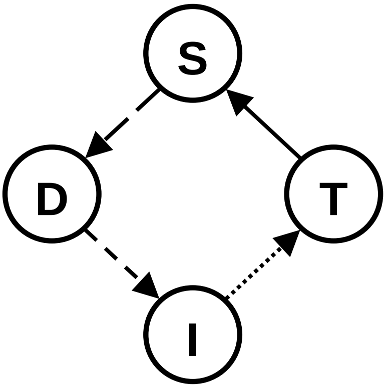

Figure 1. The basic combat network represents the simplest situation in which one side can influence another.

Each of the four links in figure 1 is shown with a different type of line in order to emphasize the fact that the flows across these links may be very different. In particular, some links may represent purely physical interactions, while others may entail both physical processes and information flows. The figures in this paper utilize the basic elements of graph theory. For more details on graph theory the interested reader is referred to Chartrand (1984).

Cares (2005) described the simplest complete (two-sided) combat network as having 36 possible links. While the number of possible links for eight nodes (four each for BLUE and RED) is 64, we were able to exclude 28 and reduce that number to 36 based on the following important assumptions:

- Targets are passive; their only role is to be sensed and influenced. Therefore, 12 links from Targets to any nodes other than a Sensor were excluded.

- Sensors take no action; they provide information to Deciders and Sensors. Therefore, 10 links from Sensors to any nodes other than a Sensor or own Decider were excluded.

- Deciders act only through Influencers but can be sensed. Therefore, 6 links from Deciders to any adversary nodes except a Sensor were excluded.

The resulting BLUE (depected in black) and RED (depicted in gray) combat networks are shown in figure 2.

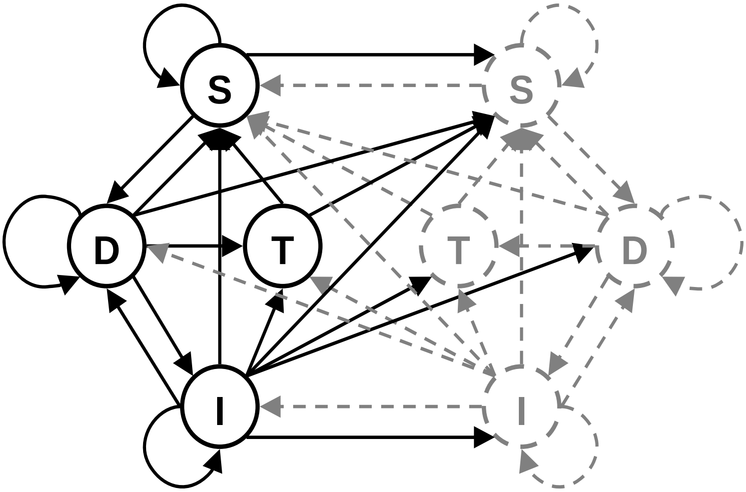

Figure 2. The simplest complete combat network represents all the ways in which Sensors, Deciders, Influencers and Targets interact meaningfully with each other.

When the BLUE/RED symmetry is taken into account, the number of link types is reduced to 18. These are listed in table 1, where the nodes are identified as in figure 2. Links between a node and itself in figure 2 have been interpreted as connecting two different nodes of the same type and side.

Table 1. Types of Links Available in the IACM

Link Type	From	To	Interpretation	Link Type	From	To	Interpretation
1	S_{BLUE} S_{RED}	S_{BLUE} S_{RED}	S detecting own S, or S coordinating with own S	**10**	I_{BLUE} I_{RED}	D_{BLUE} D_{RED}	I attacking own D, or I reporting to own D
2	S_{BLUE} S_{RED}	D_{BLUE} D_{RED}	S reporting to own D	**11**	I_{BLUE} I_{RED}	I_{BLUE} I_{RED}	I attacking own I, or I coordinating with own I
3	S_{BLUE} S_{RED}	S_{RED} S_{BLUE}	S detecting adversary S	**12**	I_{BLUE} I_{RED}	T_{BLUE} T_{RED}	I attacking own T
4	D_{BLUE} D_{RED}	S_{BLUE} S_{RED}	S detecting own D, or D commanding own S	**13**	I_{BLUE} I_{RED}	S_{RED} S_{BLUE}	I attacking adversary S, or S detecting adversary I
5	D_{BLUE} D_{RED}	D_{BLUE} D_{RED}	D commanding own D	**14**	I_{BLUE} I_{RED}	D_{RED} D_{BLUE}	I attacking adversary D
6	D_{BLUE} D_{RED}	I_{BLUE} I_{RED}	D commanding own I	**15**	I_{BLUE} I_{RED}	I_{RED} I_{BLUE}	I attacking adversary I
7	D_{BLUE} D_{RED}	T_{BLUE} T_{RED}	D commanding own T	**16**	I_{BLUE} I_{RED}	T_{RED} T_{BLUE}	I attacking adversary T
8	D_{BLUE} D_{RED}	S_{RED} S_{BLUE}	S detecting adversary D	**17**	T_{BLUE} T_{RED}	S_{BLUE} S_{RED}	S detecting own T
9	I_{BLUE} I_{RED}	S_{BLUE} S_{RED}	I attacking own S, or S detecting own I	**18**	T_{BLUE} T_{RED}	S_{RED} S_{BLUE}	S detecting adversary T

The interpretation of some of the links (types 1, 4, 9, 10, 11, and 13 in table 1) is ambiguous. This was recognized in the initial development of the IACM (Cares 2005), and resolving this issue was described as both “the next major advance” in the development of the model and a requirement for “practical” (i.e., quantitative) analysis based on it. The simulations presented here are a step in this direction, since they employ only basic combat networks similar to figure 1, but with the Target replaced by an adversary Sensor or Influencer. These “combat cycles” (Cares 2005) contain only links of types 2, 3, 6, 13, and 15. Of these, only type 13 is ambiguous. Both interpretations of this link will be used, but the context of the model always makes clear which is intended.

Once the IACM has been defined in terms of a network of nodes and links, the language and tools of graph theory (see, for example, Chartrand 1984) can be used for both description and analysis. A concise description of any graph is provided by the adjacency matrix A, in which the row and column indices represent the nodes, and the matrix elements are either one or zero according to the rule: $A_{ij} = 1$, if there exists a link from node i to node j and $A_{ij} = 0$, otherwise. Many properties of a graph or network can be calculated directly from the adjacency matrix, and two are of particular interest here. Since combat power or influence can be exerted only when there exists a connected cycle that includes the node to be influenced, the detection of cycles in the graph is of great importance. One method used in studying the evolution of complex adaptive systems (chemical, biological, social, and economic) is calculation of the principal (maximum) eigenvalue of the adjacency matrix (Jain and Krishna, 1998). The existence of a real, positive principal eigenvalue of A_{ij} is guaranteed by the Perron-Frobenius theorem, and this eigenvalue λ_{PFE} (and the corresponding eigenvector) are often referred to as the Perron-Frobenius Eigenvalue (eigenvector). It is readily shown (Jain and Krishna, 1999) that for a graph with no closed cycles $\lambda_{PFE} = 0$. For a graph with a single cycle of any length, one obtains $\lambda_{PFE} = 1$. Graphs with more complicated cycle structures have $\lambda_{PFE} > 1$. This had led to the proposal (Cares 2005) that λ_{PFE} be adopted as a measure of the ability of a network to produce feedback effects in general and combat power specifically in the case of the IACM. This is essentially the hypothesis explored in the present work.

An alternative, but closely related approach is based on the fact that A^n (the n^{th} power of the adjacency matrix) can be used to obtain the number of distinct paths connecting any pair of nodes (Chartrand 1984). Specifically, $(A^n)_{ij}$, which is the ij matrix element of A^n, is equal to the number of distinct paths of length n connecting nodes i and j. In particular, $(A^n)_{ii}$ is the number of distinct closed paths from node i back to itself. If node i is an adversary Target T, then $(A^n)_{TT}$ is the number of distinct combat cycles of length n that include T. This represents the number of different ways that T can be engaged by the opposing force. In general, combat cycles must be of length at least four, and if the links are restricted to the types shown in figure 1, they must be of length exactly four. In this case, the matrix element

$(A^4)_{TT}$ is equal to the number of combat cycles that pass through the Target T and is therefore a potential measure of the combat power that can be brought to bear on it. Under special conditions that will be described below, it is possible to establish a quantitative connection between λ_{PFE} and $(A^4)_{TT}$, lending further support to the hypothesis that λ_{PFE} can be used as a measure of effectiveness for a distributed, networked force or organization.

A Basic Agent-Based Model Using the IACM

The structure of the IACM makes it clear that the λ_{PFE} is a quantifiable metric with which to measure the organization of a networked force, but is it an indicator of combat effectiveness? To determine this we constructed an agent-based model representation of the IACM and conducted a series of force-on-force engagements using opposing forces of equal assets and capabilities, but differing in their connectivity arrangements or configurations. These differences in connectivity often, but not necessarily, lead to unequal λ_{PFE} values.

The agent-based paradigm was utilized for this purpose because the resulting models provide the ability to account for small unit organization, maneuver, and the networked effects that are the focus of our investigation. An additional advantage of utilizing an agent-based model was the ability to work around the ambiguities of link interpretation in the IACM. For example, instead of a mutually exclusive choice between defining a directional link from a BLUE Influencer to a RED Sensor (type 13 in table 1) as either the Influencer "targeting" the Sensor or as the Sensor "sensing" the Influencer, both abilities can be represented in the agent-based model. The agent-based modeling environment utilized for this research was NetLogo (Wilenski 1999).

The first challenge in modeling the IACM concerned the adjacency matrix representation of the network. The IACM as originally described by Cares (2005) uses a single adjacency matrix to reflect the collective organization of both BLUE and RED forces. In this approach, the λ_{PFE} value is dependent on the configurations of both the BLUE and RED forces and might well represent the extent to which feedback effects occur in the engagement. Obviously, BLUE and RED each seek separately to maximize their own networked effects while minimizing those of the opposing force. This cannot be represented by a single λ_{PFE} value, so we calculate separate values (λ_{BLUE} and λ_{RED}) to reflect the potential networked effects of the configurations of each of the opposing forces. These calculations required the adjacency matrices include a single Target node representative of all the enemy forces capable of being targeted. In other words, the values of λ_{BLUE} and λ_{RED} are determined solely by the arrangement of their respective assets, independent of the asset arrangement of the opposing force.

The code of the agent-based model closely follows the logic of the IACM, with a few notable exceptions. Agents served as Sensors, Deciders, and Influencers, but Targets were not included as they served no purpose other than to absorb losses. Given that this work represents a “first cut” effort, including Target agents with no detect, direct, or influence capabilities would only serve to clutter the results. Additionally, Deciders cannot be destroyed in the present model. This was done in recognition of their unique role in connecting multiple Sensors and Influencers. Destruction of a Decider typically renders a number of other nodes useless (effectively destroyed), making it a particularly high value target. Since targets are detected and engaged in random order in our model, we wished to give all targets equal value in order not to generate atypical engagements that might bias the results.

The agent rules sets, themselves, function in accordance with the IACM. Sensors detect enemy nodes within the sensing range parameter, and communicate that information to their assigned (connected) Deciders. Deciders communicate the sensing information to their assigned Influencers. Influencers destroy the nearest enemy node that is both “sensed” by a Sensor connected to that Influencer's Decider, and within the influencing range parameter. Deciders direct Sensor movement towards areas of suspected enemy nodes. Deciders direct Influencers to move towards the nearest "sensed" enemy node. All nodes are assumed to perform their functions perfectly and instantaneously. Errors and delays representing technological and human performance factors will be addressed in follow-on work. First efforts are addressed in a later section of this article. Most importantly, the rule sets and parameter values for both BLUE and RED agents were identical.

Structure of the Experiment

In order to best associate any difference in force effectiveness to the difference in connectivity, the opposing forces consisted of the same number of Sensors, Deciders, and Influencers, differing only in the manner in which they were arranged (i.e., linked). To preclude any bias between Sensors and Influencers, both forces contained equal numbers of them with equal capabilities (i.e., the sensing range was chosen equal to the influencing range, and the speeds of movement of the two types of node were equal). Consequently, the composition of both forces followed an X-Y-X-1 (Sensor-Decider-Influencer-Target) template.

For any particular values of X and Y, there is a finite number of ways to arrange those assets. In order to gain a "first order" understanding of the IACM, we made two key scoping decisions. First, each Sensor and Influencer would only be connected to one Decider (but any given Decider could be connected to multiple Sensors and Influencers). Second, the connectivity within any X-Y-X-1 force was limited to only those "vertical" links necessary to create combat cycles (i.e., link types 2, 3, 6, 13, and 15), which are the essence of the λ_{PFE} (the most basic element of the IACM). As noted below, future work will include "horizontal" links between Sensors, Deciders, and Influencers, such as link types 1, 5, and others. This can significantly enhance both the λ_{PFE} value and the performance of any given network configuration, but it requires the introduction of additional rules to manage and exploit the information carried by these links. The present model provides a baseline for assessing the effect of adding additional types of links. In addition the simplification used here is sufficient to insure that $(\lambda_{PFE})^4$ is equal to $(A^4)_{TT}$, providing the exact, quantitative relationship mentioned previously between λ_{PFE} and the number of combat cycles.

While the X-Y-X-1 template significantly scoped the focus of this effort, the number of possible configurations for a given force still becomes large very quickly. For example, there are a total of nine possible ways to distribute four Sensors and four Influencers across three Deciders (see figure 3). No matter how you distribute them, one Decider will have two Sensors linked to it, and one Decider (which may or may not be the same Decider) will have two Influencers assigned to it. Fortunately, since the nodes of the IACM are generic it is possible to reduce this set by eliminating those configurations that are, in effect, identical. The only *meaningful* difference between the nine possible configurations of a 4-3-4-1 networked force is whether the Decider that is linked to two Sensors is the same Decider that is linked to two Influencers. All other possible configurations are duplicative of the first two (and are shaded gray). Adding a single Sensor and Influencer yields a 5-3-5-1 networked force, which can be organized in 36 different ways. By applying this same logic, we reduce those 36 possible configurations to only eight meaningfully different configurations. Even with these most basic of examples, the difference between the number of possible configurations and number of meaningfully different combinations becomes quite apparent.

Configuration Number	Number of Sensors linked to Decider 1	Number of Sensors linked to Decider 2	Number of Sensors linked to Decider 3	Number of Influencers linked to Decider 1	Number of Influencers linked to Decider 2	Number of Influencers linked to Decider 3
1	2	1	1	2	1	1
2	2	1	1	1	2	1
3	2	1	1	1	1	2
4	1	2	1	2	1	1
5	1	2	1	1	2	1
6	1	2	1	1	1	2
7	1	1	2	2	1	1
8	1	1	2	1	2	1
9	1	1	2	1	1	2

Figure 3. There are nine possible configurations of a 4-3-4-1 networked force, but only two (unshaded) are meaningfully different.

Identifying the meaningful configurations is crucial for the purpose of scoping the problem. While a 7-3-7-1 networked has 225 possible configurations, applying this same logic reduces this to a much more manageable number of only 42 meaningfully different configurations. Testing each of the 225 possible configurations of a 7-3-7-1 networked force against all 225 possible configurations of an opposing 7-3-7-1 networked force would require 50,625 unique engagements, but 42 combinations would only require 1,764 unique engagements. Since the number of meaningful combinations for any given set of nodes is a function of the number of unique values of the allocation combinations of X across Y, we attempted to define the function in order to automatically generate the combinations. This was not a simple task. Although the allocation resembles a partition problem, the exact numerical sequence of the numbers of meaningful combinations was difficult to establish. Since determining what this function might be is not the purpose of this research, we calculated the numbers of meaningful combinations for all X-Y-X-1 forces where X ≤ 10 and Y ≤ 7 using a simple algorithm based on the numbers of unique values for the distributions of Sensors and Influencers across the Deciders. The resulting totals are summarized in figure 4:

		Number of Deciders (Y)				
		3	**4**	**5**	**6**	**7**
Numbers of Sensors (X) and Influencers (X)	**3**	1				
	4	2	1			
	5	8	2	1		
	6	19	9	2	1	
	7	42	27	9	2	1
	8	78	74	30	9	2
	9	139	168	95	31	9
	10	224	363	248	105	31

Figure 4. The numbers of meaningful combinations of all X-Y-X-1 networked forces where X ≤ 10 and Y ≤ 7.

Identical configurations always have the same λ_{PFE} value; however, it is possible for meaningfully different configurations to share the same λ_{PFE} value. The adjacency matrices for all meaningful configurations will only differ in two sections (see the unshaded sections of an example adjacency matrix in figure 5), regardless of the total numbers of Sensors, Deciders, or Influencers. These unshaded sections reflect the connectivity of each Sensor and Influencer to a particular Decider, and vary by configuration based on the allocation of Sensors and Influencers across the Deciders. The shaded areas represent the absolute absence of any links between those types of nodes (such as the "horizontal" links discussed earlier), or the absolute existence of links between those types of nodes (such as the links from all BLUE influencers to the RED Target). Since fourteen of sixteen sections of the adjacency matrices for each of the 42 configurations are identical, the variance between the λ_{PFE} values is greatly reduced.

To

		S	**S**	**S**	**S**	**S**	**S**	**S**	**D**	**D**	**D**	**I**	**I**	**I**	**I**	**I**	**I**	**I**	**T**
	S	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	S	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	S	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	S	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	S	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	S	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	S	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	D	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0
From	**D**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	T	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0

Figure 5. An adjacency matrix for one of the 42 meaningfully different configurations of a 7-3-7-1 networked force.

In the case of a 7-3-7-1 networked force, the 42 meaningfully different configurations had 30 unique λ_{PFE} values ranging from 1.821 to 2.280. The full range of mathematical values for a λ_{PFE} of an adjacency matrix containing 18 nodes is from 0 (for a network with no links at all) to 18 (for a maximally connected network). Note that the range of λ_{PFE} values for the 42 meaningful combinations of a 7-3-7-1 force is only a small segment of this full range due to the few differences between the links within any two of those configurations. The cause of this constrained range, however, is significant and becomes apparent when applying the statistical measures from various studies of network systems compiled by Cares (2005).

Of all the network statistics referenced in those studies, the λ_{PFE} was the only one that varied in value between the 42 meaningful configurations; all others remained constant. Each configuration consists of the same numbers of nodes (18) and links (28). Each configuration shares a similar skewed degree distribution and, consequently, since each path within these configurations is the shortest path, the betweeness value for each configuration must also be skewed. Each configuration lacks any direct connectivity between its largest hubs, such as between Deciders or from any Decider directly to the Target node. Likewise, the characteristic path length, clustering coefficient, path horizon, neutrality rating, and susceptibility of each of these configurations is identical. Given that the λ_{PFE} is the only one of these metrics that varies between these configurations, it is the only one of these metrics that might measure any potential variation in the effectiveness of these 42 configurations.

Since the focus of this effort is to gain insight into the relationship between the λ_{PFE} value and the effectiveness of a networked force, the agent-based model rules of engagement were quite simple. Engagements continued until either all of the Sensors and Influencers of one force were annihilated, or both forces were incapable of continued combat (i.e., neither side contained a functioning combat cycle). A single run of the agent-based model will result in a BLUE win, a RED win, or an undecided result.

Initial Results

A trial experiment was conducted to investigate whether this approach is feasible, and the results are promising. Various force-on-force engagements were modeled utilizing the 42 meaningfully different configurations of a 7-3-7-1 networked force for both BLUE and RED. Since each of these configurations contains the same numbers of Sensors, Deciders, and Influencers, differing only in their connectivity, it is most likely that any difference in performance would be a consequence of this connectivity difference. A comprehensive test of each of these 42 configurations against each other required 1,764 different engagements. Each engagement was represented by 30 replications, each with a random distribution of the BLUE and RED nodes across the battlespace. A graphical representation of the results is presented in figure 6.

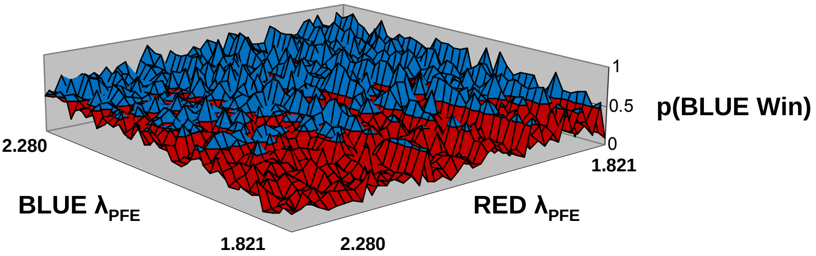

Figure 6. The probability of a BLUE Win for each of the 42 BLUE configurations (with λ_{BLUE} values varying from 1.821 to 2.280) against each of the 42 RED configurations (also with λ_{RED} values varying from 1.821 to 2.280). Surface values > 0.5 are shaded blue and surface values < 0.5 are shaded red.

These initial results indicate that as the BLUE force is organized to enhance its networked effects (i.e., the λ_{PFE} value increases) its effectiveness generally increases. While the resulting surface is far from smooth a general trend does appear: the smaller the λ_{PFE} value, the smaller the probability of a win. The outlying configurations may be due to the increased vulnerability of those configurations but continued investigation is necessary. This trend becomes more apparent in figure 7 where the probability of a BLUE win is averaged over all RED configurations. Note that many BLUE configurations had an identical λ_{PFE} value (there were 13 unique λ_{PFE} values for the 42 configurations). Clearly, it appears that the probability of a BLUE win increases for those BLUE configurations with a greater λ_{PFE} value. A simple linear regression confirms this with a coefficient of determination (R^2) equal to 0.896.

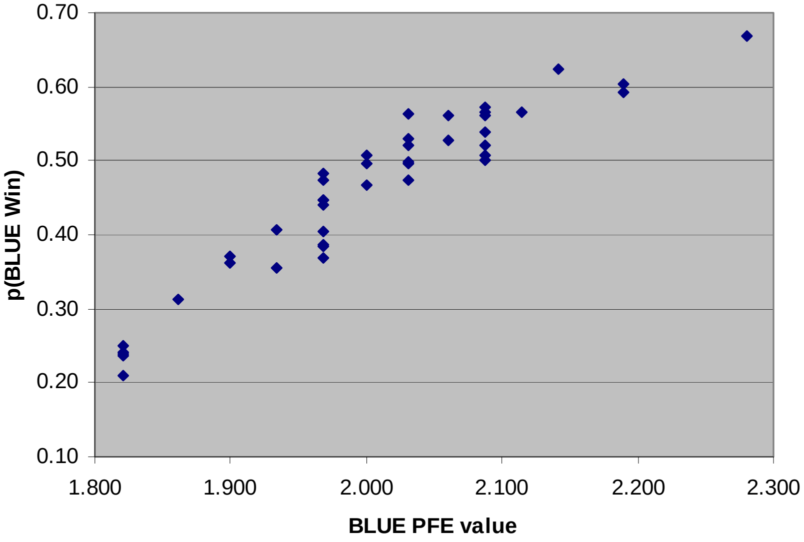

Figure 7. The average probability of a BLUE win for each of the 42 meaningfully different configurations of a 7-3-7-1 BLUE force.

These initial results are tentative. They are the result of a series of experiments conducted in support of an ongoing PhD thesis at Old Dominion University. Future work within this research must evaluate if this trend holds for other configurations as well, and then show how to generalize these insights.

Related and Future Work

So far, agent-based models were used in support of finding closed mathematical solutions. The insights gained from such efforts should not be underestimated. However, the assumptions may simplify the underlying problem too much for application in other domains of simulation systems, in particular training and support to operations (Sokolowski and Banks 2008). Therefore, ongoing work is in progress at the Virginia Modeling Analysis and Simulation Center (Bowen 2008, Tolk 2008) and at Alidade Incorporated (Bell 2008) to eliminate several of the simplifying assumptions used in the present work and to extend the IACM.

In the present work, the rules governing the actions of each node and the strategy for communication between nodes were executed with complete certainty. Many military applications, however, must work with probabilities instead. In addition to probabilities associated with the nodes (for example, probability of detection or probability of kill), communication probabilities must be introduced. This results in a re-interpretation of the adjacency matrix A. The row and column indices still represent the nodes, and the matrix elements represent the links. Where no link exists, the matrix element is zero. Where a link exists, the matrix element can adopt a value between zero and one, that is, $A_{ij} = x$ (with $0 < x \leq 1$), where x represents the likelihood that the intended use of this link is accomplished. The probability distribution of A_{ij} can be specified by the model developer, and the expected value x can be used in connection with many well-known methods for network analysis. When the link represents assured communication, x becomes equal to one, and the adjacency matrix assumes the form used in the present work.

In an effort to make the IACM more useful to traditional combat model developers for applications in the domains of training and operational support, Tolk et al. (2008) have proposed the addition of a new type of node, the *Communication* node. This node can be used in a number of ways. It can represent a communication probability less than one, rather than assigning this function to a link. It can provide bidirectional communication, as when a Decider both receives reports from a Sensor and tasks the Sensor to (for example) change position or area of observation. It can also extend the range of communication between the other nodes or provide communication around obstacles. In military operations communications is the foundation of orchestrated campaigns. Insuring communications by distributing and protecting the means (communication nodes) as well as denying the opponent the gained situational awareness by destroying or jamming his communication nodes can contribute decisively to the success or failure of a campaign.

Figure 8 shows the resulting enhanced IACM as implemented in a prototype (Bowen 2008). In this prototype, the interpretation for links between Influencers and Targets are hit and kill probabilities – P(Hit) x P(Kill) –, sensing probabilities for links between Targets and Sensors – P(Sense) –, and probabilities for successful communications between nodes – P(Commo). Furthermore, every node is interpreted as a target for the opposing force.

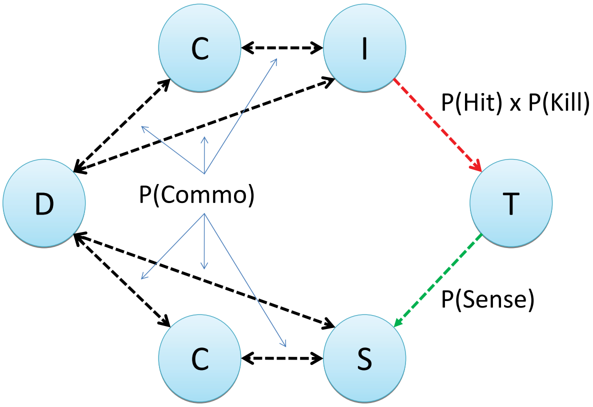

Figure 8. The enhanced IACM includes communication nodes and uses probability values in the adjacency matrix.

This enhanced IACM eliminates some of the restrictions on link type imposed in the present work. Additional restrictions are removed in models under development (Bell 2008) that provide for coordination among multiple Deciders, sharing of control of an Influencer by several Deciders, and sharing of Sensor reports among Deciders. These models focus on the planning process: the principal role of the Deciders is to develop and distribute sensing and engagement plans to be executed by the Sensors and Influencers. Since the additional links available in these models can be used to develop added combat power, it is expected that, as in the present work, greater values of λ_{PFE} will be associated with increases in combat effectiveness.

An ambitious prototypical application of the IACM (Bowen 2008) integrates it into a larger framework for agent-based combat simulation. As the model described before, this version is also implemented in Netlogo (Wilenski 1999). In this first prototype that may evolve into a new generation of combat models, everything is modeled as an agent: environmental objects (trees, buildings, roads, etc.), combat systems (Influencers, Sensors, Deciders), and the effects (communication, attrition, and sensing). Each entity represents one or more roles as defined in the IACM. The agent executions result in a bipartite directed graph that connects entity agents (environment objects and combat systems) via effect agents as shown in figure 9. In this interpretation of the model, an Influencer creates an effect agent with the desired effect.

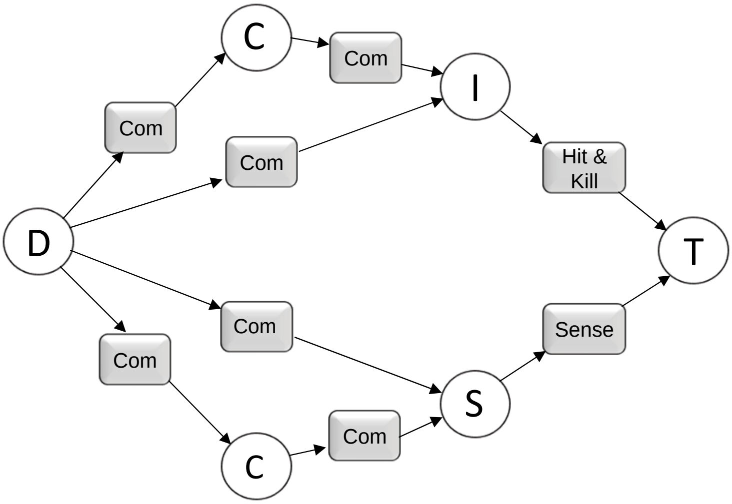

Figure 9. A bipartite directed graph of an example combat cycle in the enhanced IACM.

While in traditional models this effect is directed against an intended Target, in this model it is the effect agent that identifies which Target or Targets with which it is going to connect. This allows modeling of all effects that influence combat significantly, including those that are normally unintentional such as fratricide or self-jamming of communications. It also allows the cascading of effects and other effect-based models as envisioned by Smith (2002). The initial results obtained from a demonstration model are very promising, exhibiting the ability to represent network centric operations and demonstrating the employment of effect agents to allow a more realistic agent interaction with the environment and to extend the effect of an interaction beyond the two primary parties involved.

Summary & Conclusion

Meeting the security challenges of the twenty-first century will require innovative approaches to implementing the functions of command and control in the Information Age. Selecting the right approach requires an understanding of the potential networked effects of a combat force resulting from quantifiable metrics that properly represent the interdependencies and complex local behaviors of Information Age warfare.

This paper presented an initial attempt to achieve such understanding through the use of the Perron-Frobenius Eigenvalue (λ_{PFE}) as a measure of the ability of a network to produce feedback effects in general and combat power specifically in the case of the IACM. The results of the agent-based modeling presented in this paper indicate that the value of the λ_{PFE} is a significant measurement of the performance of an Information Age combat force. Consequently, the IACM can provide useful insights to inform the difficult decisions and trade-offs during the ongoing transformation into an Information Age combat force. The ideas presented here can be applied to the development of a new generation of combat simulations to support war fighting at the operational and tactical levels. While no practical systems have yet been implemented, the success of initial prototypes provides reason to believe that it will be possible to overcome the obstacles that often block the use of simulation tools to support analysis, planning, and execution of current operations.

The IACM can be generalized beyond attrition applications. Since the IACM is focused on network capability, the abstract representation of the acts of sensing (information), deciding, and influencing (whether it be combat or some other action taken) enable it to model almost any activity involving planning and decision making. The nodes represent capabilities and the connections the accessibility (and, if the enhanced IACM is applied, the probability to have access to the capability). Each mission consists of certain required capabilities and their connectivity can therefore be represented as a network. The likelihood of success for a mission can be directly mapped to the connectivity of its required capabilities. That connectivity can be informed by the quantitative metric (λ_{PFE} value) addressed in this work. As such, this paper is not limited to merely addressing net-centric attrition but can be applied to all kinds of net-centric operations as described in the NATO Code of Best Practice for C2 Assessment (2002), among others.

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