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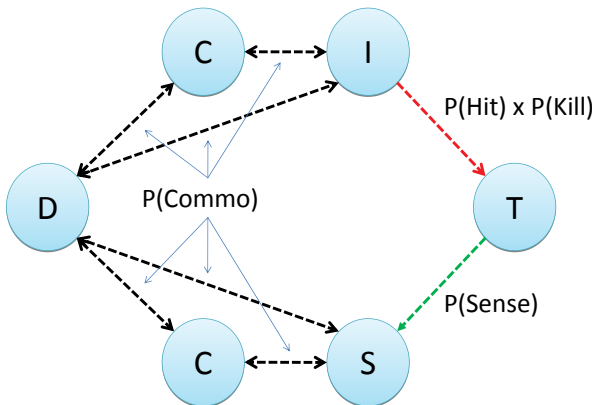
So far, agent-based models were used in support of finding closed mathematical solutions. The insights gained from such efforts should not be underestimated. However, the assumptions may simplify the underlying problem too much for application in other domains of simulation systems, in particular training 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 prob-

ability 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.

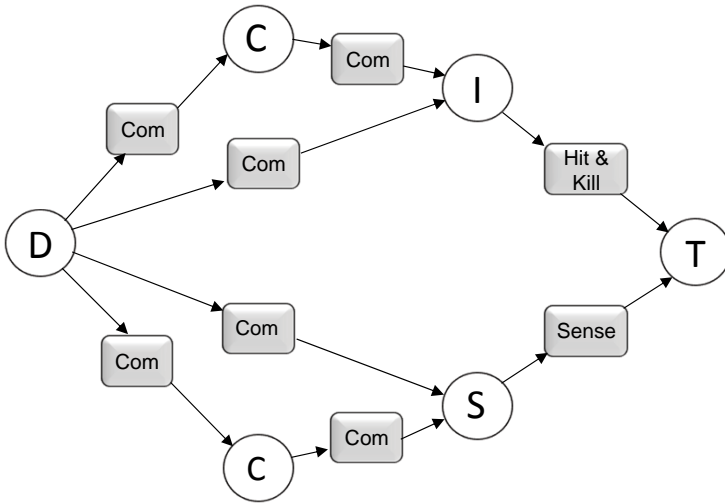
Figure 8 shows the resulting enhanced IACM as implemented in a prototype (Bowen 2008). In this prototype, the interpretation for links between Influencers and Targets are hit and kill probabilities –  $P(\text{Hit}) \times P(\text{Kill})$  –, sensing probabilities for links between Targets and Sensors –  $P(\text{Sense})$  –, and probabilities for successful communications between nodes –  $P(\text{Commo})$ . 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  $\lambda_{\text{PFE}}$  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 ( $\lambda_{\text{PFE}}$ ) 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  $\lambda_{\text{PFE}}$  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 ( $\lambda_{\text{PFE}}$  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.

## References

- Alberts, David S. 2007. Agility, Focus, and Convergence: The Future of Command and Control. *The International C2 Journal*, Vol. 1 No. 1, [http://www.dodccrp.org/html4/journal\\_v1n1.html](http://www.dodccrp.org/html4/journal_v1n1.html) (accessed April 24, 2008).
- Bell, Michael I. 2008. Private Communication.
- Bowen Robert J. 2008. *An Agent-based Combat Simulation Framework in Support of Effect-based and Net-centric Evaluation*. Thesis at Old Dominion University, Norfolk.
- Cares, Jeff. 2005. *Distributed Networked Operations*. iUniverse, New York.
- Cebrowski, Arthur K., and Garstka, John J. 1998. Network-Centric Warfare: Its Origin and Future. *United States Naval Institute Proceedings* 124: 28-35.
- Chartrand, Gary. *Introductory Graph Theory*. Dover Publications, 1984.
- Jain, Sanjay, and Krishna, Sandeep. 1998. Autocatalytic Sets and the Growth of Complexity in an Evolutionary Model. *Physical Review Letters* 81: 5684-5687.

- Jain, Sanjay, and Krishna, Sandeep. 1999. Emergence and growth of complex networks in adaptive systems. *Computer Physics Communications* 121-122: 116-121.
- Joint Publication 1-02*. 2001. Department of Defense dictionary of military and associated terms. [http://www.dtic.mil/doctrine/jel/new\\_pubs/jpl1\\_02.pdf](http://www.dtic.mil/doctrine/jel/new_pubs/jpl1_02.pdf) accessed, September 19, 2008).
- NATO Code of Best Practice for C2 Assessment, Rev.Ed.* CCRP Press, 2002.
- Smith, Edward A. 2002. *Effect Based Operations: Applying Network Centric Warfare in Peace, Crisis, and War*. CCRP Press.
- Sokolowski, John A., and Banks, Catherine M., editors. 2008. *Principles of Modeling and Simulation: A Multidisciplinary Approach*. John Wiley & Sons.
- Tolk, Andreas, Bowen, Robert J., and Hester, Patrick T. 2008. Using Agent Technology to Move From Intention-Based to Effect-Based Models. *Winter Simulation Conference Proceedings*, IEEE Press, 863-871.
- Wilenski, Uri. 1999. *NetLogo*. Center for Connected Learning and Computer-based Modeling, Northwestern University, Evanston, IL. <http://ccl.northwestern.edu/NetLogo/>