AFOSR Project Final Report

Formulating a Theoretical Framework for Assessing Network Loads for Effective Deployment in Network-Centric Operations and Warfare

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1. Introduction

The Network Centric Operations/Warfare doctrine aims to leverage the technological strides in the communication and information systems to network sensors and weapons platforms and provide a better situational awareness to both the war fighter and the commanders at various levels. Network-Centricity aims to flatten the hierarchy by fostering better interaction between nodes with different specialization. This close coupling will help in self-synchronization and encourage initiative in tactical level commanders. Real time access to information from the battle field will help in fine tuning of plans and a quick reaction to changes on the ground.

Networking the numerous and varied sections of the military is a dauntless task. The resultant network infrastructure is very complex, with multiple sub-network and multiple hierarchies. The networks are also heterogeneous, encapsulating different technologies, organizations, weapon systems etc. NCO/NCW has also introduced new challenges for the Testing & Evaluation (T&E) Community. Traditional T&E has focused on evaluating the performance of standalone systems. Realistic Network-Centric scenarios are more elaborate involving a host of systems, for testing even a single component. The performance of the component in a network can be different than when tested alone. Therefore, NCO/NCW testing has to be more integrated and this can be cost prohibitive. Effective Modeling and Simulation (M&S) methods that can realistically model various aspects of the network has become vital.

As part of our work on the AFOSR research project titled “Formulating a Theoretical Framework for Assessing Network Loads for Effective Deployment in Network-Centric Ops & Warfare”, a novel framework for analyzing the performance of the network was developed. This framework is called Network Centric Operations Performance and Prediction (N-COPP). N-COPP is a component based framework that models the basic aspects of performance analysis of a complex network. It has plug-n-play property for quick incorporation of existing analysis tools and to keep up with the change in technology. We will describe the framework in detail in the next section. For initial

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14. ABSTRACT
Advances in technology lead to a shift towards Network-Centric Operations (NCO) and Network-Centric Warfare (NCW) within the military. While much work in NCO/NCW has focused on developing the components based on information sharing and cross awareness (e.g. conceptual models for co-operability and the common operating picture (COP)), the lynchpin is a robust network infrastructure. However, little is known about the overall effectiveness and performance of NCO/NCW networks in general. Determining how robust or stable an existing infrastructure (network) will be and to pinpoint weaknesses or faultiness is an important and critical concern, especially since these networks need to be able to be employed in an adaptive and dynamic environment. Determining if an existing NCO/NCW network infrastructure is indeed robust and reliable is a major undertaking due to the inherently large-scale and complex nature of interaction. Employing theoretical models which can be used to analyze and predict performance (e.g. scalability, reliability, etc) is particularly important in order to design a network that is realistically deployable.
The goal of this project is the design of a theoretical framework to assess and predict the effectiveness and performance of networks and their loads.

15. SUBJECT TERMS
Network Centric Operations; networking, performance, modeling and simulation; mathematical models

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validation of the framework, we looked at the problem of modeling the network layer dynamism of an NCO/NCW system. We used metrics like connectivity, load and capacity to analyze the performance of the system in various conditions. Although the initial study looked at the data flow in the network, we cannot directly use these results to analyze "network-centric metrics" like situational awareness. The successive work in modeling Situational Awareness allowed us to demonstrate how N-COPP can be used to model dynamism in multiple layers - network layer (hardware layer) and the information layer (decision making layer) and how changes in one layer can mapped to the other. The work described in this report has been published in [2][3][3][3][7]. We will now describe in some detail the N-COPP framework, followed by the work on modeling Situation Awareness.

2. Goals and Objectives

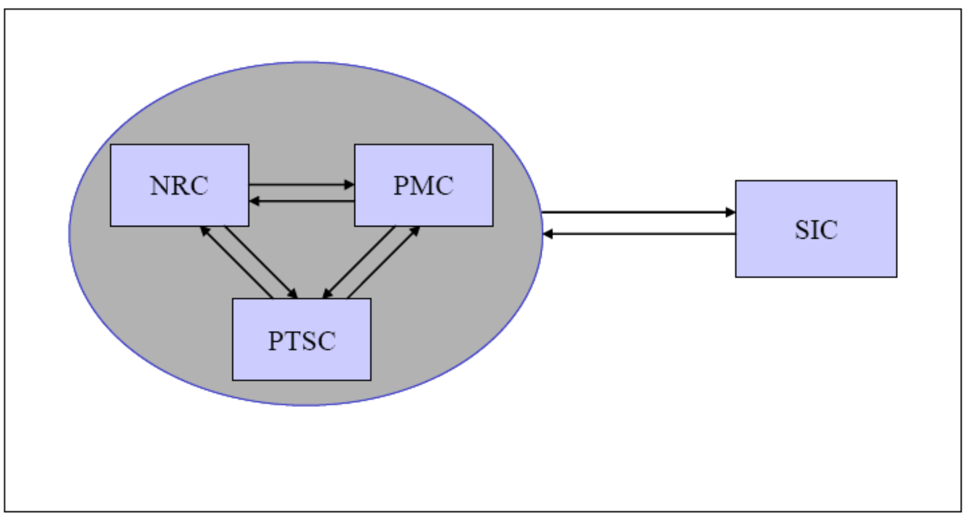
The goal of this project was the design of a theoretical framework to assess and predict the effectiveness and performance of networks and their loads for deployment in Network Centric Operations (NCO) and Network Centric Warfare (NCW). The framework must be imbued with the ability to pinpoint bottlenecks and suggest corrections and modifications leading to more effective and deployable networks. The framework is decomposable in order to allow for flexibility in description, prediction and analysis. Towards that end, the objectives of this project were:

- research and design a theoretical framework for network load that considers node variety (e.g. live, virtual, constructive) to be utilized for prediction and analysis using key mathematical and theoretical modeling paradigms from graph theory and large-scale distributed network models;
- design a flexible and component-based framework with plug-and play metrics and methodologies for wide applicability and for ease in prediction and analysis;
- refine, develop, and implement framework which can measure key performance metrics
- find and/or build testbeds/simulation framework; and validate utility of framework in the domain of situational awareness

3. Network Centric Operations Performance and Prediction (N-COPP)

In this section we present results addressing the first two bullets in goals and objectives.

In this project, we researched and designed the Network Centric Operations Performance and Prediction (N-COPP) framework is a generic, flexible, modular based framework for conducting performance analysis of NCO/NCW networks. It has plug-n-play characteristics that allows for quick implementation, embedding or modification of existing tools or models within the framework. This is critical for the NCO/NCW systems where network heterogeneity and rapid technological evolution are the norms. Since NCO/NCW systems are actually network of networks or system of systems, multi-scale analysis is essential. Due to its ability to represent sub-networks in varying detail, N-COPP is able to perform multi-scale analysis. A more detailed description of N-COPP can be found in [2].



Network representation Component (NRC)
Performance Measures Component (PMC)
Performance Tool Suite Component (PTSC)
Sub-model Interaction Component (SIC)

Fig. 1: Network Centric Operations Performance and Prediction (N-COPP) Framework [2]

3.1 Design and Implementation in N-COPP

The components of the N-COPP model are:

a) Network Representation Component (NRC): The network structure is represented in this component using graph-theoretic methods. The nodes and edges of the network graph have labels corresponding to network properties that need to be modeled. The labels have weights representing their values. Examples of labels include link bandwidth, node processing power, node battery life etc. NRC has the ability to model network of network where each node may represent either a single network device or whole sub-network(s). Appropriate coarse grained parameters can be defined for nodes that represent whole sub-networks.

b) Performance Measures Component (PMC): This component contains functions that map network states at different time stamps. These functions can be implemented in the form of algorithms that represent the future values of the network labels and weights. It is clear that by modeling the network aspects and its dynamism in separate components, changes in network structure/technology (NRC) can be easily incorporated without completely redesigning PMC.

c) Performance Tool Suite Component (PTSC): Although NRC and PMC represent the network states and network dynamism respectively, the performance tools and methodologies are required to do the actual analysis. These tools are implemented in the PTSC suite.

d) Sub-model Interaction Component(SIC): Based on the analysis of the network, recommendations can be made to optimize certain network behaviors. This aspect of the framework is modeled in the SIC component.

N-COPP is decomposable with well defined mapping between its different components. Hence different combinations of the components can help in representing different aspects of NCO/NCW. For example, by definition NRC represents the state of the network at a snapshot. By using the functional mappings in PMC, we can represent the network dynamism over a period of time. Hence a combination of NRC and PMC models the dynamic state of the network over a period of time. Other combinations of the components and their utility are given below.

NRC => Network model for fixed snapshot

NRC+PMC=>Dynamic Network model over time interval

NRC+PTSC => Performance analysis for fixed snapshot

NRC+PMC+PTSC => Performance analysis over time interval

NRC+PMC+PTSC+SIC => Controllability, Bottleneck Detection, Modifications/Suggestions, etc

3.2 Benefits to T&E

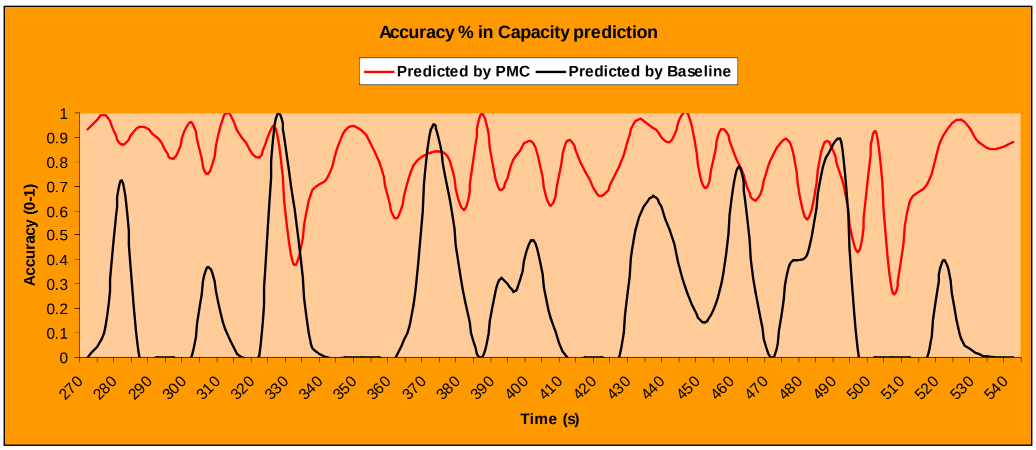
Due to its ability to do multi-scalar analysis, N-COPP can be used to generate a realistic simulation environment for testing a single or group of components. Thus, Network-Centric testing can be done in a cost effective manner. Due to component based architecture and plug-n-play architecture, components and analysis algorithms can be easily added or removed to provide a wide spectrum of testing. Telemetry is a key aspect of T&E in the Air Force. With the advent of the iNET architecture where various sensors on the test component will be networked, the effect of the telemetry network on the network centric systems need to be studied. A description of these issues and how N-COPP can help have been described in [3][3].

4. Modeling Network layer dynamism in N-COPP

In this section, we discuss results addressing the third bullet of the goals and objectives.

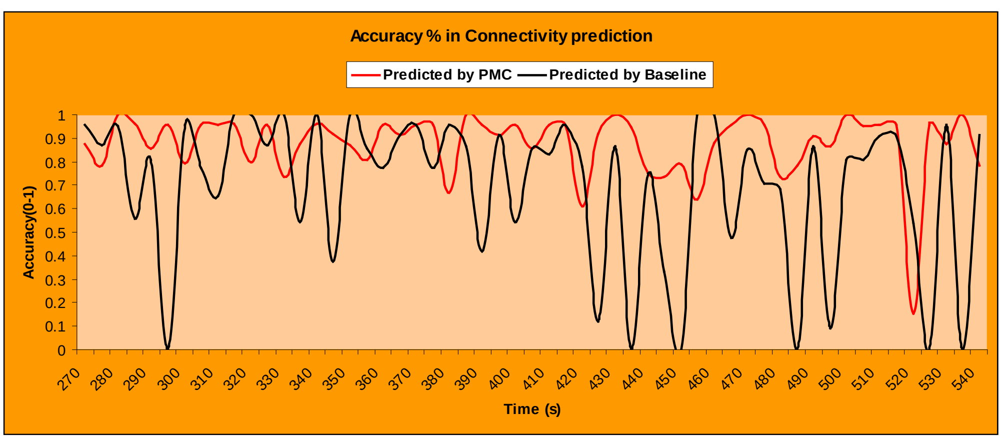
One of the crucial aspects of NCO/NCW systems that N-COPP models is network dynamism. It not only has the ability to represent and simulate snapshots in time of the networks, but also represents the mapping between network time shots. In order to do initial validation of the N-COPP framework, we model the network dynamism in an ad-hoc wireless network with a hierarchical structure consisting of multiple sub-networks. The source of dynamism in the network is due to the mobility of the nodes and due to varying data rates in the network. The change in node position and mobility rates leads to changes in node and link characteristics such as link latency, effective bandwidth etc. The data generation rates at sensor nodes depend on the ground situation. A fast moving combat situation leads to higher data rates. Also, due to node failures, congestions can occur in intermediate nodes. We model the network architecture in the NRC component. Since we are representing both the dynamism due mobility and data rates, we have appropriate labels and weights for the nodes and links in the NRC such as node speed, directional vector, data generation rates etc. Some of these labels are probabilistic measure to simulate a stochastic behavior of the nodes. The performance metrics that we use are connectivity, capacity and load. Connectivity is a measure of the number of nodes that are connected to the gateway nodes or base stations. Capacity measures the radio resource in wireless network and load is measured in terms of the average queuing length at the nodes. These three metrics are widely used in network science to measure network performance. The PMC components have predictive algorithms for forecasting future mobility states of the nodes. Thus the predictive algorithms act as functional mapping between successive snapshots of the node mobility states. Similarly, we model the data layer dynamism by predicting future queuing lengths in the nodes.

Thus we have shown how we can model different aspects of the NCO/NCW network – architecture, dynamism in a flexible manner within N-COPP. Now we validate if they are indeed effective by comparing against baseline system that does not model network dynamism. In the following figures (Figure 1, Figure 2) we provide a subset of the results comparing the dynamism modeled within PMC and the baseline. For the complete results, please refer to [7]. From the average accuracy values in the figures, we see that dynamism models in the PMC have a better performance than baseline.



Average Accuracy: Predicted by PMC – 0.82 Predicted by Baseline – 0.27

Figure 1 Accuracy of Capacity Prediction [7]



Average Accuracy: Predicted by PMC – 0.89 Predicted by Baseline – 0.74

Figure 2 Accuracy of Connectivity Prediction [7]

We have shown that even in such rapidly changing environment as NCO/NCW, dynamism can be modeled and used to predict future values of the network state with some accuracy. Although we have been able to model the data layer, NCO/NCW envisions better coordination between nodes through better information sharing. Information sharing is more than efficient data passing between nodes, it is about Situational Awareness that straddles both the network/data layer and semantic information layer. Both these layers have dynamism in them that interacts with each other. Modeling this interaction is the challenge we undertake in the next section.

5. Modeling Situational Awareness in NCO-PP

In this section we present results addressing the last bullet in goals and objectives.

Improved situational awareness is one of the important benefits of applying the NCO/NCW doctrine. With the evolution of the war fighter as both a sensor and weapons platform, it is able to capture real time information from the battlefield and feed it to tactical-level and theatre-level commanders. This provides them with a more complete and up to date picture of the evolving situation on the frontlines. This is termed as Situational Awareness (SA). According to Endsley[1], SA is defined as “the perception of elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future”. Although advanced communication and networking capabilities of NCO/NCW leads to more information being available at the command level and enables self-synchronization, there are important issues in SA specific to NCO/NCW domain that need to be studied. One of the crucial issues is the dynamism of the underlying network, its effect on information flow and subsequent effect on SA. One example of this dynamism is the constant change in the position of wireless sensor nodes in battle conditions. This in turn will lead to change in the bandwidth of the links connecting these nodes to the central fusion nodes. Hence messages may get garbled or lost. Due to the integrated nature of NCO/NCW systems, dynamism in one part of the network can have a widespread effect. How does dynamism in the network layer change the overall quality of SA? Developing realistic models of the dynamism will help in performance analysis of SA process. It will also help in developing effective resource allocation algorithms that will anticipate such changes and will proactively deploy resources to mitigate the effects of dynamism. Another critical issue is effect of network hierarchy on SA. The information from the sensors flow through a hierarchy of fusion and command nodes. In order to avoid information overflow at the higher level command nodes, there is a filtering process in the intermediate nodes. Critical pieces of information are identified and only these are passed up the hierarchy. How does this filtering process affect SA? – is another important question in NCO/NCW.

We studied these issues in SA within the N-COPP framework by implementing relevant algorithms and methodologies and analyzing their performance. The basic modeling principle used here is to represent the dynamism in the network and information layer separately and provide functional mapping between these layers. It is the modular and plug-n-play capabilities of N-COPP that enables this. The results from this work have been described in detail in [3]. This performance study was done on simulated sensor networks consisting of sensor, relay and fusion nodes arranged in a tree-like hierarchy. The sensor nodes are placed accordingly to randomly-generated geographical coordinates and move in a stochastic way using a predefined velocity vector. The sensor nodes are said to be able to detect events, which are incidents of importance such as IED explosion, car bombing etc. These are not single events, rather a chain of events that is observed by the sensors. The information gathered by the sensors is passed on to relay nodes that act as base stations to re-relay the information to the fusion nodes. The architecture was chosen based on the real world assets available to the military. The links are also simulated using stochastic models whose parameters can be easily changed.

5.1 Design and Implementation in N-COPP

The information layer consisting of the chains of events and the network layer consisting of nodes and their links are modeled in the NRC using graph theoretic and probabilistic reasoning techniques. The chains of events are modeled using Bayesian Knowledge Bases (BKBs)[6] since uncertainty and causality can be adequately represented. Bayesian Knowledge Bases has all the advantages of Bayesian networks and can also be used with incomplete information. The physical sensor networks are modeled as a graph with the nodes and edges having weights and labels representing the various parameters such as link delay, bandwidth, node functionality etc.

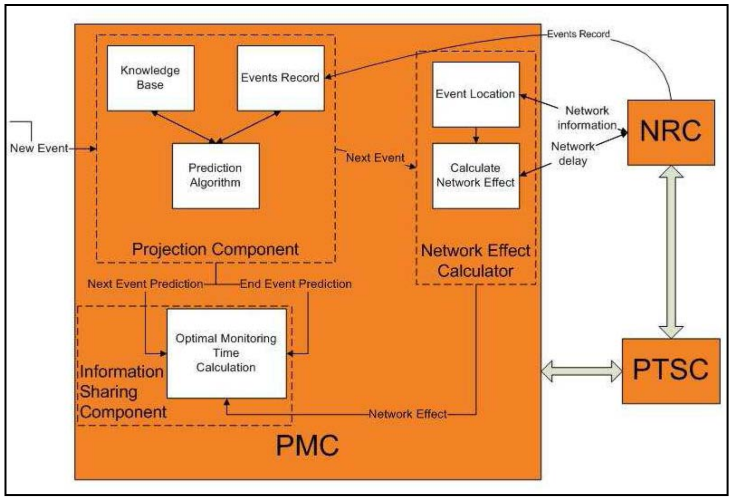


Fig 4. Performance Management Component for Modeling SA[5]

We represent the dynamism of the network and information layers in the Performance Management Component. By predicting future conditions in the network and information, we can estimate the delay in getting a particular piece of information. This is critical in NCO/NCW scenarios where many rapidly developing events are happening in tandem. The fusion and command nodes have to decide on which subset of the events to concentrate on. The network delay will have a significant effect on the propagation of information in the network and consequently should be a factor in the nodes deciding on the appropriate monitoring time. We incorporate prediction algorithm in PMC to find the set of events likely to happen in the information layer. The various sub-components used in PMC are shown in Fig 4. Their details are described in [3]. Based on the locations where these events are predicted to occur, the conditions in the relevant sections of the network are estimated. By combining these two pieces of information, we can calculate the time interval for monitoring these events. We use a cost-reward framework to represent the information filtering process, where the rewards and cost for monitoring an event chain increases with the hierarchy level of the node. Calculating the monitoring time is based on trying to maximize the reward and minimize the cost.

Although, estimating network conditions to calculating time is important for efficient use of resources (processing at a node), node and link failures can lead to an event not being monitored. Allocating resources in the form of extra sensor nodes can help in mitigating this effect. The predictions algorithms described earlier can be used in allocating these resources. Proactive resource allocation where network performance predictions are used to preemptively allocate resources have been implemented in SIC shown in Fig 5.

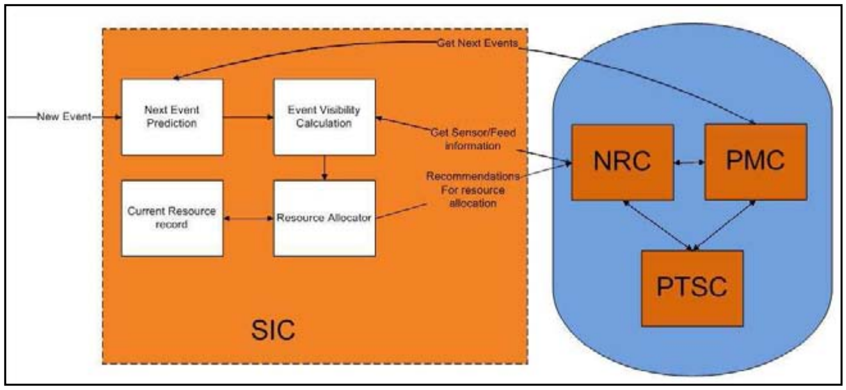


Fig. 5 Performance Management Component for Modeling SA[5]

5.2 Results

As part of the experimental study using the above design and implementation, three experiments were conducted. Performance metrics based on the correctness and completeness of the Common Operating Picture (COP) were defined and was used to compare the performance of the various algorithms in the experimental study. The first experiment looked into the performance of doing information filtering at each network level versus not doing any filtering. The Signal to Noise Ratio (SNR) metric, which is defined as the ratio between the number of successful event-chains to the total number of event-chains, is used as the performance metric to compare the system that uses information filtering (denoted as Static in Fig. 6) with the baseline (denoted as Primitive in Fig. 6. A higher SNR value for a system means that the system is able to detect false alarms quicker and valuable processing resources at higher level fusion nodes are not wasted on them. From Fig 6, we see that the Static system has a consistent better SNR value than the Primitive which means that information filtering process leads to better SA.

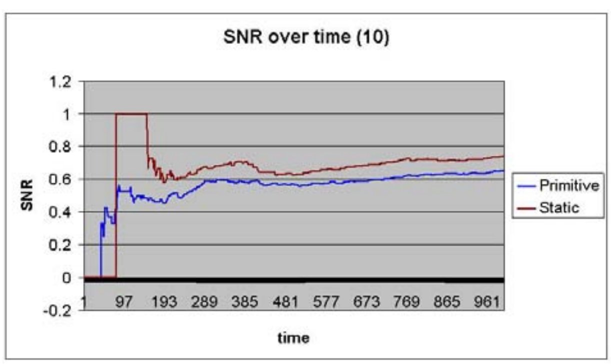
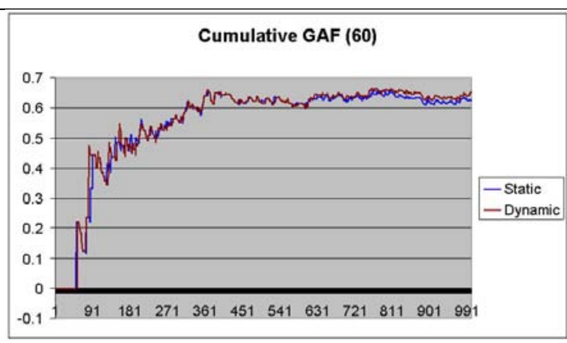
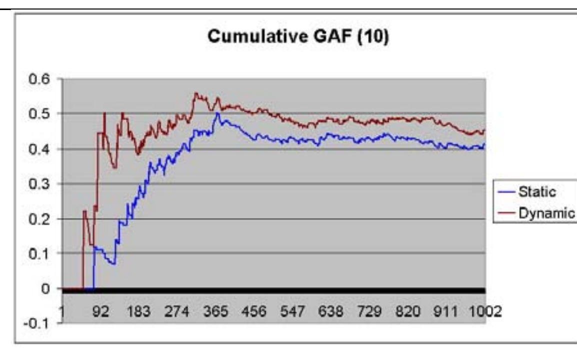


Fig. 6 Experiment 1 - Signal-to-Noise Ratio (SNR) Over Time [5]

The second experiment compared two methods for calculating event monitoring time– one that used network state information (dynamic method) and the other did not (Static method), to show that modeling network state makes the information sharing process more efficient. The experiment was conducted under various dynamism rates. Dynamism is simulated by introducing node failures and is measured as the average time steps between two successive node failures. As the node failure increase, the network delay increases and consequently the time for a particular event chain to propagate up the network hierarchy increases. Since this experiment is focused on demonstrating that calculating the event monitoring times using network state will lead to more efficient use of resources, we use a metric called the General Awareness Factor (GAF) which is the ratio of the number of events from successful event chains monitored by the fusion nodes to the events from all the successful event chains. In short GAF measures the important events that were not detected because enough monitoring time was not allocated. Fig. 7 shows the cumulative GAF values over time for different network dynamism rates. It is noted that the advantage of using the Dynamic system becomes very clear when the dynamism rates are high. Since NCO/NCW system work in highly dynamic domain, incorporating network dynamism in the information sharing algorithms leads to more efficiency.



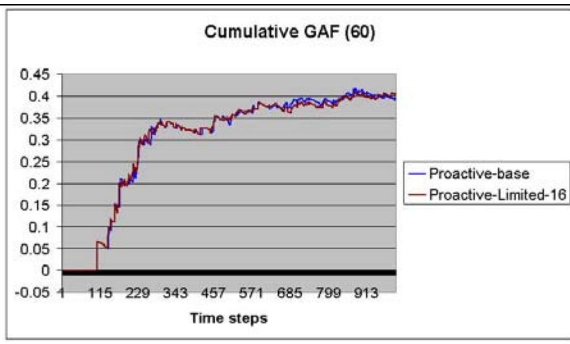
(a)Avg. Duration between failures = 60 (timesteps)



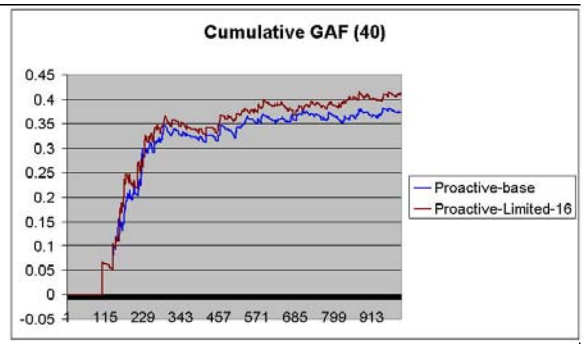
(b)Avg. Duration between failures = 10 (timesteps)

Fig. 7 Experiment 2 Cumulative General Awareness Factor (GAF) with different dynamism rates [5]

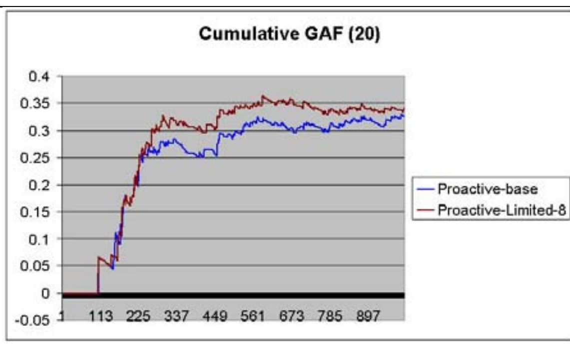
The final experiment looked at resource allocation and how resource allocation algorithm can use the network conditions to proactively deploy resource in critical regions. Deploying extra resources in critical regions can mitigate the effects of the node failures and improve SA. AS noted before, predictive algorithms in the SIC combines information about current and future network conditions and likelihood of certain events happening, to determine the regions where the extra resource in the form of sensor nodes need to be deployed. We use the GAF metric to compare performance of the proactively resource allocating systems, denoted as Proactive-Limited-*a* (in Fig. 8) where *a* is the number of extra sensor nodes available, with the baseline (Proactive-Base). Proactive-base system does not use the network information to deploy the extra resources. From the results in Fig. 8, we see that the Proactive-Limited system performs between than Proactive-Base at various dynamism rates. The three experiments validated our network dynamism model and also show how N-COPP can be used to model the interactions between the information and network layers. For more details of the experimental setup and results, please refer [5].



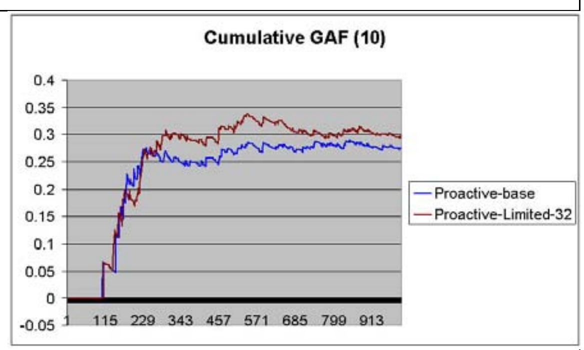
(a)Avg. Duration between failures = 60 (timesteps)



(b)Avg. Duration between failures = 40 (timesteps)



(c)Avg. Duration between failures = 20 (timesteps)



(d)Avg. Duration between failures = 10 (timesteps)

Fig. 8 Experiment 3 Cumulative General Awareness Factor (GAF) with different dynamism rates [5]

6. Concluding Remarks, Future Directions and Transition Opportunities

The goals and objectives of this project were met and discussed in the previous sections of this report.

In regards to future directions, NCO/NCW straddles the physical, information, social and cognitive domains of warfare. The physical domain consisting of network devices and the information domain consisting of processes such as SA has been the focus of our research. An important element, that is also an interesting research problem, is modeling the Human-In-The-Loop(HILT). Looking at NCO/NCW simply as the internetworking of various devices is a limited approach. Human decision making is an important part of NCO/NCW performance and as such analyzing the human aspects should be part of performance studies. As T&E moves to Network Centric Systems, their procedure will have to measure human-centric metrics such as decision making, team formation & performance etc to accurately measure the network-centricity of the modern military systems. Understanding the social aspects of NCO/NCW is a big part of this. Methods from computational social science can be used to model the social and cultural aspects of NCO/NCW systems

Furthermore, the PI has written papers with collaborators at Edwards AFB (Flight Test Center) which may serve as a continued transition point for R&D.

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