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Service-Oriented Architecture Afloat: A Capabilities-Based Prioritization Scheme

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Preface & Acknowledgements

Welcome to our Tenth Annual Acquisition Research Symposium! We regret that this year it will be a "paper only" event. The double whammy of sequestration and a continuing resolution, with the attendant restrictions on travel and conferences, created too much uncertainty to properly stage the event. We will miss the dialogue with our acquisition colleagues and the opportunity for all our researchers to present their work. However, we intend to simulate the symposium as best we can, and these *Proceedings* present an opportunity for the papers to be published just as if they had been delivered. In any case, we will have a rich store of papers to draw from for next year's event scheduled for May 14–15, 2014!

Despite these temporary setbacks, our Acquisition Research Program (ARP) here at the Naval Postgraduate School (NPS) continues at a normal pace. Since the ARP's founding in 2003, over 1,200 original research reports have been added to the acquisition body of knowledge. We continue to add to that library, located online at www.acquisitionresearch.net, at a rate of roughly 140 reports per year. This activity has engaged researchers at over 70 universities and other institutions, greatly enhancing the diversity of thought brought to bear on the business activities of the DoD.

We generate this level of activity in three ways. First, we solicit research topics from academia and other institutions through an annual Broad Agency Announcement, sponsored by the USD(AT&L). Second, we issue an annual internal call for proposals to seek NPS faculty research supporting the interests of our program sponsors. Finally, we serve as a "broker" to market specific research topics identified by our sponsors to NPS graduate students. This three-pronged approach provides for a rich and broad diversity of scholarly rigor mixed with a good blend of practitioner experience in the field of acquisition. We are grateful to those of you who have contributed to our research program in the past and encourage your future participation.

Unfortunately, what will be missing this year is the active participation and networking that has been the hallmark of previous symposia. By purposely limiting attendance to 350 people, we encourage just that. This forum remains unique in its effort to bring scholars and practitioners together around acquisition research that is both relevant in application and rigorous in method. It provides the opportunity to interact with many top DoD acquisition officials and acquisition researchers. We encourage dialogue both in the formal panel sessions and in the many opportunities we make available at meals, breaks, and the day-ending socials. Many of our researchers use these occasions to establish new teaming arrangements for future research work. Despite the fact that we will not be gathered together to reap the above-listed benefits, the ARP will endeavor to stimulate this dialogue through various means throughout the year as we interact with our researchers and DoD officials.

Affordability remains a major focus in the DoD acquisition world and will no doubt get even more attention as the sequestration outcomes unfold. It is a central tenet of the DoD's Better Buying Power initiatives, which continue to evolve as the DoD finds which of them work and which do not. This suggests that research with a focus on affordability will be of great interest to the DoD leadership in the year to come. Whether you're a practitioner or scholar, we invite you to participate in that research.

We gratefully acknowledge the ongoing support and leadership of our sponsors, whose foresight and vision have assured the continuing success of the ARP:

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Service-Oriented Architecture Afloat: A Capabilities-Based Prioritization Scheme

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Abstract

To increase combat effectiveness by networking the warfighter and to easily modify and expand its existing network architecture, the United States Navy requires shipboard computer systems that are network-centric and service-based and that support open architectures. However, they are limited by the radio frequency bandwidth that is available for shipboard communications. As a result, some network applications must take priority over others. The current Navy prioritization scheme was not designed with the needs of the warfighter as the primary focus nor does it allow for dynamically changing priorities based on changing threats. A prioritization scheme is proposed that optimizes network performance based on warfighter needs. The scheme is developed using the Capabilities-Based Competency Assessment process introduced by Suttie & Potter (2008) applied to an air detect-to-engage scenario for a carrier strike group underway. A comparison is made between the proposed prioritization scheme and traditional Navy schemes using simulation. Results show our prioritization scheme consistently reduced latency and increased throughput for mission relevant applications. These improvements translate directly to more relevant information getting to decision-makers sooner, which leads to "information superiority," ultimately enhancing warfighting capability.

Introduction

The Program Executive Office for Command, Control, Communications, Computers, and Intelligence (PEO C4I) Masterplan summarizes the major programs of the Department of the Navy (DoN) applicable to network operations, providing outlines of planned future capabilities, their major characteristics, and timelines for their implementation. It includes a mandate for fielded computer systems to be network-centric, service-based, and support open architectures. This will allow the Navy to field a rapid, adaptable warfighting network, easily tailored to the task at hand which will increase combat effectiveness. Implementation of this capability is limited by the network resources—specifically radio frequency (RF) communications bandwidth—which the Navy has at its disposal (PEO C4I, 2011). This means some network applications must take priority over others.

To understand the needs of the warfighter, this study looks at the centerpiece of U.S. naval strategy, the carrier strike group (CSG). Naval carriers are dynamic platforms equipped with a wide variety of systems which may be used for both combat and non-combat missions. The carrier is escorted by vessels equipped with sensors and weapons designed for battle at sea, each of them manned by technically proficient crews capable of not only naval combat but also disaster and humanitarian relief. Given the ability to reach distant locations in a timely manner and its operational flexibility, the CSG often provides the first American response to natural disasters both in the U.S. and abroad. As the central instrument of war and peace for the Navy, the CSG is an ideal place to start thinking about a prioritization scheme focused on the warfighter.

The Navy manages network Quality of Service (QoS) using the Automated Digital Network System (ADNS). The current network prioritization scheme implemented on ADNS is designed to optimize network performance based on application characteristics and does not rank applications based on their use by the warfighter in a combat environment. While this approach may work for a bandwidth-rich environment typically found in the civilian sector, it does not fully support the main purpose of Navy tactical networks, that is, warfighting.

In this study, we use the Capability-Based Competency Assessment (CBCA) suggested by Suttie and Potter (2008) to link CSG air detect-to-engage mission essential task lists (METLs) to the personnel and systems required to complete them. These competencies act as operational nodes on which the high-level architecture is developed using the Department of Defense Architectural Framework (DoDAF) Version 1.5 products to capture the roles and responsibilities of each of the individuals who make up a ship's air defense team.

The resulting prioritization scheme aligns operational nodes and services within the overall system architecture so that commanders are able to more effectively use existing network resources to accomplish required tasks within a compressed time frame. By linking the identified systems to the application types ADNS recognizes, we provide mission-specific justification for the prioritization of one network application over another. Finally, we develop a simulation model that captures the current Navy data processing environment. The model is used to compare our prioritization scheme to current network prioritization templates in the context of an air detect-to-engage scenario.

This study illustrates the use of an architectural model to align warfare commander's priority and intent with existing network capabilities and provides a common tool for communicating warfare commander's intent to those responsible for carrying out that intent. This approach should be used to help Navy networks achieve the warfighting capacity for which they were designed.

Current Bandwidth Allocation Scheme

Given the different roles and missions that the CSG is expected to support, flexibility in communications priorities is important. As air operations move from providing defense capability to enabling the movement of supplies and evacuation of the wounded, network priorities must be able to shift. This idea extends logically to varying tactical missions as well. The priorities during air defense operations are not the same as those during an anti-submarine scenario or even normal underway steaming. Clearly, the overall effectiveness of the CSG will be maximized by giving priority to mission-critical applications, which change as the mission changes.

The idea of mission-based network prioritization has not been lost on the fleet at large. There is an increased demand for the ability to modify QoS priorities, based on mission-specific tasking (Rambo, 2011). The goal is to reduce network response times and increase network throughput of the mission-critical information, thus providing more time for the commander to make the "right" choices, leading to increased mission effectiveness and less wasted network resources.

The Navy currently uses the Automated Digital Network System (ADNS) to allocate bandwidth at sea. Initially fielded in the late 1990s, ADNS works by routing outbound data from the ship through the various radio frequency (RF) paths available for its transmission. One of the important capabilities of ADNS is the delivery of basic QoS capability. QoS enables the network to make "smart" decisions when available network resources are overtaxed by the amount of information they are being required to route (Rambo, 2011).

ADNS has evolved over the years to improve bandwidth management and enhance QoS administration; however, there is still room for improvement. The current ADNS version, Increment Three (ADNS INC III), enables QoS through static application prioritization. ADNS works to mark data packets generated by these applications and then transmits them through a "packetshaper" that assigns a priority to the traffic being transmitted. These packets are then sorted into bins according to their assigned prioritization and transmitted accordingly. The prioritization scheme is determined by the Naval Cyber Forces (NCF) command and can only be modified through an extended process which is not subject to change by ship's force (Rambo, 2011).

Shipboard networks are divided into Top Secret/Sensitive Compartmentalized Information (TS/SCI), Secret, Unclassified, and separate Coalition classification enclaves. There is an additional enclave dedicated to network overhead and encryption. A "type of service" header is assigned within each classification enclave to route data packets generated by shipboard applications to various network queues. Each queue is allocated a minimum amount of bandwidth.

Once data packets have been routed to their appropriate queues, transmission is dictated by either First In First Out (FIFO)—that is, the first data packet to arrive is the first to leave—or by Cisco Weighted Random Early Detection (WRED). WRED works by having the network router (ADNS in this case) randomly drop IP packets being sent by applications. The dropping of packets signals that the network is congested, causing the applications that are generating the packets to slow down the rate of transmission. Although the dropping of packets is random, the probability of a drop is not. Applications assigned a higher priority have a lower probability of drop and thus, a higher throughput. Additionally, if applications are not utilizing the minimum bandwidth allowed, that bandwidth is shared with other applications.

The prioritization in ADNS is done via a formal submission process and the application priority is validated by Naval Cyber Forces (Rambo, 2011). Given the changing priorities of separate mission areas, it is imperative that shipboard personnel be able to assign prioritizations dynamically to shipboard network services. This need continues to grow as the Navy's Consolidated Afloat Networks and Enterprise Services (CANES) system is fielded.

CANES will serve to consolidate and replace five existing legacy networks afloat. These systems include the Integrated Shipboard Network System (ISNS), Sensitive Compartmented Information (SCI) Networks, and Combined Enterprise Regional Information Exchange System Maritime (CENTRIXS-M). Using the Service-Oriented Architecture (SOA)[1] concept, CANES will eliminate redundant legacy hardware and replace them with a single, consolidated system. According to the CNO's CANES Initial Implementation and Action Message, DTG 071927Z DEC 09, all shipboard systems that will be fielded after the implementation of CANES must be compatible with the new common network hardware.

[1] Lund et al. (2007) defined Service-Oriented Architecture (SOA) in the military context as "a way of making military resources available as services so they can be discovered and used by other entities that need not be aware of those services in advance."

This single, common computing environment will provide the necessary framework to implement QoS at a higher level of granularity.

The Capabilities-Based Competency Approach

The Capabilities-based Competency Assessment (CBCA) was developed at the Naval War College for manpower analysis. It seeks to identify functional roles working within a team construct versus looking at billets and shipboard occupations. Functional roles are linked to "subtasks" which together define the complete mission-level tasking. The major distinction of CBCA is the focus on capability versus a set of competencies (Suttie & Potter, 2008). Once the *capability* inherent to the role is understood, its relationship to other roles working in the total system can be comprehended.

Unlike the traditional, billet-based allocation of personnel, CBCA links METLs to the personnel and systems required to complete them. It defines "roles" which act as critical nodes that correspond to a DoDAF Operational Node Connectivity Description (OV-2; Suttie, 2011) of the overall operational architecture. These roles are capability based and independent of the personnel assigned to complete them.

This study uses the CBCA approach by first identifying METLs related to a CSG air detect-to-engage scenario. The METLs are then used to describe a set of competencies including operations, personnel, and system requirements inherent to air defense operations. The Service-Oriented Architecture framework is formed by assigning METLs to the operational nodes responsible for their execution. These relationships can be captured in a DoDAF Operational Activity Model Description (OV-5). This model is completed in conjunction with a DoDAF Systems Functionality Description (SV-4), which not only captures the decomposition of the top-level activity, but also identifies the systems used to enable functionality. Finally, the relationships between the operators, their responsible actions, and the systems used to complete those actions are captured via a DoDAF Operational Activity to Systems Function Traceability Matrix (SV-5a). By doing so, the relationships between the operational nodes and the systems that each node uses to accomplish those tasks are identified.

These products are used to understand the relationships between operator and machine and allow the warfare commanders to assign the correct prioritization to the systems at their disposal. Once form has been matched to function, it is possible to understand which nodes and, as a result, which systems are needed to complete an aggregate task. This process provides justification and realization of the most beneficial arrangement for network prioritization. By assigning the highest level of prioritization to those network applications needed to accomplish mission-appropriate tasking, a strike group's network resources are used to their fullest capability. The performance of all other systems that are not crucial to the completion of the assigned tasking should be sacrificed in order to benefit those that are imperative.

Defining the Operational Nodes

Before system prioritization can take place, the users that will operate the system must be identified. For the CSG air detect-to-engage scenario, this is accomplished using a DoDAF OV-2 diagram showing the relationships between a single air-defense unit (ADU) and the off-ship warfare commanders and coordinators (see Horton, 2012, p. 23). The next step is to identify the tasks associated with each user related to air defense operations. These tasks can be found in the Navy's Universal Naval Task List (UNTL) discussed in the next paragraph.

The UNTL describes tasks that can be completed by naval forces. The UNTL is used by commanders to determine what tasks can be accomplished by the naval elements under their commands. METLs are derived from this list and are used to support a commander's assigned mission. They serve as a command's list of tasks that are considered essential for mission accomplishment (Chief of Naval Operations, Commandant, U.S. Marine Corp, Commandant, U.S. Coast Guard, 2007). The UNTL is subdivided into separate task levels for each level of warfare. The prefix for tactical level tasks is TA, thus naval tasks at the tactical level are known as Navy Tactical Tasks (NTA). An examination of the UNTL reveals which NTA's are relevant to air defense. By using the descriptions provided in the UNTL for each NTA, it is possible to compile a list of those tasks which are related to air defense (see Horton, 2012, p. 34).

A DoDAF OV-5 describes the operations required to complete a mission and shows the flow between operational activities. The model is constructed by taking each of the NTAs identified as relevant to air defense operations, establishing a hierarchy of those tasks, and mapping each NTA to the operational node responsible for its completion (see Horton, 2012, p. 36).

Having identified the operational activities involved in the process of conducting air defense and linking each of these activities to the operational node responsible for their completion, the next step is to identify the information systems that each of those operational nodes require to complete their assigned tasking. Linking the form to function will provide the justification for our prioritization scheme.

Identifying Systems Required for Air Defense Operations

The Command, Control, Communications, Computers, and Intelligence (C4I) Masterplan serves to summarize the major attributes of DoN network-centric systems. The Masterplan provides C4I system baselines for each type of ship, including carriers and ships assigned to the CSG. These baseline descriptions may be used to identify systems which communicate via ADNS. By using the system descriptions presented in the C4I Masterplan, a list was developed of those systems required to conduct air defense operations (Table 1).

It should be noted that while the systems chosen provide a good representative sample of those systems which may be used in air-defense operations, this list should by no means be considered exhaustive. The C4I Masterplan provides only system overviews and does not give detailed explanations of each system and its capabilities. In order to correctly identify each relevant system, subject matter experts on each would need to be consulted, and personnel familiar with the entire C4I portfolio would need to compile an exhaustive list. For purposes of this study, however, it is sufficient to include these systems to illustrate our approach.

Table 1. Air Defense Net-Centric Systems
(adapted from PEO C4I, 2011)

System Name	Description	Ship Type
Ship's Signal Exploitation Equipment (SSEE) Increment E/F	Provides: 1) Direction finding (DF) 2) Signal acquisition 3) Hostile Forces Integrated Targeting Service (HITS) 4) Digital Receiver Technology (DRT) geolocation capability 5) Integrated signal analysis and select National Security Agency (NSA) applications via the Cryptologic Unified Build (CUB) toolbox	CVN, CG, DDG
AN/USQ-172(V)10 Global Command and Control System–Maritime (GCCS–M)	Provides: 1) Unit location and amplifying information 2) Fuses, correlates, filters, maintains, and displays location and attribute information on friendly, hostile, and neutral land, sea, and air forces, integrated with available intelligence and environmental information to develop Common Operational Picture (COP) 3) Aides decision-maker	CVN, CG, DDG
Distributed Common Ground System–Navy (DCGS–N)	Provides: 1) Integrates shared intelligence data, information, and services between various intelligence and decision-making entities 2) Distributable intelligence products	CVN
Naval Integrated Tactical Environment System, Variant IV (NITES–IV)	Provides: 1) Operational and tactical METOC support to Navy, Marine Corps, and Joint Forces engaged in worldwide operations, ashore and afloat 2) Distributes gathered meteorological data	CVN

Using these systems, we can capture the capabilities each one provides. This is accomplished using a System Functionality Description. The DoD (2007) guidance in *Architecture Framework, Version 1.5, Volume II*, defines a System Functionality Description (SV-4a) as documenting system functional hierarchies and system functions and how data flows between them. A System Functionality Description for air defense is constructed by taking each of the systems identified as relevant to air defense operations and breaking them down to their required functionality. The relationships between those systems are then mapped, providing the structure of the viewpoint (see Figure 1).

Having now identified the functionality that each air-defense unit provides, we are ready to link the system function to the operational tasks we previously identified. This is accomplished using a Systems Functional Traceability Matrix, as described in the next section.

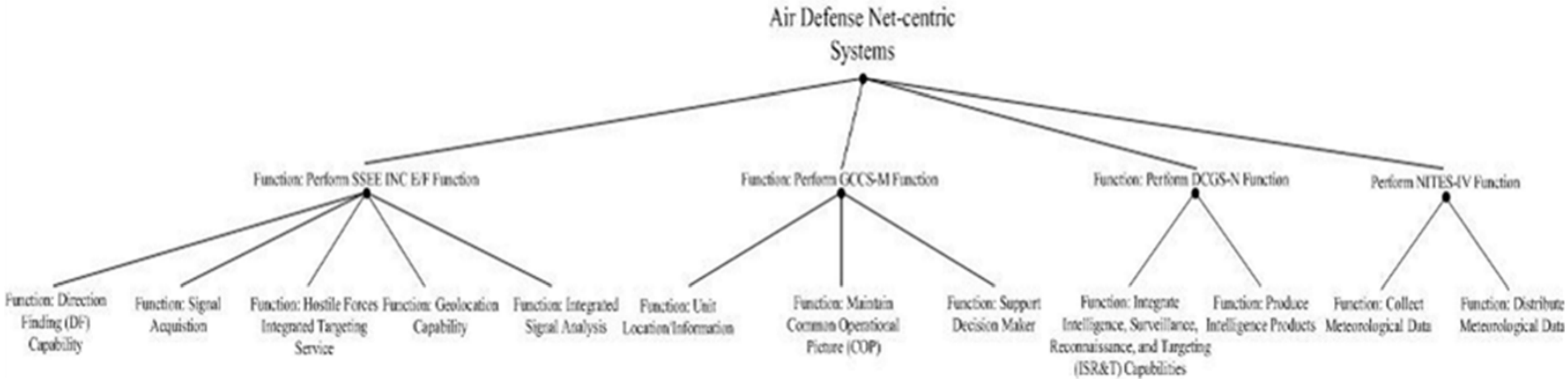

Figure 1. Conduct Air Defense (DoDAF SV-4a) System Functionality Description

Linking Operational Activities to Systems Functions

A Systems Functional Traceability Matrix (DoDAF SV-5a) documents the relationship between the operational activities and system functionality present in the overall architecture (see Table 2). Those systems which are being used by an operator to complete a task are indicated with an X in Table 2. For now, only those systems that connect to the Global Information Grid (GIG) via an Internet Protocol (IP) pipeline have been mapped. As new systems are fielded to be deployed on CANES, this diagram would need to grow to include them. The dashed area indicates that those systems are not currently available for those users.

By identifying the systems used by operators to complete assigned tasks, it is possible to identify the systems most useful to a mission, in this case, air operations. These are the systems which should be given priority in an air detect-to-engage scenario. This methodology can be applied to any given mission or tasking.

Each information system has now been linked to the task associated with its use, and each task has been linked to the operator who completes that task. Our proposed prioritization scheme will place each of the identified systems at the top of the priority scheme. A comparison of the current priority scheme and our proposal will be outlined in the next section.

Table 2. Conduct Air Defense SV-5a, Systems Function Traceability Matrix

OPERATIONAL ACTIVITIES		SYSTEM FUNCTIONS: NITES - IV		DCGS-N		GCCS-M			SSEE INC E/F				
		2) Distribute Meteorological Data	1) Collect Meteorological Data	2) Produce Intelligence Products	1) Integrate Intelligence, Surveillance, Reconnaissance, and Targeting Capabilities	3) Support Decision Maker	2) Maintain Common Operational Picture	1) Unit Location Information	5) Integrated Signal Analysis	4) Geolocation Capability	3) Networks Forces Integrated Targeting Service	2) Signal Acquisition	1) Direction Finding (DF) Capability
BW	NTA 5 - Exercise Command and Control					X	X	X					
BW	NTA 5.1 - Acquire, Process, Communicate Information and Status	X	X	X	X				X	X	X	X	X
BW	NTA 5.2 - Analyze and Assess Situation			X	X	X	X	X					
BW	NTA 5.4 - Direct, Lead, and Coordinate Forces					X	X	X					
BW	NTA 6 - Protect the Force												
BW	NTA 6.1 - Enhance Survivability												
BW	NTA 6.1.1 - Protect Against Combat Area Hazards												
BW	NTA 6.5 - Perform Consequence Management												
IQ	NTA 2 - Develop Intelligence	X	X	X	X	X	X	X	X	X	X	X	X
IQ	NTA 2.1 - Plan and Direct Intelligence Operations			X	X								
IQ	NTA 2.2 - Perform Collection Operations and Management			X	X				X	X	X	X	X
IQ	NTA 2.3 - Process and Exploit Collected Information and Intelligence			X	X								
IQ	NTA 2.4 - Conduct Analysis and Produce Intelligence	X	X	X	X	X	X	X					
IQ	NTA 2.5 - Disseminate and Integrate Intelligence			X	X	X	X	X					
IQ	NTA 2.6 - Evaluate Intelligence Operations			X	X								
IQ	NTA 5.5 - Conduct Information Warfare (IW)								X	X	X	X	X
FOTC	NTA 6.1.1.3 - Positively Identify Friendly Forces					X	X	X					
CO	NTA 3 - Employ Firepower												
CO	NTA 6.5.2 - Coordinate Damage Control Operations												
TAO	NTA 3.1 - Process Targets					X	X	X					
TAO	NTA 3.2 - Attack Targets												
AAWC	NTA 2.2.1 - Collect Target Information												
AAWC	NTA 3.2.7 - Intercept, Engage, and Neutralize Enemy Aircraft and Missile Targets (Defensive Counter Air)												
EW	NTA 2.2.3 - Perform Tactical Reconnaissance and Surveillance								X	X	X	X	X
EW	NTA 3.2.5 - Conduct Electronic Attack												
EW	NTA 5.5.4 - Conduct Electronic Warfare Support (ES)								X	X	X	X	X
ISC	NTA 3.1.5 - Conduct Tactical Combat Assessment												

Quality of Service Model

Quality of Service (QoS) management for shipboard IP networks is implemented by marking IP packets using the “type of service” (ToS) header field. The Automated Digital Network System (ADNS) uses the first six bits within the header to mark each packet with a Differentiated Services Code Point (DSCP; Automated Digital Network System, 2011). These DSCP markings can be used to separate network traffic into class bins which can be used to implement separate controls in off-ship transmission. The routing of packets is done without regard for the security level classification.

To test the effectiveness of a prioritization scheme in the current Navy environment, we need to model the DSCP process used by ADNS. A stochastic simulation was developed using the *ExtendSim 8* software to model this process. Figure 2 shows the basic outline of the model that will be used to aid discussion of QoS implementation within ADNS. It is important to note that our simulation focuses on how prioritization schemes impact data throughput and latency within the context of the air detect-to-engage scenario. We are not modeling the events that might occur in the scenario, but rather using the scenario to understand the expected information requirements and data traffic within each phase of an air detect-to-engage (DTE) scenario.

ADNS separates network traffic into five separate Community of Interest (COI) local area networks (LANs). They are SECRET, TS-SCI, UNCLASS, CENTRIXS (coalition), and an additional classification for Cipher Text Core Traffic (Automated Digital Network System, 2011) and are shown on the left side of Figure 2. Each LAN is comprised of various IP-based network applications which are classified according to queuing doctrine, such as First-In, First-Out (FIFO) or Class-Based Weighted Fair Queuing (CBWFQ). These applications are listed within the *Traffic Classes, Packet Marking, and Priority Processing* documentation provided by the Program Manager, Warfare (PMW) 160 Office.

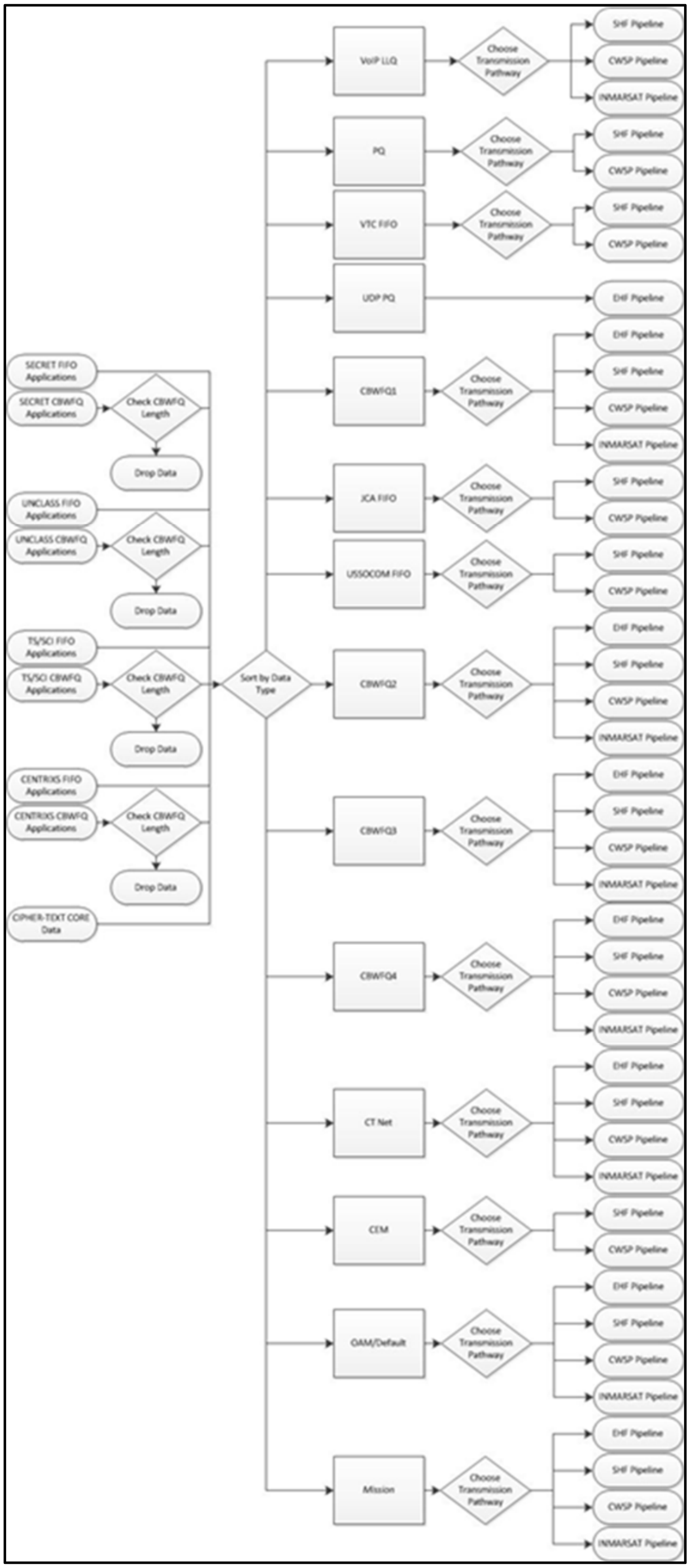

Figure 2. Flow Diagram Representation of ExtendSim 8 Model

Each of the applications which comprise the COI LANs is represented in our model by a block that creates "packets" at a random interval. Mean inter-arrival time for each type of application varies depending on the type of service it performs, as shown in Table 3.

Table 3. Application Type Inter-Arrival Parameters

Application Type		Mean Inter-Arrival Period	Standard Deviation
Video		33 ms	1 ms
VoIP		100 ms	10 ms
Data		200 ms	20 ms
Network Overhead		50 ms	1 ms

The inter-arrival periods were modeled using a normal distribution, bounded by zero on the left side, with a standard deviation, as indicated in Table 3. Although network traffic behavior is usually "bursty" and the inter-arrival times are not typically normally distributed, we chose the normal distribution for simplicity. In addition, we use a "worst case" scenario in which every application is creating the maximum amount of data possible, with 1,500 bytes per packet. While the two simplifying assumptions introduced in our model would most likely not occur in real-life, they facilitate comparison of prioritization schemes and limit the number of independent variables in the model.

Each of the packets generated in the simulation was marked with a priority based upon the type of information it is carrying. This marking allows for the packet to be routed to one of the fourteen separate queues, as shown in Figure 2. ADNS currently specifies 13 different queue types, based upon network application behavior (Automated Digital Network System, 2011). We introduce a 14th *Mission Queue* which is reserved for those applications deemed most relevant to air defense operations based on our previous analysis. This is the simplest way to test our proposed prioritization scheme against the existing ADNS scheme. Actual implementation of the prioritization scheme by the Navy might differ based on network configuration and other considerations.

The model is designed to incorporate only those bandwidth pipelines available to a particular class of ship. Thus, CVNs will be allowed the CWSP, SHF, and EHF pipelines, and DDGs and CGs will be allowed the SHF, EHF, and INMARSAT pipelines. The model works to balance the load between each of the transmission pipelines available to each queue type shown in Figure 2.

The model checks each time step to see which queues require bandwidth and which do not. It will first subtract that amount of bandwidth that has been assigned to the queues that currently require it from the total amount of bandwidth available. Then it will parse out the remaining bandwidth following the same percentage assignment schedule as outlined in the *Traffic Classes, Packet Marking, and Priority Processing* documentation provided by the PMW 160 Office.

ADNS uses two methods for the queuing doctrine applied to each queue. First, applications which are weighted equally within the same queue are handled by a FIFO methodology. Second, applications which are weighted differently, though routed to the same queue, are handled using CBWFQ with Weighted Random Early Detection (WRED). CBWFQ will route those packets with a higher priority at the expense of those with a lower priority. This is accomplished by randomly dropping lower priority packets once a queue has reached a pre-determined length. In our model, we sample the current queue length for each time step. If the sampled queue length falls within the set boundaries, packets are dropped according to scheduled packet drop probability.

Within ADNS, random dropping denies the originating application a receipt acknowledgment and forces the application to retransmit the packet. Eventually, this causes the originating application to slow down its transmission rate, allowing higher priority applications to transmit at a faster rate (Automated Digital Network System, 2011). In our model, this metric is captured by measuring the amount of packets that actually were transmitted and comparing that value to the amount of packets that were created. This gives a percentage of actual throughput and will be used as a measure to compare the effectiveness of a given priority scheme as it applies to mission-specific applications.

Results and Conclusion

The simulation model was designed to measure latency and throughput. Latency refers to the timeliness of data. By recording latency, we gain an understanding of how long it takes for data to be created, routed, and then transmitted. Throughput refers to how much of the data created is actually transmitted in the time allowed. Throughput is an indicator of the quality of the transmission.

The air detect-to-engage scenario consists of three stages—surveillance, escalation, and terminal. During the surveillance phase, there is no threat and normal air defense operations are in effect. The surveillance phase provided baseline measurements of latency and throughput using current ADNS settings. Average percent throughput and latency for both the carrier (CVN) and the cruiser/destroyer (CRUDES) escorts over a total of 30 runs were recorded.

Next we modeled the escalation phase. During this phase, the strike group receives indications of a pending attack on the high value unit (HVU). In response, the strike group commander will probably increase the threat warning posture which brings the force to a higher state of readiness in preparation for a possible attack via the air. To support this condition, we propose the prioritization scheme shown in Table 4 because it prioritizes the systems designed to aid anti-air warfare.

The bandwidth percentages assigned to each queue are intended to minimize latency and maximize throughput of systems relevant to air defense, while minimizing the impact to other systems. It should be noted that these percentages are notional, but should be selected so that they support the information needs of the commander.

Table 4. CBCA Bandwidth Allocation Scheme—Escalation Phase

Escalation Phase				
	CWSP	SHF	EHF	INMARSAT
Group 1	33%	19%	N/A	N/A
CEM	15%	25%	N/A	N/A
VTC	12%	12%	N/A	N/A
JCA	18%	12%	N/A	N/A
SECRET (CBWFQ1)	12%	7%	27%	17%
UNCLAS (CBWFQ2)	6%	4%	12%	7%
CENTRIXS (CBWFQ3)	6%	4%	12%	4%
SCI (CBWFQ4)	13%	5%	17%	14%
Other				
VoIP (LLQ)	384 kbps	384 kbps	N/A	57 kbps
PQ (FMV)	10%	10%	N/A	N/A
UDP	N/A	N/A	10%	N/A
USSOCOM	24%	24%	N/A	N/A
CTNet (CONTROL)	1%	1%	2%	2%
OAM/Default	11%	25%	5%	41%
Mission	21%	21%	15%	15%

Table 4 shows the queues currently utilized with the ADNS (Automated Digital Network System, 2011) as well as a Mission queue that implements our prioritization scheme. The four columns presented in Table 6 represent the four transmission paths available to the strike group ships: Commercial Wideband Satellite Program (CWSP)—CVN only, Super High Frequency (SHF), Extremely High Frequency (EHF), and International Maritime Satellite (INMARSAT)—CRUDES only (Automated Digital Network System, 2011). The values in each block represent the percentage of bandwidth available on each transmission path, that is, column, applied to each queue, that is, row, with the exception of Voice over Internet Protocol (VoIP), which is a flat amount.

In the escalation phase, we assume that the traffic output of systems relevant to air defense would increase due to the now-present threat and the information being gathered about it. For modeling purposes, we doubled the data output in this phase. The average latency (milliseconds) and throughput (percentage) over 30 runs was recorded and compared with latency and throughput for each data type for each prioritization scheme.

The third phase of evaluation is the terminal phase. During this phase, the inbound threat has fired its weapon at the HVU, prompting the commander to further escalate the strike group’s readiness posture. To support this condition of readiness, we propose the prioritization scheme shown in Table 5. The bandwidth percentages selected for this phase reflect an increased amount of air-defense relevant network traffic. Again, percentages are notional. Actual percentages would be based on the commander’s priority and intent.

Table 5. CBCA Bandwidth Allocation Scheme—Terminal Phase

Terminal Phase				
	CWSP	SHF	EHF	INMARSAT
Group 1	30%	15%	N/A	N/A
CEM	15%	25%	N/A	N/A
VTC	12%	12%	N/A	N/A
JCA	18%	12%	N/A	N/A
SECRET (CBWFQ1)	12%	7%	25%	15%
UNCLAS (CBWFQ2)	6%	4%	11%	7%
CENTRIXS (CBWFQ3)	6%	4%	10%	4%
SCI (CBWFQ4)	13%	5%	15%	13%
Other				
VoIP (LLQ)	384 kbps	384 kbps	N/A	57 kbps
PQ (FMV)	10%	10%	N/A	N/A
UDP	N/A	N/A	10%	N/A
USSOCOM	22%	22%	N/A	N/A
CTNet (CONTROL)	1%	1%	2%	2%
OAM/Default	10%	25%	5%	37%
Mission	27%	27%	22%	22%

The data output of the air defense applications was again effectively doubled—now four times the initial value, assuming that the traffic output of those applications would increase significantly during the terminal phase.

Independent two-sample, single-tailed Student t-tests were conducted to determine whether there is a statistically significant difference between the baseline latency and throughput and the latency and throughput using our prioritization scheme. The results are shown in Tables 6–9.

Table 6. CARRIER Latency Hypothesis Test Results

CARRIER LATENCY HYPOTHESIS TEST						
APPLICATION NAME	PHASE	H_o	H_a	t_{obsv}	t_{crit}	Reject H_o
High Priority Applications	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	153.023	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	95.038	1.672	Yes
GCCS-M, NETPREC	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	84.214	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	123.864	1.672	Yes
Time Sync, Chat, Cop, HFDF	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	162.315	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	30.383	1.672	Yes
Email, CERCIS, OS/BD, PARA126,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	128.046	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	29.111	1.672	Yes
Name Resolution, Encryption, File	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	190.009	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	27.310	1.672	Yes
EVCP, Big Brother, ISRT	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	210.461	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	26.628	1.672	Yes

Table 7. CRUDES Latency Hypothesis Test Results

CRUDES LATENCY HYPOTHESIS TEST						
APPLICATION NAME	PHASE	H_o	H_a	t_{obsv}	t_{crit}	Reject H_o
High Priority	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	101.763	1.672	Yes
Applications	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	56.621	1.672	Yes
GCCS-M, NETPREC	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	99.548	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	53.294	1.672	Yes
Time Sync, Chat,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	173.293	1.672	Yes
Cop, HFDF	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	55.064	1.672	Yes
Email, CERCIS,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	174.240	1.672	Yes
OS/BD, PARA126,	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	57.352	1.672	Yes
Name Resolution,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	157.239	1.672	Yes
Encryption, File	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	60.639	1.672	Yes
EVCP, Big Brother,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	161.854	1.672	Yes
ISRT	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	51.898	1.672	Yes

Table 8. CARRIER Throughput Hypothesis Test Results

CARRIER THROUGHPUT HYPOTHESIS TEST						
APPLICATION NAME	PHASE	H_o	H_a	t_{obsv}	t_{crit}	Reject H_o
High Priority	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	1.015	-1.672	No
Applications	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-1.172	-1.672	No
GCCS-M, NETPREC	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	0.448	-1.672	No
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-0.685	-1.672	No
Time Sync, Chat,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-3.247	-1.672	Yes
Cop, HFDF	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-21.000	-1.672	Yes
Email, CERCIS,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-1.206	-1.672	No
OS/BD, PARA126,	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-22.156	-1.672	Yes
Name Resolution,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-3.808	-1.672	Yes
Encryption, File	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-21.693	-1.672	Yes
EVCP, Big Brother,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-2.424	-1.672	Yes
ISRT	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-22.553	-1.672	Yes

Table 9. CRUDES Throughput Hypothesis Test Results

CRUDES THROUGHPUT HYPOTHESIS TEST						
APPLICATION NAME	PHASE	H_o	H_a	t_{obsv}	t_{crit}	Reject H_o
High Priority	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	8.063	-1.672	No
Applications	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-1.514	-1.672	No
GCCS-M, NETPREC	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-9.655	-1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-1.472	-1.672	No
Time Sync, Chat,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-427.218	-1.672	Yes
Cop, HFDF	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-158.074	-1.672	Yes
Email, CERCIS,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-445.372	-1.672	Yes
OS/BD, PARA126,	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-158.543	-1.672	Yes
Name Resolution,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-387.054	-1.672	Yes
Encryption, File	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-169.129	-1.672	Yes
EVCP, Big Brother,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-373.809	-1.672	Yes
ISRT	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-160.739	-1.672	Yes

We note that there is a statistically significant decrease in the average latency associated with each of the selected applications using our prioritization scheme as compared to default ADNS settings. Our results also indicate statistically significant increases in throughput using our prioritization scheme for most applications; however, there is no significant difference for some applications. We note decreases in percent throughput for the *High Priority Applications* data types for both the CARRIER- and CRUDES-type ships during the Escalation Phase as well as GCCS-M, NETPREC data types for the CARRIER during the Escalation Phase when using our prioritization scheme. This decrease in percent throughput is offset by marked decreases in associated latency which should be taken into consideration when implementing our process for network prioritization.

An important question is whether the differences noted in Tables 6–9 are practically significant. One of the primary reasons for the selection of the air detect-to-engage scenario is that time is often at a premium. For example, consider the time savings for the CRUDES class ships during the terminal phase of engagement. Our prioritization scheme saves on average, approximately 9s in time delays for our selected applications as compared to the default ADNS prioritization scheme. In order to understand the importance of this time savings, we use the cruising speed of a typical hostile missile, the C-801 (595 knots). Using the formulas for time distance, we see the actual distance the missile may travel in this allotted time is almost one and a half nautical miles.

$$
\begin{aligned}
d &= vt \\
d &= (0.165 nmi/s)(9s) \approx 1.486 nmi
\end{aligned}
\tag{1}
$$

So ultimately, what does the time/distance savings buy us? As the Navy becomes more and more net-centric, more shipboard systems will be used in the identification and prosecution of hostile targets. Every millisecond we save in the transmission of data results in increased ranges at which we may engage hostile targets. This means more time for human decision-makers to draw conclusions and more opportunities for us to put ordnance on target. In their book, *Human Factors in Simple and Complex Systems*, Proctor and Van Zandt (2008) defined a reaction-time task as that which requires a person to respond to a stimulus as quickly as possible. They highlighted recent work conducted in continuous information accumulation. They noted that the fastest possible human reaction to visual stimuli is 150 ms. This reaction time slows linearly, following a log2 scale, with the number of possible stimuli and responses available to the operator.

If we assume the previously described mean reaction time, we see that the time savings described in this paper are within the threshold of human reaction. This is critical as it allows for an actual physical response by a human operator. The more the latency of our selected data is reduced, the more time the human decision-maker has to react to the visual stimulus. This impact is even more pronounced if we consider the near instantaneous reaction time of automated systems. Given an autonomous response capability, milliseconds saved in transmission time can directly translate to whether an enemy target may be destroyed in the allotted time or if it will strike its intended target.

We have demonstrated a process that seeks to align system prioritization with operator needs based upon mission tasking. We accomplish this by linking operational tasking to warfighters and identifying those systems used by the warfighters to accomplish said tasking. Our work may be seen as a guideline for the development of network prioritization schemes which seek to optimize Navy networks for combat and are in keeping with the philosophy of net-centric warfare (NCW). Ideally, this approach will help strike group commanders see their networks as true weapon systems and help bring to the forefront those network systems relevant to the mission-at-hand.

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