The Ninth International

Command & Control Research and Technology Symposium

Paper Title:

Utilizing Network-Enabled Command and Control Concepts to Enhance ASW Effectiveness

Topical Areas:

Network Centric Operations Transformation
Network Centric Applications
C2 Modeling and Simulation
C2 Assessment Tools & Metrics

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Abstract

This report describes an analysis of two selected concepts for improving Anti-Submarine Warfare (ASW) performance and effectiveness by means of network-enabled sharing of information during ASW operations. These concepts are identified as Shared Situational Awareness (SSA) and Collaborative Information Environment (CIE). It is shown that the application of queueing theory models provide useful tools for quantitatively estimating the value-added of implementing these concepts. In addition, queueing theory can be used to examine the tradeoffs between "information systems" and "shooters." In general, queueing theory can support analysis whenever military operations, such as ASW, can be characterized as "demand for service" processes. For the SSA and CIE concepts, an ASW tactical situation (TACSIT) is described and then metrics are defined and quantified by means of queueing models. Insights, conclusions and recommendations are then developed from the parametric quantitative results about the potential improvements to ASW performance and effectiveness achievable through implementation of these network-enabled concepts.

Executive Summary

Introduction

There have been a number of studies written about the perceived benefits of network-centric warfare (NCW), but few of these studies have taken an analytical view, and produced quantitative results. Given the variety of opinion in the literature, and the military interest in network-centric concepts, the five allied countries (Australia, Canada, New Zealand, United Kingdom and United States) of "The Technical Cooperation Program (TTCP)," Maritime Systems (MAR) Group, Action Group One (AG-1) decided to initiate, in 2001, a network-centric maritime warfare (NCWM) study to redress the lack of quantitative evidence and to help provide guidance on network-centric capability investments in their respective countries.

The mandate of MAR AG-1 is to study and measure the impact of NCW, and to provide guidance on NCW issues to the MAR Group.

This paper reports on possible network-enabled improvements to Anti-Submarine Warfare (ASW) performance and effectiveness. In particular, the analysis addresses the following two hypotheses:

1. In coalition force ASW, network-enabled Shared Situational Awareness (SSA) can reduce false contact loading, by means of data correlation and fusion of the information obtained and provided by individual search elements, and thereby improve search effectiveness.

2. Sensor operators in a Collaborative Information Environment (CIE) can reach-back to ASW experts to improve classification performance against both target and non-target contacts.

AG-1 used two US-developed queueing models that incorporate reneging (leaving a queue after entry) and balking (inability to enter a queue) to execute the computations needed to quantitatively analyze these hypotheses.

Findings

In this study, we show, using queueing theory and the analysis of two tactical situations (TACSITs), that network-centric concepts can enable SSA and CIE. Both SSA and operator-expert collaboration in a CIE are shown to improve ASW performance and effectiveness. Evidence supporting the two hypotheses is provided and specific war fighting findings are:

1. Improving classification performance against both benign contacts and targets of interest can increase ASW effectiveness. In effect this reduces the arrival rate of benign contacts, which thereby increases the probability of acquiring targets of interest.

2. An accurate surface picture, shared among the ASW units, could improve ASW effectiveness. Networking the force for information transfer is a key

enabler of this aspect of SSA. Real-time connectivity between force elements is needed.

3. Networking the force can enable a CIE, which through the increase of classification performance might increase the probability of ASW success. Synchronous collaborative tools are needed to enable this collaboration.

Significance

NCW is a high-level war-fighting concept that has generated a great deal of debate. While the implementation of networks will happen, the character and use of these networks can vary widely. The work in this study is a first step in developing the processes and methodologies required to quantitatively analyze NCW in terms of war-fighting effectiveness. One of the main results is the requirement for NCW to be refined into operational and tactical applications. Quantitative linkage of NCW to war-fighting effectiveness is not possible in any meaningful way if this does not happen.

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Glossary

Term	Meaning
ACINT	Acoustic Intelligence
AR	Arrival Rate
ASuW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
CI	Contact Investigation
CIE	Collaborative Information Environment
C4I	Command, Control, Communications, Computer and Intelligence
CRN	Contact Refinement Node
CSG	Carrier Strike Group
ESG	Expeditionary Strike Group
IG	Inverse Gaussian
ISR	Intelligence, Surveillance and Reconnaissance
LCS	Littoral Combat Ship
MIO	Maritime Interception Operations
NCASW	Network-Centric ASW
NCMW	Network-Centric Maritime Warfare
NCW	Network-Centric Warfare
RBC	Reach-Back Cell
SA	Situational Awareness
SSA	Shared Situational Awareness
TACSIT	Tactical Situation
TDA	Tactical Decision Aids
TOI	Target of Interest

1 INTRODUCTION

1.1 Administrative Background

The five allied countries (Australia, Canada, New Zealand, United Kingdom and United States) of “The Technical Cooperation Program (TTCP)”, Maritime Systems (MAR) Group, Action Group One (AG-1), have undertaken, beginning in 2001, a collaborative study to investigate the broad issues and concepts of Network-Centric Warfare (NCW), referred to herein as Network-Centric Maritime Warfare (NCMW) for maritime operations. The study also intends to quantify the value-added of networking in coalition force maritime operations, in order to help shape the TTCP countries’ respective national acquisition strategies. This analytic study is designed to provide MAR Group and national customers with guidance on the implications of NCMW for coalition maritime force capabilities and enabling interoperable Command, Control, Communications, Computer and Intelligence (C4I) capabilities.

In addition to the clear benefits derived from the five allied countries participating in this study, the conduct of this study also supports the Network Centric initiatives of the United States Department of Defense and the United States Navy. Specifically, this study is a first step in laying out a process for the rigorous analysis called for by the Assistant Secretary of Defense for Networks and Information Integration (ASD NII) in *Information Superiority: Making the Joint Vision Happen* and also called for by the Director of Force Transformation in *Network Centric Warfare: Creating a Decisive Warfighting Advantage*.

The rigorous analysis conducted in this study also supports the *Department of Defense Net-Centric Data Strategy* and the *Department of Defense Joint Net Centric Capabilities* initiatives articulated by ASD NII in May and July of 2003 respectively. While this study was conducted, and this report prepared, in a coalition context, the results can be readily extrapolated for national needs of any nation. For the United States, in particular, given the Department of Defense and Department of the Navy increasing emphasis on Return on Investment, this study provides one way ahead to determine the value of networked forces and may assist the DoD and DoN in selecting the appropriate metrics to influence Return on Investment decisions.

There have been a number of reports written about the perceived benefits of NCW, but few studies have taken an analytical view, and produced quantitative results [5]. Given the variety of opinion in the literature and the military interest in network-centric concepts, TTCP MAR AG-1 decided to conduct a NCW study to redress the lack of quantitative evidence and to assist in providing guidance on network-centric capability investments. In order to address unique national interests, as well as study issues of breadth and depth, this study was broken down into two major component studies, simply titled: Study A and Study B. The AG is to complete its work by September 2004.

Study A is an assessment of the broad issues and concepts in NCMW. A number of broad issues papers including a “first principles” paper are being written to help define what NCMW means to coalition warfare, and to survey a broad range of applicable operational research tools (e.g., queueing theory, Petri nets, agent-based models) that may be useful in the analysis of NCMW [1]. Study A will also conduct an analytical investigation into the effects of net-centricity on operational issues such as Intelligence, Surveillance and Reconnaissance (ISR) and force-level collaborative planning.

Study B is an assessment of tactical level NCMW issues, with an in-depth analysis of NCMW in various littoral maritime tactical situations (TACSITs). Specifically, three maritime warfare TACSITs were studied: (1) Maritime Interception Operations (MIO), (2) Anti-submarine Warfare (ASW), and (3) Anti-surface warfare (ASuW)/Swarm attack [6].

This report is specifically concerned with the analysis of the Study B ASW TACSIT. Ultimately, this study is intended to provide guidance, identify investment options, and help shape acquisition strategy within each TTCP nation regarding the merits of networking and network-centric capabilities in coalition force maritime operations.

1.2 Overview

NCMW consists of military operations that are enabled by appropriately linking elements of the maritime force. Connectivity among appropriate force components is an essential ingredient for achieving this enablement. However, more than just connectivity is needed. New concepts for conducting maritime warfare also need to be developed. Two of these concepts, Shared Situational Awareness (SSA) and a Collaborative Information Environment (CIE), have been identified for ASW applications, and are explored herein.

The ability to support SSA and CIE are two expected benefits of networking the maritime force. Particular instantiations of these benefits are expected to be important for improving the effectiveness of ASW.

Situational Awareness (SA), in essence, means knowing what is going on within a volume of space and time. Then, SSA means that two or more individuals understand a particular circumstance in the same way [7]. In this study we examine the possibility of using network-enabled SSA to reduce false contact loading in ASW to increase ASW effectiveness.

A CIE is the aggregation of infrastructure, capabilities, people, procedures, and information to create and share the data, information, and knowledge that enables collaboration among a selected group of individuals or organizations [8]. In this study we examine the possibility of using a CIE to connect individual forward deployed ASW sensor operators with an ASW expert, such as an ashore Acoustic Intelligence (ACINT) expert, in order to augment operator expertise, enhance operator performance, and mitigate the relatively poor target vs. non-target classification performance of some sonar operators.

We found that the aspects of SSA and CIE, as just described, could be analyzed using queueing theory [9]. In fact, any “demand-for-service” system, or any system with a waiting line for service that can experience congestion, can be analyzed using queueing theory. Therefore, to the extent that a military task or system fits into a demand-for-service framework, they are analyzable by queueing theory [10].

The U.S. developed two queueing model tools, called QDET [11] and QSIM [12] that were used to conduct quantitative parametric analyses of the SSA and CIE ASW concepts. A number of general conclusions were drawn from the analysis that provide evidence of the value of networking ASW forces, and also provide some indication of where network-centric applications might be focused.

The SSA and CIE ASW concepts were conceived, in part, through extensive dialog with others in the U.S. Navy's ASW community, particularly with representatives of the Navy Warfare Development Command and the Program Executive Office – Integrated Warfare Systems who is developing, among other things, a Common Undersea Picture (CUP) capability for U.S. ASW forces.

1.3 Scope

This report describes how we tied assumed levels of network-centric capability to operational ASW effectiveness. The analyses addressed the following two hypotheses:

1. In coalition force ASW, network-enabled SSA can reduce false contact loading, by means of data correlation and fusion of the information obtained and provided by individual search elements, and thereby improve search effectiveness.
2. Sensor operators in a CIE can reach-back to ASW experts to improve classification performance against both target and non-target contacts.

Parametric analyses were conducted to verify these two hypotheses. Also, the parametric analyses allowed us to study the tradeoff between “information systems” and “shooters” (i.e., “bits” vs. “bangs”) in order that an appropriate balance could be struck. Quantitatively based insights were obtained on how these network-enabled ASW concepts can improve ASW performance and effectiveness. The method and derived results can be used to estimate and quantify the value-added of specific network-enabled system improvements to ASW.

1.4 Outline

A summary of the key elements of queueing theory that are pertinent to studying the SSA and CIE concepts is presented in Chapter 2. Chapters 3 and 4 contain analyses of SSA and CIE in ASW, respectively. Specific conclusions and insights are summarized in Chapter 5.

2 ELEMENTS OF QUEUEING THEORY

This chapter summarizes the elements of queueing theory [13] that are needed to study the network-enabled SSA and CIE concepts.

2.1 Description of a Queueing System

Figure 1 depicts a multiple-server queueing system. For our purposes, there are seven important queueing system characteristics that need to be considered, and each is described below. We use ASW sensor contacts as an example, as summarized in Table 1.

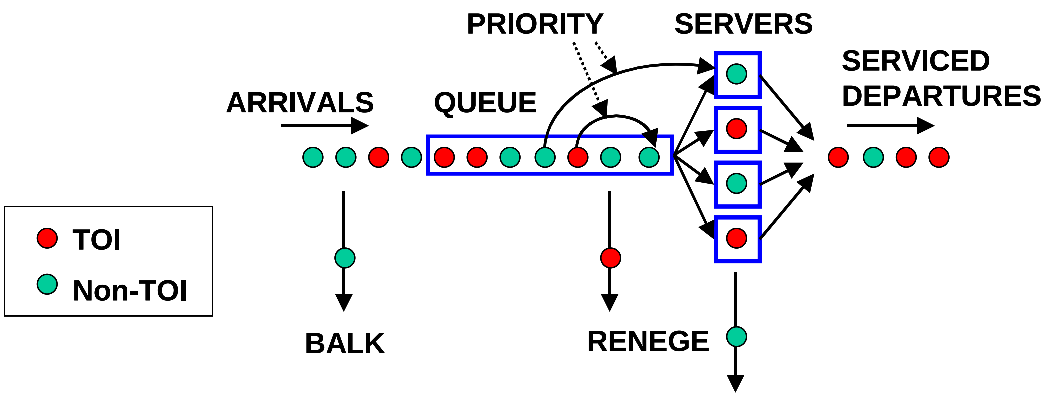

Figure 1: Depiction of a Queueing System

Queueing System Characteristic	ASW Equivalent
Arrival Pattern	Targets, interfering objects, system generated false contacts
Service Pattern	Contact prosecution process based on classification decision
Loss Processes	Detection threshold selection (balking) Contact can be lost (reneging)
Queue Discipline	Prioritization of sensor contacts for investigation
System Capacity	Maximum number of contacts that are managed at a given time
Service Channels	Number of elements available for a given function
Service Stages	Set of end-to-end ASW stages (search, localization, prosecution)

Table 1: Queueing Characteristics of ASW

2.1.1 Arrival Pattern

"Arrival pattern" is the statistical pattern of input ("customers") into the queueing system. Arrival pattern into the system is described by a probability distribution of the time between successive arrivals or an arrival rate. An example is the arrival of targets of interest (TOI) and non-TOI to an ASW sensor system.

2.1.2 Service Pattern

"Service pattern" is described in terms of service rate or service time. An example is the time it takes to do whatever is necessary to classify a sensor contact. Clearly, many parallel servers can serve more contacts per unit time than fewer servers.

2.1.3 Loss Processes (Balking and Reneging)

A customer is said to "balk" if upon arrival the queue is full and he is declined service. An example of balking is the adjustment of sensor gain to reduce the number of contacts on a display.

Once entering a queue, a customer can wait until served or can leave without service. A customer is said to "renege" if he leaves the queue without being served after having waited for some time. Reneging can occur from the queue itself or from a service process. Reneging is analogous to losing sensor contact as the contact moves out of sensor coverage.

2.1.4 Queue Discipline

"Queue discipline" describes the order in which customers are selected for service once in the queue. In our work, for simplicity, we assume first in/first out (FIFO) service. A more detailed analysis might consider other queue disciplines such as priority service schemes.

2.1.5 System Capacity

"System capacity" describes the maximum size of the queue or the maximum number of customers that the queue can hold. Queues can be either finite or infinite in capacity. The number of contacts that can be practically held on a sensor display is an example of system capacity.

2.1.6 Service Channels

The number of "service channels" refers to how many servers can simultaneously service customers. An example is the number of contact investigation units that are available to classify contacts.

2.1.7 Service Stages

The term "service stages" refers to the possibility of a customer having to go through a number of processes before he is considered to be completely served. An example is detection, classification, and prosecution stages in an ASW engagement.

2.2 Queueing Metrics and Models

There are many metrics that are associated with queueing processes. For our purposes, there are three metrics that are most important:

1. P_{ACQ}, the probability of a customer acquiring service,
2. W_{ACQ}, the mean waiting time in queue until service begins, and
3. LR, the customer loss rate due to either balking or reneging (which is equal to (1-P_{ACQ}) x Arrival Rate (AR)).

These queueing metrics are readily translatable into metrics associated with ASW operations as will be shown (for metrics 1 and 2) in Chapters 3 and 4.

Ancker and Gafarian [14] derived equations to calculate the three metrics for the following case: arrivals are assumed to follow a Poisson process and enter a system with multiple servers working in parallel. The service times of each of the servers is assumed to follow the exponential distribution described by the mean service time. An arrival balks if the queue size (at the time of arrival) is greater than or equal to a specified number. Otherwise, the arrival enters the single queue and waits to be served on a first-come, first-served basis. Reneging is also included in the model and the time to renege from the queue is an exponentially distributed random variable.

Bedow [15] developed equations that calculate the three queuing metrics that were derived by Ancker and Gafarian, but in a form that is readily programmable. The program is called QDET [11].

A simulation model called QSIM [12] was developed and utilized in conjunction with the software application EXTEND [16]. The purpose of these simulation models is to handle calculations for queueing systems that do not obey the Ancker and Gafarian assumptions.

3 SHARED SITUATIONAL AWARENESS (SSA)

3.1 Concept and Hypothesis

SSA means that two or more individuals understand a particular circumstance in the same way [3]. First and foremost, connectivity between distributed systems is needed to achieve SSA.

In this chapter we examine the possibility of using network-enabled SSA to reduce false contact loading in ASW, and thereby increase ASW effectiveness. Our hypothesis is:

- In coalition force ASW, network-enabled SSA can reduce false contact loading, by means of data correlation and fusion of the information obtained and provided by individual search elements, and thereby improve search effectiveness.

3.2 Analysis

3.2.1 Background and TACSIT

Submarines, particularly diesel submarines operating on battery in a complex littoral environment, are difficult to detect, in part because both their passive and active signatures are low. In addition, if contact is gained, it is often held only intermittently. Further compounding the ASW problem is the fact that littoral regions of interest generally contain many kinds and quantities of false contacts. Table 2 shows examples of false contacts that interfere with the detection of the target of interest (TOI). The false contact problem can be exacerbated by more powerful sensors because the number of contacts detected increases approximately as the square of detection range.

PASSIVE SONAR	ACTIVE SONAR	RADAR
Surface vessels Own ship lines Consort signatures Decoys Biologics	Surface vessels Reverberation Fish schools & whales Bottom pinnacles Shallow water wrecks Decoys Wakes and knuckles Fronts and eddies	Surface vessels Sea surface structure Navigation buoys Fishing buoys Fixed man-made structures Garbage

Table 2: Examples of False Contacts in ASW

There are several “costs” associated with reacting to false contacts:

1. Reactive forces may be diverted or employed unnecessarily,
2. Fuel, sonobuoys, and weapons may be expended unnecessarily,
3. Reactive forces may not be available when needed, and
4. Prosecution of real TOI may be delayed or missed.

These adverse events are often observed in real world exercises. One might ask: to what extent can network-enabled SSA mitigate some of these problems?

In order to explore the false contact problem and test the above SSA hypothesis, an ASW TACSIT, as shown in Figure 2, was assumed. In Figure 2a, the case with limited SSA, a Blue forward barrier submarine detects and misclassifies a surface vessel as a TOI and diverts from its planned search track to investigate. This diversion can cause detection of the TOI to be delayed or missed entirely.

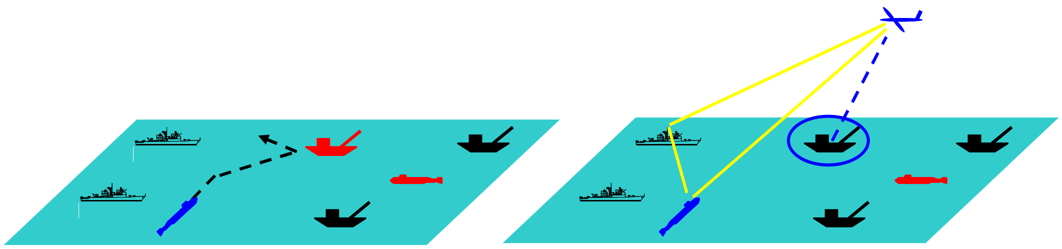

Figure 2: TACSIT for False Target Reduction Concept

In Figure 2b, the case with network-enabled SSA, it is assumed that an air platform can provide surveillance of the region of interest and transmit an accurate surface picture to an assumed "Contact Refinement Node (CRN)". It is also assumed that the Blue submarine also transmits information about the suspected TOI to the CRN. The network allows the CRN to be forward or on land. The task of the CRN is to assist with or conduct data alignment, correlation, localization and target motion analysis, and classification across sensor contacts and tracks. The CRN shares this information in near real-time with all Blue ASW forces, including the submarine. The result of these activities is that the Blue submarine stays on its intended search track and does not become diverted by the non-TOI, as is the case without network-enabled SSA.

3.2.2 Metrics and Numerical Results

Consider the following end-to-end ASW metric:

$$P_{ASW} = P_D \, P_{CL} \, P_{LOC} \, P_{ATK} \quad (1)$$

where

P_{ASW} = probability of successfully attacking the threat,

P_D = probability of detecting the threat,

P_{CL} = probability of classifying the threat,

P_{LOC} = probability of localizing the threat to within weapon launch criteria,

P_{ATK} = probability of successful attack

and all phases are to be accomplished before attack by the threat. Each of these engagement phases has queueing aspects, but we are mainly concerned with P_{CL}.

P_{CL} can be decomposed as

$$P_{CL} = P_{ACQ}\, P(T|t) \qquad (2)$$

where

P_{ACQ} = probability of a customer acquiring service,

$P(T|t)$ = probability that an actual toi is classified as a TOI,

and where upper-case letters represent the classification decision about the given object, and lower-case letters are used to represent what an object actually is. Clearly, increasing P_{ACQ} increases P_{CL}, thereby increasing P_{ASW}.

$P(T|t)$ cannot be calculated from first principles, except for very simple cases; empirical data must be relied upon. However, progress can be made on calculating P_{ACQ} from queueing and subsidiary models and we can obtain useful insights from the results. The basic procedure is shown in Figure 3.

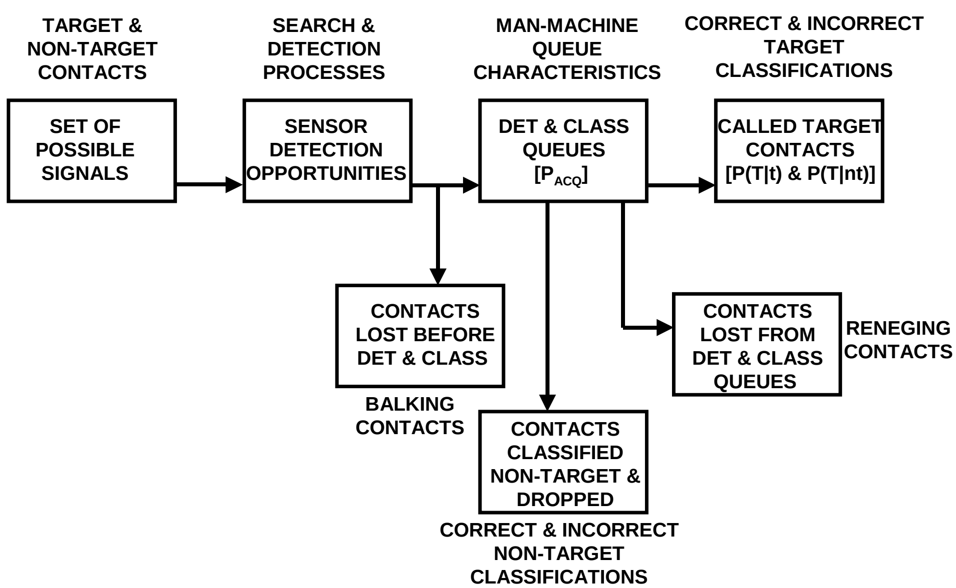

Figure 3: Method to Calculate Probability of Acquisition, P_{ACQ}

In the model, we first need a realistic estimate of the number of TOI and non-TOI that will produce sensor contacts. This number can be considerably larger than the actual number of objects. For given sensor and contact properties, and dynamics, we can then calculate the arrival rate of contacts (customers) to the sensors. The Arrival Rate (AR) is thus comprised of the sum of TOI and non-TOI arrival rates.

Some of the TOIs and non-TOIs are detected by sonar and need to be classified. Most of the arrivals are classified easily and are quickly identified as being a non-TOI. However, a portion of the arrivals may be difficult and time consuming to classify as a non-TOI because of the overlap with selected submarine attributes. As a result, detection and classification queues can form in highly cluttered regions.

Added complexities are balking and reneging. Contacts pass into and out of sensor coverage or have some finite lifetime that is often exponentially distributed [1]. If such a loss happens within a queue or within service, then the contact is said to have reneged. If it occurs before entry to the detection and classification processing queues, then the contact is said to have balked.

All of these factors are incorporated in our multi-contact queueing model. The primary output needed is the probability that an arbitrary contact is acquired and completes detection and classification processing, P_{ACQ}. The probabilities of calling a target a target (a hit or correct classification, P(T|t)) and calling a non-target a target (a false alarm or incorrect classification, P(T|nt)) are then multipliers to the probability of acquisition to obtain P_{CL}, as shown by Equation 2.

Figure 4 shows a graph of P_{ACQ} as a function of contact arrival rate (AR) for classification. Contact AR for the combination of TOI and non-TOI varies from 0 to 10 Contacts per hour. In Figure 4, mean time to renege (hold contact) is assumed to be 15 minutes. The four curves are for different mean service times of 15, 30, 60, and 120 minutes, corresponding to a parametric sweep of time to classify a contact by whatever process.

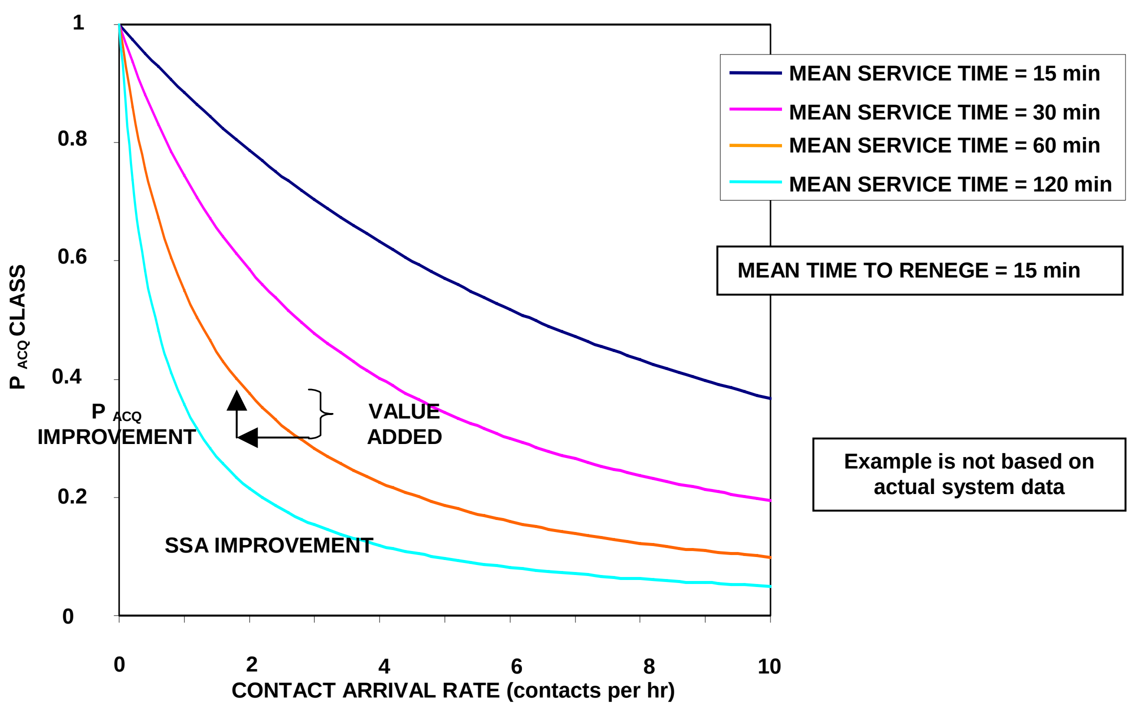

Figure 4: Effect of Improved SSA on Probability of Acquisition, P_{ACQ}

With reference to the SSA ASW TACSIT, we now interpret the curves in Figure 4. It is seen directly from Figure 4 that, as contact AR increases, P_{ACQ} decreases. This result occurs because as AR increases, balking and reneging can occur. As the queue size grows, some of the possible contacts balk because they cannot enter the queue and some of the contacts in the queue renege because they take too long to be serviced.

One effect of SSA is to decrease the AR of non-TOI to the classification system. There are a number of possible ways this can occur within SSA, for example, by surveillance of a portion of the non-TOI field, as previously described. It can also occur by the use of sophisticated Tactical Decision Aids (TDA) which can correlate some sensor contacts with non-TOI objects or phenomena (such as reverberation prediction with active sonar). As shown in Figure 4, the decrease in the AR of non-TOI results in a higher P_{ACQ} against the TOI. This effect of improved SSA, yielding a higher P_{ACQ}, can be parametrically analyzed using graphs such as Figure 4. As an example, the case of reducing contact AR by one third (from 3 to 2 contacts per hour) is shown. The resulting delta improvement in P_{ACQ} can then be read directly from the graph. This exemplifies the value-added of SSA on reducing contact AR, and in turn, increasing ASW effectiveness.

For a given reduction in contact AR, and all else being constant, the improvement in P_{ACQ} depends on what portion of the AR range we are in. That is, the local rate of change of P_{ACQ} with AR is the determining factor. If the system is highly congested due to large AR, then a small reduction in AR has little effect and the system remains overloaded. At the "knees", a small decrease in AR can result in a large improvement to P_{ACQ}. For small AR, P_{ACQ} improvement can be either small or large, as indicated by the graph.

Figure 5 shows the effect of the number of Contact Investigation (CI) units (number of servers) on P_{ACQ} for a nominal mean CI time (or service time) of 60 minutes and a mean renege time of 15 minutes. For a given AR, the improvement in P_{ACQ}, resulting from more CI units, can be directly read from the graph. Clearly, reducing non-TOI AR and increasing the number of CI units yield positive improvements in ASW effectiveness. Furthermore, curves such as Figures 4 and 5 allow the tradeoff between "information" and number of servicing units/platforms to be analyzed.

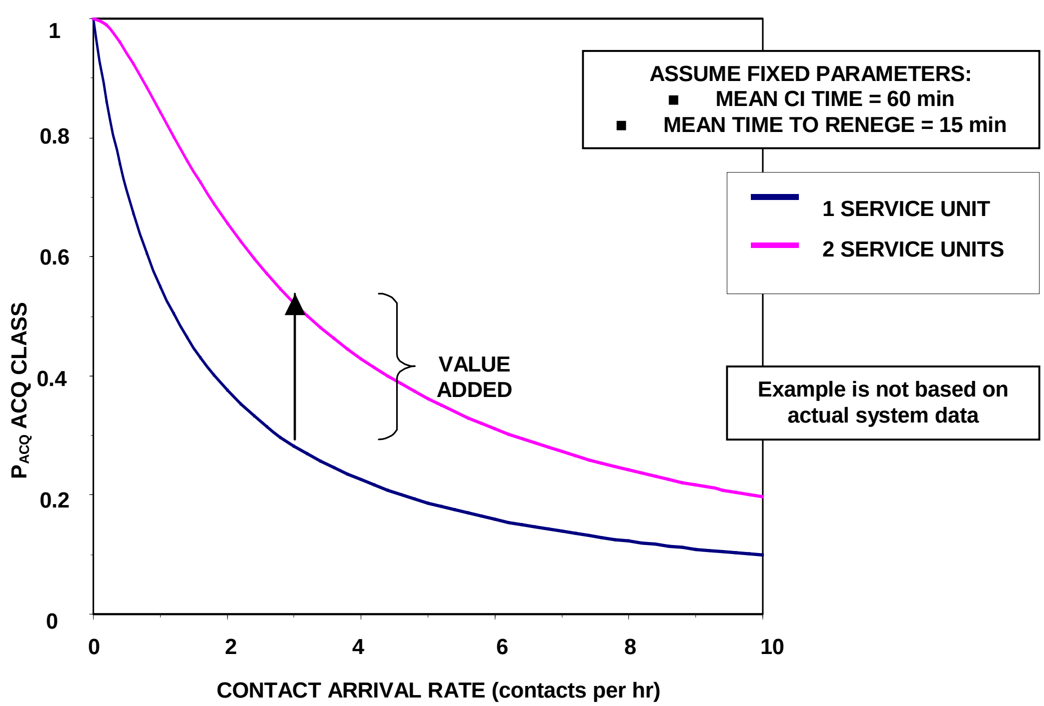

Figure 5: Effect of Number of Contact Investigation Units on Probability of Acquisition, P_{ACQ}

Figure 6 shows Loss Rate (LR) for the same parameter values as in Figure 4. Again, the losses are due to both balking and reneging. Figure 6 indicates that improving SSA decreases the non-TOI AR, which decreases the likely LR of TOI.

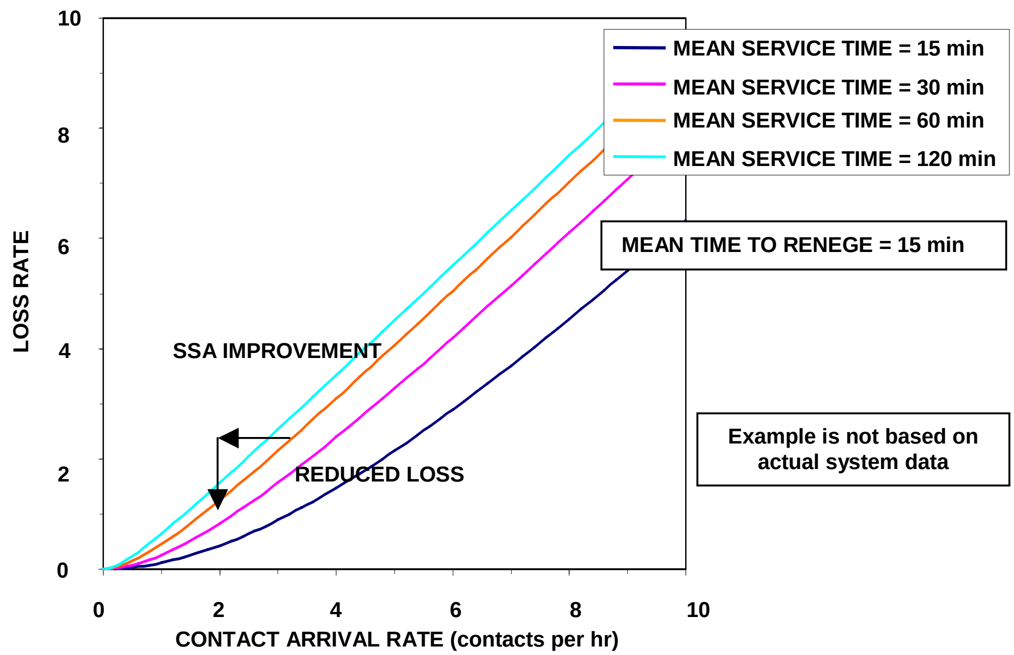

Figure 6: Effect of Improved SSA on Loss Rate, LR

Finally, Figure 7 shows the Waiting Time (W) for service to begin. Improved SSA decreases W, which is likely to improve ASW effectiveness since elapsed time is usually directly connected to possible range closure by the threat submarine.

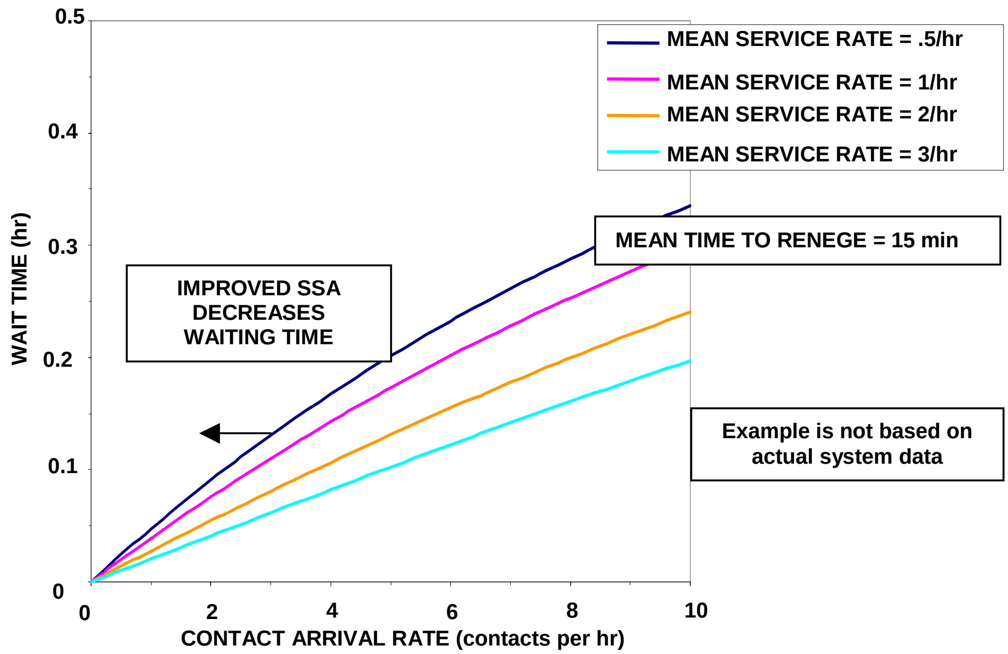

Figure 7: Mean Waiting Time, W, for Classification Service

3.2.3 Summary of Findings

The principal findings of this study of SSA on false contact loading in ASW are as follows:

1. Queueing theory can provide a framework for the analysis of the SSA ASW concept because SSA is a “demand for service” process
2. Improving classification performance against both benign contacts and targets of interest can increase ASW effectiveness. In effect, this reduces the arrival rate of benign contacts, which thereby increases the probability of acquiring targets of interest.
3. An accurate surface picture, shared among the ASW units, could improve ASW effectiveness. Networking the force for information transfer is a key enabler of this aspect of SSA. Real-time connectivity is needed.
4. An alternative method for increasing ASW effectiveness is to employ more ASW units, i.e., increase the number of servers.
5. The queueing theory framework can be used to analyze the tradeoff in benefits between shared information and force size (i.e., “bits” vs. “bangs”).

In this chapter we examined the possibility of using network-enabled SSA to reduce false contact loading in ASW to increase ASW effectiveness. Our hypothesis was:

- In coalition force ASW, network-enabled SSA can reduce false contact loading, by means of data correlation and fusion of the information obtained and provided by individual search elements, and thereby improve search effectiveness.

Our findings provide quantitative evidence that supports this hypothesis.

4 COLLABORATIVE INFORMATION ENVIRONMENT (CIE)

4.1 Concept and Hypothesis

A Collaborative Information Environment (CIE) is the aggregation of infrastructure, capabilities, people, procedures, and information to create and share the data, information, and knowledge that enables collaboration among a selected group of individuals or organizations [4].

In this chapter we examine the possibility of using a CIE to connect individual forward deployed ASW sensor operators with an ASW expert, such as an ashore Acoustic Intelligence (ACINT) expert, in order to mitigate the relatively poor target vs. non-target classification performance of some sonar operators. Also, we examine the possibility of using network-enabled CIE to improve the overall ASW classification performance and effectiveness of forward-deployed force elements. Our hypothesis is:

- Sensor operators in a CIE can reach-back to ASW experts to improve classification performance against both target and non-target contacts.

4.2 Analysis

4.2.1 Background and TACSIT

In recent years, the U. S. Navy has noted a general decline in ASW operational proficiency. ASW is recognized as being a complex problem and a number of causal factors have contributed to this decline. The relatively poor ASW detection and classification performance (primarily due to lack of operational training opportunities) of some fleet sonar operators has been identified as one of the problems. This problem might be further exacerbated by the need to provide increased ASW manning for distributed forces such as Carrier Strike Groups (CSG), Expeditionary Strike Groups (ESG), and multiple Littoral Combat Ships (LCS). In addition, some coalition forces may have limited ASW experience.

Once sensor contact is made on an object or phenomenon, the detection and classification problem is, in essence, an analysis and decision making problem. There are many determinants of decision making behaviour, including [17]:

1. Problem complexity,
2. Time available,
3. Number/quality of alternatives,
4. Perceived risks,
5. Information presentation rate,
6. Individual differences in cognitive and decision styles, and
7. Level of expertise.

A small percentage of sonar operators are considered experts at what they do; for example, Acoustic Intelligence (ACINT) riders on ASW platforms. Therefore, it might be possible to use the network, with additional infrastructure, to link sensors, operators, experts (not collocated with forward operators), and Tactical Decision Aids (TDAs) to improve ASW performance. This concept is an extension of the Reach-Back Cell (RBC) concept which is depicted in Figure 8a (adapted from [18]).

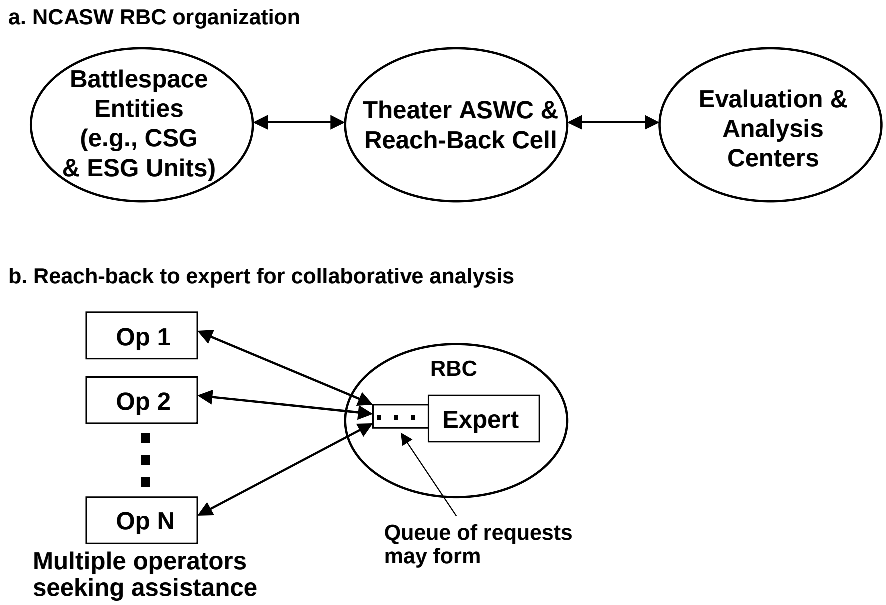

Figure 8: Organization for Reach-back to ASW Expert

The RBC normally provides:

1. Environmental assessment,
2. Sensor performance predictions,
3. Red-cell wargaming,
4. Initial ASW battlespace assessment,
5. Initial plans, including unit stationing, tactics, and sensor employment,
6. Submarine contact database management,
7. Submarine contact information fusion,
8. Ongoing analyses and assessments of mission execution,
9. *And can provide sensor/threat experts to advise forward operators.*

Figure 8b depicts the linkage of forward sensor operators to an ASW expert. Figure 8b forms the basis of the CIE concept and TACSIT that we consider. Multiple operators are forward and linked by means of a connectivity infrastructure to an expert threat analyst and sensor operator. The operators and expert can be considered as being embedded in a CIE. The expert would usually respond to requests for assistance by the operators. Because of the nature of ASW, including the problem that holding time may be short, the CIE requires synchronous tools to allow collaboration between simultaneously engaged participants. In addition, the expert will need to be aware of the ASW context and history experienced by each operator. This amount of information can be used to define the network architecture and the characteristics of network infrastructure.

It might also be useful to operate the operator-expert linkage in a "reach-forward" mode. In the reach-forward mode the expert, with knowledge of the operator's local ASW context, can recommend sensor employment and lineup to best conduct the ASW mission. This may be a particularly useful idea as ASW sensor systems, whether manned or unmanned, become more distributed.

4.2.2 Metrics and Numerical Results

The key queueing characteristics of decision making is summarized in Table 3.

Queue Characteristic	Warfare Equivalent
Arrival Pattern	Reports and requests per unit time
Service Pattern	Decisions per unit time
Loss Processes	Saturation (balking) Perishability of the event (reneging)
Queue Discipline	First come, first served with priorities
System Capacity	Maximum number of decision making tasks that can be handled
Service Channels	Usually one
Service Stages	Set of end-to-end decision making stages

Table 3: Queue Characteristics of C^2 and Decision Making

Equation (2) in Section 3.2.2, used to analyze SSA, can also be used as the primary metric for the analysis of CIE. However, we need to separate the probability of correctly classifying a contact by a fleet operator and an expert:

$$P_{CL\ Op} = P_{ACQ\ Op}\ P(T|t)_{Op} \tag{3}$$

$$P_{CL\ Exp} = P_{ACQ\ Exp}\ P(T|t)_{Exp} \tag{4}$$

where

P_{ACQ} = probability of a customer acquiring service,
$P(T|t)$ = probability that an actual toi is classified as a TOI,

and where upper-case letters represent the classification decision about the given object and lower-case letters are used to represent what an object actually is. The subscripts "Op" and "Exp" represent operator and expert, respectively.

Consider the case where an operator has a contact ($P_{ACQ\ OP} = 1$) and $P(T|t)_{Op}$ is a parameter with values 0.3, 0.4, and 0.5. $P(T|t)_{Exp}$ is assumed to be equal to 0.9. These are reasonable values for $P_{ACQ\ Op}$ and $P_{ACQ\ Exp}$. $P_{ACQ\ Exp}$ is interpreted as the probability that an operator's request for assistance can be serviced by the expert. $P_{ACQ\ Exp}$ is calculated using QSIM [8] and EXTEND [16] because the service time distribution is Inverse Gaussian (IG) and the queueing metrics cannot be calculated by formula.

There is both theoretical and experimental evidence to indicate that decision making times are IG distributed [19]. We assume a mean service time for an expert assisting an operator to be IG distributed with a mean of 20 minutes [20]. Figure 9 shows this distribution. Using this IG function, and the above values for P(T|t), P_{CL} was calculated and is shown in Figure 10.

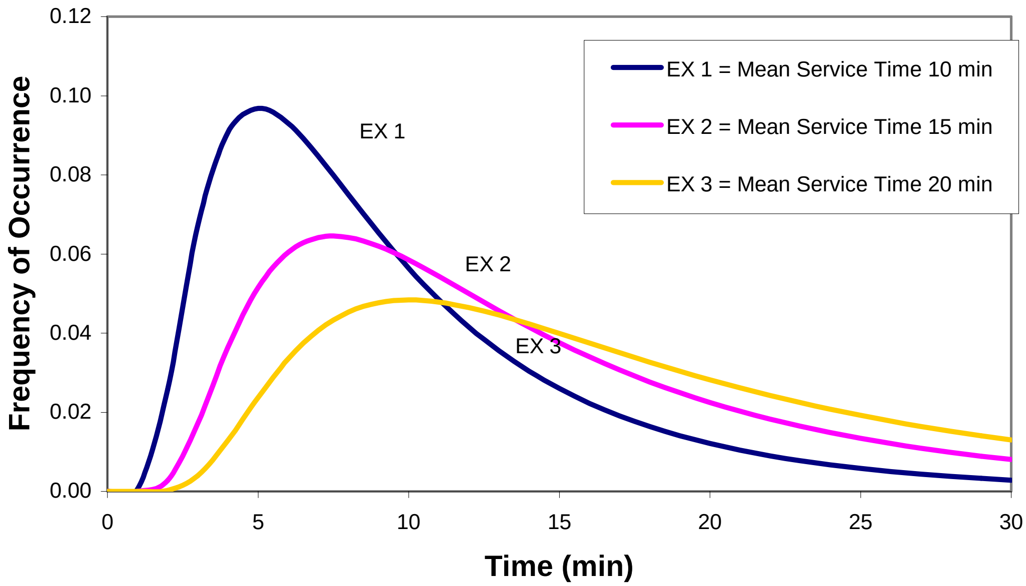

Figure 9: Inverse Gaussian Representation of Analytical Decision Time

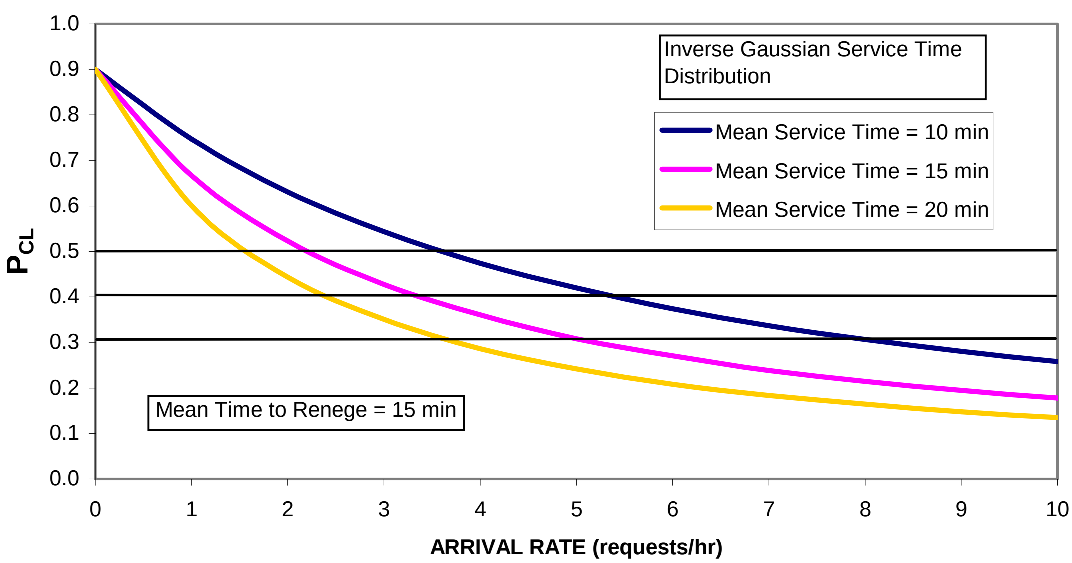

Figure 10: Probability that Expert Acquires a Specific Report as a Function of Workload

Figure 10 compares $P_{CL\ Op}$ and $P_{CL\ Exp}$, with $P_{CL\ Exp}$ shown as a function of the Arrival Rate (AR) of requests to the expert. Figure 10 indicates that there exists an AR in which requests for assistance are not serviced because the workload to the expert becomes too high. The workload problem is probably worse than just described because human error increases as workload increases beyond some level.

4.2.3 Summary of Findings

The principal findings of this study of CIE on ASW effectiveness are as follows:

1. Queueing theory can provide a framework for the analysis of the value of the operator-expert CIE because this collaboration is a “demand for service” process.
2. Networking the force can enable a CIE which, through the increase of classification performance, might increase of ASW effectiveness. Synchronous collaborative tools are needed to enable this collaboration.
3. Expert workload may need to be controlled to avoid “missing” requests for assistance.

In this chapter we examined the possibility of using network-enabled CIE to enable sensor operator-expert collaboration in order to improve ASW classification performance and effectiveness. Our hypothesis was:

- Sensor operators in a CIE can reach-back to ASW experts to improve classification performance against both target and non-target contacts.

Our findings provide evidence that supports this hypothesis.

5 CONCLUSIONS AND RECOMMENDATIONS

Queueing theory was shown to provide a useful framework for quantitatively analyzing warfare tasks and enablers that can be characterized as "demand for service". It was shown that ASW metrics could be described in terms of queueing theory metrics. Models were developed and applied to quantify these metrics.

In this study we showed, through the analysis of two ASW TACSITs, that network-centric concepts can enable Shared Situational Awareness (SSA) and a Collaborative Information Environment (CIE). Both SSA and operator-expert collaboration in a CIE were shown to improve ASW performance and effectiveness. Specific warfighting findings include:

1. ASW effectiveness can be increased by improving classification performance against both benign contacts and targets of interest. In effect, this reduces the arrival rate of benign contacts, which thereby increases the probability of acquiring targets of interest.
2. An accurate surface picture, shared among the ASW units, could improve ASW effectiveness. Networking the force for information transfer is a key enabler of this aspect of SSA. Real-time connectivity is needed.
3. Networking the force can enable a CIE which, through the increase of classification performance, might increase ASW effectiveness. Synchronous collaborative tools are needed to enable this collaboration.

The results from this analytic effort indicate that selected NCMW ASW concepts, if implemented, should have positive effects on ASW effectiveness. For example NCMW applications that decrease the mean time to service contacts, in general, improve effectiveness. Furthermore, applications that decrease the arrival rate of unwanted contacts can improve the detection and classification of ASW targets of interest.

We analyzed two hypotheses:

1. In coalition force ASW, network-enabled SSA can reduce false contact loading, by means of data correlation and fusion of the information obtained and provided by individual search elements, and thereby improve search effectiveness.
2. Sensor operators in a CIE can reach-back to ASW experts to improve classification performance against both target and non-target contacts.

Our analysis provided quantitative evidence that supports both of these hypotheses.

It is recommended that the details of the implementation of the SSA and CIE concepts be examined so that actual application can be achieved. For coalition forces, these details include:

1. Developing real-time connectivity between appropriate platforms, and
2. Solving the multi-level and multi-national security issues for coalition force ASW.

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