# Effecting Quality of Service Across Systems of Systems

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**Abstract.** The ability for diverse communication networks to adapt to changing mission characteristics, such as priority, have been a recognized challenge across Systems of Systems. Within the Department of Defense, mechanisms do not exist to extract dynamic mission features for use in defining Service Level Agreements (SLA) and for use within Quality of Service (QoS) provisioning. These mechanisms, were they to exist, would also serve a wide range of non-defense enterprises. This paper provides background on QoS and SLAs within the current military context. We then offer a research approach to improve on the network-focused, QoS mechanics. Using OpNet, early simulations reproduce the competing cross-mission information environment and serve as the foundation for continued "mission-aware" QoS research.

## Introduction

Today, organizations have come to depend on networks for critical functions and basic services. Whether the organizations are companies, governments, educational institutions, militaries or charities, they all access information across networked systems. Within the Department of Defense (DoD), the operation of interconnected and networked military weapon systems is termed Network Centric Operations (NCO) (Alberts, Garstka, and Stein 1999). Each military unit has different capabilities, purpose and mission and uses networked information in very different ways. While the various units and their missions are highly synchronized in time and space, the mission priorities and the flow of information often varies in importance with time. The units however share a significant similarity - they and their missions depend heavily on information resources as well as the access to this information. This information delivery dependence includes elements of timeliness, accuracy and availability.

The mission drives many aspects of organizing, assessing, planning and executing. Training, purchases, organizational relationships, investment and maintenance are all driven by mission. Managing pathways to the information is another form of investing to accomplish the mission. These pathways lie across the network of tactical, strategic and leased communications. In the United States DoD this network of networks is known as the Global Information Grid (GIG) (Department of Defense 2009a) and is where NCO occurs.

The challenge for the DoD lies in the diversity of "edge" systems, hosts and applications on the GIG (Kurose and Ross 2007); where there are necessarily tactical and mobile communications and the high likelihood of changing missions. As we adjust our focus towards the edge, the devices and links often serve a smaller range of purposes and users. The end users on the edge are constrained by terrain, electromagnetic interference, and mobility meanwhile mission taskings and information requests lead to peak traffic loads. One solution to this problem would be to manage the flow of information during the peak use periods so the most critical information advances first with other information following based on its importance. This solution is often referred to as Quality of Service (QoS).

Quality of Service (QoS) describes the level of performance which an information flow receives from a network. Some networks such as circuit-switched networks are designed to dedicate a set number of resources to a fixed number of flows. Packet-switched networks are designed to accommodate a variable number of flows with variable resources for those flows. A well-designed QoS system can meet the information flow requirements of all users even with limited resources while offering various levels of performance. The criteria by which the QoS scheme is designed are provided in the service level agreement (SLA) and service level specification (SLS). The SLA and SLS assign performance levels to information flows and represent agreement between user groups with a mission and one or many network service providers.

Meeting the information flow requirement of all users is difficult because it requires knowing the information flow requirement for a particular user, all its competing users and their relative importance. Often the needed source information can be found in the SLA. Investigating how users are organized and then examining the organizations' missions allows for prioritizing competing requirements.. This can also provide insight to compare organizations with differing missions and differing service characteristics. These requirements may be captured in the form of information exchange requirements (IERs) and influence the formation of SLAs. A systems engineering methodology invoking appropriate architectural information such as DoDAF (Department of Defense 2009b) may be used to develop the IERs, SLA and especially the final QoS provisioning as shown in Figure 1.

Figure 1. Bridging Mission characterization to QOS algorithms

A construct in which mission information is incorporated into QoS systems' actions enables superior functioning for the entire system. QoS is sometimes introduced to networks in order to ensure graceful degradation for the applications. Graceful degradation allows applications and their users to continue operating, albeit at a reduced efficiency, when network conditions are not ideal (Randell, Lee, and Treleaven 1978, 123-165). QoS sourced to a mission design allows the graceful degradation concept to apply across many types of users and missions. QoS sourced to a mission design allows the system of systems to upgrade gracefully as well, ensuring services can recover from downtime in the right order and ensuring precious bandwidth is used efficiently when the network is recovering to full strength. The interconnected systems which make up the "core", the mesh of interconnected routers moving information between hosts and applications (Kurose and Ross 2007), serve a wide variety of information flows. Having mission information for each flow enables better management and decision-making in the core. Mission information for each flow also serves the networks at the edge, where resources are often limited. Finally, these networks operate in a dynamic environment where elements move, events happen and missions along with their relative priorities change. Mission information for each flow helps the networked system of systems to continue to operate effectively in the dynamic environment.

Lastly, there is a strong relationship between QoS provisioning and system-of-systems engineering. The Office of the Secretary of Defense (OSD) Engineering Guide to System-of-Systems (Department of Defense 2008) details the different engineering activities for the SoS, in relation to system-level engineering. Ensuring performance and quality attributes continues to be a challenge in SoS efforts. This concept can be a great aid in working towards isolating and identifying contributors within the SoS and perhaps drive down the overall complexity. Anunciado proposed an approach to establishing dynamic Command and Control (C2) nodes in an enterprise environment (Anunciado 2006, 178). Macro policies and micro policies which are executed by network components have strong analogies to requirement interdependencies. Macro policies are stipulated by stakeholders and set the high-level operation of the SoS and micro policies follow by directing specific nodes in order to realize the goals of the macro policy. (Ye, Lai, and Farley 2003, 225-237; Intanagonwiwat et al. 2003, 2-16).

## Background/ Previous Research

### *Mission-Oriented Quality of Service*

Previous research emphasized the benefit of both context and mission-awareness for application task and behavior (Loyall et al. 2009). Previous research also emphasized the benefit of context and mission-awareness for network security requirements and information protection success (Mitchell et al. 2008) . These efforts developed a unique middleware framework which offered services to applications as well as to network control devices to improve quality of service performance. These efforts did not address capturing mission context information in a format which can be universally represented in the QoS control common on network routers. Mujumdar captured QoS parameters in association diagrams starting with missions but did not include an in-depth analysis of relative mission relationships as they relate to QoS or how a dynamic mission situation might be represented (Mujumdar 2005). Others recommended further research to raise the QoS level of abstraction from network-centric (IP address, traffic class, etc.) to more abstract classes like high reliability or high priority (Dasarathy et al. 2005, 246-255) – these are categories which can be organized to serve defined missions.

### *Mission Prioritization and Characterization*

Enhancing activities more closely aligned with the mission delivers better overall performance of the mission. This concept was demonstrated in dynamic mission re-planning USAF flight demonstrations and in the Defense Advanced Research Projects (DARPA) Program Composition for Embedded Systems (PCES) (Loyall et al. 2005, 88-97). This concept was further demonstrated by enhancing the mentioned activities using QoS tools (Loyall and Schantz 2008). This concept holds true for resources which are dedicated to a specific mission a priori and especially holds true when there are no significant changes to the mission after the resources have been programmed. For networks which provide the infrastructure and information flows for operations, dedication to singular missions and non-subjectivity to mission dynamics is unrealistic. A more realistic view accepts that a single network and its devices serve many missions simultaneously. This realistic view also accepts that missions will change in importance and goals over time. For systems operating in this reality, the method by which the association is carried between mission and QoS is very important.

These connections between mission, systems engineering and quality of service drive to the heart of many concepts outlined by Cebrowski and his team in their NCO concept. Much valuable research has enhanced QoS capabilities and the application of this toolset but ultimately, aligning network performance and operation tools with objectives closely tied to strategy will ensure consistent operation of the network. Ensuring consistency and concordance among architecture views is a responsibility of the systems engineer. By providing these linkages, all designers, operators and maintainers involved in the GIG SoS can further ensure operational views, systems views and technical views are consistent with one another. Said another way, QoS implementations built bottom-up, and optimized for operations using as a basis the missions handed from top-down will deliver optimal performance for the infrastructure of the network system of systems.

### *Mission Decomposition*

Often the resulting organization stems from a functional allocation or functional decomposition. These strategies in the body of existing work will be examined here. Network Centric Operations (NCO) has motivated many studies looking at assessing mission effectiveness against the communications necessary to execute the mission. The Boeing Company performed a study looking at Command and Control, Intelligence, Surveillance and Reconnaissance (C2ISR) requirements for communications channels by performing a functional allocation among entities in that system of systems (Carson et al. 2005, 264-268). They augmented time-sensitive targeting (TST) models with parametric representations of communication systems and measured the effectiveness of the TST missions. They found upper and lower thresholds for communication performance by adjusting communication performance until mission performance of a downstream Unmanned Aerial Vehicle element was affected.

Functions which are prime for automation include strategy to task decomposition, prioritization and task scheduling, and establishing metrics and performance assessment (Brown 2001). Using automated decision tools for network configuration, promoted by the author to improve task performance, can effect better network performance. Functional decomposition and allocation are key activities which a systems engineer must consider when designing a system. Synthesis and decomposition are specific functions which have an algorithmic formulation that assist in developing capabilities by aggregating system elements and recursively partitioning a system into distinct entities (Ravichandar, Arthur, and Broadwater 2006). Another method of functional decomposition is the Function Analysis Systems Technique (FAST) (Wixson 1999) where a process is followed to identify the functions and components to accomplish a mission. The technique involves visually depicting a process flow of functions and purposes against a waterfall timeline depicting precedence and is highly compatible with Value Engineering efforts.

The size and complexity of military endeavors requires that military missions be decomposed so resources and personnel may be organized to accomplish the mission. The United States military prescribes force and resource decomposition in a variety of manuals for operations as well as systems engineering (Department of Defense 2003; 2004, Chapter 4; 2008; 12th Air Force 1996). A process to decompose Strategy to Objective to Mission to Task is tied closely to the planning and executing of military operations.

Other militaries follow similar procedures, evidenced in the military mission decomposition study conducted for a NATO Defence Requirements Review (Armstong 2005). In this study, a method is provided to decompose military mission ranging from peacekeeping to collective defense into component tasks to develop force requirements. A simple view of a decomposition of military mission is available in Figure 2. Here, the overall military objective is divided into operations, intelligence and logistics missions. Those missions are also subdivided and finally, specific tasks are laid out in the last column. If specific applications and their data and timing requirements are drawn against the tasks, then those applications and their data flows also receive an association with mission through the functional decomposition. Likewise, if effort is put into prioritizing the missions and submissions for a phase of operations, then the applications and their flows which are associated with those submissions may also receive this prioritization.

| Mission | Submission | SubSubmission |
|---|---|---|
| Operations | | |
| Operations | Plan | |
| Operations | Plan | Build Target List |
| Operations | Plan | Build No-Strike List |
| Intelligence | | |
| Intelligence | Collection | |
| Intelligence | Collection | Build Collection Plan |
| Intelligence | Analysis | |
| Intelligence | Analysis | Assemble Data |
| Intelligence | Analysis | Identify Shortfalls |
| Intelligence | Analysis | Task Collectors |
| Logistics | | |
| Logistics | Transportation | |
| Logistics | Storage | |

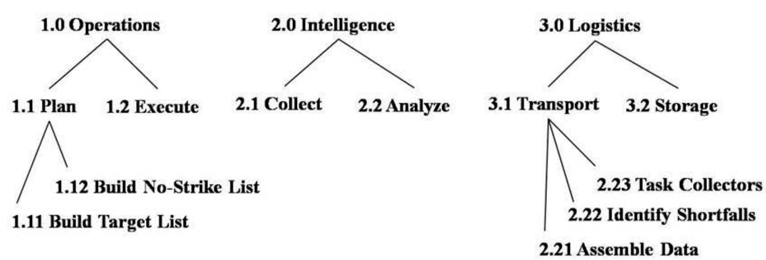


Figure 2. Mission Decomposition

## *Military Communications*

With respect to communication resources, the Defense Information Systems Agency (DISA) provides communications capabilities and infrastructure for much of the U.S. DoD. DISA manages a complex activity to organize and plan communications capabilities in support of military forces. These activities involve working with individual military service elements as both providers of network capabilities and providers of systems which utilize the network. DISA also collaborates with combatant commanders under whom the service elements' systems will operate on the networks to accomplish missions. Finally, DISA contracts with civilian network service providers to provide valuable, tailored communications resources for use by the military. One aspect of this process includes managing efficient access to satellite communications (SATCOM), some of which comprise the DoD's most agile and responsive communications capabilities. On these SATCOM channels, some of the DoD's most expensive comms due to life cycle costs, flow strategic and tactical communications alike and include military satellites as well as commercial satellites. DISA manages the SATCOM access program through a process by which requirements are identified, documented and prioritized. The requirements include long-standing SATCOM needs as well as short-term and contingency needs organized in primary layers and detailed with a specific number of attributes. In addition, DISA's SATCOM directive prioritizes all communications into major priority categories each having sub-priorities (Department of Defense 2007). Managing the SATCOM allocation and operations is an ongoing process affecting missions at every level and region of the DoD.

New capabilities for forces executing combat operations in the field carry equally complex communications structures. The Airborne Communications Node, once a concept matured through a DARPA demonstration, is now providing immediate communications to forces in the CENTCOM theater in the form of a Battlefield Airborne Communications Node (BACN) (Richards 2009). Much like SATCOM, BACN technology provides immediate bandwidth to any forces in the field, strategic to tactical. Operationally however, BACN is very difficult to manage it to its full capability. STRATCOM is responsible as the Joint Task Force Global Network Operations (JTF-GNO) (McKee and Ranne 28 Jun 2006). To see out this responsibility, STRATCOM introduced the concept of a Global NetOps Tasking Order (GNTO). Likewise, the Air Force Institute of Technology (AFIT) and its research partners continue developing the Network Tasking Order (NTO) concept (Compton, Hopkinson, and Graham 2008, 1-7). Both the GNTO and NTO promote organizational and technical structures to accomplish the planning, establishment and maintenance of communication resources to benefit the overall mission. GNTO or NTO, with additional feedback and adding mission dynamics, could dynamically aid use of resources like BACN in the future. Now that flexible, agile and capable communications systems with QoS exist for military applications, it is of even greater importance that decompositions of military missions be applied directly to the communications resources and devices of the GIG.

## *Quality of Service*

Quality of Service (QoS) has many definitions which depend on an application's QoS context. In most cases, QoS refers to a level of performance which is managed in a three-part process on an information technology (IT) network. The first part begins when the level of performance is expressed as a need and communicated from application to network in the form of a requirement. Next, the network then uses the requirement to schedule and reserve resources. Finally, the network responds back to the application confirming the requirement and communicating the reservation of needed resources to fulfill the requirement. After these steps, the application may operate within the bounds of its stated requirements with assurances that the network will support its operations. There are many nuances to this process involving how the requirements are communicated, what levels of service may be requested and promised, how the reservation is maintained and managed as both new requests arrive and previous requests age, and how various network entities participate in the process. Often, Service Level Agreements (SLA) with Service Level Specifications (SLS) or multiple individual contracts are used to manage this process.
Quality of Service, originating with the telecommunications industry to measure call quality on the switched telephone network, has similarities to service quality. Service quality has its origins in SERVQUAL, originally conceived to help service organizations assess the perception of their customers (Parasuraman, Zeithaml, and Berry 1985, 41-50). Service quality may also be reflected in the context of a system's purpose or an organization's mission. Contracts between businesses

and organizations are perhaps the most basic and common representation of this concept. These contracts are related in terms of service for a cost measured in dollars. Goals and performance of these businesses and organizations are also related in terms of cost, profit and loss also measured in dollars. Goals, performance, cost, profit and loss may also be distributed amongst an organization's subcomponents if an adequate structure exists to do so. With such a distribution, the need for enhanced services like QoS may be identified, justified and even characterized.

Quality of service in the network context is negotiated using one of various metrics. Bandwidth is the common term most frequently attributed to application requirements and network capabilities. Bandwidth refers to the size of a data channel in terms of how much information can transit the channel per unit time. It is sometimes difficult to measure actual bandwidth at a given time, especially in a complex network. Therefore, other metrics can infer performance in real, measurable terms more appropriately than bandwidth. These metrics may include end-to-end delay or latency, end-to-end jitter (variance of delay), bit error rate, packet loss rate, packet loss ratio, queueing delay and queue size and even the remaining available bandwidth.

Quality of Service efforts may involve an application negotiating its data stream into a class of service which affords it the needed performance. This is known as a differentiated services model and applications may be categorized into these classes a priori. QoS efforts may also involve an application negotiating a specific performance level for its needs. This is known as an integrated services model. The integrated services model requires the application to establish a performance level for each of its data streams. An application having multiple data streams with differing purpose, priority or routes may find the integrated services model more appropriate than the differentiated services model.

Whether by class or by flow, QoS provides a valuable method by which applications can manage and track performance of their data streams. QoS may also allow for applications to adapt and use the network as-is or as the network changes. QoS also helps to institute fairness and resource sharing policies. These sharing policies allow applications to request the resources they need as well as allow the network to manage its resources and meet those needs.

## *Service Level Agreements (SLA) and Specifications (SLS)*

If Quality of Service is central to delivering performance on a network of networks system, then the method by which the QoS policy is achieved is critical. Service Level Agreements (SLA) can provide overarching guidance on multiple contracts or arrangements. Likewise, the SLA provides the chief means by which QoS is established. This is done mainly by providing a single place where requirements and user expectations as well as provider promised service levels are recorded (Doshi et al. 2006). User communities are organized around a mission and are represented by mission planners (MP) who enact the user requirements on the network through SLAs with the network service providers. Often these requirements will be expressed in the form of information exchange requirements (IERs) with connectivity requirements outlined in a Mission Service Level Agreement (MSLA). An MSLA may outline various technical, financial and other needs and is the basis by which the MP can negotiation individual SLAs with various providers. Consequently, multiple, separate providers may offer resources to a single user community organized around a concerted mission. The MSLA and SLA may be negotiated within a process which also specifies the information to populate the MSLA and SLA. The MSLA includes mission-related, technical

and geographical information. The SLA includes SLS technical specifications of network performance. These specifications may include QoS metrics mentioned earlier as well as throughput, committed informaiton rate,peak information rate, committed burst size, packet loss/error ratio, spurious packet rate, service availability/unavailability and denial probability, mean down time and mean time between service unavailablity (Doshi et al. 2006).
A useful SLA is between user and network service providers as well as between network service providers themselves and includes an effective combination of the above SLSs.

## Method - Mission to QoS Process

The overall objective of this research is to propose a method for closely aligning mission and QoS as well demonstrate the improvement if this alignment were established. The following tasks, completed and taken together, provide a well-rounded and thorough analysis of the research question. These primary tasks are

1. Deliver a solution to translate from High-Level Objectives to Network Infrastructure to Application Management

2. Demonstrate in scenarios that quality of service influenced by objectives and mission priorities offers greater network performance

Tasks 1 and 2 may be viewed together as a sequential mixed research method. Task 1 takes an inductive approach by organizing and characterizing missions to tasks to network elements - a more observational/ qualitative method. Task 2 takes a deductive approach by building and simulating scenarios around QoS principles and theory, with a hypothesis of increased performance across dynamic missions and network loads.

*We hypothesize that if QoS mechanisms in the network are configured for the mission priorities then the network and critical applications/users will exhibit better performance.*

The research described in this paper develops a framework for bringing mission emphasis down to the network planning and action level. This research also provides evidence through simulation of the power of this concept on dynamic networks. As both the mission changes and the user/network environment change, it becomes necessary to change the QoS decision points used on the network devices. This research investigates the extent and depth to which those changes must propagate in order to remain consistent with the overall IERs, SLA and mission prioritization. The research proposed here builds on previous work by establishing a useful, high-level of abstraction for low-level devices. It will also provide the connectivity between systems for the purpose of managing QoS effectively throughout the system of systems.

### *Translate from Mission-High to Network Infrastructure to Application Management*

The mapping from strategy and commander's intent down to network devices is a critical piece. Having a thoroughly researched procedure to deliver this mapping is an important step in establishing effective QoS on a network. This task focuses on well-known QoS protocols such as differentiated services code point (DSCP) and resource reservation protocol (RSVP) to establish a good foundation for the entire research effort. Here, a method will be detailed to translate mission objectives through organizations, into planning documents, Information Exchange Requirements (IERs), to the service level agreeements (SLA) and specifications (SLS) and finally into network devices.  Figure 3 shows the DoDAF views which capture these elements for use in building IERs.

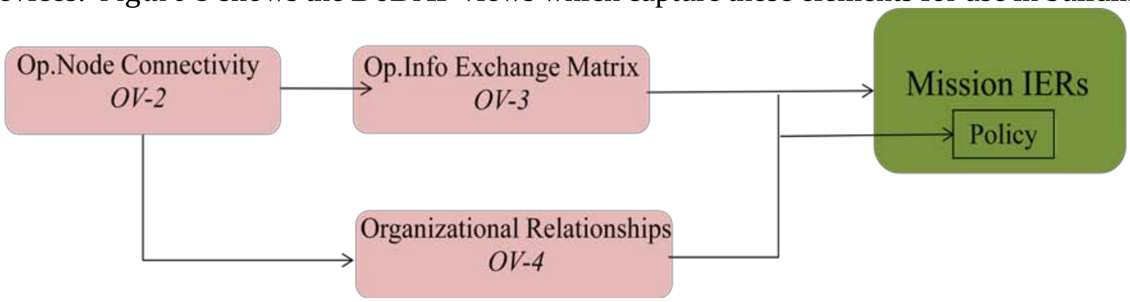


Figure 3. Extraction of Mission IER characteristics

In this task, high-level guidance such as commander's intent and strategy will be analyzed.  The existing methods to subdivide resources, apply them under a strategy, define missions for subordinate organizations, flow down objectives and priorities and decompose them into guidance and taskings will also be examined.  This task will also catalogue appropriate methodologies for subdividing and decomposing objectives into action.

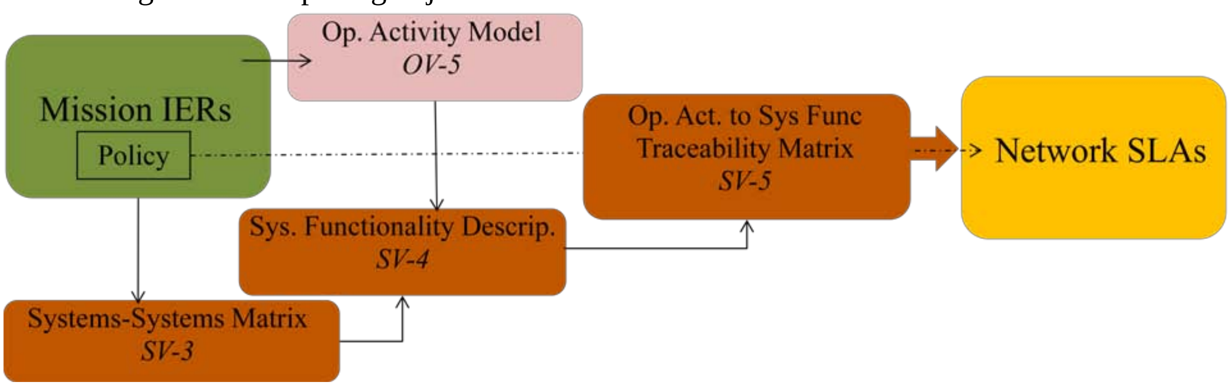


Figure 4. Extraction of User/Application Service Level Agreements (SLA)

The decomposition of objectives and flow down can be ultimately captured in the SLA and its SLS.   The supporting organizations provide infrastructure and resources, including communication links and equipment,  used by multiple other units to carry out their missions in line with the SLA and SLS.  How these resources are divided under a QoS strategy and then used must be governed by the mission and related back to underlying strategy.  Figure 4 demonstrates how the SLAs may be developed with this consistency.  This study will provide a consistent representation and method by which mission and tasking may arrive as an influence for the QoS protocols by referencing existing guides for breaking down strategy and mission..

## *Demonstrate that quality of service influenced by mission priorities offers greater network performance*

The ultimate goal of any research is to present a better solution for an unsolved or partially solved problem.  In Task 1, a method will be developed to translate high-level mission objectives to configuration items for network devices.  With this in hand, a mission planner working with a network planner could modify network configuration to better support the network. Without the results of this task, a network planner could still configure the network by hand if a full decomposition of missions and their relative importance were built and available. It is the goal of Task 2 to demonstrate that a network configured with relative mission priorities in mind, will perform in a superior manner to the network that did not benefit from such planning.

In this task, we will simulate the operation of the network and gather statistics important to the success of key applications such as end-to-end delay and throughput. We will also overlay basic queuing and QoS protocols making a properly functioning network. This functioning network will have QoS configurations which are optimized for the current, stated mission. As often happens, the mission will change and we will represent this by modifying the behavior of the applications which are the sources and sinks for the data streams. Without network modifications, we expect the behavior-adjusted applications to perform sub-optimally..

We will then re-program the network for the alternate missions. Again, this can be done explicitly and mainly by inspection. It is proposed that a superior method for executing this programming would result from Task 1 however, Task 2 has a goal of demonstrating that any network giving significance to mission in its network planning will experience improved performance. Once the results of Task 1 become available, those results may also be used to reprogram the network with an alternative configuration. Having reconfigured the network, we will capture important statistics to demonstrate that when mission changes and associated applications shift behavior, the alternate network QoS configuration provides superior performance.

Dynamic mission is a ready challenge for any service network. Other dynamics are also likely. Networks which have mobile elements must contend with degraded signal-to-noise ratios, link dropouts, link failures and packet losses. These mobility issues may lead to network topology variations. Topology variations may also result from other issues, even in non-mobile, wireline networks. Attacks and denial of service may impact topology. Misconfiguration, routing table inaccuracies or interference may also impact the topology of wired or wireless networks ultimately affecting the speed and efficiency of the network in servicing its various missions. This task will investigate these affects and also investigate how mission-oriented QoS would offer improvements to the topology variations.

## Early Analysis

The network in Figure 5 assembles a series of four user nodes and four server nodes. It provides separate sources, sinks and flows with separate purposes in order to begin the investigations for this study. For these simulations, each user node executes a specific single purpose by accessing a single, different server.

The network primarily utilizes 10baseT links having 10Mbps capacity. The one exception to this is the link between routers which are E1s having a data rate of 2Mbps capacity and total capacity of 4Mbps. This network very basically simulates any possible network arrangement where network bandwidth is constrained. Most network models have an over-provisioned core and it is the edge links which are constrained. This network may represent this case by assuming the constrained link between routers is an edge link. The more interesting problem prevalent for the military is the competition for resources in the core of the network. These networks nicely represent this problem by placing a lower capacity link in the primary pathway for all data streams.  To pass data over these lower capacity links, the routers will make routing and admission decisions on packets.  The QoS arrangements installed on the routers will convey policy and also provide criteria by which the routers can act.

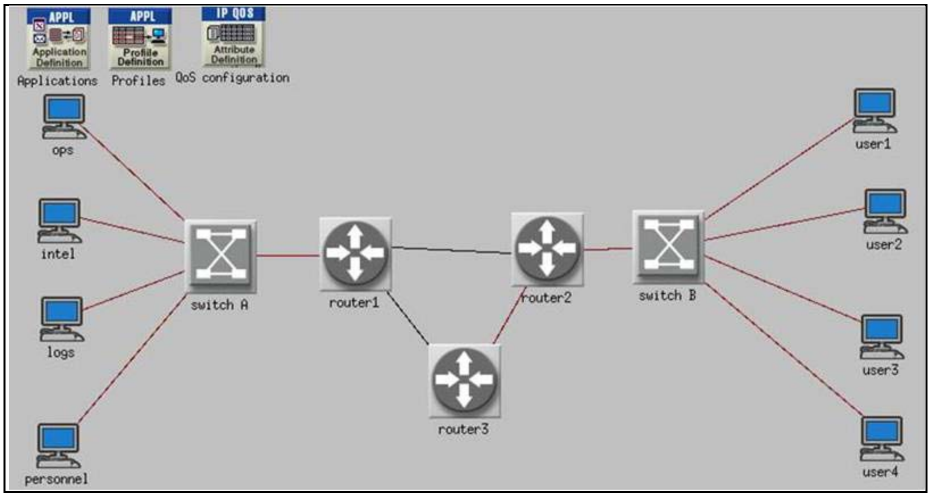


Figure 5. Initial OpNet simulation

These routers establish queues for the interface and QoS arrangement both.  The queues for the interfaces ensure packets are not automatically dropped when the router mediates between links of varying capacity.  The queues for the QoS arrangement govern how packets are retrieved and processed from the interface queue.

The server nodes carry the labels "ops", "intel", "logs" and "personnel".  These labels serve to differentiate sources, destinations and traffic.  For these simulations, the user nodes "user1", "user2", "user3" and "user4" run applications dedicated to ops, intel, logs and personnel missions respectively.  Applications and database pulls using transmission control protocol (TCP) were limited since its congestion control algorithm inhibits the growth of queues to their limit.  Packets failing to arrive at the destination do not initiate an ACK packet acknowledgement response preventing source transmission of further packets.  For this study, UDP applications were primarily used achieving constant transmission rate regardless of packet delivery, queue or drop.  TCP-based applications provided some background traffic which is typical for most networks.  Delay intolerance of TCP-based applications must be factored when designing a network and its QoS support.

Basic QoS arrangements influenced labeling of packets at source and how queues were established and exercised on the routers.  The networks were operated using first-in-first-out (FIFO) queues as well as priority queues (PQ).  Packets are not specially labeled in the FIFO arrangement and the FIFO queues simply queue packets until reaching their limit at which point they drop the oldest packets.  PQ labels packets based on a pre-arranged priority and services lower priority queues only when the next higher priority queue is empty.  Simulations were run both with applications directly assigned a priority as well as with a differentiated services (diffserv) model using separate Differentiated Services Code Points (DSCP) for each application.  The DSCP codes convey relative priorities to be then then used by routers operating under the diffserv ruleset.

From a performance perspective for this experiment, diffserv DSCP QoS and direct PQ QoS are identical. For the basic scenario, nearly the same effort was required to program PQ directly as to program PQ under DSCP. Still, for more complex cases, DSCP aids arranging QoS considerably.

The four categories of applications experience vastly different performance under FIFO queuing and DSCP/direct PQ queuing. FIFO has only a single queue with no priorities in the network performance. Here, each server receives the same priority and the queue fills with all categories of packets. End-to-end delay is high for all sources. Regardless of an applications priority, all applications and missions are served equally poorly.

When DSCP/direct PQ QoS is introduced for ops, intel, logs and personnel prioritized high to low respectively, the performance changes dramatically. Ops traffic experiences very little delay with no queue maintained. Intel, logs and personnel queues accrue 2, 5 and 37 packets respectively. End-to-end delay was similarly reflected with ops, intel, logs and personnel experiencing near zero, 0.09, 0.21 and 0.84 seconds respectively. Prioritizing the sources carried an effect.

The performance described here is typical for a static network. Great effort to prioritize applications and then program the network devices is worthwhile if the network will not change. However, if the network topology changes shape or if the objective adjusts then the prioritizing and programming steps must be revisited. Additional complications occur if resources organized under one structure are offered for use by other structures or for alternate missions.

In this network ops and logistics sources have similar rates and data types but ops has higher priority. What can we expect if the real mission-related priorities were reversed? A mission with logistics primary and ops secondary, the network is not configured to perform well. This sort of priority may occur during the build-up of forces prior to an operation or engagement or during the draw-down following. A network which can move to support this need would indeed be valuable.

## Summary

The ongoing study described here presents performance considerations as the mission adjusts as we expect it will during the execution of a campaign. There are numerous examples which make the case for quick and effective reprogramming of network resources on the GIG. On 11 Sep 2001, when it was critical to track and identify every aircraft in the United States, the National Air Traffic Control system did not have the resolution or connectivity to provide all this information (Belger 2004). Yet, even if it had, the appropriate command centers and decisionmaking systems were not oriented to accept this type of information and give it appropriate precedence. Similarly, within a combat operation, a combat-search and rescue (CSAR) event often takes precedence over many other pre-planned activities, yet currently many network resources can not be quickly applied to this high priority need. (Gocmen 2009) During the recent fires around the city of Los Angeles, it was realized that the spread of fires put at risk a key hilltop on which sat numerous communications towers and antennas (Associated Press 2009). Analysis revealed a long list of organizations and missions dependent on the towers yet no immediate process was available to reroute communications and maintain all the top priority communications.

The network performance detailed here provides a snapshot of a much larger problem. For the DoD, which must retain contingency operating capability for most of its operations, the ability to reprogram networks quickly and shift performance from mission to mission is critical; especially as net-centric operations concepts have become reality and GIG dependency has increased dramatically. For commercial networks, there is also a need to improve agility and performance of networks to deal with emergency events like fires, floods, hurricanes and terrorist attacks so first responders may function and then critical services return first as the network recovers.

Quality of Service offers a capability for a network to degrade gracefully. With the examples mentioned, it is clear that both graceful degradation and graceful upgrade or recovery are both meaningful goals. These capabilities are possible if network QoS is oriented to serve the mission.

## Biographies

Major Vinod D. Naga is a Systems Engineering PhD candidate at the Air Force Institute of Technology. His research focuses on improving quality of service for DoD networks. Maj Naga previously served as a technical liaison officer to a non-DoD agency, a field operations officer, a C2ISR technology transition manager and a program manager for E-8 JSTARS moving target indicator radar technology at the Air Force Research Laboratory.

John Colombi, Ph.D. is an Assistant Professor of Systems Engineering at the Air Force Institute of Technology. He leads sponsored research in systems and enterprise architectural analysis, quality of service and Human Systems Integration. Before joining the faculty, Dr. Colombi led command and control systems integration efforts, systems engineering for the E-3 AWACS aircraft, served at the National Security Agency developing biometrics and information security and ran communications networking research at Air Force Research Laboratory.

Michael R. Grimaila is an Associate Professor of systems and engineering management at the Air Force Institute of Technology. His research interests include the management of information assurance, IA metrics, economics of software protection, and cyber damage assessment. He has been employed with Rockwell International and Texas Instruments, and serves as an intellectual property expert witness and consultant.

Kenneth Hopkinson is an Assistant Professor of Computer Science at the Air Force Institute of Technology. His research interests focus on simulation, networking, and distributed systems. More specifically, he looks at fault-tolerant and reliable approaches to mobile wireless networks as well as security and reliability in critical infrastructures with a concentration on communication-based protection and control systems in the electric power grid.

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