Dynamic Resource Allocation for Network Aware Applications

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***Abstract*—Network aware applications provide opportunities for adaptive resource allocations for both network resources and distributed hosting of critical applications. We propose an Automatic Dynamic Resource Management (AutoDRM) architecture for efficiently managing shared resources in tactical network environments without human operator intervention. The AutoDRM architecture was developed to resolve the resource contention issues and to improve the quality of service in tactical network environments. The information herein describes key components of the AutoDRM architecture. An experimental end-to-end network prototype test bed consisting of simulated satellite communications (SATCOM) and an OPNET system-in-the-loop (SITL) scenario was also developed to host the AutoDRM system. Experimental test results demonstrate that network performance such as packet delay and packet loss are greatly improved when AutoDRM is deployed.**

***Index Terms*—Network Performance, OPNET, Quality of Service, Resource Management, Tactical Network.**

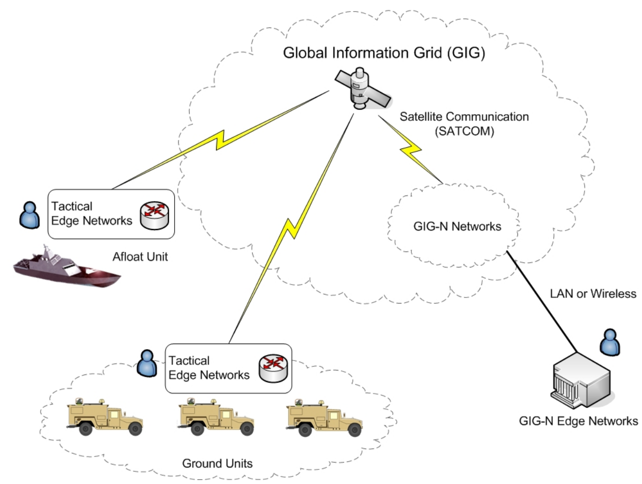


Fig. 1. Operational View of Tactical Edge Networks

I. Introduction

Providing End-To-End (ETE) Quality of Service (QoS) in the Department of Defense's (DoD) Global Information Grid (GIG) network is vital for supporting communication activities in tactical missions [1] [2]. An initial step towards such an ETE QoS support in the large-scaled network is to ensure that computing resources in each edge network domain are managed efficiently and in accordance with the GIG architectural framework [3] [4] [5]. Future computing requirements for diverse tactical missions rapidly increase the complexity of the heterogeneous tactical edge networks such as the existing Total Ship Computing Environments (*TSCE*) [6], Consolidated Afloat Networks and Enterprise Services (*CANES*) [7], and Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance systems (*C4ISR*) [8], and Force XXI Battle Command Brigade and Below (*FBCB2*) system [9]. Fig. 1 illustrates an operational view of tactical edge networks[1]. These tactical systems consist of many computing and networking devices highly integrated within a common network infrastructure in order to alleviate the number of tasks previously performed by human operators. Services are provided to variety of user devices across heterogeneous networks and access configurations.

New applications are enabled to perform a negotiation with host and network services to meet desired QoS objectives. These new applications are referred to as "network aware" applications and are highly integrated with a common network infrastructure [10]. The systems often provide real-time services such as Voice-over-IP (VoIP), streaming video, real-time messaging and other time-sensitive tactical applications that require stringent QoS guarantees with limited computing and networking resources. Each time-constrained application demands resources at different levels in order to achieve various QoS requirements. Without an adequate resource management solution, simultaneous increases in all QoS levels can result in resource contention which impacts the overall system performance. An automated method to dynamically allocate resources based on prioritization across multi-dimensions (*e.g.* traffic classes, user precedence..*etc.*) and multi-choices (*e.g.* QoS policies) is needed to address such a technical challenge. The development of AutoDRM architecture leverages the performance monitoring capability of a network management system (NMS) and policy-based QoS capability in the network domain. AutoDRM does not replace the overall network management system for the network domain. It merely serves as a supplemental function to the NMS by providing the capability

[1]GIG-N Networks refer to Tier 3 GIG networks (*e.g.* Defense Information Systems Network (*DISN*), Warfighter Information Network-Tactical (*WIN-T*)..*etc.*). GIG-N Edge Networks refer to user networks that connect through Tier 3 networks to the GIG black core [4].

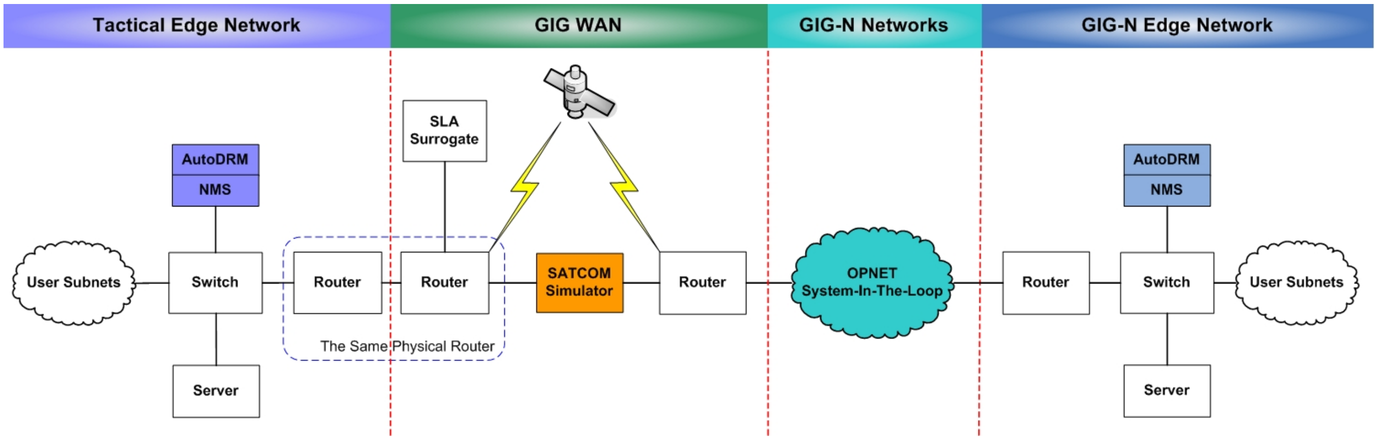


Fig. 2. End-To-End Network Prototype Test Bed

for efficiently utilizing the resources within the context of a tactical edge network domain.

A significant amount of research in dynamic resource management has been studied in various contexts. Rajkumar *et al.* [11] [12] developed a QoS-based resource allocation model (Q-RAM), which establishes an analytical approach to distribute system resources among multiple applications while maximizing the utility function. Harada *et al.* [13] and Stankovic *et al.* [14] proposed adaptive resource allocation methods based on feedback control theories. In the context of shipboard computing environments, Lardieri *et al.* [8] developed a multi-layered resource management framework in enterprise distributed real-time and embedded (DRE) systems. They primarily focused on managing the dynamics of computing resources in response to mission mode changes and/or resource load changes. Dasarathy *et al.* [15] developed a CORBA-based multi-layer management framework to manage changes in network resources, work load, and mission requirements at the network layer. Their study described the interactions of four key network QoS components: bandwidth broker, flow provisioner, network performance monitor, and network fault monitor.

In this experimental study, we do not explore specific approaches to QoS policies but for completeness in the discussion recognize that there are many potential approaches such as load balancing, content based routing, or dynamic selection among multiple paths. These approaches move the route selection functionality to the application or transport layer, through the use of overlay networks of cooperating end systems. Such strategies enable consideration for end-to-end performance management and supports use of informed transport protocols and approaches that can appropriately use the AutoDRM QoS architecture concept.

Constraint based routing, for example comprises both policy and QoS routing. QoS routing includes considerations for application requirements as well as the availability of network resources. However, this implies additional needs for managing routing such as dissemination of dynamic information and more complex computations for route path determination. Moen [16] has proposed the idea of using only local information for node performance measurements for use in calculating paths in overlay networks as a strategy for simplifying the computations. Previous studies in tactical network environments focused on providing a middleware framework to achieve QoS objectives.

TABLE I
DEFINITION OF THE PARAMETERS [11] [12] [17]

Name	Notation
Service (or Application)	$\{S_1,S_2,S_3,..,S_n\}$
Shared Resources	$\{r_1,r_2,r_3,..,r_m\}$
Maximum Resources	$\{R_1,R_2,R_3,..,R_m\}$
QoS Requirements	$\{Q_{i1},Q_{i2},Q_{i3},..,Q_{nm}\}$
QoS Achieved	$\{q_{i1},q_{i2},q_{i3},..,q_{nm}\}$

This paper focuses on the architectural concept of AutoDRM as well as the development of a network architecture prototype test bed to support the experimental study. The remaining portion of this paper is organized as follows. Section II reviews the theories related to the dynamic resource management problem. Section III provides an overview of the edge network architecture in the tactical network environments. An ETE tactical edge network prototype test bed is also illustrated. Section IV presents the architectural concept of AutoDRM as well as details of each key functional component in the AutoDRM architecture. Section V describes the experimental setup based on a use case consisting of three user scenarios. SectionVI discusses the experimental test results. Finally, section VII provides conclusions of this experimental study and discusses future research efforts.

II. Background Theory

The dynamic resource management problem is generally formulated based on the 0-1 Knapsack problem which is known to be *NP-Hard* [18] [17]. Table I defines the sets of general parameters in the resource management problem. A system can provide n number of independent services (*e.g.* VoIP, streaming video, real-time messaging..*etc.*), $n \geq 1$. There are m number of shared resources (*e.g.* processing capacities, queue sizes, network bandwidth..*etc.*), $m \geq 1$. Each service S_i requires a set of shared resources r_j to accomplish

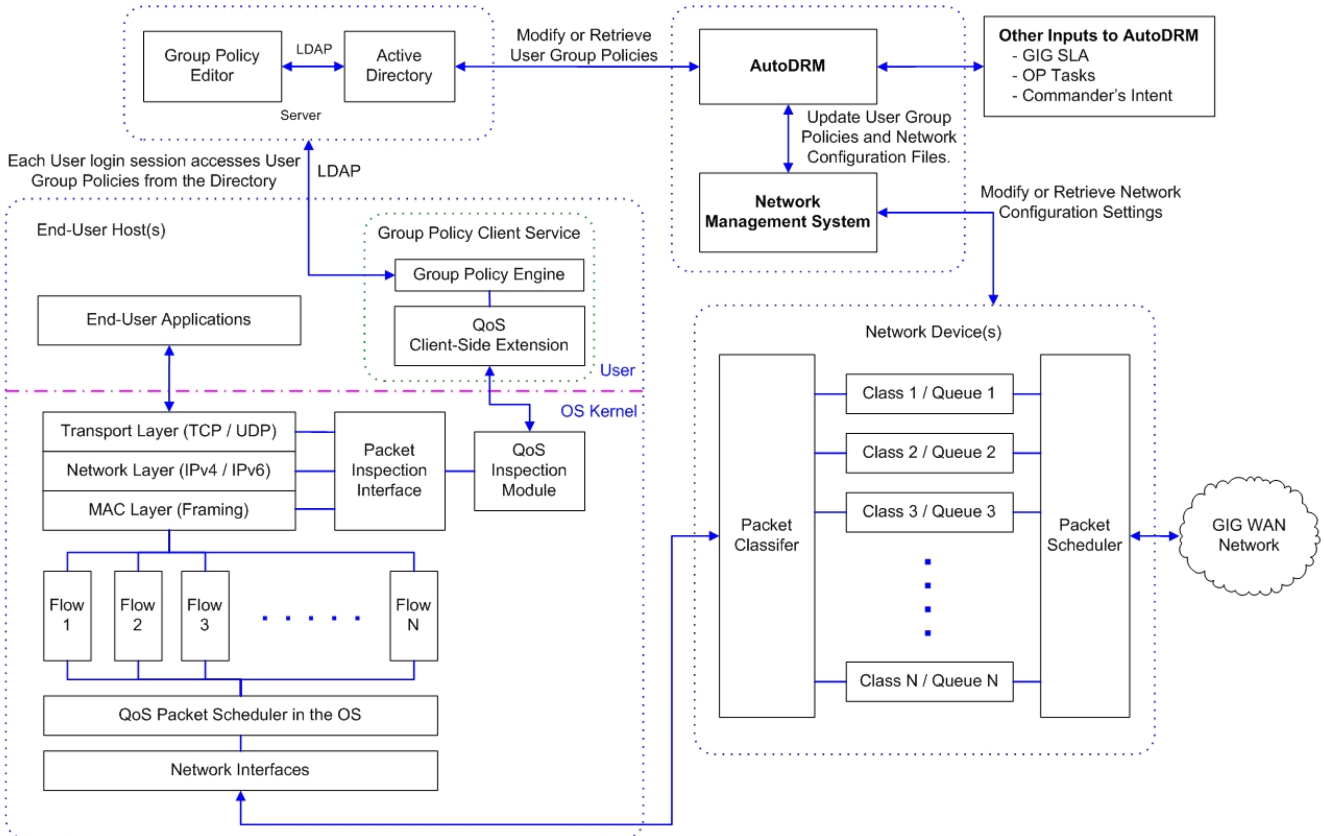


Fig. 3. AutoDRM QoS Architectural Concept

its QoS objectives, where $i \in \{1..n\}$ and $j \in \{1..m\}$. A portion of resource r_j allocated to a service S_i is denoted by r_{ij}. Since each service often needs to meet a set of QoS requirements (*e.g.* packet latency, packet loss ratio..*etc.*), Q_{ij} represents a QoS requirement based on a service S_i consuming a shared resource r_j. This is done under the constraint that the total amount of resources is finite such that $\sum_{i=1}^{n} r_{ij} = R_j$ and $\sum_{j=1}^{m} R_j = \mathbb{R}$, where R_j is the maximum amount of each shared resource and $\mathbb{R}$ is the total available resources in the system. Since all of the resource requests may not necessarily be satisfied in a resource constrained environment, an actual achieved QoS level is represented by q_{ij} such that $q_{ij} \in Q_{ij}$. In order to accomplish adequate QoS levels for each service, the following condition must be met.

$$Maximize \sum_{j=1}^{m} x_i \cdot q_{ij} \quad subject\ to \quad \sum_{j=1}^{m} x_i \cdot r_{ij} \leq R_j$$

$$where \quad i = \{1, ..., n\} \quad and \quad x_i = \{0, 1\}$$

Fundamental theories in developing real-time near-optimal heuristics are discussed in [12] [13] [18] [17]. These approaches involve sorting orders in each data set and gradually assigning a portion of each shared resource r_j to each service S_i. When a QoS level q_{ij} satisfies the requirement Q_{ij}, the iterative process to assign resources is halted. Otherwise, it will continue to assign a greater portion from each resource r_j to each service until the upper limit of that resource R_j has been reached. If a QoS requirement for a service has not been satisfied after a specific resource R_j has been exhausted, a decision to accept the current quality or downgrade resources from other lower priority services is required. The priorities of services are determined by aggregated QoS policies in the network domain. This dynamic process repeats itself until reaching a stable state.

III. Network Architecture

A. Tactical Edge Network

The current *TSCE* system implements the Navy's open architecture strategy and has achieved a full commercial off-the-shelf (COTS) solution. Inspired by the concept of Service Oriented Architecture (SOA), *CANES* system aims to perform more tactical functions while reducing the physical footprint by consolidating the network architecture across multiple security enclaves [7]. *TSCE* and *CANES* are distributed real-time enterprise systems typically deployed on tactical afloat units. Both systems provide various services for the user communities in the tactical edge networks. Since these services are deployed in a common network, they often compete for shared resources. Examples of these shared resources in the systems include processor units, memory devices, storage

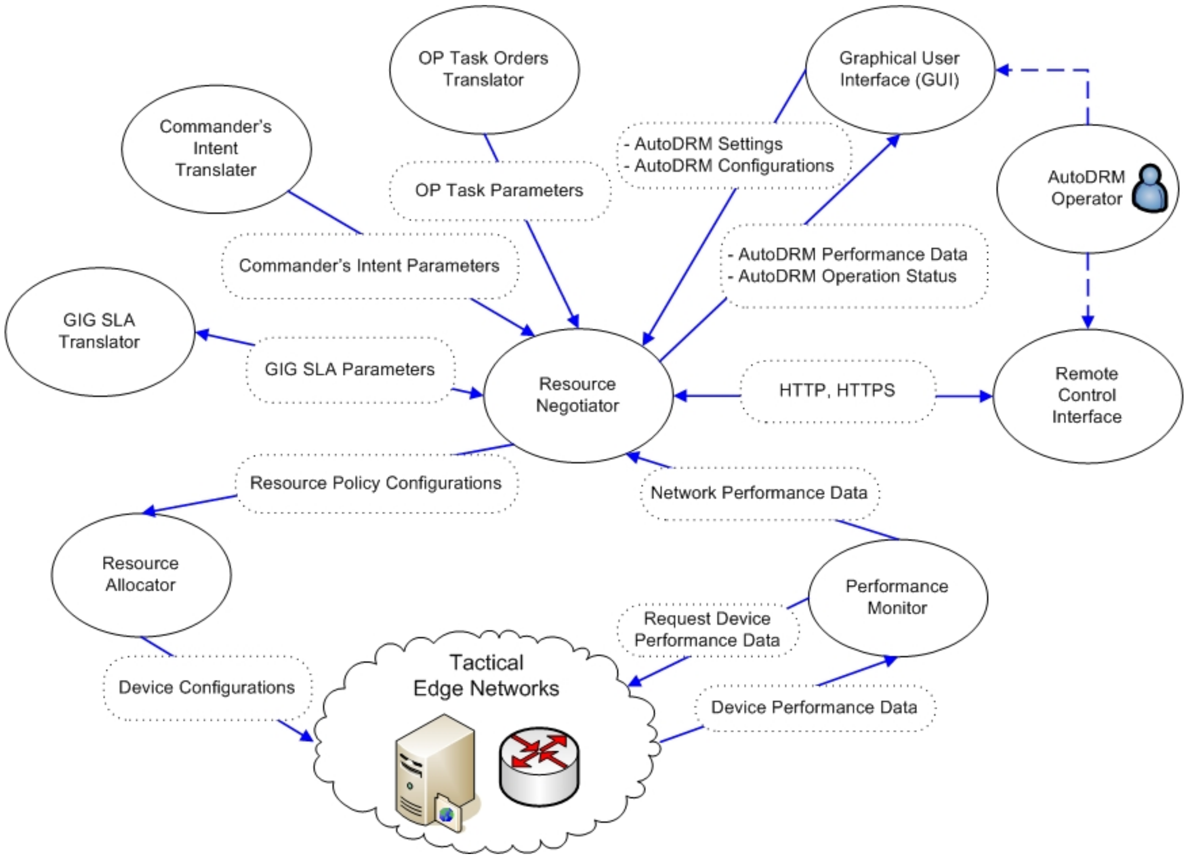


Fig. 4. AutoDRM Functional Block Diagram

disks, networking devices, security devices, and others that have finite constraints. To ensure that each service is performed at adequate QoS levels, the AutoDRM function is required in these edge networks.

B. End-To-End Network Prototype Test Bed

An experimental ETE network prototype test bed as shown in Fig. 2 was developed in order to host the AutoDRM system. In order to maintain consistency with the operational view in Fig. 1, the prototype network includes four representative network domains: Tactical Edge network, GIG Wide Area Network (WAN), GIG-N networks, and GIG-N edge network. The tactical edge network is simulated by a Local Area Network (LAN) group consisting of several PCs, a network switch, and a gateway router. For the purpose of simplifying the prototype test bed development, the router between the tactical edge network and the GIG WAN is shared. Two Virtual LANs (VLANs) were configured to represent the respective network domains. In practice, a gateway router from the tactical edge network is connected to another router residing in the GIG WAN domain. A satellite communications simulator configured with the same settings as in [19], is used to simulate the network characteristics across a long latency SATCOM link. An OPNET System-In-The-Loop [20] scenario was developed to simulate the latency and packet loss rate in the GIG-N networks. The GIG-N edge network is assumed to mirror the tactical edge network in the prototype test bed.

IV. AutoDRM Software Architecture

AutoDRM interfaces with a NMS to provide a dynamic resource management capability for the tactical edge networks. Fig. 3 illustrates the QoS concept in the AutoDRM architecture. In the context of QoS, network devices such as routers and switches can be conceptually represented with a network packet classifier, various queues, and a packet scheduler. Depending on the priority tag marked in each packet header and number of traffic classes, incoming packets are examined and classified into different outgoing queues. Departures of the outgoing packets are scheduled using a queuing technique (*e.g.* priority queuing, weighted fair queuing..etc.). QoS policies using differentiation service (DiffServ) [21] [22] can be configured in each network device to control the behavior of these QoS related components.

As shown in Fig. 3, an end-user host system (*i.e.* PC, server..etc.) executes heterogeneous user applications while utilizing services provided by a common set of network protocol stacks (*i.e.* TCP/IP) in the operating system kernel [23]. AutoDRM can retrieve and modify user group policy objects (GPO) which are stored in the Active Directory of the network domain server. Each GPO defines the QoS parameters such as data throttle rate and Differentiated Services Code Point (DSCP) value at the application level on a per-user or per-computer basis. Upon authentication of a user login session, the group policy client service retrieves user group

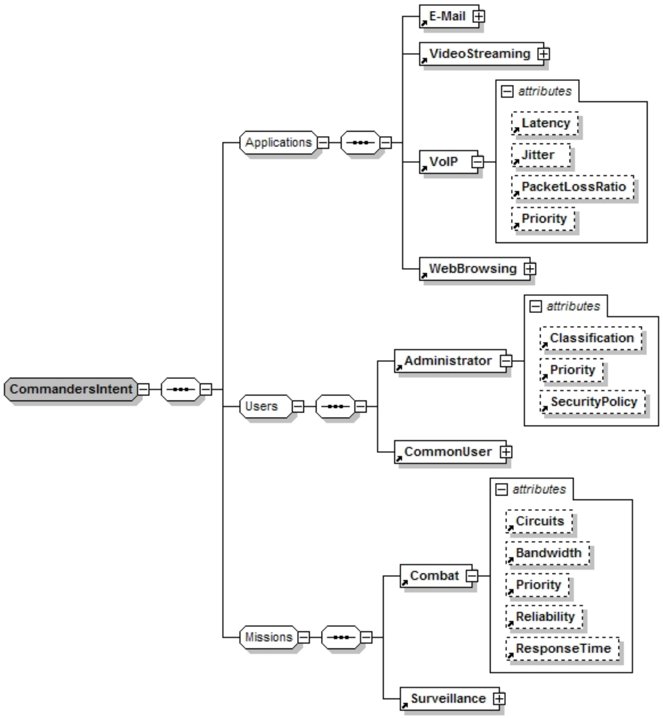


Fig. 5. An Example of Commander's Intent Schema

policies from the Active Directory server. Depending on the user's privilege or the IP address of a host system, GPO enforces the behavior of the network traffic generation from each application. More technical details of this policy-based QoS architecture is discussed in [23]. Based on the dynamics of the network performance measures, AutoDRM utilizes the technology by remotely updating the GPOs via external scripts.

To accomplish the QoS objectives in AutoDRM, Fig. 4 illustrates functional components of AutoDRM which includes Graphical User Interface (GUI), remote interface, several input translators, resource negotiator, performance monitor, and resource allocator. The standalone GUI provides a user friendly interface for the system administrator and mission planning operator to perform initial setup and any subsequent system-level update. The remote user interface provides a convenient method to remotely control the AutoDRM system. The following subsections describe detailed functions of the translators, resource negotiator, performance monitor, and resource allocator.

A. Input Translator

Several built-in translators are required for AutoDRM in order to parse and translate structured documents containing Commander's Intent [24], operational task orders (OP Task), and GIG Service Level Agreement (SLA) [25]. Commander's Intent describes the network and application performance parameters required by the tactical commander. The operational task orders are typically mission specific and are the derivatives of communication plans for tactical units. The input parameters from GIG SLA can be derived from Service Level

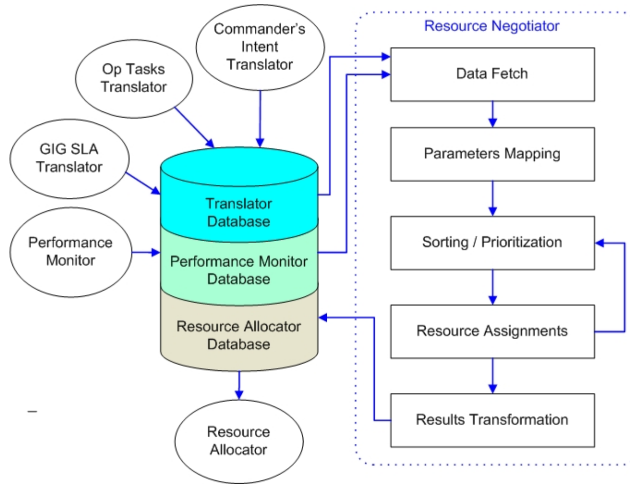


Fig. 6. AutoDRM Resource Negotiator Functional Block Diagram

Specifications (SLS) which is a subset of GIG SLA. The SLS defines the communication parameters for the edge user communities to subscribe to the GIG networks. All of the input parameters are assumed to be contained in structured documents (*e.g.* XML). Fig. 5 illustrates an example of the Commander's Intent schema. The operational task orders and GIG SLA are assumed to be formatted in a similar fashion. A parsing function first parses through the structured documents to extract a set of key communication attributes. A translating function then converts the extracted attributes into measurable parameters and stores the information in a translator database.

B. Resource Negotiator

The core function of AutoDRM is the resource negotiator, which determines the resource allocation based on real-time network performance measurements and notifications from NMS. The resource negotiator exploits a real-time near-optimal heuristic algorithm to determine the resource assignments. Fig. 6 depicts the functional block diagram of the resource negotiator. There are five fundamental functions in the resource negotiator: data fetch function, parameters mapping, sorting based on prioritization, resource assignments, and results transformation.

The data fetch function retrieves translated parameters such as bandwidth, packet delay, packet loss and other measurable network parameters from the translator database and the performance monitor database. The mapping function maps input parameters into a multidimensional array data structure where each array represents a services set, a resources set, a QoS set and other required data sets. The sorting function uses sorting algorithms (*e.g.* quick sort, binary sort..*etc.*) to efficiently sort each data set based on the prioritization of each item within the data set. The real-time near-optimal heuristic algorithm takes the mapped data set and gradually assigns resources to each task in order to minimize the error between the requested QoS levels and the actual QoS levels [13]. The results from the algorithm are transformed in the results transformation function. The main objective of the results transformation function is to convert the acceptable resource assignments into actual user group policies and/or network configuration formats that can be used to regulate the QoS behavior of the devices in the edge network domain. For storage efficiency, a centralized database is shared among translators, a performance monitor and the resource allocator. A scheduler in the resource allocator will then update the GPOs in the network domain using external scripting methods and/or network device configuration updates via NMS.

C. Performance Monitor

The performance monitor in AutoDRM exploits the rich set of network monitoring features in NMS to collect real-time network performance measurements through Simple Network Management Protocol (SNMP). The major categories of these features include service polling, data collection, events and notifications [26]. By leveraging the monitoring features in NMS, the performance monitor function constantly retrieves network performance information from the NMS into the performance monitor database in AutoDRM. In addition, the performance monitor also interfaces with the Active Directory server containing the GPOs. Modification of any GPO is updated in the database as well. Database updates are monitored by the resource negotiator. In the event of any network performance change (*e.g.* bandwidth saturation, increase of packet loss ratio, increase in average packet delay..*etc.*), the resource negotiator re-evaluates the QoS requirements and re-computes resource assignments to mitigate the possibility of resource contention in the network domain. The performance monitor makes use of common remote scripting tools and the development toolkits provided by the NMS for developing the required software interfaces.

D. Resource Allocator

The resource allocator is primarily responsible for scheduling the configuration updates in the network domain. Similar to the performance monitor, the resource allocator in AutoDRM also interfaces with the NMS to modify the network configurations in each individual network device as well as updating user group policies in the network domains by remote scripting methods. In the event of degraded network performance, the resource negotiator responds with an updated resource allocation and stores the necessary changes into the shared resource allocator database. The resource negotiator sends out notifications to the resource allocator which then updates the configurations of affected network devices and the host systems.

V. Experimental Setup

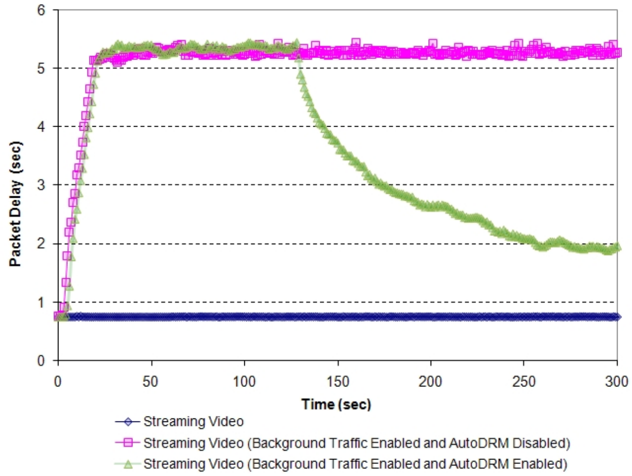
To investigate the effectiveness of the AutoDRM system, a relevant use case consisting of three test scenarios was developed for the experimental setup. The use case assumes a user in the tactical edge network is receiving a mission critical streaming video service from a video server residing in the GIG-N edge network. The network traffic flow representing a streaming video service is simulated as an User Datagram Protocol (UDP) flow using Distributed Internet Traffic Generator (DITG) [27]. A NMS deployed in the tactical edge network monitors real-time network performance. The NMS is pre-configured to generate asynchronous notifications (*i.e.* SNMP traps) to the AutoDRM system when certain network thresholds are met (*i.e.* packet delay $\geq$ 5 seconds, packet loss $\geq$ 20 pkts). Upon receiving the notifications, AutoDRM determines that the streaming video service has the highest priority among other background traffic flows. Thus, the system provides preferential service to the streaming video flow by allocating more resources to it. The AutoDRM resource allocator achieves this goal by updating the policy-based QoS parameters in the Active Directory as well as updating QoS policies in the configurations of the router and the switch within the edge network domain.

For the purpose of performance comparison, three test scenarios with different configurations were performed. Each test scenario had different network traffic conditions. The first test scenario consists of a single streaming video traffic flow without any background network traffic load. This test scenario established a baseline test result. Two test scenarios consisting of a streaming video traffic flow with mixed background traffic flows were also performed. One test scenario was with AutoDRM enabled and another test scenario was with AutoDRM disabled. The background network traffic contains nine heterogeneous UDP and TCP flows. Since the performance of the mission critical streaming video was under investigation, the packet delay and packet loss were the two key QoS performance metrics of interests in this experimental setup.

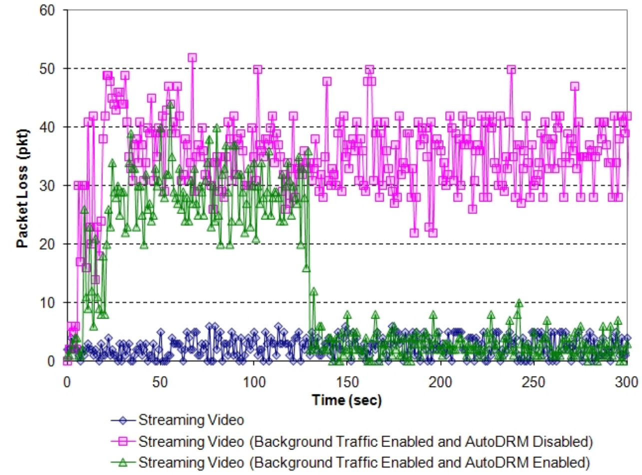
VI. Results and Discussion

The experimental results for each test scenario are shown in Fig. 7. The measurements are primarily focused on the QoS performance of the streaming video traffic flow over an initial period of five minutes. The QoS performance results include the packet delay as shown in Fig. 7(a) and the packet loss as shown in Fig. 7(b). As illustrated in Fig. 7(a), the baseline end-to-end packet delay for the streaming video flow without any background network traffic is 0.8 seconds. When the streaming video service is running with background network traffic and with AutoDRM system disabled, the end-to-end packet delay quickly surges to more than 5 seconds after 20 seconds of run time. The packet delay stays at 5 seconds throughout the remaining duration of this test scenario. With AutoDRM system enabled, the NMS generates asynchronous notifications when the packet delay exceeds 5 seconds threshold at 20 seconds of run time. The packet delay for the streaming video flow starts to decrease after 130 seconds of run time. The packet delay becomes stable after 250 seconds of run time.

As shown in Fig. 7(b), baseline packet loss for the streaming video flow is less than 10 packets at any given time interval. With AutoDRM system disabled, streaming video flow running with background network traffic results in packet loss ranges from 20 to 50 packets after about 10 seconds of run time. With AutoDRM system enabled, the NMS generates asynchronous notifications when the packet loss exceeds 20



(a) Packet Delay (sec)



(b) Packet Loss (pkt)

Fig. 7. AutoDRM Experimental Results

packets threshold at 10 seconds of run time. The streaming video flow running with background network traffic shows improvement of packet loss to less than 10 packets at 130 seconds of run time. It can be concluded that AutoDRM system takes more than 100 seconds reaction time to improve both QoS performance metrics of the streaming video flow in this experimental setup. The time is mostly spent on making calls to external scripting methods, waiting for GPO to be updated, and waiting for the network devices' configurations to be updated. These actions take approximately 120 seconds stabilization time. The test results also show that packet delay performance is improved by 60% and packet loss performance is improved by 66% in this test scenario.

VII. Conclusion

The framework of Automatic Dynamic Resource Management architecture has been developed in this experimental study. An end-to-end network prototype test bed consisting of real network devices, a simulated SATCOM link, and an OPNET SITL scenario was also developed to host the AutoDRM system. Three test scenarios representing three different network traffic conditions were executed. The test results demonstrate improved QoS performance in terms of packet delay and packet loss. The results from these scenarios indicate that AutoDRM system can be a vital function to enhance the network QoS performance.

Developing a practical approach for providing ETE QoS management services through automatic and dynamic mechanisms has attracted interest from the user communities. To achieve the objective, it is important to recognize the necessity to incorporate network performance and connectivity data with service request information associated with the application and the specific services available or supported by the network. This capability becomes even more important as network aware applications become available which will be able to take full advantage of the resource negotiation process presented in this paper. Future research efforts include using the developed end-to-end prototype test bed for exploring dynamic QoS optimization mechanisms and policies specifically recognizing the need to derive network performance from the Commander's Intent.

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Disclaimer

The opinions, findings, results, recommendations, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the official views and positions of Lockheed Martin Corporation or any U.S. government agency.

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