Controlling Quality-of-Service in a Distributed Real-time and Embedded Multimedia Application via Adaptive Middleware

Richard E. Schantz, Joseph P. Loyall, Craig Rodrigues
BBN Technologies
Cambridge, MA, USA
{schantz, jloyall, crodrigu}@bbn.com

Douglas C. Schmidt
Vanderbilt University
Nashville, TN, USA
d.schmidt@vanderbilt.edu

Abstract

A challenging problem for distributed real-time and embedded (DRE) systems is control and adaptation of resources to maintain the best possible application performance in the face of changes in load and available resources. This paper presents two contributions to R&D activities in the DRE domain. First, we describe the structure and functionality of an advanced middleware platform (based on our QuO adaptive middleware framework and the TAO Real-time CORBA middleware suite) for developing DRE applications that adapt to changes in resource availability to meet quality of service (QoS) requirements. Second, we present case study results of a DRE multimedia application for Unmanned Aerial Vehicle (UAV) video distribution, developed using this middleware platform in conjunction with QoS-enabled operating systems and networking technologies. We describe the design of the UAV multimedia application using our middleware platform and report empirical results showing how adaptive behavior and end-to-end resource management techniques are used to meet timeliness requirements, even in the face of processing power and network bandwidth restrictions that are characteristic of many types of DRE systems. Our results show that our middleware infrastructure can effectively coordinate resource allocation end-to-end and adapt application behavior to continue to meet QoS requirements over changing environments.

1 Introduction

1.1 Emerging Trends and Technologies

Next-generation distributed real-time and embedded (DRE) systems must collaborate with multiple remote sensors, provide on-demand browsing and actuation capabilities for human operators, and respond flexibly to unanticipated situational factors that arise at run-time [3,17]. For example, new and planned emergency response systems are incorporating Unmanned Air Vehicles (UAVs) to send video images to processes that distribute the video to the proper control stations, which in turn contain video displays and other video processing applications,

such as automatic target recognition (ATR), that analyze the video and trigger appropriate responses, including revised tasking for the UAV-based video sensors. In these types of DRE systems, end-to-end control and adaptation of various application quality of service (QoS) properties (such as latency, jitter, throughput, dependability and security) are essential to maintain the best possible performance in the face of changes in available computing and networking resources and changes in mission requirements. The computing and networking infrastructure must therefore be flexible enough to support varying workloads at different times during an application's lifecycle, while also maintaining highly predictable and dependable behavior. Controlling the end-to-end real-time behavior of such DRE systems is a crucial dimension of their delivered QoS, as is adaptively managing the tradeoffs among competing demands and optimizations.

The recent focus on user control over QoS aspects [6,7] stems from technology advances in research areas such as resource allocation policies, synchronization of streams in DRE multimedia applications, and assured communication in the face of high demand over shared resources. The focus on QoS has led to the development of a number of improvements to commonly available computing and networking infrastructures that can recognize and react to environmental changes. At the heart of these infrastructures is *middleware*, which is systems software that resides between the applications and the underlying operating systems and networks to provide reusable services that can be composed, configured, and deployed to create DRE applications rapidly and robustly [10]. Figure 1 illustrates the following two middleware layers that are central to the focus of this paper:

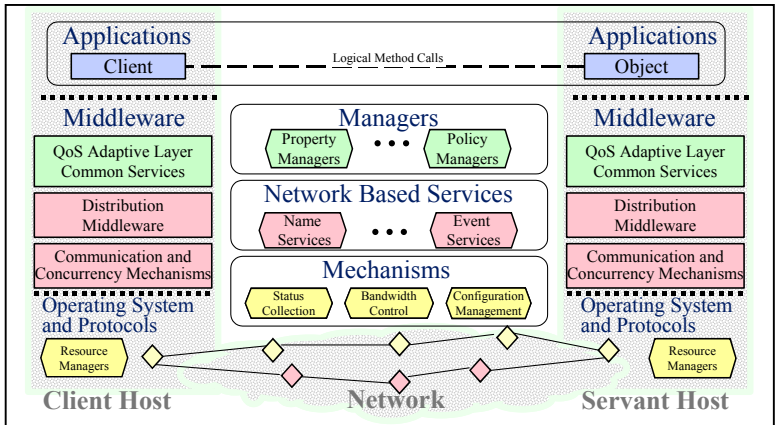


Fig. 1. Layers of Middleware

- ***Distribution middleware*** – This layer of middleware encapsulates lower-level operating system and networking mechanisms to provide a higher level programming model that automates common distributed programming tasks. Examples of commercial-off-the-shelf (COTS) distribution middleware include CORBA [9], Java RMI [14], and Microsoft's COM+ [1].
- ***QoS adaptive middleware*** – This emerging layer of middleware provides the abstractions necessary to adapt to

changing conditions and requirements for applications by bridging the gap between (1) an application's QoS needs across its multiple parts and (2) the middleware services and infrastructure that provide QoS. An example of QoS adaptive middleware is the Quality Objects (QuO) framework [16].

1.2 Towards Adaptive Middleware for DRE Systems

As computing and networking performance continues to increase, so too does application demand for more control over computing and networking resources through the middleware interface. In particular, the DRE multimedia applications outlined in Section 1.1 have stringent requirements (such as the need for streaming data transport, time-sensitive performance, and demanding QoS characteristics oriented toward human factors) and characteristics (such as workloads that can vary significantly at run-time) that need focused support from middleware. In turn, this increases the demands on end-to-end system resource management to coordinate multiple end-to-end resource needs simultaneously and mediate resource needs across multiple applications so they can (1) continue to respond adequately during both anticipated and unanticipated operational changes in their run-time environment and (2) ensure that critical applications acquire the necessary resources at the expense of less critical applications.

Meeting the growing demands of DRE multimedia applications motivates the need for adaptive middleware-centric QoS management abstractions and techniques that can (1) integrate control and measurement of resources end-to-end, (2) mediate the resource requirements of multiple (often competing) applications, and (3) dynamically adjust resource allocation in response to changing requirements and conditions. Our earlier middleware R&D efforts on these topics have focused on The ACE ORB (TAO) [12] and the Quality Objects (QuO) framework [7], which leverage Real-time CORBA [9] to provide efficient, scalable, and predictable middleware structures and services, and adaptive QoS management policies, respectively, to support end-to-end DRE system QoS requirements. TAO is a high-performance distribution middleware layer targeted for DRE applications with both deterministic and statistical QoS requirements, as well as best-effort requirements. The QuO framework is a QoS adaptive middleware layer that runs on existing middleware and enables DRE applications to specify (1) their QoS requirements via rule-based contracts, (2) the system elements that must be monitored and controlled to measure and provide QoS, and (3) the structure and behavior for adapting to QoS variations that occur at run-time.

This paper extends our earlier work with TAO and QuO by combining these adaptive middleware frameworks with multimedia middleware services (such as the CORBA Audio/Video Streaming Service [8]), real-time operat-

ing systems (such as Real-time Linux [13]), and QoS-enabled networking protocols (such as IntServ [15] and DiffServ [5]) to develop robust DRE multimedia applications that can adapt to changes in resource availability to better meet their end-to-end QoS requirements. Our approach is presented in the context of a DRE multimedia application for UAV video distribution (section 2), in which a video flow from a UAV source adapts to meet its mission QoS requirements (such as timeliness and video quality) in the face of restrictions in processing power and network bandwidth. We discuss distinct multi-layer behaviors that can be used to control resources and adapt to limitations and restrictions in processing power and network bandwidth (sections 3&4). We present and analyze empirical results (section 5) we gathered to evaluate this application in the context of an open experimentation platform (OEP)[1] developed to evaluate these technologies in operational systems. Our results show how adaptation can be controlled effectively by applying integrated resource management end-to-end and by superimposing application-level policies managed via middleware to regulate performance problems caused by processor and/or network load.

2 Applying Managed QoS to DRE Systems: the UAV Case Study

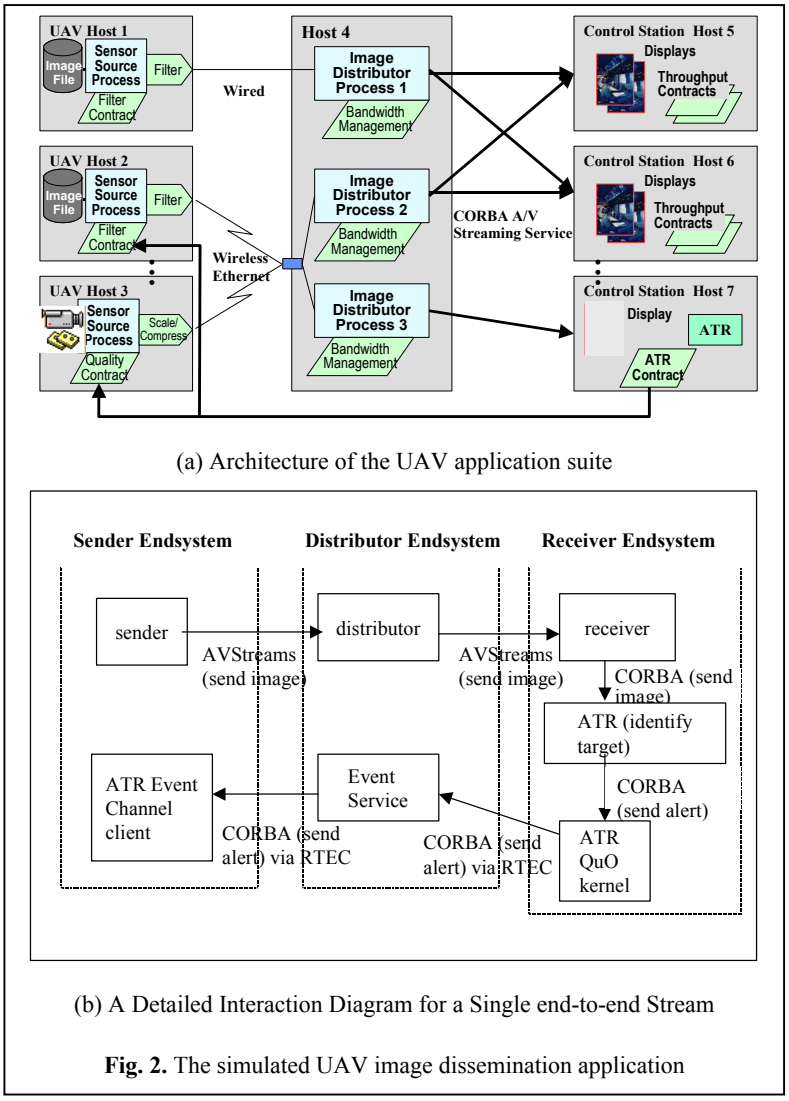
This section presents a case study of a DRE multimedia application for UAV video distribution, where multi-layer resource management mechanisms are coordinated via middleware to ensure video flows can meet their mission QoS requirements (such as timeliness, jitter, and image resolution) by adapting to restrictions in available processing power and network bandwidth. The resulting application architecture shown in Figure 2 adaptively controls video transmission captured from cameras via a distribution process to viewers on various computer displays using the following three stage pipeline:

1. ***Sensor sources***, (endsystems 1-3) including processes with live camera feeds (and those that simply replay from a pre-recorded file to simulate airborne sensors), which send video images to
2. ***Distributor processes***, (endsystem 4) which are responsible for distributing the video to one or more
3. ***Receivers***, (endsystems 5-7) including human-oriented video displays and CPU-intensive image processing

[1] An OEP is a hardware/software laboratory capability environment incorporating COTS infrastructure and representative applications operating in it, which can be modified and augmented with technology and application innovations, toward evaluating their contribution to technical challenges in that context. We are currently using the Emulab facility at the University of Utah (http://www.emulab.net) to host the UAV application OEP environment.

software.

Our UAV application suite uses the QuO and TAO middleware outlined in Section 1.1 to manage QoS by engaging application adaptive behavior, such as dropping frames, requesting resource reservations, indicating prioritization among data streams, and ensuring transparent fault recovery in a bounded amount of time. It also exhibits a wide variety of characteristics (such as constrained resources, varying conditions and configurations, and varying data and processing characteristics) that are representative of a broad class of time-sensitive, mobile, and dispersed operation multimedia DRE applications, especially in the domains of pervasive computing, remote sensing, hazardous operating environments, and automated process control.



(a) Architecture of the UAV application suite

(b) A Detailed Interaction Diagram for a Single end-to-end Stream

Fig. 2. The simulated UAV image dissemination application

In the context of our UAV application, managing real-time end-to-end QoS requires supporting and coordinating the following measures of operational effectiveness:

- ***Minimal frame rate.*** Full motion video is typically 30 frames per second (fps), but smooth video is still acceptable above 20 fps. Our UAV application uses variable frame rates as low as 2 fps for human viewing and lower for image processing.
- ***Minimal latency.*** Some uses of sensor information (such as remote piloting) require remote end viewers to see an accurate and timely view of the sensor data, which implies a minimal latency requirement. Studies have indicated that humans can perceive a delay of more than 100-200 ms, which provides a lower bound timeliness requirement in cases where the video is meant for human viewing and precision action.
- ***Minimal jitter.*** Controlling the smoothness of the video can have greater impact on the perceived quality than

the frame rate. Common strategies for reducing jitter (such as buffering) are not as useful in real-time video because of the timeliness constraints.

- ***Image quality.*** The image must be of high enough quality (i.e., have the requisite image size, pixel depth, etc.) for the purpose it is being used, e.g., video must be large enough and clear enough to discern details that humans need.
- ***Coordination of multiple activities.*** The middleware, in conjunction with OS, network, and application directives, must control and coordinate the necessary allocations and tradeoffs that are made to ensure that the highest priority streams and the most important characteristics (e.g., frame rate, latency, and jitter) are favored, even while other, less important characteristics may be minimized or neglected.

Satisfying the measures of operational effectiveness outlined above requires managing resources (particularly CPU and network bandwidth) along the entire path from video source to sink. It also involves trading off one property (e.g., timeliness) against another property (e.g., fidelity) based on the particular requirements of end-users at that moment.

All remote operation calls in our UAV application are made via the TAO real-time ORB [11]. The TAO implementation of the CORBA Audio/Video (A/V) Streaming Service [8] is used to establish the video streams and to transport the data. We encode QoS measurement, control, and adaptation directives and policies throughout the UAV application via QuO contracts [7] that are responsible for managing the resource and application/data adaptation necessary to achieve an appropriate end-to-end QoS matched to the circumstances relevant at that time.

3 Resource Management for DRE Multimedia Applications

This section describes the various priority- and reservation-based OS and network resource management mechanisms we have integrated and evaluated within our QoS management framework for DRE multimedia applications based on QuO and TAO. The OS and network mechanisms are *necessary* conditions for establishing end-to-end QoS, but they are not *sufficient* by themselves. To achieve end-to-end QoS, therefore, we use a middleware-mediated QoS management framework to control and coordinate these individual resource management mechanisms, augmented with additional adaptation mechanisms for making dynamic adjustments and modulating the application's footprint for using resources as discussed in this section.

3.1 Mechanisms for Prioritized and Reserved Management of Computing and Networking Resources

Achieving end-to-end QoS for DRE multimedia applications requires management and control of the processing resources on endsystems in a distributed system and the network resources that connect them. Below we describe mechanisms that (1) prioritize competing network traffic using standard Internet technologies and (2) reserve pre-specified amounts of processor time on endsystem computers.

Priority-based OS resource management. The management of CPU resources in most operating systems has traditionally been handled by assigning priorities to tasks in the system (usually threads or processes) and applying scheduling algorithms to assign each task a share of CPU time. Standards-based COTS middleware has historically lacked features that leverage these priority-based OS resource management capabilities, which made it hard to ensure and coordinate predictable platform processing behavior via middleware. To remedy this omission, the Real-time CORBA 1.0 specification [9] defines standard features that support end-to-end predictability for operations in fixed-priority CORBA applications, thereby enabling fine granularity allocation, scheduling, and control of key endsystem OS resources.

The TAO implementation supports the standard Real-time CORBA interfaces and QoS policies. As a result, DRE applications that use TAO have standard ways to configure (1) *processor resources* via end-to-end priority preservation mechanisms, thread pools, intra-process mutexes, and a global scheduling service, (2) *networking resources* via protocol properties and explicit bindings, and (3) *memory resources* by bounding request buffering and thread pool size. Our earlier work [11] describes how these priority-based OS resource management mechanisms have been applied to UAV mission computing systems.

Reservation-based OS resource management. An alternative to priority-based OS resource management is to reserve sufficient resources *a priori* for estimated application needs. TimeSys has applied this approach to resource management by implementing a CPU reservation feature for their TimeSys Linux OS. An application – or a middleware proxy for the application – running on top of the TimeSys OS can specify its QoS requirements for timeliness, and their underlying resource kernel [13] will manage the OS resources so that these requirements can be met. For CPU resources, TimeSys Linux allows applications to specify their timeliness requirements by specifying parameters for *compute time* and *period*. If the resource kernel can allocate resources that meet these requirements, it grants an application a *reserve*, which guarantees that for every period, the application will have the

requested amount of CPU compute time and will not be pre-empted.

Although TimeSys Linux provides mechanisms for reserving OS CPU resources, the QuO and TAO middleware are ultimately responsible for determining who gets the reserved capacity, how much, and for how long. These policy decisions are performed by the higher-level middleware since it retains the end-to-end perspective to set the lower-level OS resources appropriately. We have worked with the University of Utah to develop a CORBA-based CPU reservation manager that (1) is the local agent for setting up reservations on an endsystem and (2) translates various representations of reservation specification into the style supported by TimeSys Linux.

Priority-based network resource management. The Internet Engineering Task Force (IETF) Differentiated Services (DiffServ) architecture [5] provides different types or levels of service for IP network traffic. Individual traffic flows can be made more resistant to packet dropping (and hence get preferential delivery) by setting the value of each IP packet's DiffServ field appropriately. An IP header has an eight bit DiffServ field that encodes router-level QoS into (1) six bits of DiffServ Codepoint (DSCP), which enables 64 service categories of per-hop behavior, and (2) two bits of explicit congestion notification. The middleware is responsible for adding the appropriate QoS management DSCP encoding to the data packet headers to specify the appropriate type of service within the multi-application environment. DiffServ-enabled routers then use the DSCP to differentiate the network traffic.

We have implemented enhancements to TAO and QuO that leverage DiffServ capabilities. First, TAO provides an efficient and flexible way of setting the DSCP by extending its Real-time CORBA protocol properties so that priority can be propagated to requests as they transit the network and OS resources. Based on various factors (such as resource availability, application conditions, and operational requirements), the QuO middleware can change these priorities dynamically by marking application streams with appropriate DSCPs to ensure appropriate priority handling against lower priority competing traffic. Second, TAO provides a mechanism to map Real-time CORBA priorities to DiffServ network priorities. The TAO ORB provides a priority-mapping manager that QuO uses to install a custom mapping to override the default mapping.

Reservation-based network resource management. Setting DSCPs as discussed above makes traffic flows less likely to be dropped due to network congestion in routers. There is no way in this model, however, to *guarantee* a level of service to a traffic flow unless it is the single highest priority traffic at each intermediate step. As with the OS-level resource reservations discussed earlier, it is also desirable to request resources from the network to help guarantee properties (such as latency or bandwidth of network traffic) across some competing flows by

reserving appropriate capacity in advance.

To address these issues, the IETF developed the Resource Reservation Protocol (RSVP) [15], also commonly referred to as IntServ (for Integrated Services), which is a new reserved capacity mechanism to augment IP. Whereas the DiffServ mechanisms outlined earlier merely classify and prioritize packets for different service levels, IntServ reservations allocate and coordinate router behavior along a communication path flow to ensure the reserved end-to-end bandwidth. Our earlier work [11] describes how IntServ reservation-based network resource management mechanisms were applied to UAV applications via the CORBA A/V Streaming Service provided with TAO.

3.2 A QoS Management Framework for DRE Multimedia Applications

The OS and network resource management mechanisms described in Section 3.1 can be used in various combinations that reflect tradeoffs of integrated methodology, current practice, widespread availability, or maximum performance/cost advantage. To enable effective coordination and control of these individual and aggregate end-to-end resources, we have created elements of a QoS management framework for DRE multimedia applications by integrating the TAO and QuO middleware outlined in Section 1.1 with the mechanisms described in Section 3.1 that manage lower level OS and network resources. The primary focus of the resource management control strategies is to ensure that more important application tasks get the resources they need to complete their actions at the expense of – or isolated from – other less important tasks. In many cases this is not sufficient to achieve managed QoS objectives, either because there may still be insufficient resources available or because it may be more appropriate to share resources using gradations of service levels that could operate simultaneously, each with diminished resources. To complement the resource control strategies, our QoS management framework supports adaptive strategies that seek to dynamically change the resource consumption of an individual DRE application. By intelligently modifying the approach to the application functionality (e.g., by using alternative algorithms, changing heuristics, or being more selective about degrees of fidelity for various aspects of a computation), we can often change the way an application performs its task (and indirectly shape/reduce the amount and timing resources needed to perform that task) to dynamically adapt to the current load, resource availability, or operating conditions prevalent at the time. Section 4 describes key adaptive strategies used by our UAV application.

4 Using Adaptation to Maintain Real-time QoS Under Reduced Resource Availability in the UAV Multimedia Application

This section describes how we augmented and applied application-level adaptation to complement resource control by shaping the interactions between components so they can continue to meet the QoS requirements under diminished resources available to the application. Adaptation and QoS management is necessary since a bottleneck may occur in our UAV application because at some point along the video transport path there are not enough resources to send the entire video to the viewers in real time. A bottleneck can also occur when one or more of the competing UAVs has (or gains) priority access to significant fractions of the available resources, while the rest must operate within the diminished resources available. When such a bottleneck is detected, we use adaptation techniques to mitigate the damage to our QoS objectives. Depending on user requirements, it is possible to omit some frames of the video entirely, yet still retain an end-user video that displays the motion of the scene in real time without the total fidelity of continuously displayed motion achieved at frame rates of 24 frames or more per second.

To perform data filtering in the UAV prototype, we employ the technique of reducing the transmitted frame rate, e.g., from the distributor to the viewer or between the video source and the distributor. In one important mode of operation, the frame rate must not be reduced in such a way as to create a "slow motion effect," i.e., a vehicle that crossed the field of view of the video source camera in say, 2.5 seconds, should still cross the viewer in 2.5 seconds. A video source attempts to transmit data at the standard rate of 30 fps, which is received at that rate (when system resources permit), but an adaptive behavior can be interposed that sends out a smaller number of frames representing the action that occurs during each second. The subset to be sent is selected by *dropping* some frames from the video, and also sending out the remaining frames at a reduced rate.

The implementation of data filtering to reduce the volume of video data is dependent on the video encoding format. MPEG encoded video results in sequences of 15 frames each of which consist of an independent I frame, as well as 10 derived B frames and 4 derived P frames (see figure 3, and [2] for a synopsis of MPEG encoding of video). One second of video at the full rate of 30 fps requires two sequences of these frames. The best frame-dropping strategies drop B-frames when only a few frames needed to be

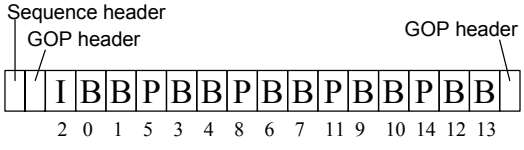


Fig. 3. Sequence of frames in MPEG file

dropped. There are 20 B-frames in each second of video, so this technique can bring the sending rate down to a still effective 10 frames per second. To drop more frames, P-frames can then be dropped. I-frames can be dropped only if intervals of 1 second or more between images are acceptable, which in our application it was not.

For practical implementation reasons we chose to drop frames entirely in such a way that the remaining frames were to be displayed at a constant rate. This strategy provided us with three significantly different levels of QoS among which to adapt the application, as determined by the frame rate: (1) 30 fps, which is done by transmitting the video intact to provide the highest level of QoS, (2) 10 fps, which is done by dropping all B-frames from the video and transmitting all the I- and P-frames, which preserves most perception of motion in the video scene, and (3) 2 fps, which is done by dropping all P- and B-frames from the video and transmitting all I-frames, which loses the finer details of motion and some very short-lived actions. We then adaptively switch among these three frame rates by assigning each frame rate to a different region of a QuO contract, and setting the frame-dropping strategy at any given time according to the current region (and indirectly the currently available resources). Below 2 fps, the application would go dormant, until appropriate conditions were restored, because these were below the threshold of operator usability.

In the video used in our experiments, I-frames averaged approximately 13,800 bytes, P-frames approximately 5,000 bytes, and B-frames approximately 2,900 bytes. The approximate size in bits per second (bps) of two average MPEG encoded sequences (the bandwidth requirement for one-full second at a full 30fps) is therefore (2(13,800) + 8(5,000) + 20(2,900)) * 8 = 1,004,800. If we drop to 10 frames per second by eliminating the B-frames, the bandwidth required falls to approximately (2(13,800) + 8(5,000)) * 8 = 540,800 bps, and if we drop to 2 fps by also eliminating the P-frames, the required bandwidth falls to approximately 2(13,800) * 8 = 220,800, i.e., reducing the frame rate from 30 to 10 (a 67% reduction) reduces the bit rate by 46%, and reducing the frame rate from 30 to 2 (a 93 % reduction) reduces the bit rate by 78%.

5 Empirical Results of End-to-end Resource Management Experiments

This section presents and analyzes selected samples of results from experiments that cover end-to-end management capabilities stemming from the integration of the individual resource management techniques within our middleware-mediated QoS management framework. These experiments evaluate the ability of multiple resource management technologies coordinated via middleware to effectively and predictably maintain end-to-end QoS as systems scale to include more participants and more competing load.

5.1 Experimental Design and Hardware/Software Testbed

To test the hypothesis that middleware-coordinated CPU and network management working together can maintain end-to-end QoS in systems with constrained and loaded processors and links, we conducted a set of experiments that ran up to 14 simultaneous simulated UAVs sending imagery to the simulated ground control stations (distributors) and control centers (receivers). The number of image streams was enough to overload the networks transporting the imagery and control information, and to overload the processors executing the image processing systems.[2] We measured the ability of the resource management mechanisms to control resource allocations sufficiently for an image stream designated as most critical (the experimental case) to consistently sustain the resources needed to complete the application requirements (i.e., detecting and reporting identified targets in imagery data), as contrasted with other competing image streams not marked as critical (the control cases).

In this series of experiments, each of the 14 senders transmitted a sequence of images at a constant rate of 2 fps, in accordance with the application architecture depicted in Figure 2. For a single image stream, a sender process sends images to a distributor and the distributor transmits these images to a receiver. The receiver transmits images to an automated target recognition (ATR) program. If the ATR identifies a target in the image stream, it sends a notification to a QuO contract monitoring the imaging components, which in turn propagates the alert via the TAO Real-time Event Channel [4] to an Event Channel client program. When this client program receives the alert, it performs a round-trip time calculation designed to measure the overall time that elapsed from (1) when an image with a target in it was sent from the sender to (2) the time when an alert notification reached the ATR Event Channel client. This time represents the desired end-to-end capability for which we are trying to maintain a predictable QoS footprint under heavy load.

In this experiment, there was contention for both network and CPU resources due to the number of processes involved in simultaneously trying to deliver and identify objects in the 14 image streams. Our coordinated QoS management framework capability was configured to attempt to sustain the end-to-end performance of a designated image stream (the 7th stream, out of the 14). The coordinated QoS management capability under test combined DiffServ network prioritization and CPU reservations. For stream 7, we applied DiffServ network prioritization (over other competing, non-prioritized traffic) using QoS management setup to introduce this behavior be-

[2] In contrast, our earlier experiments [11] introduced artificial load on targeted processors or links. Our experiments reported in this paper produced more realistic loading of the entire system end-to-end.

tween the sender and distributor, and between the distributor and receiver. In addition, we applied the CPU reservation behavior to the ATR for stream number 7 (only). The CORBA object in the ATR that received the frames was encapsulated by a QuO delegate that was responsible for determining the magnitude of the CPU reservation requested from the CPU broker. The policy used in this experiment adjusted the CPU reservation request to the highest value seen in processing the five previous frames. This adaptive policy works well in general since it can quickly adapt to spikes in usage without overprovisioning for long periods of time. For this experiment, we used a "strict priority" contention policy that favors high-priority processes when making reservations. Under that policy, the designated high priority UAV stream would be granted its reservation request regardless of the requests of the other activities.

Experiments were performed on hardware and software provided by the University of Utah's Emulab testbed. Each node in our experiments included an 850 MHz Intel Pentium III processor with 512MB PC133 ECC SDRAM, and appropriate communication interfaces for both experimental and experiment control networks. The software configuration for our experiments included Red Hat Linux 7.3, TimeSys v3.1 (selected nodes), FreeBSD 4.8 on "router" nodes, modified to support QoS for network traffic using the (ALTQ) extensions, TAO v.1.3.3, QuO v.3.0.11, and CPU Broker v1.

5.2 Managed End-to-end Measurements and Analysis

The following are sample, measured testbed results indicating how our integrated middleware-mediated QoS management framework can sustain adequately predictable QoS results under heavy competing load using realistic application scenarios.

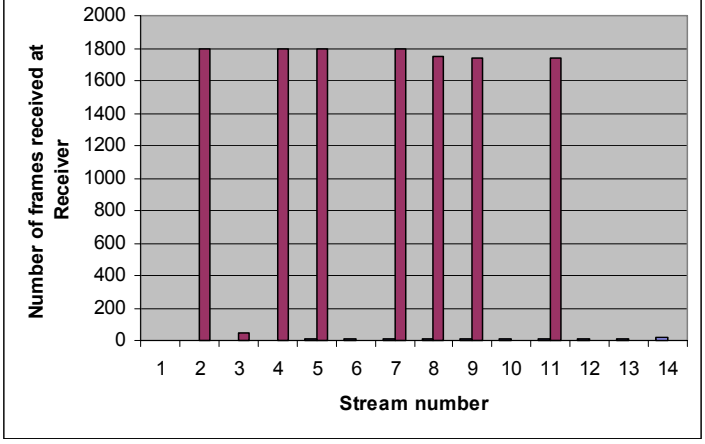


Fig. 4. Number of Frames Received; Stream 7 uses a CPU Reservation and Diffserv Priority

Measurement 1: Number of frames received at receiver. For this measurement, the number of images received at each of the competing receivers was recorded. Stream 7 (only) was prioritized for its network traffic using DiffServ and used CPU Reservations to ensure adequate processing resources. Figure 4 shows that UAV#7 received all of its frames (as did unmanaged UAV's #2,4,5), while some of the rest received

most of their frames (#8,9,11), and most (#1,3,6,10,12,13,14) received hardly any service at all, as measured by the number of frames that arrived during the experimentation interval. Since frames are received prior to the CPU intensive processing of the ATR, this measure is largely dominated by controlling network behavior.

Measurement 2: Number of ATR alert control messages received. For this measurement, the number of ATR Alert control messages, which were received by the ATR Event Channel client program, was recorded. Stream 7 was prioritized with DiffServ and CPU Reservations. These alert messages are sent only after identification of an object of interest by the CPU intensive ATR. Figure 5 shows that only stream #7 successfully identified all of its target objects (as evidenced by receiving all of its alerts). All of the other (unmanaged) streams missed completing the identification cycle (or couldn't get their identifying signal to the collector) at least some of the time, with most (#1,3,5,6,8-14) missing almost all of the identification opportunities. The key factor here is the use of CPU reservation to ensure timely processing of the CPU intensive activity.

Out of the 14 image competing streams, half of them did not even come close to receiving and processing even a non-trivial fraction of their intended workload, as shown in Figure 4. The DiffServ prioritized stream processed its intended workload with no observed packet loss. The most significant observations of this experiment were:

- In this and all subsequent runs of the experiment, the prioritized stream (the seventh stream) always reached the receiver endsystem with no observed packet loss. The behavior of non-prioritized streams was not reproducible over multiple runs of the experiment, i.e., sometimes these streams reached the receiver endsystem and sometimes they did not. Which ones did and did not would vary from trial to trial.

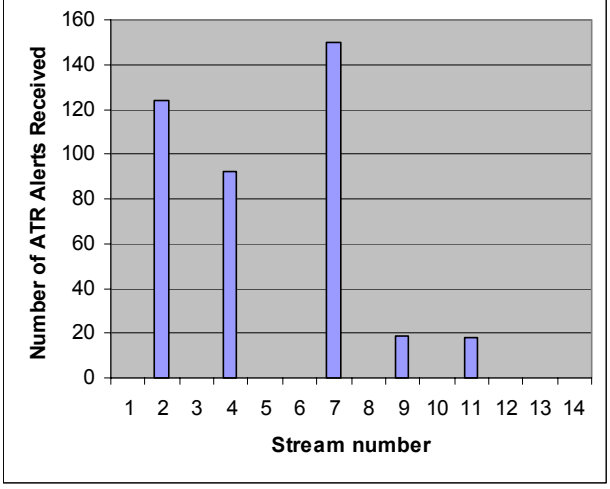


Fig 5. ATR alerts successfully detected; Stream 7 uses a CPU reservation and Diffserv Priority

- The number of ATR Alert control messages for the prioritized and CPU reserved stream was significantly higher than for any of the other streams. Nine out of the fourteen streams (64%) did not produce ATR Alert control messages indicating successful object identification, and requiring successful and timely upstream delivery and processing. Stream 7 produced all 150 alerts, which reached the ATR Event Channel

client. This was 21% better than the next best stream (Stream 2), which produced 124 alerts. The prioritized stream performed much better than the non-prioritized streams for two reasons: (1) DiffServ prioritizing stream 7 reduced the packet loss compared to other streams, so images with targets in them were more likely to reach the ATR for processing and (2) reserving CPU resources for ATR 7 significantly improved the ability of this ATR to process images and identify targets in a timely fashion despite competing load.

The most significant conclusion drawn from these empirical results (as well as from other, unreported results) is that by using a multi-layer middleware-mediated QoS framework that integrates resource management mechanisms (such as DiffServ network priorities and TimeSys Linux CPU reservations), the end-to-end path of a critical, multi-host application exhibits (1) *higher performance* (delivery of all object identification alerts) and (2) *better predictability* (consistently, timely delivery of video images and no observed packet loss) than other less critical applications competing for limited network and CPU resources.

6 Concluding Remarks

Developing distributed real-time and embedded (DRE) systems that can maintain the best possible application performance in the face of changes in available resources is an important and challenging R&D problem. This paper describes the design and performance of a QoS management framework that adaptively controls the end-to-end behavior of DRE multimedia applications by applying resource management techniques for both processing and communication tasks. This QoS management framework integrates QoS-enabled middleware (such as TAO and QuO), multimedia middleware services (such as the CORBA Audio/Video Streaming Service), real-time operating systems (such as Real-time Linux) and QoS-enabled networking protocols (such as IntServ and DiffServ) to develop robust DRE multimedia applications that can adapt to changes in resource availability to meet their QoS requirements.

Our experiments reported in this paper used a combination of CPU reservation along with network priority for end-to-end control of resources management policy to effect the controlled QoS behavior reported for our UAV video distribution application. Our results showed how integrated resource management techniques can be effective in sustaining predictable QoS results under very heavy competing load. Our future work will present the results of efforts that combine the middleware-mediated managed resource approach with the adaptation approach used to dynamically change application profiles and combine design time analytic approaches with runtime adaptive behavior approaches.

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