Applying Reflective Middleware Techniques to Optimize a QoS-enabled CORBA Component Model Implementation

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Abstract

Although existing CORBA specifications, such as Real-time CORBA and CORBA Messaging, address many end-to-end quality-of-service (QoS) properties, they do not define strategies for configuring these properties into applications flexibly, transparently, and adaptively. Therefore, application developers must make these configuration decisions manually and explicitly, which is tedious, error-prone, and often suboptimal. Although the recently adopted CORBA Component Model (CCM) does define a standard configuration framework for packaging and deploying software components, conventional CCM implementations focus on functionality rather than adaptive quality-of-service, which makes them unsuitable for next-generation applications with demanding QoS requirements.

This paper presents three contributions to the study of middleware for QoS-enabled component-based applications. It outlines reflective middleware techniques designed to adaptively (1) select optimal communication mechanisms, (2) manage QoS properties of CORBA components in their containers, and (3) (re)configure selected component executors dynamically. Based on our ongoing research on CORBA and the CCM, we believe the application of reflective techniques to component middleware will provide a dynamically adaptive and (re)configurable framework for COTS software that is well-suited for the QoS demands of next-generation applications.

1 Introduction

Emerging trends and challenges: Distributed applications are increasingly being developed via the standard interfaces, protocols, and services defined by distributed object computing (DOC) middleware, such as CORBA [1] or Java RMI [2]. DOC middleware that allows clients to invoke operations on remote objects without concern for where the object resides [3]. In addition, DOC middleware shields applications from non-portable details related to the OS/hardware platform they run on and the communication protocols and networks used to interconnect distributed objects.

Next-generation applications require DOC middleware that is adaptive and configurable, as well as efficient, predictable, and scalable. For instance, the demand for embedded multimedia applications is growing rapidly and hand-held devices, such as PIMs, Web-phones, Web-TVs, and Palm computers, running multimedia applications, such as MIME-enabled email and Web browsing, are becoming ubiquitous [4]. Ideally, these embedded multimedia applications should be *configured automatically* using standard DOC middleware components, rather than *programmed manually* from scratch. Meeting the QoS demands of next-generation applications requires the resolution of many research challenges, however, such as adapting to frequent bandwidth changes and disruptions in the established connections, maintaining cache consistency, and addressing various restrictions on memory footprint size and power consumption [5].

DOC middleware based on CORBA should be well-suited to provide the core communication middleware for the next-generation distributed applications outlined above. For instance, recent additions to the CORBA specification, such as Real-time CORBA [6] and CORBA Messaging [7], address many end-to-end quality-of-service (QoS) properties. These specifications standardize interfaces and policies for defining and controlling various types of application QoS properties.

Historically, however, the standard CORBA specification has not addressed component implementation or configuration issues effectively. For example, the CORBA 2.x [1] specification did not standardize interfaces to (1) initialize and deploy services dynamically or (2) enable different service implementations to interact portably with each other via standard interfaces. Moreover, many "cross-cutting" [8] service implementation properties, such as memory and bandwidth management, concurrency, dependability, security, and power management, are tightly coupled into the application structure and behavior of CORBA servants. As a result, programming applications directly using standard CORBA 2.x APIs has often yielded (1) brittle servant implementations that are hard to optimize, maintain, and enhance and (2) overly static or non-standardized mechanisms for bootstrapping and (re)configuring ORB components and services [9].

To address these problems, therefore, the OMG adopted the CORBA Component Model (CCM) specification [10]. The CCM defines a framework for generating distributed servers into which developer can configure custom component logic. In theory, the adoption of the CCM should reduce the effort required to integrate portable components that implement services and applications. Moreover, the CCM should simplify the reconfiguration and replacement of existing application services by standardizing interconnections among components and interfaces.

In practice, however, the CCM standard and implementations are as immature today as the underlying CORBA standard and ORBs were three to four years ago. For instance, CCM implementations are not yet particularly efficient, predictable, or scalable. Moreover, commercial CCM vendors are largely targeting the requirements of e-commerce, workflow, report generation, and other general-purpose business applications. The middleware requirements of these applications focus on functionality and interoperability, however, with little emphasis on assurance of, or control over, mission-critical QoS properties, such as timeliness, precision, dependability, minimal footprint, and power consumption [11]. As a result, it is not feasible to use contemporary off-the-shelf CCM implementations for applications with demanding QoS requirements.

Solution approach → Reflective middleware: Our prior research on CORBA middleware has explored many aspects of ORB endsystem efficiency, predictability, and scalability, including static [12] and dynamic [13] scheduling, event processing [14], I/O subsystem [15] and pluggable protocol [16] integration, synchronous [17] and asynchronous [18] ORB Core architectures, systematic benchmarking of multiple ORBs [19], and optimization principle patterns for ORB performance [20]. This paper focuses on another key dimension in the ORB endsystem design space: *applying reflective middleware techniques to implement QoS-enabled versions of the CCM*.

Reflective middleware is a term that describes a loosely organized collection of technologies designed to manage and control hardware/software system resources based on mounting R&D experience with distributed applications and systems [21]. Reflective middleware techniques enable autonomous changes in application behavior by adapting core software and hardware mechanisms dynamically without the need for explicit control by applications or end-users [22]. Figure 1 illustrates the key architectural focal points where we

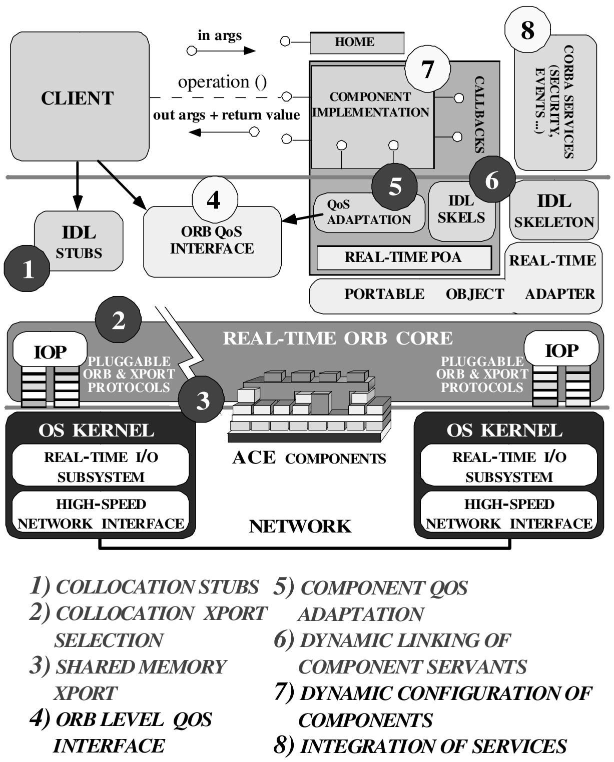


Figure 1: Focal Points of Reflective Techniques for CORBA Middleware

are applying reflective middleware techniques to improve the configurability and adaptiveness of QoS-enabled CCM implementations. In this paper, we illustrate how reflective middleware techniques are being applied to improve the adaptivity of the following CORBA and CCM mechanisms.

- **Selecting optimal communication mechanisms:** To present a homogeneous programming model for application developers, CORBA hides the location of objects from client applications. By examining an object's location reflectively, however, a CORBA ORB can select an optimal communication mechanism automatically when it *binds* an object reference [23]. To avoid violating the CORBA object model, however, this selection must occur without direct application intervention so that middleware performance and predictability can be optimized transparently. Robust and automated ORB collocation support [20] is necessary since the CCM encourages complex, dynamically changing object composition relationships [24].

• **Managing QoS properties of components in their containers:** In the CCM, a *container* manages the implementation of a component by encapsulating it within a run-time environment that provides certain services, such as security, event notification, and transactions. In addition, CCM containers should be extended to manage certain QoS properties of component implementations, including memory and bandwidth management, concurrency, dependability, security, and power management. Such extensions would allow ORB endsystems to support dynamic QoS configuration since they could inspect and adjust a component's QoS properties via its container. By factoring QoS adaptation policies and mechanisms into containers, components developers can defer the selection of a component's QoS requirements until run-time, thereby enhancing component flexibility and adaptability.

• **Dynamically (re)configuring selected parts of component implementations:** Next-generation applications will increasingly run in wireless and mobile network configurations where there may be no *a priori* knowledge of (1) the appropriate implementation of service components and (2) the optimal partitioning of service components onto network nodes. Activation of components must occur in real-time, which means that component initialization must not become a bottleneck. Thus, on-demand linking/unlinking mechanisms are necessary to (re)configure component implementations dynamically. The lifecycle for linking/unlinking of these components must be optimized using reflective middleware techniques to minimize footprint, prolong battery life, maximize extensibility, and meet key application QoS requirements more adaptively.

We are applying these reflective middleware techniques at various levels, ranging from the ORB Core up to CORBA Component Model services. The vehicle for this research is TAO [12], which is an open-source, CORBA-compliant ORB designed to support applications with demanding QoS requirements.[1] Figure 1 illustrates how CORBA components, capabilities, and services are being integrated into the TAO ORB endsystem.

Paper organization: The remainder of this paper is organized as follows: Section 2 (1) motivates key challenges faced when designing CCM implementations to support QoS-enabled applications and (2) outlines the reflective middleware techniques we are applying to address these challenges; Section 3 describes empirical results from some of our efforts to date; and Section 4 presents concluding remarks.

[1]The source code and documentation for TAO can be downloaded from `www.cs.wustl.edu/~schmidt/TAO.html`.

2 Applying Reflective Middleware Techniques to Resolve Key Design Challenges for QoS-enabled CCM Implementations

This section describes the key research challenges that CCM developers must address to support QoS-enabled applications and outlines the reflective middleware techniques we are applying to address these challenges.

2.1 Challenge 1: Achieving QoS-enabled Location Transparency Adaptively

Context: Location transparency is an important feature of the CORBA programming model. It allows applications to invoke operations via well-defined interfaces, without having to be concerned with where the target components reside.

Problem: A straightforward strategy for implementing location transparency is to treat all operations as remote invocations that are sent via IIOP over TCP/IP. This strategy imposes unnecessary communication overhead, however, when an object resides within the same host or the same address space as the client. Thus, quality ORBs must determine the actual location of a target object to optimize performance, while shielding developers from these details to simplify programming.

As shown in [25], an ORB can improve performance substantially by determining the location of target objects and then invoking operations using the most efficient communication mechanism. For example, when invoking an operation on a target component collocated on the same host, an ORB should choose a communication mechanism, such as shared memory, that is more efficient than "loopback" TCP/IP. This selection process is called the "collocation optimization."

It is important, however, that collocation optimizations be implemented in a "QoS-enabled" manner. In another words, applying collocation optimizations should not interfere with QoS mechanisms provided by the underlying ORB endsystem. For instance, two real-time ORB endsystem mechanisms defined by the Real-time CORBA specification are *prioritized scheduling* and *QoS-enabled communication channels* [26]. Prioritized scheduling ensures that applications requiring QoS support receive enough resources to meet their deadlines. QoS-enabled communication channels ensure the ORB endsystem's communication infrastructure allocates sufficient bandwidth, CPU, and memory resources to satisfy application QoS requirements end-to-end.

Solution → Reflective selection of optimal communication mechanisms: To select an optimal communication mechanism, an ORB must apply collocation optimizations *reflectively* at run-time. In general, these optimizations must be invisible to ORB users to avoid violating CORBA's object model transparency. Moreover, although certain collocation optimization mechanisms (such as direct function calls or shared memory) may be *faster* than other communication mechanisms (such as TCP loopback or message queuing), a QoS-enabled ORB must select a communication mechanism based on their client/object QoS requirements. For example, to avoid incurring priority inversion, a reflective QoS-enabled collocation optimization mechanism could establish multiple connections to partition ORB communication between client and server threads with different QoS requirements.

When object migration occurs, an ORB must re-select the optimal communication mechanism. To support migration, an operation invocation will receive a LOCATION_FORWARD message and a new object reference will be examined. As with the original binding, the ORB should determine the appropriate communication mechanism reflectively, taking into account the QoS characteristics of the various clients and objects involved in the migration.

Applying reflective collocation mechanisms in TAO: Figure 2 illustrates how TAO is designed to support reflective collocation mechanisms. TAO determines an object's location

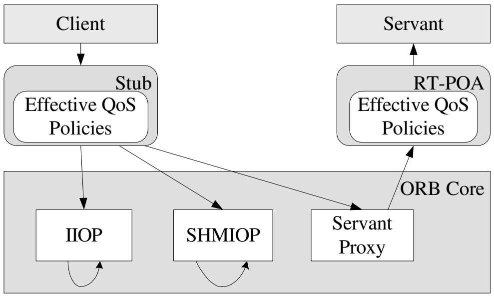


Figure 2: Reflective Selection of Optimal Communication Mechanisms in TAO

when it binds an object reference [23] or receives a LOCATION_FORWARD message. If the object is local to the process, TAO also considers the QoS policies associated with the object to guide its selection of an appropriate communication mechanism, which may not necessarily be the "fastest" mechanism.

For instance, connections and threads are often used to differentiate QoS requirement levels and execution priorities [26]. To minimize priority inversion, however, TAO avoids multiplexing connections with traffic that possesses different QoS requirements [17]. Thus, via reflection, TAO may decide to use a less efficient, but more predictable, collocation mechanism after examining the effective policies of an object reference.

2.2 Challenge 2: Changing Component QoS Properties Adaptively

Context: Next-generation applications require greater QoS support from their middleware. In CORBA-based middleware, this QoS support is provided by ORB endsystems [12]. For instance, the OMG defines the Real-time CORBA [26] and CORBA Messaging [7] specifications to standardize how applications interact with the QoS and real-time mechanisms that OS's provide.

Problem: Even with the adoption of Real-time CORBA and CORBA Messaging, component developers still must program applications manually to utilize the real-time or messaging capabilities of an ORB. Unfortunately, this manual process is tedious, error-prone, and often sub-optimal because application developers must explicitly program end-to-end [27] QoS factors, such as service level (*e.g.*, deterministic vs. best-effort) and flow specifications [28].

One reason that programming sophisticated QoS support manually is hard is because it cuts across [8] many aspects of functionality provided by components. For example, a multimedia application running on an OS that provides zero-copy buffer optimizations [29] may need to interact with many OS mechanisms to acquire/release buffers, control flow rate, pace the flow, and reserve bandwidth. Moreover, programming these complex QoS properties manually tends to tightly couple components to particular OS QoS mechanisms [22], which yields sub-optimal performance when applications must switch adaptively among different QoS mechanisms on different OS platforms and networks.

Solution → Reflective management of component QoS properties by their containers: QoS-enabled CCM implementations must be designed to extract QoS properties from their components and integrate these properties together through dynamic configuration and composition. For instance, each CCM container uses a dedicated POA to manage the interfaces supported by its managed component. Thus, containers, not application programmers, should be responsible for configuring QoS properties of components reflectively, based on criteria such as priorities, deadlines, or network conditions, such as congestion.

A container is an ideal entity to manage a component's QoS policies because (1) POAs are the key policy designators in both the Real-time CORBA and CORBA Messaging specifications and (2) the component model encourages composition of unrelated objects [24]. Therefore, a container provides a central repository that allows unrelated implementation objects to collaborate without explicit prior knowledge of their existence or QoS properties.

Applying container-based QoS adaptivity in TAO: Figure 3 illustrates the design of TAO's CCM container model.

To isolate the QoS properties of a component into its managing

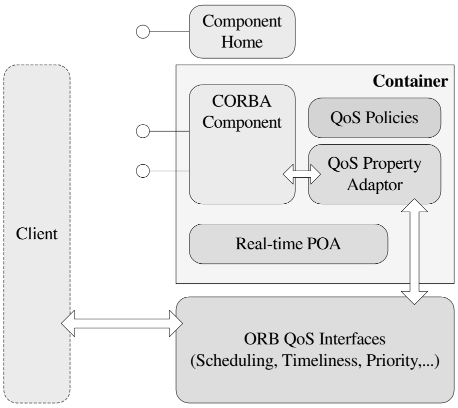


Figure 3: Managing Component QoS Properties via Containers

container, TAO's CCM implementation supports the following capabilities:

1. A component's QoS properties can be configured reflectively by its container. For instance, QoS reflection mechanisms can allow a component to specify or monitor its QoS requirements and provide feedback on the performance status of the component to its managing container.

2. Deployment information in component descriptors can be extended to deploy components using containers with different QoS properties. For example, assume a logging service component must forward large amount of data to a central logging repository in a timely manner. With a container implementation that supports QoS adaptation, developers can deploy the original component with this container and specify the QoS requirements to enhance the timeliness of the component.

By decoupling component implementations from the QoS configuration mechanisms defined by containers, TAO allows QoS-unaware components to be reused with various QoS properties in different applications without modifying their implementations. Moreover, it is easier to monitor and control the dynamic behavior of an implementation with different QoS configurations.

2.3 Challenge 3: Changing Component Behavior and Resource Usage Adaptively

Context: Component implementations in the CCM are call *executors* and are packaged into assembly files that can be linked dynamically. The use of assembly files enables the installation of components on generic *component servers*. We will refer to assembly files as dynamic-linked libraries (DLLs) in the remainder of this paper as they form the building block of assembly files. A component server may serve a large number of components, some of which will be used frequently and others less frequently.

In general, developers of next-generation component-based applications may not know *a priori* the most effective strategies for (1) implementing components or (2) collocating/distributing multiple component executors into processes and hosts. If developers commit prematurely to a particular configuration of components, however, this can impede flexibility, reduce overall system performance and functionality, and unnecessarily increase resource utilization. Often, initial component configuration decisions may prove to be suboptimal over time, *e.g.*, as platform upgrades or increased workloads require the redistribution of certain components to other processes and hosts.

In general, it desirable to make component configuration or implementation decisions as late as possible in an application's development and deployment cycle. Moreover, for applications with high availability requirements, it may be necessary to perform component updates online, *i.e.*, *without* having to modify or shut down an application obtrusively.

Problem: Although the number of components configured into a component server may be large, not all installed components will be used simultaneously. Care must be taken when a container chooses its DLL linking/unlinking strategy – keeping unused DLLs linked into an application for extended periods can consume limited system resources, particularly memory. Conversely, linking and unlinking DLLs upon every method invocation not only degrades system performance, but can also consume other system resources, such as battery power in mobile devices.

Solution → Reflective linking/unlinking of component executors: To address the problems mentioned above, component servers should reflectively manage the lifetimes of their executor DLLs. The following two patterns – Component Configurator [30] and Evictor [3] – can help to guide this process:

• **Component Configurator pattern:** The Component Configurator pattern decouples the implementation of services from the time when they are configured. This pattern supports various (re)configuration strategies that component servers can use to link/unlink the DLL containing component executors implementations on-demand.

For example, during the initial component configuration phase, a component server can use the Component Configurator pattern to (1) dynamically link its executors from DLLs that contain these components and (2) set up the interconnections specified by the components' assembly descriptors. When an updated implementation is available, the Component configurator pattern can also be used to unlink, then re-link, component executors dynamically.

• **Evictor pattern:** The Evictor pattern describes a general strategy for limiting memory consumption. This pattern can be used by component servers to reflectively passivate component executors that are used infrequently and unlink their DLLs. For instance, a component that generates authentication certificates may be used only at the beginning of a session. Once a certificate is generated, therefore, it need not be retained during the remaining secure session.

Both the Component Configurator and Evictor patterns should be guided by policies and environmental conditions. For example, the Component Configurator pattern can be used to reconfigure component implementations based on information available in CCM component descriptors, such as applying `componentfeatures`. `Componentfeatures` is an XML entity in component descriptor that describes a component's capabilities and operation policies. Likewise, eviction policies should reflect common usage patterns based on periodic ORB endsystem monitoring mechanisms or resource management strategies.

Applying dynamic (re)configuration in TAO: TAO's CCM implementation supports the following capabilities that enable dynamic (re)configuration of component executors.

• **On-demand linking:** On-demand linking of component interface implementations is achieved in TAO via a combination of the Component Configurator pattern [30], the ACE Service Configurator framework [31] that implements this pattern, and standard CORBA `ServantManagers` [32]. The ACE Service Configurator framework dynamically links and unlinks component executors stored in DLLs. Two types of `ServantManager` are supported by a POA: (1) `ServantActivators`, which activate/deactivate servants in a POA's active object map on-demand and (2) `ServantLocators`, which are designed to implement user-defined object demultiplexing and servant lifetime managing mechanisms on a per-invocation basis.

TAO's CCM framework enhances containers to provide their own `ServantLocators` that link in the necessary component executors from DLLs on-demand, as shown in Figure 4. The same mechanism in TAO's CCM also detects the availability of new component implementations and switches to use these updated versions automatically. For instance, TAO's `ServantLocators` can detect updated DLLs containing component executors and delegate the actual work to ACE Service Configurator to link these executors on-demand. This feature helps minimize system resource usage by not linking component executors until they are accessed. In addition, TAO's CCM implementation enhances component descriptors to provide meta-information that the ACE Service Configurator uses to swap component executors dynamically.

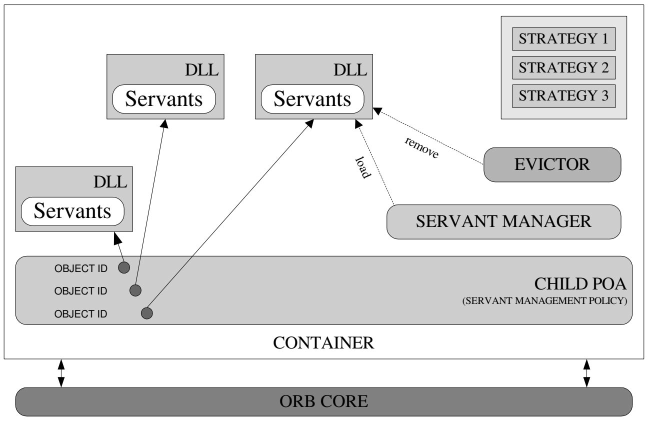


Figure 4: Dynamic Linking/Unlinking of Component Parts via `ServantLocator`

• **Eviction:** TAO's CCM implementation defines a usage query interface that returns certain usage information, such as frequency of use and time of last use, of executors. Internally, TAO's CCM implementation uses an *evictor* mechanism, which queries components' usage interfaces and applies eviction policies to determine whether to passivate a component executor and unlink its DLL.

Component descriptors can also be extended to include eviction strategies or to predefine component usage patterns that provide hints to TAO's CCM evictor mechanism. The activation of TAO's evictor mechanism can be controlled by policies selected by component server developers. Eviction can then be triggered either periodically or in response to events generated by system resource monitors that track CPU load and memory usage.

3 Current Progress and Empirical Results

In this section, we report the results of our ongoing efforts to enhance TAO to support the reflective middleware techniques described in Section 2.

Current Progress: We have added a QoS adaptation layer that shields TAO from differences among the QoS interfaces on different OS platforms. Key capabilities in this adaptation layer include (1) support for prioritized scheduling by partitioning requests for different QoS requirement into different threads and servicing these threads through different endpoints, (2) support for initializing endpoint QoS properties, such as bandwidth reservation and flow pacing, (3) support for portable scheduling control so the ORB can schedule requests adaptively based on the QoS requirements of objects.

These mechanisms are then used to implement the QoS-aware containers described in Section 2.1.

We have implemented a container prototype that supports the on-demand linking and eviction of component executors described in Section 2.3. We are currently strategizing the eviction mechanism and will integrate it with TAO's CCM component usage reflection support.

TAO supports two co-process collocation mechanisms [25] and several other co-host optimization mechanisms via its pluggable protocols framework [16]. Currently, however, TAO just allows reflective selection of co-process collocation optimizations, though we are adding a more comprehensive collocation selection mechanism, outlined in Section 2.1. The remainder of this section presents empirical results of performance comparisons of the collocation optimization mechanisms supported by TAO.

Measurement techniques: The following four ORB communication optimization mechanisms were measured in these experiments:

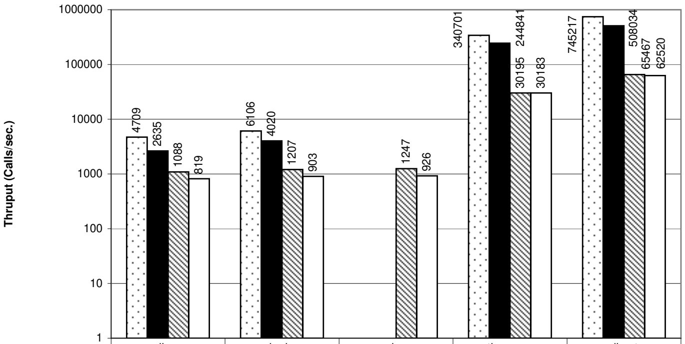
1. Shared-memory transport for optimizing co-host communication;
2. UNIX domain socket, which is also a co-host optimization mechanism;
3. *Thru_POA* co-process collocation optimization [25]; and
4. *Direct* co-process collocation optimization.

Compared to invoking a method on `local` interface, which is a new interface type in the CCM, invoking a method using the *Direct* collocation strategy incurs just one extra virtual function call. Thus, it indicates the benefits of declaring an interface `local`.

We measured the performance of TAO's collocation optimization mechanisms by invoking operations that sent a sequence of 4 and 1,024 elements of type `long`. Both server and client ran on the same host, allowing us to compare the performance gain of applying each optimization mechanism. The performance of IIOP is measured as a baseline for non-optimized communication.

Hardware/OS Benchmarking Platforms: The tests were conducted using a Gateway PC with two 500 Mhz Pentium-III CPUs running Microsoft Windows 2000 and an a Ultra-SPARC with four 300Mhz UltraSparcs running SunOS 5.7. We compiled the test on NT using Microsoft Visual Studio with Service Pack 3 and on Solaris using egcs version 2.91.60, but using full optimization.

Results: Figure 5 shows the performance of TAO's collocation optimization mechanisms compared with the IIOP baseline. Shared-memory transport is labeled as SHMIOP and UNIX domain transport is labeled as UIOP in the figure.



	iiop	shmiop	uiop	thru_poa	direct
NT small seq	4709	6106		340701	745217
NT long seq	2635	4020		244841	508034
Sun small seq	1088	1207	1247	30195	65467
Sun long seq	819	903	926	30183	62520

Collocation Mechanisms

Figure 5: Buffered One-way Request Throughput for Various TAO Protocols

The results in this figure illustrate the importance of configuring an ORB's collocation selection mechanism reflectively to take advantage of OS platform the ORB runs on. For example, on Windows NT, the performance of SHMIOP is $\sim$50% faster than that of IIOP. However, it it only marginally faster (10%) than IIOP on UNIX, due to the higher overhead of process-level semaphores on UNIX compared with Windows NT. Thus, UIOP outperforms actually SHMIOP on Solaris.

Our current implementation of SHMIOP in TAO uses the loopback localhost pseudo-device interface as a signaling mechanism. Thus, we notify the ORB's reactive [30] event loop via a socket on each send operation. We expect the performance of SHMIOP will be enhanced greatly after we implement a multi-threaded version of SHMIOP. As a thread only services requests from one connection in TAO, the multithreaded SHMIOP implementation can use a more efficient signaling mechanism, such as semaphores. Moreover, since we no longer need to emulate the socket stream buffer which is required for reactive SHMIOP implementation, we can take advantage of "zero-copy" shared memory buffers and further improve performance. However, the current SHMIOP implementation is required to support applications that are not multi-threaded.

4 Concluding Remarks

Recent CORBA specifications define more comprehensive support for QoS, configurability, and automated server development. In particular, the CORBA Component Model (CCM) [10] defines standard interfaces, policies, and services for structuring, integrating, and deploying CORBA components. Likewise, the Real-time CORBA [6] and CORBA Messaging [7] specifications address many end-to-end quality-of-service (QoS) properties.

However, our experience using CORBA in a wide variety of projects suggests that the new generation of CORBA specifications will be unsuitable for an important class of QoS-enabled applications unless ORB implementations apply *reflective middleware techniques* to automate the selection and adaptation of key QoS properties. The reflective middleware techniques we are focusing upon currently include (1) selecting optimal communication mechanisms, (2) managing QoS properties of CORBA components in their containers, and (3) (re)configuring selected parts of component executors dynamically. We are applying these techniques to TAO, which is our platform for implementing, optimizing, and experimenting with QoS-enabled CCM.

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