The Design and Performance of an Adaptive CORBA Load Balancing Service

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Abstract

CORBA is increasingly popular as distributed object computing middleware for systems with stringent quality of service (QoS) requirements, including scalability and dependability. One way to improve the scalability and dependability of CORBA-based applications is to balance system processing load among multiple server hosts. Load balancing can help improve system scalability by ensuring that client application requests are distributed and processed equitably across a group of servers. Likewise, it can help improve system dependability by adapting dynamically to system configuration changes that arise from hardware or software failures.

This paper presents four contributions to research on CORBA-based load balancing. First, we describe deficiencies with common load-balancing techniques, such as introducing unnecessary overhead or not adapting dynamically to changing load conditions. Second, we present a novel adaptive load balancing service that can be implemented efficiently using standard CORBA features. Third, we describe the key design challenges we faced when adding this load balancing service to our CORBA ORB (TAO) and outline how we resolved the challenges by applying patterns. Finally, we present the results of benchmark experiments that evaluate the pros and cons of different load balancing strategies empirically by measuring the overhead of each strategy and showing how well each strategy balances system load.

Keywords: Middleware, patterns, CORBA, load balancing.

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1 Introduction

Motivation: The growth of online Internet services during the past decade has increased the demand for scalable and dependable distributed computing systems. For example, e-commerce systems and online stock trading systems concurrently service many clients that transmit a large, often bursty, number of requests. To protect initial hardware investments and avoid overcommitting resources these systems scale incrementally by connecting servers via high-speed networks and either purchasing new servers as the number of clients increase or leasing server cycles during peak hours.

An increasingly popular and cost effective technique to improve networked server performance is *load balancing*, where hardware and/or software mechanisms determine which server will execute each client request. Load balancing mechanisms distribute client workload equitably among back-end servers to improve overall system responsiveness. These mechanisms can be provided in any or all of the following layers in a distributed system:

• **Network-based load balancing:** This type of load balancing is provided by IP routers and domain name servers (DNS) that service a pool of host machines. For example, when a client resolves a hostname, the DNS can assign a different IP address to each request dynamically based on current load conditions. The client then contacts the designated back-end server, unaware that a different server could be selected for its next DNS resolution. Routers can also be used to bind a TCP flow to any back-end server based on the current load conditions and then use that binding for the duration of the flow.

High volume Web sites often use network-based load balancing at the *network* layer (layer 3) and *transport* layer (layer 4). Layer 3 and 4 load balancing (referred to as "switching" in the trade literature [1]), use the IP address/hostname and port, respectively, to determine where to forward packets. Load balancing at these layers is somewhat limited, however, by the fact that they do not take into account the content of client requests. Instead, higher-layer mechanisms–such as the so-called layer 5 switching described below–perform load balancing in accordance with the content of requests, such as pathname information within a URL.

• **OS-based load balancing:** This type of load balancing is provided by distributed operating systems via *clustering*, *load sharing*[1], and *process migration* [2] mechanisms. Clustering is a cost effective way to achieve high-availability and high-performance by combining many commodity computers to improve overall system processing power. Processes can then be distributed transparently among computers in the cluster.

Clusters generally employ load sharing and process migration. Balancing load across processors–or more generally across network nodes–can be achieved via *process migration* mechanisms [3], where the state of a process is transferred between nodes. Transferring process state requires significant platform infrastructure support to handle platform differences between nodes. It may also limit applicability to programming languages based on virtual machines, such as Java.

• **Middleware-based load balancing:** This type of load balancing is performed in middleware, often on a per-session or per-request basis. For example, layer 5 switching [1] has become a popular technique to determine which Web server should receive a client request for a particular URL. This strategy also allows the detection of "hot spots," *i.e.*, frequently accessed URLs, so that additional resources can be allocated to handle the large number of requests for such URLs.

This paper focuses on another type of middleware-based load balancing supported by *object request brokers* (ORBs), such as CORBA [4]. ORB middleware allows clients to invoke operations on distributed objects without concern for object location, programming language, OS platform, communication protocols and interconnects, and hardware [5]. Moreover, ORBs can determine which client requests to route to which object replicas on which servers.

Middleware-based load balancing can be used in conjunction with the specialized network-based and OS-based load balancing mechanisms outlined above. It can also be applied on top of commodity-off-the-shelf (COTS) networks and operating systems, which helps reduce cost. In addition, middleware-based load balancing can provide semantically-rich customization hooks to perform load balancing based on a wide range of application-specific load balancing conditions, such as run-time I/O vs. CPU overhead conditions.

[1]"Load sharing" should not be confused with "load balancing," *e.g.*, processing resources can be *shared* among processors but not necessarily *balanced*.

Our previous research on middleware has examined many dimensions of ORB endsystem design, including static [6] and dynamic [7] scheduling, event processing [8], I/O subsystem [9] and pluggable protocol [10] integration, synchronous [11] and asynchronous [12] ORB Core architectures, ORB fault tolerance [13], systematic benchmarking of multiple ORBs [14], patterns for ORB extensibility [15] and ORB performance [16]. This paper focuses on another dimension in the CORBA research domain: *the design and performance of middleware-based load balancing mechanisms developed using standard CORBA*. Our approach is based on standard CORBA features available in any ORB compliant with the CORBA 2.3 [4] (or later) specification. This approach can also be generalized to other distributed object computing middleware, such as COM+ and Java RMI, that offer similar features.

CORBA load balancing example: To illustrate the benefits of middleware-based load balancing, consider the CORBA-based online stock trading system shown in Figure 1. A distributed online stock trading system creates sessions through which trading is conducted. This system consists of multiple back-end servers–called *replicas*–that process session creation requests sent by clients over a network. A replica is an object that can perform the same tasks as the original object. Server replicas that perform the same operations can be grouped together into *back-end server groups*, which are also known as *replica groups* or *object groups*.

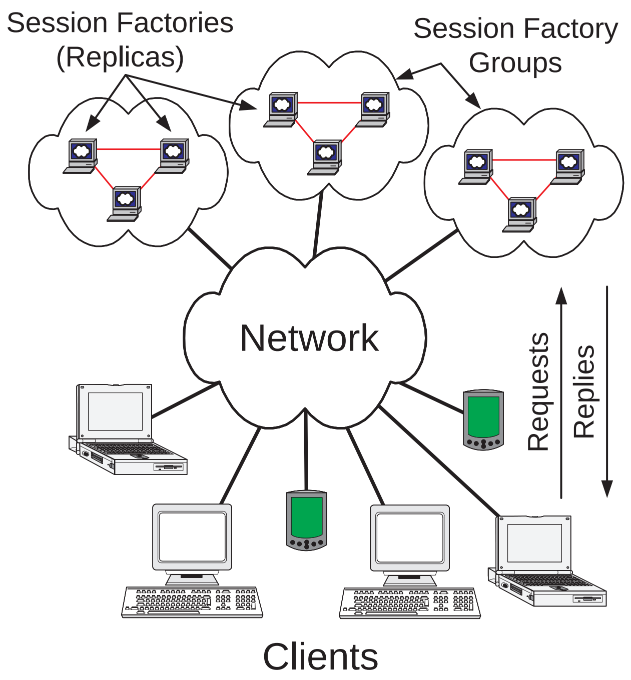

Figure 1: A Distributed Online Stock Trading System

For the example in Figure 1, a *session factory* [17] is replicated in an effort to reduce the load on any given factory. The load in this case is a combination of (1) the average number of session creation requests per unit time and (2) the total amount of resources employed currently to create sessions at a given location. Loads are then balanced across all replicas in the session factory replica group. The replicas need not reside at the same location.

The sole purpose of session factories is to create stock trading sessions. Therefore, factories need not retain state, *i.e.*, they are *stateless*. Moreover, in this type of system client requests arrive dynamically–not deterministically–and the duration of each request many not be known *a priori*.

These conditions require that the distributed online stock trading system be able to redistribute requests to replicas dynamically. Otherwise, one or more replicas may potentially become overloaded, whereas others will be underutilized. In other words, the system must *adapt* to changing load conditions. In theory, applying adaptivity in conjunction with multiple back-end servers can

- Increase the scalability and dependability of the system;
- Reduce the initial investment when the number of clients is small; and
- Allow the system to scale up gracefully to handle more clients and processing workload in larger configurations.

In practice, achieving this degree of scalability and dependability requires a sophisticated load balancing service. Ideally, this service should be transparent to existing online stock trading components. Moreover, if incoming requests arrive dynamically, a load balancing service may not benefit from *a priori* QoS specifications, scheduling, or admission control and must therefore adapt dynamically to changes in run-time conditions.

CORBA's rich set of features provides the means to realize an adaptive load balancing service. CORBA is an effective choice for distributed systems due to the inherent distribution and common heterogeneity of clients and servers written in different programming languages running on different hardware and software platforms. In this context, CORBA can simplify system implementation because it offers a language- and platform-neutral communication infrastructure. Moreover, it reduces development effort by offering higher level programming abstractions that shield application developers from distribution complexities, thereby allowing them to concentrate their efforts on stock trading business logic.

In theory, having multiple back-end servers can (1) increase the scalability and dependability of the system, (2) reduce the initial investment when the number of clients is small, and (3) allow the system to scale up gracefully to handle more clients and processing workload in larger configurations. In practice, achieving this degree of scalability and dependability requires a sophisticated load balancing service. Ideally, integrating support for such a service should be transparent to existing online stock trading components. Moreover, if incoming requests arrive dynamically, a load balancing service may not benefit from *a priori* QoS specifications, scheduling, or admission control and must therefore *adapt* dynamically to changes in run-time conditions.

The CORBA load balancing service described in this paper fulfills the needs of applications with high scalability requirements, such as the online stock trading system described above. In contrast, neither the network-based nor OS-based load balancing solutions provide as straightforward, portable, and economical a means of adapting load balancing decisions based on application-level request characteristics, such as content and duration.

Paper organization: The remainder of this paper is organized as follows: Section 2 summarizes the requirements of CORBA-based load balancing services and outlines the pros and cons of alternative solution architectures; Section 3 describes the design of our load balancing service, which is based on standard CORBA features and implemented using the TAO open-source[2] CORBA-compliant ORB; Section 4 evaluates the performance of alternative load balancing strategies empirically; Section 5 compares our adaptive middleware-based load balancing service with related work and outlines our future plans for enhancing TAO's load balancing service; and Section 6 presents lessons learned and concluding remarks. For completeness, Appendix A presents an overview of the standard CORBA reference architecture [4].

2 Requirements and Alternative Solution Architectures

This section first describes the types of requirements that a CORBA-compliant load balancing service should be designed to address. Next, it presents an overview of several alternative load balancing architectures suitable for CORBA-based applications.

2.1 Requirements for a CORBA Load Balancing Service

The OMG CORBA specification provides the core capabilities needed to support load balancing. In particular, a CORBA load balancing service can take full advantage of the *request*

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

forwarding mechanism[3] mandated by the CORBA specification [4]. A CORBA server application can use this mechanism to forward client requests to other servers *transparently*, *portably*, and *interoperably*.

The CORBA specification, however, does not *standardize* load balancing interfaces. Nor does it specify load balancing mechanisms, which are left as implementation decisions for ORB providers. Below, therefore, we describe the key requirements that CORBA load balancing services should be designed to address.

Support an object-oriented load balancing model: In the CORBA programming model objects are the unit of abstraction and system architects reason about objects in order to manage their available resources. Thus, the granularity of load balancing in CORBA should be based on objects, rather than, *e.g.*, processes or TCP/IP addresses. Moreover, a load balancing service and ORB should coordinate the interactions amongst *multiple* object replicas. Sets of multiple object replicas are called *object groups* or *replica groups*.

Client application transparency: Distributing work load amongst multiple servers should require little or no modifications to the way in which CORBA applications are developed normally. In particular, a CORBA load balancing service should be as transparent as possible to clients and servers. Likewise, a general principle in CORBA is that client implementations should be as simple as possible. A CORBA load balancing service that follows this principle should therefore require no changes to clients whose requests it balances.

Server application transparency: Although load balancing should ideally require few modifications to servers, this goal is hard to achieve in practice. For example, load balancing a stateful CORBA object requires the transfer of its state to a new replica. The application implementation must either perform the transfer itself or define hooks that allow the load balancing framework to perform the state transfer as unobtrusively as possible [18].

The situation for stateless CORBA servers is different. In this case, the implementation of an server object's *servant*[4] should require no changes to support load balancing. Yet changes to the server *application* may still be required under certain conditions. For example, some applications may define *ad hoc* load metrics, such as number of active transactions or user sessions. In practice, collecting these metrics may require some modifications to server application code.

Dynamic client operation request patterns: Load balancing services can be based on various client request patterns. For example, load balancers for certain types of systems assume client requests occur at deterministic or stochastic rates that execute for known or fixed durations of time. While these assumptions may apply for certain types of applications, such as continuous multimedia streaming [19], they do not apply in complex Internet or military [20] environments where client operation request patterns are dynamic and the duration of each request may not be known in advance. In this paper, therefore, we focus on load balancing techniques that do not require *a priori* scheduling information.

Maximize scalability and equalize dynamic load distribution: Although it is common practice to design lightweight load distribution capabilities, *e.g.*, based on extensions to naming services [21], these approaches do not balance dynamic loads equitably, which limits their scalability. Thus, a CORBA load balancing service must increase system scalability by maximizing dynamic resource utilization in a group of servers whose resources would not otherwise be used as efficiently. By improving resource utilization via load balancing, the overall scalability of the server group should be enhanced significantly.

Increase system dependability: Load balancing services can also handle certain types of server failures. By using administrative interfaces or automated policies, for example, clients that access a crashed or failing server can be migrated to other servers until the failure is resolved. Load balancing services need not provide full fault-tolerance capabilities, however, *i.e.*, it should not be the role of a load balancing service to detect and mask failures [22, 23]. Instead, they should provide mechanisms to handle those failures efficiently when they are detected by administrators or other components in the system.

Support administrative tasks: System administrators may need to add new object replicas dynamically, without disrupting or suspending service for existing clients. A good CORBA load balancing service should allow the dynamic addition of new replicas and adjust to the new load conditions rapidly. Likewise, the service should allow the removal of replicas for upgrades, preemptive maintenance, or re-allocation of system resources.

Minimal overhead: A CORBA load balancing service should not introduce undue latency or networking overhead since otherwise it can actually reduce–rather than enhance–overall system performance. In particular, an implementation that (1) increases the average number of messages per-request or (2) uses a single server to process all requests may be inappropriate for high-performance and/or large-scale applications. Section 4 illustrates empirically how certain load balancing strategies can degrade overall performance due to excess overhead.

[3]The standard CORBA LOCATION_FORWARD GIOP message used to facilitate this request forwarding mechanism is discussed in Section 3.3.1.

[4]The servant is a programming language entity that implements object functionality in a server application.

Support application-defined load metrics and balancing policies: Different types of applications have different notions of load. Thus, a CORBA load balancing service should allow applications to:

- *Specify the semantics of metrics used to measure load* – For example, some applications may want to balance CPU load, whereas other applications may be more concerned with balancing I/O resources, communication bandwidth, or memory load.
- *Set policies that determine the load balancing service's semantics* – For example, some applications may want to distribute load uniformly, others randomly, and still others may want load distributed based on dynamic metrics, such as current CPU load or current time.

Support for application-defined metrics and policies need not affect client transparency because these policies can be administered solely for server replicas. Thus, clients can be shielded from knowledge of load balancing metrics and policies.

CORBA interoperability and portability: Application developers rarely want to be restricted to a single provider's ORB. Therefore, a CORBA load balancing service should not rely on extensions to GIOP/IIOP, which are standard protocols that allow heterogeneous CORBA clients and servers to interoperate. Likewise, it is desirable to avoid implementing load balanced objects by adding proprietary extensions to an ORB.

2.2 Overview of Alternative CORBA Load Balancing Strategies and Architectures

There are a variety of strategies and architectures for devising CORBA load balancing services. Different alternatives provide different levels of support for the requirements outlined in Section 2.1, as we describe below.

2.2.1 Load Balancing Strategies

There are various strategies for designing CORBA load balancing services. These strategies can be classified along the following orthogonal dimensions:

Client binding granularity: A load balancer *binds* a client request to a replica each time a load balancing decision is made. Specifically, a client's requests are bound to the replica selected by the load balancer. Client binding mechanisms include GIOP LOCATION_FORWARD messages, modified standard CORBA services, or *ad hoc* proprietary interfaces. Regardless of the mechanism, client binding can be classified according to its granularity, as follows:

- *Per-session* – Client requests will continue to be forwarded to the same replica for the duration of a *session*[5], which is usually defined by the lifetime of the client [24].
- *Per-request* – Each client request will be forwarded to a potentially different replica, *i.e.*, bound to a replica each time a request is invoked.
- *On-demand* – Client requests can be re-bound to another replica whenever deemed necessary by the load balancer. This design forces a client to send its requests to a different replica than the one it is sending requests to currently.

Balancing policy: When designing a load balancing service it is important to select an appropriate algorithm that decides which replica will process each incoming request. For example, applications where all requests generate nearly identical amounts of load can use a simple round-robin algorithm, while applications where load generated by each request cannot be predicted in advance may require more advanced algorithms. In general, load balancing policies can be classified into the following categories:

- *Non-adaptive* – A load balancer can use non-adaptive policies, such as a simple round-robin algorithm or a randomization algorithm, to select which replica will handle a particular request.
- *Adaptive* – A load balancer can use adaptive policies that utilize run-time information, such as the amount of idle CPU available on each back-end server, to select the replica that will handle a particular request.

2.2.2 Load Balancing Architectures

By combining the strategies described above in various ways, it is possible to create the alternative load balancing architectures described below. In the ensuing discussion, we refer back to the requirements presented in Section 2.1 to evaluate the pros and cons of these strategies *qualitatively*. Section 4 then evaluates these different strategies *quantitatively*.

Non-adaptive per-session architectures: One way to design a CORBA load balancer is make to the load balancer select the target replica when a client/server session is first established, *i.e.*, when a client obtains an object reference to a CORBA object–namely the replica–and connects to that object, as shown in Figure 2.

Note that the balancing policy in this architecture is *non-adaptive* since the client interacts with the same server to which it was directed originally, regardless of that server's load conditions. This architecture is suitable for load balancing

[5]In the context of CORBA, a *session* defines the period of time during which a client is connected to a given server for the purpose of invoking remote operations on objects in that server.

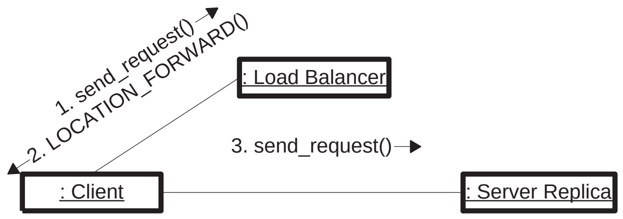

Figure 2: A Non-Adaptive Per-Session Architecture

policies that implement round-robin or randomized balancing algorithms.

Different clients can be directed to different object replicas by either using (1) a middleware activation daemon, such as a CORBA Implementation Repository [25] or (2) a lookup service, such as the CORBA Naming or Trading service. For example, Orbix [26] provides an extension to the CORBA Naming Service that returns references to object replicas in either a random or round-robin order.

Load balancing services based on a per-session client binding architecture can be implemented to support many requirements defined in Section 2.1. For example, per-session client binding architectures generally satisfy requirements for application transparency, increased system dependability, minimal overhead, and CORBA interoperability. The primary benefit of per-session client binding is that it incurs less run-time overhead than the alternative architectures described below.

Non-adaptive per-session architectures do not, however, satisfy the requirement to handle *dynamic* client operation request patterns adaptively. In particular, forwarding is performed only when the client binds to the object, *i.e.*, when it invokes its first request. Overall system performance may suffer, therefore, if multiple clients that impose high loads are bound to the same server, even if other servers are less loaded. Unfortunately, non-adaptive per-session architectures have no provisions to reassign their clients to available servers.

Non-adaptive per-request architectures: A non-adaptive per-request architecture shares many characteristics with the non-adaptive per-session architecture. The primary difference is that a client is bound to a replica *each time* a request is invoked in the non-adaptive per-request architecture, rather than *just once* during the initial request binding. This architecture has the disadvantage of degrading performance due to increased communication overhead, as shown in Section 4.2.

Non-adaptive on-demand architectures: Non-adaptive on-demand architectures have the same characteristics as their per-session counterparts described above. However, non-adaptive on-demand architectures allow re-shuffling of client bindings at an arbitrary point in time. Note that run-time information, such as CPU load, is not used to decide when to rebind clients. Instead, clients could be re-bound at regular time intervals, for example.

Adaptive per-session architecture: This architecture is similar to the non-adaptive per-session approach. The primary difference is that an adaptive per-session can use run-time load information to select the replica, thereby alleviating the need to bind new clients to heavily loaded replicas. This strategy only represents a slight improvement, however, since the load generated by clients can change after binding decisions are made. In this situation, the adaptive on-demand architecture offers a clear advantage since it can respond to dynamic changes in client load.

Adaptive per-request architectures: A more adaptive request architecture for CORBA load balancing is shown in Figure 3. This design introduces a front-end server, which is a

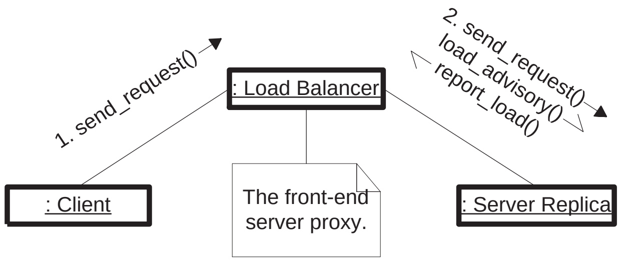

Figure 3: An Adaptive Per-request Architecture

proxy [27] that receives all client requests. In this case, the "front-end server" is the load balancer. The load balancer selects an appropriate back-end server replica in accordance with its load balancing policy and forwards the request to that replica. The front-end server proxy waits for the replica's reply to arrive and then returns it to the client. Informational messages–called *load advisories*–are sent from the load balancer to replicas when attempting to balance loads. These advisories cause the replicas to either accept requests or redirect them back to the load balancer.

The primary benefit of an adaptive request forwarding architecture is its potential for greater scalability and fairness. For example, the front-end server proxy can examine the current load on each replica before selecting the target of each request, which may allow it to distribute load more equitably. Hence, this forwarding architecture is suitable for use with adaptive load balancing policies.

Unfortunately, this architecture can also introduce excessive latency and network overhead because each request is processed by a front-end server. Moreover, two new network messages are introduced:

1. The request from the front-end server to the replica; and

2. The corresponding reply from the back-end server (replica) to the front-end server.

In addition, to ensure that the system is scalable and dependable (*e.g.*, no single point of failure), multiple intermediate servers may be required. This configuration in turn requires complex algorithms that propagate the current load information to all front-end servers. It also requires a mechanism to assign clients to the correct front-end server. In a sense, therefore, the load balancing problem must be solved both for back-end *and* front-end servers, which complicates system design and implementation.

Adaptive on-demand architecture: This architecture is the primary focus of the remainder of this paper. As shown in Figure 4, clients receive an object reference to the load balancer

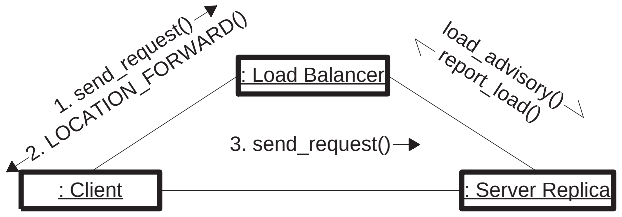

Figure 4: An Adaptive On-Demand Architecture

initially. Using CORBA's standard LOCATION_FORWARD mechanism, the load balancer can redirect the initial client request to the appropriate target server replica. CORBA clients will continue to use the new object reference obtained as part of the LOCATION_FORWARD message to communicate with this replica directly until they are redirected again or finish their conversation.

Unlike the non-adaptive architectures described earlier, adaptive load balancers that forward requests on-demand can monitor replica load continuously. Using this load information and the policies specified by an application, a load balancer can determine how equitably the load is distributed. When load becomes unbalanced, the load balancer can communicate with one or more replicas and request them to use the standard CORBA LOCATION_FORWARD mechanism to redirect subsequent clients back to the load balancer. The load balancer will then redirect the client to a less loaded replica. Upon receipt of a LOCATION_FORWARD message, a standard CORBA client ORB re-contacts the load balancer, which then redirects the client transparently to a less heavily loaded replica.

Using this architecture, the overall distributed object computing system can (1) recover from unequitable client/replica bindings while (2) amortizing the additional network and processing overhead over multiple requests. This strategy satisfies most of the requirements outlined in Section 2.1. In particular, it requires minimal changes to the application initialization code and no changes to the object implementations (servants) themselves.

The primary drawback with adaptive on-demand architectures is that server replicas must be prepared to receive messages from a load balancer and redirect clients to that load balancer. Although the required changes do not affect application logic, application developers must modify a server's initialization and activation components to respond to the load advisory messages mentioned above. Advanced ways of overcoming this drawback are discussed in Section 5.3.

It is possible to overcome some drawbacks of adaptive on-demand load balancers, however, by applying standard CORBA portable interceptors [28], as discussed in Section 5.3. Likewise, implementations based on the patterns [29] in the CORBA Component Model (CCM) [30] can implement load balancing without requiring changes to application code. In the CCM, a *container* is responsible for configuring the portable object adapter (POA) [5] that manages a component. Thus, TAO's adaptive on-demand load balancer just requires enhancing standard CCM containers so they support load balancing, without incurring other changes to application code.

3 The Design of the TAO CORBA Load Balancing Service

This section describes the design of an adaptive load balancing service in TAO [6], which is a CORBA-compliant ORB that supports applications with stringent QoS requirements. TAO's load balancing service makes it easier to develop distributed applications in heterogeneous environments by providing application transparency, high flexibility, scalability, run-time adaptability, and interoperability.

3.1 Component Structure in TAO's Load Balancing Service

Figure 5 illustrates the components[6] in the TAO's load balancing service, which supports adaptive load balancing and on-demand request forwarding. Each of these components is outlined below:

Replica locator: This component identifies which replicas will receive which requests. It is also the mechanism that binds clients to the identified replicas. The replica locator can be implemented portably using standard CORBA portable object adapter (POA) mechanisms, such as servant locators [5],

[6]The term *component* used throughout this paper refers to a "component" in the general sense, *i.e.*, an identifiable entity in a program, rather than in the more specific sense of the CORBA Component Model [30].

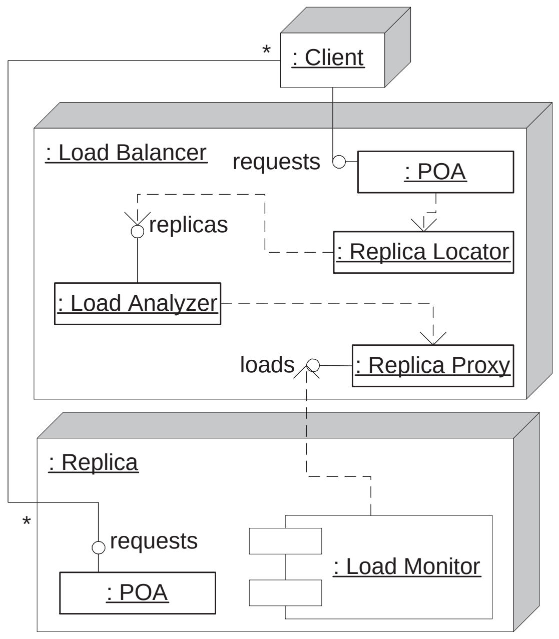

Figure 5: Components in the TAO Load Balancing Service

which implement the Interceptor pattern [29]. The Replica locator forwards each request it receives to the replica selected by the load analyzer described below.

Load monitor: This component (1) monitors loads on a given replica, (2) reports replica loads to a load balancer, and (3) responds to load advisories sent by the load balancer. As depicted in Figure 6, a load monitor can be configured with

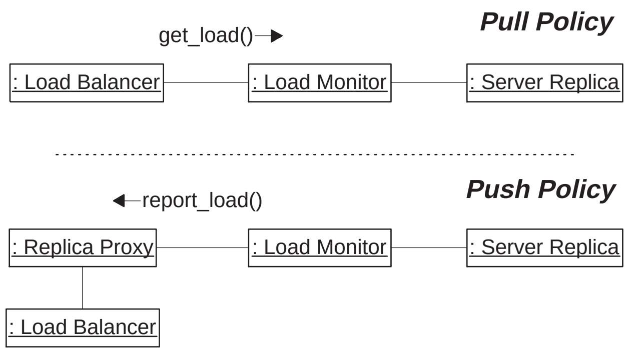

Figure 6: Load Reporting Policies

either of two policies:

- *Pull policy* – In this mode, a load balancer can query a given replica load on-demand, *i.e.*, "pull" loads from the load monitor.
- *Push policy* – In this mode, a load monitor can "push" load reports to the load balancer.

A load monitor also processes load advisories sent by the load balancer and informs replicas when they should accept requests versus forward them back to the load balancer.

Load analyzer: This component decides which replica will receive the next client request. The replica locator described above obtains a reference to a replica from the load analyzer and then forwards the request to that replica. The load analyzer also allows a load balancing strategy to be selected explicitly at run-time, while maintaining a simple and flexible design. Since the load balancing strategy can be chosen at run-time, replica selection can be tailored to fit the dynamics of a system that is being load balanced.

Replica proxy: Each object managed by TAO's load balancing service communicates with it via a unique proxy. The load balancer uses these replica proxies to distinguish different replicas to workaround CORBA's so-called "weak" notion of object identity [23], where two references to the same object may have different values. Thus, it is only possible to compare the *equivalence* of two object references. Two object references are equivalent if they refer to the same object. Otherwise, they are not equivalent if they do not refer to the same object or the ORB was unable to make this determination. It is the intentional ambiguity of the latter case that makes CORBA object identity "weak."[7] Section 3.3.5 discusses the replica proxy in more detail.

Load balancer: This component is a mediator that integrates all the components described above. It provides an interface through which load balancing can be administered, without exposing clients to the intricate interactions between the components it integrates.

3.2 Dynamic Interactions in TAO's Load Balancing Service

As described in Section 2.2, selecting a target replica using a non-adaptive balancing policy can yield non-uniform loads across replicas. In contrast, selecting a replica adaptively for each request can incur excessive overhead and latency. To avoid either extreme, therefore, TAO's load balancing service provides a hybrid solution via one of its load balancing strategies, whose interactions are shown in Figure 7. Each interaction in Figure 7 is outlined below.

1. A client obtains an object reference to what appears to be a replica and invokes an operation. In actuality, however, the client transparently invokes the request on the load balancer itself.
2. After the request is received from the client, the load balancer's POA dispatches the request to its servant locator, *i.e.*, the replica locator component.

[7] See [31] for the rationale behind CORBA's object identity semantics.

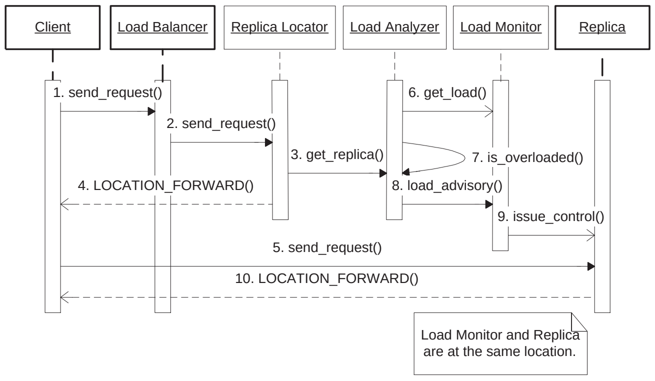

Figure 7: TAO Load Balancer Interactions

3. Next, the replica locator queries its load analyzer for an appropriate server replica.
4. The replica locator then transparently redirects the client to the chosen replica.
5. Requests will continue to be sent *directly* to the chosen replica until the load balancer detects a high load on that replica. The additional indirection and overhead incurred by per-request load balancing architectures (see Section 2.2.2) is eliminated since the client communicates with the replica directly.
6. The load balancer monitors the replica's load. Depending on the load reporting policy (see *load monitor* description in Section 3.1) that is configured, the load monitor will either report the load to the balancer or the load balancer will query the load monitor for the replica's load.
7. As loads are collected by the load balancer, the load analyzer analyzes the load on the replica.
8. If a replica becomes overloaded the load balancer can dynamically forward the client to another less loaded replica. To achieve the transparency requirements outlined in Section 2.1, TAO's load balancer does not communicate with the client application when forwarding it to another replica. Instead, TAO's load balancer issues a load advisory to the replica's load monitor.
9. The load monitor issues a control message to the replica. Depending on the contents of the load advisory issued by the load balancer, this control message will cause the replica to either accept or redirect requests.
10. When instructed by the load monitor, the replica uses the GIOP LOCATION_FORWARD message to redirect the next request sent by a client back to the load balancer.
11. At this point the load balancing cycle starts again.

3.3 Design Challenges and Their Solutions

The following design challenges were identified prior to and during the development of TAO's load balancing service:

1. Implementing portable load balancing
2. Enhancing feedback and control
3. Supporting modular load balancing strategies
4. Coping with adaptive load balancing hazards
5. Identifying objects uniquely
6. Integrating all the load balancing components effectively

These challenges and the solutions we applied to address them are discussed below. The solutions to each design challenge manifest themselves within the load balancing service components described in Section 3.1. Readers who are not interested in the design and rationale of TAO's load balancing service should skip to the performance results in Section 4.

3.3.1 Challenge 1: Implementing Portable Load Balancing

Context: A CORBA load balancing service is being implemented in accordance with the requirements outlined in Section 2.

Problem: Changing application code–particularly client applications–to support load balancing can be tedious, error-prone, and costly. Changing the middleware infrastructure to support load balancing is also problematic since the same middleware may be used in applications that do not require load balancing, in which case extra overhead and footprint may be unacceptable. Likewise, using *ad hoc* or proprietary interfaces to add load balancing to existing middleware can increase maintenance effort and may be unattractive to application developers who fear "vendor lock-in" from features that are unavailable in other middleware.

So, how can we implement load balancing transparently *without* changing applications, middleware or using proprietary features?

Solution → the Interceptor pattern: The Interceptor pattern [29] allows a framework to transparently add services that are triggered automatically when certain events occur. This pattern enhances extensibility by exposing a common interface implemented by a *concrete interceptor*. Methods in this interface are invoked by a *dispatcher*.

The Interceptor pattern can be implemented via standard CORBA POA [4] features. For example, the role of the interceptor is played by a *servant locator*[8] and the role of the

[8]Servant locators are a meta-programming mechanism [32] that allows CORBA server application developers to obtain custom object implementations dynamically, rather than using the POA's active object map [16].

dispatcher is played by a *POA*. In particular, a *replica locator* can implement the standard CORBA `ServantLocator` [4] interface provided by the POA.

Figure 8 illustrates how load can be balanced transparently using standard CORBA features. Initially, clients are given an object reference to the load balancer, so they first issue requests to the load balancer. The load balancer's servant locator intercepts those requests and forwards them transparently to the appropriate replicas. Depending on the type of client binding granularity (see Section 2.2) selected by the application, one of the following actions will occur:

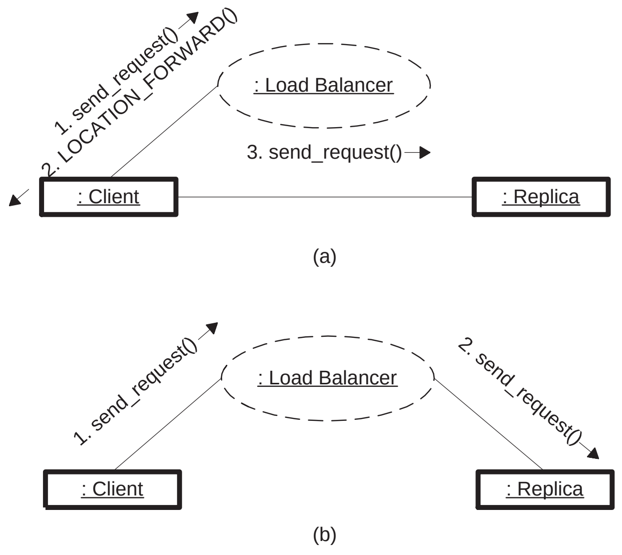

Figure 8: Load Balancing Transparency in Applications: (a) request forwarded by the client and (b) request forwarded on behalf of the client.

- The client will forward requests to the appropriate replica, as shown in Figure 8(a); or
- The load balancer will forward requests to the appropriate replica on behalf of the client, as shown in Figure 8(b).

Applying the solution in TAO: In TAO, each replica registers itself with the load balancer. Each replica then becomes a potential candidate to handle a request intercepted by the load balancer. The interception is performed by a servant locator.

TAO's load balancer implements its own servant locator, which is registered with the load balancer's POA. When a new request arrives, the POA delegates the task of locating a suitable servant to the servant locator, rather than using the servant lookup mechanism in the POA's active object map [16]. Thus, the load balancer can use the servant locator to forward requests to the appropriate replica transparently, *i.e.*, without affecting server application code.

After receiving a request, the replica locator obtains a reference to the replica chosen by the load analyzer (see Section 3.3.3) and throws a `ForwardRequest` exception initialized with a copy of that reference. The server ORB catches this exception and then returns a LOCATION_FORWARD GIOP message. When the client ORB receives this message, the CORBA specification requires it to

1. Re-issue the request to the new location specified by the object references embedded in the LOCATION_FORWARD response; and
2. To continue using that location until either the communication fails or the client is redirected again.

Thus, a server application and an ORB can forward client requests to other servers *transparently*, *portably*, and *interoperably*.

3.3.2 Challenge 2: Enhancing Feedback and Control

Context: An *adaptive* load balancing service must determine the current load conditions on replicas registered with it. A load balancer should not need to know the type of load metric beforehand, however. Moreover, a load balancer must take steps to ensure that loads across its registered replicas are balanced. These steps include (1) forcing the replica to redirect the client back to the load balancer when its load is high and (2) forcing the replica to once again accept client requests when its load is nominal.

Problem: Sampling loads from replicas should be as transparent as possible to the replicas. If load sampling was not transparent, a load balancer would have to sample loads from server replicas directly, which is undesirable since it would require replicas to collect loads. If replicas collect loads, however, application developers must modify existing application code to support load balancing. Such an obtrusive design does not scale well from a deployment point of view, nor is it always feasible to alter existing application code.

Moreover, a load balancer should not be tightly coupled to a particular load metric. Only the *magnitude* of the load should be considered when making load balancing decisions, so that a load balancer can support any type of load metric, rather than just one type of metric. The same deployment scalability issues encountered for load sampling transparency also apply here. If a load balancer were load-metric specific it would be costly to deploy load balancers for distributed applications that require balancing based on several load metrics. For example, a separate load balancer would be needed to balance replicas based on various metrics, such as CPU, I/O, memory, network, and battery power utilization.

In addition, a load balancer must react to various replica load conditions to ensure that loads across replicas are balanced. For example, when high load conditions occur, a replica must be instructed to forward the client request back to the load balancer so subsequent requests can be reassigned to a less loaded replica.

So, how can we implement a flexible load balancing service that can be extended to support new load metrics, as well as different policies to collect such metrics?

Solution $\rightarrow$ the Strategy and Mediator patterns: The Strategy [17] design pattern allows the behavior of frameworks and components to be selected and changed flexibly. For example, the same interface can be used to obtain different types of loads on a given set of resources. Only object implementations must change since load measuring techniques may differ for each type of load. Each implementation is called a "strategy" and can be embodied in an object called a *load monitor*.

A load monitor implements a strategy for monitoring loads on a given resource. The interface for reporting loads to the load balancer or to obtain loads from the load monitor remains unchanged for each load monitoring strategy. Strategizing load monitoring makes it possible to use a load balancer that is not specific to a particular type of load, such as CPU load or battery power utilization. Thus, a load balancer need not be specialized for a given type of load. This design simplifies deployment of a load balanced distributed system since one load balancer can balance many different types of load.

The Mediator [17] design pattern defines an object that encapsulates how objects will interact. In addition to playing the role of a strategy, a load monitor acts as a mediator between the load balancer and a given replica. This pattern ensures there is a loose coupling between the load balancer and the server replicas. Thus, the load balancer need not have any knowledge of the interface exported by the replica.

In its capacity as a mediator, a load monitor responds to load balancing requests sent by the load balancer. Depending on the type of request the load balancer sends to the load monitor, the replica will either continue accepting client requests or redirect the client back to the load balancer. Note that the load balancer never interacts with the replica directly – all interaction occurs via the load monitor. Similarly, the replica never interacts with the load balancer directly. Instead, it interacts with the load balancer indirectly through the load monitor.

Applying the solution in TAO: When registering a replica with TAO's load balancer, its corresponding load monitor is also registered. As shown in Figure 9, the load balancer queries the load monitor for the load on the current replica, assuming that pull-based load monitoring is being used (see Section 3.1). In other words, the load balancer receives *feedback* from the load monitor. Load balancing control messages–called *load advisories*–are then sent to the load monitor from the load balancer and set the state of the current replica load to one of the following values:

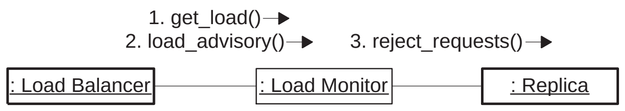

Figure 9: Feedback and Control when Balancing Loads

- *Nominal* – When the load is nominal, the replica continues to accept requests.
- *High* – A high load advisory causes the replica to redirect client requests by forwarding them back to the load balancer, at which point the load balancer forwards the request to a less loaded replica.

These two state values are the defaults provided by TAO. Users can define their own customized load states, however, by customizing the load analyzer and load monitor component implementations.

TAO's load balancer is *adaptive* due to the bi-directional feedback/control channel between the load monitor and the load balancer, which allows TAO's load balancer to administer *control*. Since the load monitor is decoupled from the load balancer it is also possible to balance loads across replicas based on various types of load metrics. For instance, one type of load monitor could report CPU loads, whereas another could report I/O resource load. The fact that the type of load presented to the load balancer is opaque allows the same load balancer–specifically the load analysis algorithm–to be reused for any load metric.

3.3.3 Challenge 3: Supporting Modular Load Balancing Strategies

Context: A distributed system employs a load balancing service to improve overall throughput by ensuring that loads across replicas are as uniform as possible. In some applications, loads may peak in a predictable fashion, such as at certain times of the day or days of the week. In other applications, loads cannot be predicted easily *a priori*.

Problem: Since certain load analysis techniques are not suitable for all use-cases, it may be useful to analyze a set of replica loads in different ways depending on the situation. For example, to predict future replica loads it may be useful to analyze the history of loads for a given object group, thereby anticipating high load conditions. Conversely, this level of analysis may be too costly in other use-cases, *e.g.*, if the duration of the analysis exceeds the time required to complete client request processing.

In some applications it may even be necessary to change the load analysis algorithm dynamically, *e.g.*, to adapt to new application workloads. Moreover, bringing the system down to reconfigure the load balancing strategy may be unacceptable for applications with stringent 24×7 availability requirements. Likewise, application developers may be interested in evaluating several alternative load balancing policies, in which case requiring a full recompilation or relink cycle would unduly increase system development effort. A load balancing service cannot simply implement all possible load balancing strategies, however, *e.g.*, application developers may wish to define application-specific or *ad-hoc* load balancing algorithms during testing or deployment.

So, how can we allow dynamic (re)configurations of the load balancing service, such as the load monitor and load analyzer, without requiring expensive system recompilations or interruptions of service?

Solution → the Component Configurator pattern: The *Component Configurator* design pattern [29] allows applications to link and unlink components into and out of an application at run-time. In TAO's load balancing service this pattern can be used to change the replica selection strategy dynamically. Thus, a load balancer can use this pattern to adapt to different load balancing use-cases, without being hard-coded to handle just those use-cases.

At times it may be necessary to load balance only a few replicas, in which case a simple load balancing strategy may suffice. In other situations, such as during periods of peak activity during the workday, a load balancing strategy may need modifications to account for increased load. In such cases, a more complex strategy may be necessary. The Component Configurator pattern makes it easy to dynamically configure load balancing algorithms appropriate for different use-cases *without* stopping and restarting the load balancer.

Applying the solution in TAO: TAO's load analyzer uses the Component Configurator pattern to customize the load balancing algorithm used when making load balancing decisions, as depicted in Figure 10. TAO's load balancing service can be configured dynamically to support the following strategies:

• **Round-robin:** This non-adaptive strategy is straightforward and does not take load into account. Instead, it simply causes a request to be forwarded to the next replica in the object group being load balanced [21].

• **Minimum dispersion:** This adaptive strategy is more sophisticated than the round-robin algorithm described above. The goal of this strategy is to ensure load differences fall within a certain tolerance, *i.e.*, it attempts to ensure that the average difference in load between each replica is minimized. The following steps are used in this on-demand adaptive strategy:

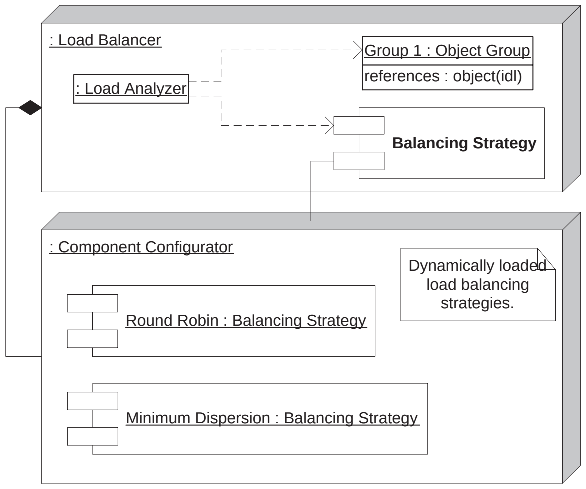

Figure 10: Applying the Component Configurator Pattern to TAO's Load Balancing Service

1. The average load across all replicas within a given object group is updated each time a load balancing decision occurs.
2. The instantaneous load on each replica is then compared to the average load.
3. If the difference between the average load and the instantaneous load is larger than the tolerance set by the *minimum dispersion* load balancing strategy, the load balancer will attempt to decrease the difference so that they fall within the tolerance.

Note that a set of replicas balanced via this strategy will not necessarily have the same load on each of them, but over time the load *dispersion* between the replicas will be minimized.

A large amount of work on load balancing strategies [33] has already been done. Many of those same strategies can be integrated in to the CORBA-based load balancing service via the Component Configurator pattern implementation described above.

3.3.4 Challenge 4: Coping With Adaptive Load Balancing Hazards

Context: A customized adaptive load balancing strategy is under development by a distributed application developer. This load balancing strategy will be used to balance loads across a group of replicas.

Problem: Adaptive load balancing has the potential to improve system responsiveness. It is hard to ensure the stability of loads across replicas when the overall state of distributed systems changes quickly due to the following hazards:

• **Thundering herd:** When a less loaded replica suddenly becomes available, a "thundering herd" phenomenon may occur if the load balancer forwards all requests to that replica immediately. If the rate at which the loads are reported and analyzed is slower than the rate at which requests are forwarded to the replica, it is possible that the load on that replica will increase rapidly. Ideally, the rate at which requests are forwarded to replicas should be less than or equal to the rate at which loads are reported and analyzed. Satisfying this condition can eliminate the thundering herd phenomenon.

• **Balancing paroxysms:** The smaller the number of replicas, the harder it can be to balance loads across them effectively. For example, if only two replicas are available then one replica may be more loaded than the other. A naive load balancing strategy will attempt to shift the load to the less loaded replica, at which point it will most likely become the replica with the greater load. The entire process of shifting the load may begin again, causing system instability.

So, how can we adapt to dynamic changes in load, but without overreacting transient, short lived or sample errors in the load metric?

Solution $\rightarrow$ Dampening load sampling rates and request redirection: The *minimum dispersion* load balancing strategy described in Section 3.3.3 can be employed to alleviate the thundering herd phenomenon and balancing paroxysms since it will not attempt to shift loads the moment an imbalance occurs. Specifically, by relaxing the criteria used to decide when loads across a group of replicas is balanced, a load balancer can adjust to large load discrepancies with less probability of experiencing the hazards discussed above. The criteria for deciding when to shift loads can also change dynamically as the number of replicas increases.

Using control theory terminology, this behavior is called *dampening*, where the system minimizes unpredictable behavior by reacting slowly to changes and waiting for definite trends to minimize over-control decisions. TAO's minimum dispersion balancing strategy does not react to changes in load immediately because its default load balancing strategy averages instantaneous load samples with older load values. The empirical results presented in Section 4.3 illustrate the effects of TAO's dampening mechanisms.

3.3.5 Challenge 5: Identifying Objects Uniquely

Context: A load balancing service that manages multiple objects is responsible for collecting and analyzing information, such as the state, health, and environmental conditions, throughout the lifetime of each object it manages. This information is obtained from the load monitor, as described in Section 3.3.2. In some applications using a *pull model* to acquire the load information may not scale well and can be hard to optimize. In contrast, *push models* can resubmit load information when it has changed beyond a pre-set threshold or after a fixed period of time.

Problem: When receiving information about the load in one replica the load balancing service should determine the source of the load information efficiently and uniquely. This goal can be achieved easily via pull models, but it is harder to implement via push models. CORBA does not provide a lightweight mechanism to determine the source of a request.[9] Moreover, as described in Section 3.1, CORBA provides *weak identity* for objects, relying on the replica object reference to distinguish them would not be portable.

So, how can we portably and efficiently determine the source of the load information?

Solution $\rightarrow$ the Asynchronous Completion Token pattern: This pattern is used to efficiently dispatch processing tasks that result from responses to asynchronous operations invoked by a client [29]. In the load balancing service, the replica proxy plays the role of an asynchronous completion token (ACT). Load monitors communicate load updates via their replica proxy objects, as shown in Figure 11. The load balancing service creates a unique replica proxy for each monitor. When the replica proxy implementation creates and caches the identity of the replica ACT and load monitor that will later use the replica proxy. This design allows the replica proxy to determine the identity of the remote replica efficiently whenever new load information is received.

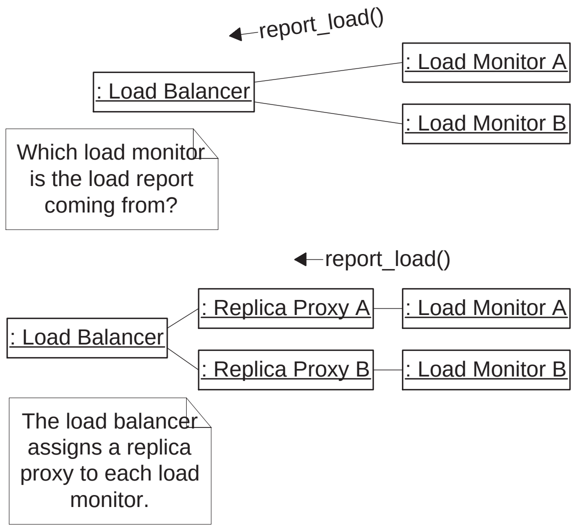

Figure 11: Identifying the Source of a Message Uniquely

[9]The CORBA Security Service [34] can authenticate client requests, but this is a much more expensive mechanism than required for many applications.

Applying the solution in TAO: TAO uses a CORBA `Object` to play the role of an asynchronous completion token. The load balancing service creates a different CORBA `Object`–called a `ReplicaProxy`–for each replica. This proxy is created when the replica registers itself with the load balancing service initially. All future communication with the load balancing service is performed through the proxy. The Asynchronous Completion Token pattern allows the load balancing service to process the requests from each replica efficiently and unambiguously.

As each load is reported to the `ReplicaProxy`, the load analyzer is notified that a new load is available for analysis. Since the `ReplicaProxy` caches the object reference of its corresponding replica, the load balancer can redirect the client to a nominally loaded replica using the cached replica object reference.

3.3.6 Challenge 6: Integrating All the Load Balancing Components Effectively

Context: As illustrated above, a load balanced distributed system has many components that interact with each other. For example, clients issue requests to replicas. Load monitors measure loads on replicas continuously and control client access to the replicas. Load analyzers decide if loads on replicas are nominal or high. Finally, replica locators bind clients to replicas.

Problem: All the components mentioned above must collaborate effectively to ensure that a distributed system is load balanced. Direct interaction between some of those components may complicate the implementation of distributed applications, however, since certain functionality may be exposed to a given component unnecessarily.

So, how can we integrate the functionality of all the load balancing components without unduly coupling all of them?

Solution $\rightarrow$ the Mediator pattern: The Mediator pattern provides a means to coordinate and simplify interactions between associated objects. This pattern shields the objects from relationships and interactions that are not needed for their effective operation.

A *load balancer* component can be used to tie together all the components listed above. It coordinates all interactions between other components, *i.e.*, it is a mediator. For example, it shields the client from the component interactions necessary to conduct load balancing. Thus, clients can remain unaware of the interactions mediated by the load balancer, which helps to satisfy application transparency requirements.

Applying the solution in TAO: As shown in Figure 5, the load balancer in TAO mediates the following types of component interactions:

• **Client binding interactions:** Rather than binding itself to a specific replica that may be highly loaded, TAO's load balancer binds the client to a suitable replica. The load balancer creates an object reference that corresponds to a group of replicas–called an *object group*–being load balanced. Instead of using an object reference that directly refers to a given replica, the client uses the object reference created by the load balancer that represents the appropriate object group. This design causes the client to invoke a request on the load balancer initially, at which point the client is re-bound to a replica chosen by the load balancer.

It is important to note that the CORBA object model was intentionally designed to decouple the object implementation from the object references that clients use to access the implementations. In TAO's load balancing service we exploit this feature of CORBA to hide the particular location, number, and characteristics of the replicas behind an object reference that points clients to the load balancing service. Clients applications are shielded by this extra level of indirection by their ORBs, and use a load balanced object just like any other CORBA object, unaware of the situation except perhaps for the difference in performance.

The load balancer also rebinds the client to another replica by using other components, such as the load monitor. In that case, a client is forwarded back to the load balancer so that the client binding process can be begin again. Thus, load balancing remains completely transparent to client applications.

• **Load monitor and load analyzer interactions:** The load balancer allows the load analyzer to be completely decoupled from load monitors. Load monitors are registered with the load balancer. This design allows the load balancer to receive load reports from each registered load monitor. These load reports are then delegated to the load analyzer for analysis. The means by which these loads were obtained is hidden from the load analyzer.

4 Performance Results

For load balancing to improve the overall performance of CORBA-based systems significantly, the load balancing service must incur minimal overhead. A key contribution of TAO's load balancing service is that it increases overall system throughput by distributing requests across multiple back-end servers (replicas) without increasing round-trip latency and jitter significantly.

This section describes the design and results of several experiments we performed to measure the benefits of TAO's load balancing strategy empirically, as well as to demonstrate the limitations with the alternative load balancing strategies outlined in Section 2.2. The first set of experiments in Section 4.2

show the amount of overhead incurred by the request forwarding architectures described in this paper. The second set of experiments in Section 4.3 demonstrate how TAO's load balancer can maintain balanced loads dynamically *and* efficiently, whereas alternative load balancing strategies cannot.

4.1 Hardware/Software Benchmarking Platform

Benchmarks performed for this paper were run using three 733 MHz dual CPU Intel Pentium III workstations, and one 400 MHz quad CPU Intel Pentium II Xeon workstation, all running Debian GNU/Linux "potato" (GLIBC 2.1), with Linux kernel version 2.2.16. GNU/Linux is an open-source operating system that supports kernel-level multi-tasking, multi-threading, and symmetric multiprocessing. All workstations are connected through a 100 Mbps ethernet switch. This testbed is depicted in Figure 12. All benchmarks were run in the POSIX

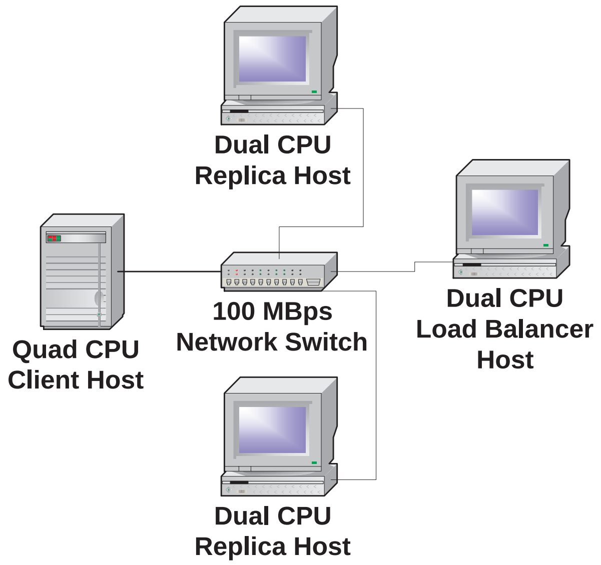

Figure 12: Load Balancing Experiment Testbed

real-time thread scheduling class [35]. This scheduling class enhances the integrity of our results by ensuring the threads created during the experiment were not preempted arbitrarily during their execution.

The core CORBA benchmarking software is based on the "`Latency`" performance test distributed with the TAO open-source software release.[10] Figure 1 illustrates the basic design of this performance test. All benchmarks use one of the following variations of the `Latency` test:

[10]See `$TAO_ROOT/performance-tests/Latency/` in the TAO release for the source code of this benchmark.

1. Classic Latency test: In this benchmark, we use high-resolution OS timers to measure the throughput, latency, and jitter of requests made on an instance of a CORBA object that verifies a given integer is prime. Prime number factorization provides a suitable workload for our load balancing tests since each operation runs for a relatively long time. In addition, it is a stateless service that shields the results from transitional effects that would otherwise occur when transferring state between load balanced stateful replicas.

2. Latency test with non-adaptive per-request load balancing strategy: This variant of `Latency` test was designed to demonstrate the performance and scalability of *optimal* load balancing using per-request forwarding as the underlying request forwarding architecture. This variant added a specialized "forwarding server" to the test, whose sole purpose was to forward requests to a target server at the fastest possible rate. No changes were made to the client.

3. Latency test with TAO's adaptive on-demand load balancing strategy: This variant of the `Latency` test added support for TAO's adaptive on-demand load balancer to the classic `Latency` test. The `Latency` test client code remained unchanged, thereby preserving client transparency. This variant quantified the performance and scalability impact of TAO's adaptive on-demand load balancer.

4.2 Benchmarking the Overhead of Load Balancing Mechanisms

These benchmarks measure the degree of end-to-end overhead incurred by adding load balancing to CORBA applications.

Overhead measurement technique: The overhead experiments presented in this paper compute the throughput, latency, and jitter incurred to communicate between a single-threaded client and a single-threaded server (*i.e.*, one replica) using the following four request forwarding architectures:

1. No load balancing: To establish a performance baseline without load balancing, the `Latency` performance test was first run between a single-threaded client and a single-threaded server (one replica) residing on separate workstations. These results reflect the baseline performance of a TAO client/server application.

2. A non-adaptive per-session client binding architecture: We then configured TAO's load balancer to use the non-adaptive per-session load balancing strategy when balancing loads on a `Latency` test server. We did this by simply adding the registration code to the `Latency` test server implementation, which causes the replica to register itself with the load balancer so that it can be load balanced. No changes to the core `Latency` test implementation were made. Since the replica sends no feedback to the load balancer, this benchmark establishes a baseline for the best performance achievable by a load balancer that utilizes a per-session client binding granularity.

3. A non-adaptive per-request client binding architecture: Next, we added a specialized non-adaptive per-request "forwarding server" to the original `Latency` test. This server just forwards client requests to an unmodified backend server. The forwarding server resided on a different machine than either the client or backend server, which themselves each ran on separate workstations. Since the forwarding server is essentially a lightweight load balancer, this benchmark provides a baseline for the best performance achievable by a load balancer using a per-request client binding granularity.

4. An adaptive on-demand client binding architecture: Finally, TAO's adaptive on-demand client binding granularity was included in the experiment by adding the *load monitor* described in Section 3.3.2 to the `Latency` test server. This enhancement allowed TAO's load balancer to react to the current load on the `Latency` test server. TAO's load balancer, the client, and the server each ran on separate workstations, *i.e.*, three workstations were involved in this benchmark. No changes were made to the client portion of the `Latency` test, nor were any substantial changes made to the core servant implementation.

Overhead benchmark results: The results illustrated in Figure 13 quantify the latency imposed by adding load balancing–specifically request forwarding–to the `Latency` performance test. All overhead benchmarks were run with 200,000 iterations. As shown in this figure, a non-adaptive per-session approach imposes essentially no latency overhead to the classic `Latency` test. In contrast, the non-adaptive per-request approach more than doubles the average latency. TAO's adaptive on-demand approach adds little latency. The slight increase in latency incurred by TAO's approach is caused by

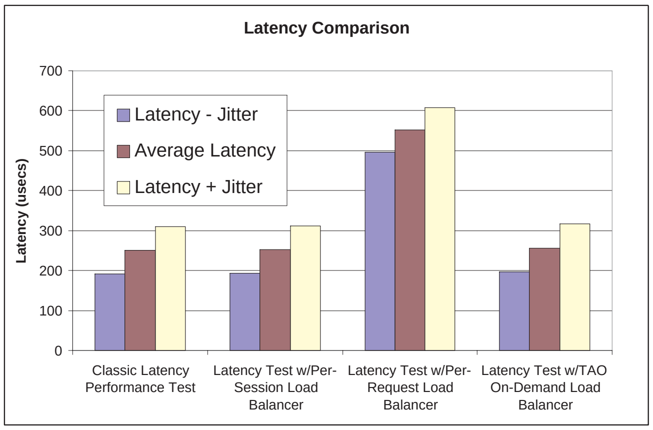

Figure 13: Load Balancing Latency Overhead

- The additional processing resources the load monitor needs to perform load monitoring; and
- The resources used when sending periodic load reports to the load balancer, *i.e.*, "push-based" load monitoring.

These results clearly show that it is possible to minimize latency overhead, yet still provide adaptive load balancing. As shown in Figure 13, the jitter did not change appreciably between each of the test cases, which illustrates that load balancing hardly affects the time required for client requests to complete.

Figure 14 shows how the average throughput differs between each load balancing strategy. Again, only one client and one server were used for this experiment. Not surprisingly, the throughput remained basically unchanged for the non-adaptive per-session approach since only one out of 200,000 requests was forwarded. The remaining requests were all sent to directly to the server, *i.e.*, all requests were running at their maximum speed.

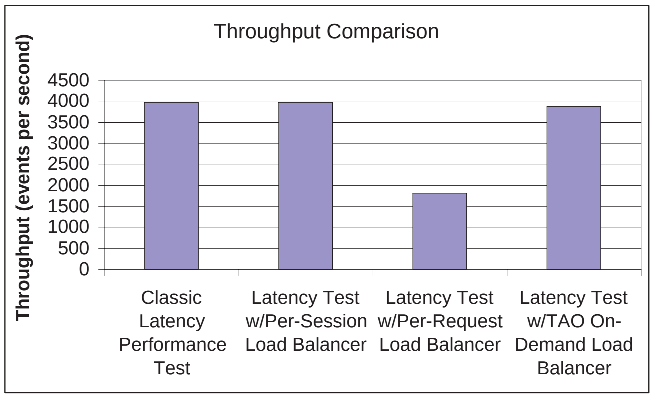

Figure 14: Load Balancing Throughput Overhead

Figure 14 illustrates that throughput decreases dramatically in the per-request strategy due to the fact that it (1) forwards requests on behalf of the client and (2) forwards replies received from the replica to the client, thereby doubling the communication required to complete a request. This architecture is clearly not suitable for throughput-sensitive applications.

In contrast, the throughput in TAO's load balancing approach only decreased slightly with respect to the case where no load balancing was performed. The slight decrease in throughput can be attributed to the same factors that caused the slight in increase in latency described above, *i.e.*, (1) additional resources used by the load monitor and (2) the communication between the load balancer and the load monitor.

4.3 Load Balancing Strategy Effectiveness

The following set of benchmarks quantify how effective each load balancing strategy is at maintaining balanced load across a given set of replicas. First, the effectiveness of the non-adaptive per-session load balancing strategy is shown. Next, the effectiveness of the adaptive on-demand strategy employed by TAO is illustrated. In all cases, we used the `Latency` test from the overhead benchmarks in Section 4.2 for the experiments.

Effectiveness measurement technique: The goal of this benchmark was to overload certain replicas in a group and then measure how different load balancing strategies handled the imbalanced loads. We hypothesized that loads across replicas should remain imbalanced when using non-adaptive per-session load balancing strategies. Conversely, when using adaptive load balancing strategies, such as TAO's adaptive load balancing strategy, loads across replicas should be balanced shortly after imbalances are detected.

To create this situation, four `Latency` test server replicas–each with a dedicated CPU–were registered with TAO's load balancer during each effectiveness experiment. Eight `Latency` test clients were then launched. Half the clients issued requests at a higher rate than the other half. For example, the first client issued requests at a rate of ten requests per-second, the second client issued requests at a rate of five requests per-second, the third at ten requests per-second, etc. The actual load was not important for this set of experiments. Instead, it was the *relative* load on each replica that was important, *i.e.*, a well balanced set of replicas should have relatively similar loads, regardless of the actual values of the load.

Effectiveness benchmark results: The results of the effectiveness tests are described below.

• **Non-adaptive per-session load balancing effectiveness:** For this experiment, TAO's load balancer was configured to use its *round-robin* load balancing strategy. This strategy does not perform any analysis on reported loads, but simply forwards client requests to a given replica. The client then continues to issue requests to the same replica over the lifetime of that replica. The load balancer thus applies the *non-adaptive per-session* strategy, *i.e.*, it is only involved during the initial client request.

Figure 15 illustrates the loads incurred on each of the `Latency` server replicas using non-adaptive per-session load balancing. The results quantify the degree to which loads across replicas become unbalanced by using this strategy. Since there is no feedback loop between the replicas and the load balancer, it is not possible to shift load from highly loaded replicas to less heavily loaded replicas.

Note that two of the replicas (3 and 4) had the same load. The line representing the load on replica 3 is obscured by

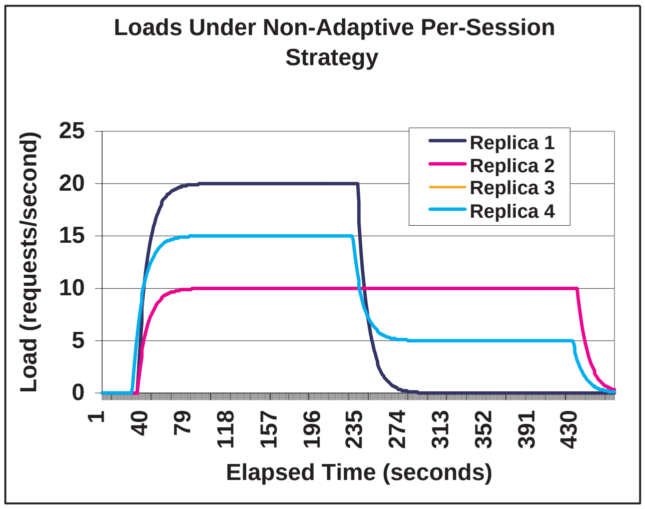

Figure 15: Effectiveness of Non-Adaptive Per-Session Load Balancing

the line representing the load on replica 4. In addition, note that the same number of iterations were issued by each client. Since some clients issued requests at a faster rate (10 Hz), however, those clients completed their execution before the clients with the lower request rates (5 Hz). This difference in request rate accounts for the sudden drop in load half way before the slower (*i.e.*, low load) clients completed their execution.

• **TAO's adaptive load balancing strategy effectiveness:** This test demonstrated the benefits of an adaptive load balancing strategy. Therefore, we increased the load imposed by each client and increased the number of iterations from 200,000 to 750,000. Four clients running at 100 Hz and another four running at 50 Hz were started and ended simultaneously.

Client request rates were increased to exaggerate load imbalance and to make the load balancing more obvious as it progresses. It was necessary to increase the number of iterations in this experiment because of the higher client request rates. If the number of iterations were capped at the 200,000 used in the overhead experiments in Section 4.2 this experiment could have ended before loads across the replicas were balanced.

As Figure 16 illustrates, the loads across all four replicas fluctuated for a short period of time until an equilibrium load of 150 Hz was reached.[11] The initial load fluctuations result from the load balancer periodically rebinding clients to less loaded replicas. By the time a given rebind completed, the replica load had become imbalanced, at which point the client

[11]The 150 Hz equilibrium load corresponds to one 100 Hz client and one 50 Hz client on each of the four replicas.

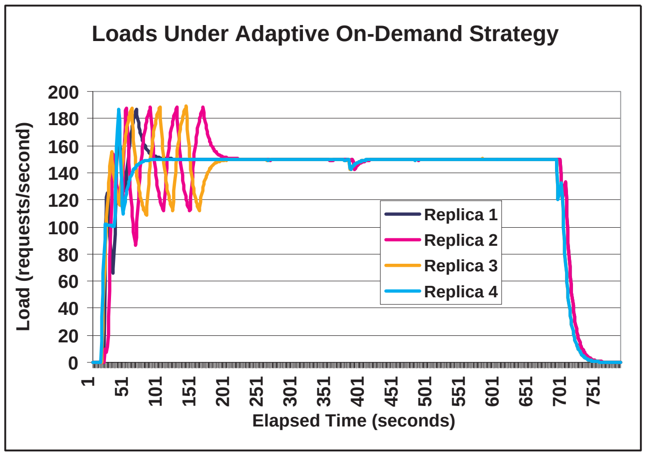

Figure 16: Effectiveness of Adaptive On-Demand Load Balancing

was rebound to another replica. These initial fluctuations are typical of the adaptive load balancing hazards discussed in Section 3.3.4.

The load balancer required several iterations to balance the loads across the replicas, *i.e.*, to stabilize. Had it not been for the dampening (see Section 3.3.4) built into TAO's adaptive on-demand load balancing strategy, it is likely that replica loads would have oscillated for the duration of the experiment. Dampening prevents the load balancer from basing its decisions on instantaneous replica loads, and to use average loads instead.

It is instructive to compare the results in Figure 16 to the non-adaptive per-session load balancing architecture results in Figure 15. Loads in the non-adaptive approach remained imbalanced. Using the adaptive on-demand approach, the overhead is minimized *and* loads remain balanced.

After it was obvious that the loads were balanced, *i.e.*, equilibrium was reached, the experiment was terminated. This accounts for the uniform drops in load depicted in Figure 16. Contrast this to the non-uniform drops in load that occured in the overhead experiments in Section 4.2, where clients were allowed to complete all iterations. In both cases, the number of iterations is less important than the fact that the iterations were executed to (1) illustrate the effects of load balancing and (2) ensure that the overall results were not subject to transient effects, such as periodic execution of operating system tasks.

The actual time required to reach the equilibrium load depends greatly on the load balancing strategy. The example above was based on the minimum dispersion strategy described in Section 3.3.3. A more sophisticated adaptive load balancing strategy could have been employed to improve the time to reach equilibrium. Regardless of the complexity of the adaptive load balancing strategy, these results show that adaptive load balancing strategies can maintain balanced loads across a given set of replicas.

5 Related and Future Work

This section outlines related research on load balancing and describes how it compares and contrasts to our work on TAO's load balancing service. We first compare our middleware-based load balancing strategies with work at other levels of abstraction. Next, we describe how our work compares with other research on CORBA-based load balancing. We finish by outlining our future research plans to enhance TAO's load balancing service.

5.1 Related Research on Load Balancing

As discussed in Section 1, load balancing mechanisms have been implemented at various levels, such as in the network, OS, and middleware. Some implementations, such as the Condor [36] and Beowulf [37] clustering systems, combine aspects from multiple levels. This paper focuses primarily on middleware-based load balancing, but many concepts and patterns used in middleware-based load balancing also apply to network-based and OS-based load balancing, as described below.

Network-based load balancing: Network-based load balancing implementations often make decisions based on the frequency with which a given location is accessed. The decision of where to service a request can be made at various stages along the path to its destination. For example, a router [38] or DNS server could decide where to send a request.

Network-based load balancing has the disadvantage that load balancing decisions are based solely on the request target, which hampers flexibility significantly. However, recent developments in network-based load balancing do take advantage of request content. These hybrid implementations [1] provide finer-grained load analysis, which can improve load balancing decisions. Nevertheless, the metric used in load balancing decisions is still restricted to the frequency with which a given target is accessed.

Unfortunately, frequency alone is not always an adequate load metric since some requests may incur large loads on the target host, *e.g.*, when Web servers process CGI requests. When combined with load balancing decisions based solely on target access frequency, the increased loads from such requests can degrade overall system performance. It is possible to analyze the content of each request to determine if it is a “high load” request, but this requires *a priori* knowledge of request behavior, which is infeasible in many distributed computing systems.

OS-based load balancing: Some distributed operating systems, such as Chorus [39], can distribute processes transparently across remote OS endsystem nodes. Other tools, such as GNU Queue [40], allow users to execute remote processes as if they were run on the local machine. Load balancing performed at this level has the advantage that it can be implemented transparently to applications. When loads are too high at their current location, running applications can be migrated to other nodes relatively transparently. As with the network-based architecture, however, load balancing at this level makes it hard to choose which metric to use when deciding where to move processes since application-level metrics and policies are not available at this level.

Middleware-based load balancing: Middleware-based load balancing implementations reside between the application and the OS/network. Middleware shields the application from tedious and error-prone low-level OS complexities, while also providing an interface to make load balancing at this level as transparent as possible. Moreover, middleware can be implemented with sufficient flexibility to overcome the disadvantages in network-based and OS-based load balancing architectures outlined above.

CORBA is an example of middleware that provides the following capabilities needed to implement an effective load balancing service:

- Application developers can customize how their system is load balanced without being restricted by the limited– and often hard-coded–metrics available in network-based and OS-based load balancing.
- Applications can select at run-time the metric(s) used it to guide load balancing decisions.
- New metrics can also be defined with relative ease by separating interface from implementation, *i.e.*, exposing a consistent interface for each implementation. Section 3.3.2 describes how a load monitoring component can be implemented for a specific load metric, yet keep the load balancing service load metric agnostic.

Moreover, a middleware-based load balancing service can be used in conjunction with network- and OS-based load balancing facilities, which supports some interesting load balancing combinations. For example, if an application just balances load based on request frequency, a middleware-based load balancer can delegate load balancing tasks to the network or OS layers. Conversely, the middleware-based load balancer itself could be load balanced at the network or OS level, thereby providing additional network/host resources for use by the middleware and other applications.

Other examples of middleware-based load balancing include some Web server implementations. Web servers can forward HTTP requests [41] to a number of hosts that replicate the target web page. Overall throughput can be increased using any of the load balancing approaches presented in this paper. The key is that the Web server performs the HTTP request load balancing.

The CORBA-based load balancing concepts detailed in this paper are generally applicable to other middleware implementations, such as COM+ [42]. In fact, a middleware-based load balancing service called *Component Load Balancing* (CLB) [43] is available from Microsoft for COM+ applications.

5.2 Related Research on CORBA-based Load Balancing

CORBA load balancing can be implemented at several levels in the OMG reference architecture, such as the following:

ORB-level: Load balancing can be implemented inside the ORB itself. For example, a load balancing implementation can take direct advantage of request invocation information available within the POA when it makes load balancing decisions. Moreover, middleware resources used by each object can also be monitored directly via this design, as described in [44]. For example, Inprise's VisiBroker implements a similar strategy, where Visibroker's object adapter [45] creates object references that point to Visibroker's Implementation Repository, called the OSAgent, that plays both the role of an activation daemon and a load balancer.

ORB-level techniques have the advantage that the amount of indirection involved when balancing loads can be reduced because load balancing mechanisms are closely coupled with the ORB *e.g.*, the length of communication paths is shortened. However, ORB-level load balancing has the disadvantage that it requires modifications to the ORB itself. Unless or until such modifications are adopted by the OMG, they will be proprietary, which reduces their portability and interoperability. Therefore, TAO's load balancing service does not rely on ORB-level extensions or non-standard features.

TAO's load balancing service does not require any modifications to the ORB core or object adapter. Instead, it takes advantage of standard mechanisms in CORBA 2.X to implement adaptive load balancing. Like the Visibroker implementation and the strategies described in [44], TAO's approach is transparent to clients. Unlike the ORB-based approaches, however, our implementation only uses standard CORBA features. Thus, it can be ported to any C++ CORBA ORB that implements the CORBA 2.2 or newer specification.

Service-level: Load balancing can also be implemented as a CORBA service. For example, the research reported in [46] extends the CORBA Event Service to support both load balancing and fault tolerance. Their system builds a hierarchy of *event channels* that fan out from event source *suppliers* to the event sink *consumers*. Each event consumer is assigned to a different leaf in the event channel hierarchy, and both fixed and adaptive load balancing is performed to distribute consumers evenly. In contrast, TAO's load balancing service can be used for application defined objects, as well as event services.

Various commercial CORBA implementations also provide service-level load balancing. For example, IONA's Orbix [21] can perform load balancing using the CORBA Naming Service. Different replicas are returned to different clients when they resolve an object. This design represents a typical non-adaptive per-session load balancer, which suffers from the disadvantages described in Section 2.2. BEA's WebLogic [47] uses a per-request load balancing strategy, also described in Section 2.2. In contrast, TAO's load balancing service does not incur the per-request network overhead of the BEA strategy, yet can still adapt to dynamic changes in the load, unlike Orbix's load balancing service.

5.3 Future Work

This paper addresses an important part of the load balancing service design space. In particular, we focus on client transparency, centralized load balancing, stateless replicas, and "best-effort" adaptive balancing policies. However, additional steps can be taken to enhance TAO's load balancing service. For example, a complete solution should also provide other capabilities, such as supporting:

- Transparent load balancing to server object replicas;
- Decentralized load balancing models;
- Distributed systems whose servers retain state;
- Enhanced server side scalability;
- Fault tolerant load balancing;
- Better quality of service; and
- Advanced replica management.

Below, we outline future work that we are conducting to address these topics.

Server transparency: It is non-trivial to achieve transparent server load balancing since obtaining feedback from a given replica and controlling it without altering server application code is hard. Fortunately, CORBA-based distributed systems can achieve server transparency by taking advantage of the following recently standardized CORBA features:

• **Portable Interceptors:** Portable interceptors [28, 32] can capture client requests transparently before they are dispatched to an object replica. For example, a *server request interceptor* could be added to the ORB where a given replica runs. Since interceptors reside within the ORB no modification to server application code is necessary, other than registering the interceptor with the ORB when it starts running.

• **CORBA Component Model (CCM):** The CCM [30] introduces *containers* to decouple application component logic from the configuration, initialization, and administration of servers. In the CCM, a container creates the POA and interceptors required to activate and control a component. These are the same CORBA mechanisms used to implement the server components in TAO's load balancing service. The standard CCM containers can be extended to implement automatic load balancing *generically* without changing application component behavior.

Decentralized load balancing models: The CORBA-based load balancing architecture described in this paper is based on a *centralized* load balancing model. Specifically, it assumes that one load balancer performs all load balancing tasks for a particular distributed system. This model simplifies the design and implementation of the load balancer, but introduces a single point of failure, which can impede system reliability and scalability.

One solution is to implement a *cooperative* load balancing service. In this model, load balancing is facilitated through a distributed set of load balancers that collectively form a single *logical* load balancing service. This model has the advantage that a single point of failure does not exist, and that no single bottleneck point exists either. Load balancing decisions would be made cooperatively, *i.e.*, each load balancer could communicate with other balancers to decide how best to balance loads across a given group of replicas.

Stateful replicas: Another issue we will address in future work involves load balancing of stateful replicas. To load balance replicas that retain state, some means of maintaining state consistency between replicas is necessary. Techniques used to achieve this consistency include (1) using reliable multicast to share the current state efficiently between multiple replicas, (2) providing hooks within a replica that allow a load balancer to perform state transfers explicitly to another less loaded replica so that request servicing can continue there, or (3) a combination of both (1) and (2). Efficient load balancing of stateful replicas is non-trivial, however, due to the additional load incurred by ensuring state consistency between replicas.

Load monitoring granularity: A server can have multiple objects running in it. If there are a many objects in the server then instantiating a load monitor (see Section 3.3.2) for each object may not scale. For example, load monitor resources, such as memory, CPU, and network bandwidth, can starve objects or processes running on the same server.

To improve the scalability of the load balancing system, we plan to support a more scalable load monitoring granularity.

Rather than instantiating a load monitor for each object on the server, a single load monitor could be associated with a group of objects that share a common load metric. For example, despite the fact that objects may implement different interfaces, all are load balanced based on CPU utilization.

We believe this design can significantly reduce the amount of resources imposed by adding server load balancing support, *i.e.*, load monitors for a large number of objects residing in the same server. However, it also introduces some complexities to the load monitor implementation. For example, suppose a load balancer detects a high load and issues a load advisory to the shared load monitor. The load monitor must now decide which objects sharing that load monitor should shed their load, *e.g.*, by forcing the client to contact the load balancer so that it can be re-bound to another replica.

Other problems can occur when multiple object groups reside on a single server. Load balancing decisions for one object group may actually interfere with load balancing decisions for another object group. Suppose both object groups are balanced based on CPU load. The load balancer detects low load conditions for the first object group, causing requests to be sent to that object group, which causes the CPU load to increase on the given server. Since the second object group is load balanced based on CPU load, the load balancer will detect a high load on the server due to the increased load caused by the requests sent to the first object group. At this point, the load balancer will cause the second object group to reject requests. Thus, the second object group is starved by the first object group. In this scenario, the two object groups must be load balanced collectively, which implies a common load monitor must be used for both object groups.

Fault tolerant load balancing: By using the adaptive CORBA-based load balancing architecture described in this paper, clients that have not been forwarded to replicas can still be denied service. Some form of fault tolerance is therefore needed to prevent this situation. Fortunately, CORBA defines a standard *Fault Tolerance* [23] service to address these types of failures.

Making a load balancing service fault tolerant by means of Fault Tolerant CORBA can alleviate one of the inherent problems with centralized load balancing: its single point of failure. It can also ensure that state within replicas is consistent, in the case of stateful replicas. This capability can simplify a load balancer implementation since the load balancer can delegate the task of ensuring state consistency between replicas to the Fault Tolerance service. One implementation of the CORBA Fault Tolerance service is DOORS [13, 48]. Since DOORS itself is a CORBA service implemented using TAO integrating it with TAO's load balancer should be straightforward.

Improved quality of service support: As mentioned in Section 3.3.4, it is hard to ensure that loads across replicas stay balanced evenly when the overall state of distributed systems changes rapidly. For example, several new replicas may be added to an object group dynamically, which cannot be predicted by a load balancer. Likewise, a poorly designed load balancing strategy cannot handle degenerate load balancing conditions, such as unstable replica loads.

Some approaches that can be used to improve the effectiveness of a given load balancing strategy are:

- Take into account past load trends in an effort to anticipate future load conditions.
- Take advantage of sophisticated algorithms based on control theory that are designed specifically to restore system equilibrium when it is perturbed by external forces. In the case of load balancing, external forces could be additional client requests or transient loads generated by other applications running over the network and end-systems.

These approaches can improve the stability of adaptive load balancing strategies so that they perform better under heavy loads or loads that change rapidly.

Advanced replica management: It is common practice to design a service that balances loads across a group of replicas supplied to it by applications explicitly. In particular, TAO's load balancing service described in this paper makes no attempt to control replica lifetime. More advanced solutions, however, can determine how replicas are created and destroyed.

For example, suppose there are only two replicas in a replica group and that their loads are high. Without additional replicas, it may be hard to maintain balanced loads. A load balancing service with the ability to create and destroy replicas on-demand may provide more flexible load balancing strategizes, *e.g.*, a load balancer could create a replica at a third location in an effort to decrease the workload on the two initial replicas.

Those familiar with fault tolerance services may recognize a similarity between their replica management strategies and those of load balancing services. Both types of services can control replica lifetimes, *e.g.*, by creating replicas on-demand. A fault tolerance service requires sufficient replicas to provide fault recovery, while a load balancing service requires enough replicas to provide balanced loads. Although the underlying functionality for each type of service is different, the interface exposed by each service can be similar. Therefore, the IDL interfaces exposed by TAO's next-generation load balancing service under development currently is based largely on the IDL interfaces standardized by the Fault Tolerant CORBA specification [23].

6 Concluding Remarks

As network-centric computing becomes more pervasive and applications become more distributed, the demand for greater scalability and dependability is increasing. Distributed system scalability can degrade significantly, however, when servers become overloaded by the volume of client requests. To alleviate such bottlenecks, load balancing mechanisms can be used to distribute system load across object replicas residing on multiple servers.

Load can be balanced at several levels, including the network, OS, and middleware. Network-based and OS-based load balancing architectures suffer from several limitations:

- The lack of flexibility arises from the inability to support *application-defined* metrics at run-time when making load balancing decisions.
- The lack of adaptability occurs due to the absence of load-related feedback from a given set of replicas, as well as the inability to control if and when a given replica should accept additional requests.

Thus, middleware-based load balancing architectures–particularly those based on standard CORBA–have been devised to overcome the limitations with network-based and OS-based load balancing mechanisms outlined above.

This paper describes the design and performance of adaptive middleware-based load balancing mechanisms developed using the standard CORBA features provided by the TAO ORB [6]. Though CORBA provides solutions for many distributed system challenges, such as predictability, security, transactions, and fault tolerance, it still lacks standard solutions to tackle other important challenges faced by distributed systems architects and developers. Chief among those missing facilities are load balancing, state caching, and state replication.

The CORBA-based load balancing service provided by TAO fills part of this gap by allowing distributed applications to be load balanced adaptively and efficiently. This service increases overall system throughput by distributing requests across multiple back-end server replicas without increasing round-trip latency substantially or assuming predictable, or homogeneous loads. As a result, developers can concentrate on their core application behavior, rather than wrestling with complex infrastructure mechanisms needed to make their application distributed, scalable, and dependable.

TAO's load balancing service implementation is based entirely on standard features in CORBA, which demonstrates that CORBA technology has matured to the point where many higher-level services can be implemented efficiently without requiring extensions to the ORB or its communication protocols. Exploiting the rich set of primitives available in CORBA still requires specialized skills, however, along with the use of somewhat poorly documented features. We believe that further research and documentation of the effective architectures and design patterns used in the implementation of higher-level CORBA services is required to advance the state of the practice and to allow application developers to make better decisions when designing their systems.

TAO and TAO's load balancing service have been applied to a wide range of distributed applications, including many telecommunication systems, aerospace/military systems, online trading systems, medical systems, and manufacturing process control systems. All the source code, examples, and documentation for TAO, its load balancing service, and its other CORBA services is freely available from URL `http://www.cs.wustl.edu/~schmidt/TAO.html`.

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A Overview of the CORBA Reference Architecture

CORBA Object Request Brokers (ORBs) allow clients to invoke operations on distributed objects without concern for object location, programming language, OS platform, communication protocols and interconnects, and hardware [5]. Figure 17 illustrates the key components in the CORBA reference model [49] that collaborate to provide this degree of portability, interoperability, and transparency.[12] Each component in the CORBA reference model is outlined below:

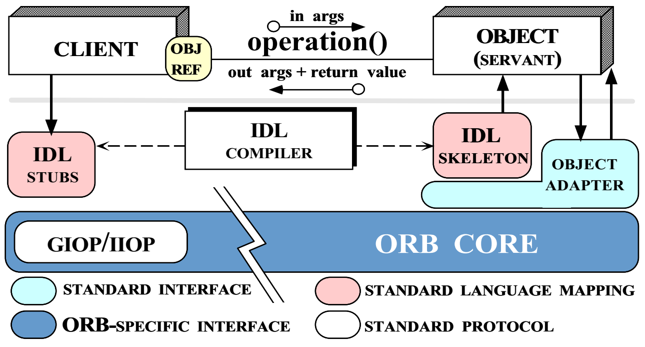

Figure 17: Key Components in the CORBA 2.x Reference Model

Client: A client is a *role* that obtains references to objects and invokes operations on them to perform application tasks. Objects can be remote or collocated relative to the client. Ideally, a client can access a remote object just like a local object, *i.e.*, `object→operation(args)`. Figure 17 shows how the underlying ORB components described below transmit remote operation requests transparently from client to object.

Object: In CORBA, an object is an instance of an OMG Interface Definition Language (IDL) interface. Each object is identified by an *object reference*, which associates one or more paths through which a client can access an object on a server. An *object ID* associates an object with its implementation, called a servant, and is unique within the scope of an Object Adapter. Over its lifetime, an object has one or more servants associated with it that implement its interface.

Servant: This component implements the operations defined by an OMG IDL interface. In object-oriented (OO) languages, such as C++ and Java, servants are implemented using one or more class instances. In non-OO languages, such as C, servants are typically implemented using functions and `structs`. A client never interacts with servants directly, but always through objects identified by object references.

[12]This overview only focuses on the CORBA components relevant to this paper. For a complete synopsis of CORBA's components see [49].

ORB Core: When a client invokes an operation on an object, the ORB Core is responsible for delivering the request to the object and returning a response, if any, to the client. An ORB Core is implemented as a run-time library linked into client and server applications. For objects executing remotely, a CORBA-compliant ORB Core communicates via a version of the General Inter-ORB Protocol (GIOP), such as the Internet Inter-ORB Protocol (IIOP) that runs atop the TCP transport protocol. In addition, custom Environment-Specific Inter-ORB protocols (ESIOPs) can also be defined.

OMG IDL Stubs and Skeletons: IDL stubs and skeletons serve as a "glue" between the client and servants, respectively, and the ORB. Stubs implement the *Proxy* pattern [17] and provide a strongly-typed, *static invocation interface* (SII) that marshals application parameters into a common message-level representation. Conversely, skeletons implement the *Adapter* pattern [17] and demarshal the message-level representation back into typed parameters that are meaningful to an application.

IDL Compiler: An IDL compiler transforms OMG IDL definitions into stubs and skeletons that are generated automatically in an application programming language, such as C++ or Java. In addition to providing programming language transparency, IDL compilers eliminate common sources of network programming errors and provide opportunities for automated compiler optimizations [50].

Object Adapter: An Object Adapter is a composite component that associates servants with objects, creates object references, demultiplexes incoming requests to servants, and collaborates with the IDL skeleton to dispatch the appropriate operation upcall on a servant. Object Adapters enable ORBs to support various types of servants that possess similar requirements. This design results in a smaller and simpler ORB that can support a wide range of object granularities, lifetimes, policies, implementation styles, and other properties.