Network-aware Mobile Programs*

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Abstract

In this paper, we investigate *network-aware* mobile programs, programs that can use mobility as a tool to adapt to variations in network characteristics. We present infrastructural support for mobility and network monitoring and show how `adaptalk`, a Java-based mobile Internet chat application can take advantage of this support to dynamically place the chat server so as to minimize response time. Our conclusion was that on-line network monitoring and adaptive placement of shared data-structures can significantly improve performance of distributed applications on the Internet.

1 Introduction

Mobile programs can move an active thread of control from one site to another during execution. This flexibility has many potential advantages in a distributed environment. For example, a program that searches distributed data repositories can improve its performance by migrating to the repositories and performing the search on-site instead of fetching all the data to its current location. Similarly, an internet video-conferencing application can minimize overall response time by positioning its server based on the location of its users. Other scenarios where mobile programs can be useful may be found in workflow management and wireless computing. The primary advantage of mobility in these scenarios is that it can be used as a tool to adapt to variations in the operating environment. Applications can use online information about their operating environment and knowledge of their own resource requirements to make judicious decisions about migration.

For different applications, different resource constraints are likely to govern the decision to migrate, e.g. network latency, network bandwidth, memory availability, server availability. In this paper, we investigate *network-aware* mobile programs, i.e. programs that position themselves based on their knowledge of network characteristics. Whether the potential performance benefits of network-aware mobility are realized in practice depend on answers to three questions. First, how should programs be structured to utilize mobility to adapt to variations in network characteristics? In particular, what policies are suitable for making mobility decisions? Second, is the variation in network characteristics such that adapting to them proves profitable? Finally, can adequate network information be provided to mobile applications at an acceptable cost?

In order to adapt to network variations, mobile programs must be able to decide when to move, what to move and where to move. There are three types of network variations which may be cause for migration: (1) `population` variations, which represent changes in the distribution of users on the network, as sites join or leave an ongoing distributed computation; (2) `spatial` variations, i.e. stable differences between in the quality of different links, which are primarily due the host's connectivity to the internet; and (3) `temporal` variations, i.e. changes in the quality of a link over a period of time, which are presumably caused by changes in cross-traffic patterns and end-point loads. Spatial variations can be handled by a *one-time placement* based on the information available at the beginning of a run. Adapting to temporal and population variations requires *dynamic placement* which needs a periodic cost-benefit analysis of current and alternative placements of computation and objects. Dynamic placement decisions have two partially conflicting goals: maximize the performance improvement from

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mobility and minimize the cost of mobility. If an opportunity for improving performance presents itself, it should be capitalized upon; however, reacting too rapidly to changes in the network characteristics can lead to performance degradation as the performance gain may not offset the mobility cost.

We investigate these issues in the context of *Sumatra*, an extension of the $Java$[1] programming environment [5] that provides a flexible substrate for adaptive mobile programs. Since, mobile programs are scarce, we developed our own mobile internet chat server. This application, called `adaptalk`, monitors the latencies between all participants and locates the chat server so as to minimize the maximum response time. We selected this application since it is highly interactive and requires fine-grain communication. If such an application is able to take advantage of information about network characteristics, we expect that many other distributed applications over the internet would be similarly successful. The resource that governs the migration decisions of `adaptalk` is network latency. To provide latency information, we have developed *Komodo*, a distributed network latency monitor.

To evaluate if mobile applications can take advantage of network-awareness, we examined the performance of `adaptalk` with and without mobility. Our evaluation had two main goals: (1) to determine the performance benefits, if any, of network-aware placement of the central chat server over a network-oblivious placement; and (2) to determine if dynamic placement based on online network monitoring provides significant performance gains over a one-time placement based on initial information. Our results are encouraging - they indicate that on-line monitoring and dynamic placement can significantly improve performance of distributed applications on the Internet.

This paper is a first step in demonstrating that distributed programs can use mobility as a tool to adapt to variations in their operating environment. The main contribution of this work is that it shows the feasibility and profitability of this approach. We establish feasibility by providing a programming interface and efficient system support for thread and object migration in Sumatra. Our experiments with Komodo and `adaptalk` indicate that network-aware programs can successfully use mobility to adapt to spatial and temporal variations in network latency over the internet.

The paper is organized as follows. Section 2 describes Sumatra and the programming model that it provides. Section 3 describes the design and implementation of Komodo. Section 4 describes the `adaptalk` application and the policy it uses to make mobility decisions. Section 5 describes our experiments and presents the results. Section 6 discusses the results and their implications. Section 7 describes related work and Section 8 provides our conclusions and plans for future work.

2 Sumatra: a Java that walks

Sumatra is an extension of the Java programming environment that supports adaptive mobile programs. Platform-independence was the primary rationale for choosing Java as the base for our effort. In the design of Sumatra, we have not altered the Java language. Sumatra can run all legal Java programs without modification. All added functionality was provided by extending the Java class library and by modifying the Java interpreter without affecting the virtual machine interface.

Our design philosophy for Sumatra was to provide the mechanisms to build adaptive mobile programs. Policy decisions concerning when, where and what move are left to the application. The main feature that distinguishes Sumatra from previous systems [3, 4, 6, 7] that support mobile programs is that *all* communication and migration happens under application control. Furthermore, combination of distributed objects and thread migration allows applications the flexibility to dynamically choose between moving either data or computation. The high degree of application control allows us to easily explore different policy alternatives for resource monitoring and for adapting to variations in resources. We believe that the space of design choices for adaptive mobile programs is yet to be mapped out and such flexibility is important to help explore this space.

Sumatra adds two programming abstractions to Java: *object-groups* and *execution engines*. An object-group is a dynamically created group of objects. Objects can be added to or removed from existing object-groups. All objects within an object-group are treated as a unit for mobility-related operations. This allows the programmer to customize the granularity of movement and to amortize the cost of moving and tracking individual objects. This

[1] *Java* is a registered trademark of Sun Microsystems

is particularly important in languages like Java because every data structure is an object and moving the state, one object at a time, can be prohibitively expensive. An *execution-engine* is the abstraction of a location in a distributed environment. In concrete terms, it corresponds to an interpreter executing on a host. Sumatra allows object-groups to be moved between execution-engines. An execution-engine may also host an active thread of control. Threads can move between execution-engines.

The principal new operations provided by Sumatra are:

Object Migration: Objects on the heap can be checked into or out of an object group at application request. Object groups may be moved between engines. During motion, objects in the object group are automatically marshalled using type-information stored in their class templates. When an object-group is moved, all local references to objects included in the group (stack references and references from other objects) are converted into *proxy references* where the new location of the object is recorded. Some objects, such as I/O objects, are tightly bound to local resources and cannot be moved. References to such objects are reset and must be reinitialized at the new site. The class template (and associated bytecode) for an object can be downloaded into an execution-engine on application request. Downloaded class-templates are cached; the `ClassLoader` checks this cache before checking the local file system.

Remote Method Invocation: Method invocations on proxy objects are transparently translated into calls at the remote site. Type information stored in class-templates is used to achieve RPC functionality without a stub compiler. Exceptions, generated at the called site are forwarded to the caller. If an object is shared between threads on different engines, it is possible that the object can move without the knowledge of one or more engines. In such cases, sending a remote method invocation to the expected site of the object returns an *object-moved* exception along with a new forwarding address to caller. The caller can handle the exception as it deems fit (e.g., re-issue the request, migrate to the forwarded location, raise a further exception and so on).

Thread migration: Sumatra allows explicit thread migration using a `engine.go()` function that bundles up the stack and the program counter and restarts execution at the specified execution-engine. To automatically marshal the stack, the Sumatra interpreter maintains a type stack, parallel to the value stack, which keeps track of the types of all variables on the stack. When a thread migrates, Sumatra transports with it, all objects that are referenced by the stack but are not a part of any object-group. All stack references to objects that are left behind (i.e were part of some object-group) are converted to references to proxy objects. After migration, many of the proxy references on the stack may actually refer to objects that are on the destination site; these references are converted to local references before the call to `go` returns.

Remote execution: A new thread of control can be created by *rexec*'ing the `main` method of a class existing on a remote engine. The arguments for the invocation are copied and moved to the remote site. Unlike remote method invocation, remote execution is non-blocking; the calling thread resumes immediately after the `main` method call is sent to the remote engine. Currently, Sumatra imposes the restriction that concurrent threads must execute on different engines. Concurrent threads communicate using calls to shared objects. The thread initiating a remote execution can share objects with the new thread by passing it references to these objects as arguments to `main`.

2.1 Example

Say we want to look through a database of X-ray images stored at a remote site and apply a quick selection algorithm to extract "interesting" lung images. These images are then subjected to a more compute-intensive cancer-detection process. One way to write the program would be to download all images from the image server and do all the processing locally. This may cause long delays due to the network traffic involved. Another approach would be to send the selection procedure to the site of the image database. Only "interesting" images would be sent back to the main program, greatly reducing network requirements. A third, and even more flexible approach would allow the shipped selection procedure to extract all the interesting images from the database but return only the *size* of the extracted images to the main program. If the size is still too big, the program may choose to move itself to the database site and perform the cancer-detection computation there rather than downloading all the data - thereby avoiding the network bottleneck while paying the cost of slower processing at the server. On the other hand if the

```
.....
lung_object = new Lung();
myengine = System.rpc.myEngine();

// Create a engine at the xray database site.
remote_engine = new Engine("xrays.gov");
// Send the lung class-template to the remote engine
remote_engine.downloadClass("Lung");
// Create a new object group.
objgroup = new ObjGroup("lung_group");
// Add the lung_object to the object group
objgroup.checkIn(lung_object);
// Move the object group to the database site
objgroup.moveTo(remote_engine);

// a remote method call selects interesting xrays
size = lung_object.query(db,"BigLungs");

// Are there too many images to bring over?
if ( size > too_many_images ) {
 // Migrate thread, process images and return.
 remote_engine.go();
 result = lung_object.detect_cancer();
 myengine.go();
}
else {
 // there are only a few interesting xrays. Fetch them
 // and process locally, using a faster native method.
 objgroup.moveTo(myengine);
 result = lung_object.n_detect_cancer();
}

// display result locally
System.display(result);
```

Figure 1: Excerpt of a Sumatra program that adaptively migrates to reduce its network bandwidth requirements

size is small, the data can be shipped over and processed locally with a faster native method. The code in Figure 1 shows this adaptive version of the code. This program makes its decision to migrate in a rudimentary fashion; a more realistic version of this application would also take network bandwidth and the relative processing power available on both machines into account for migration decisions.

3 Komodo: a distributed network latency monitor

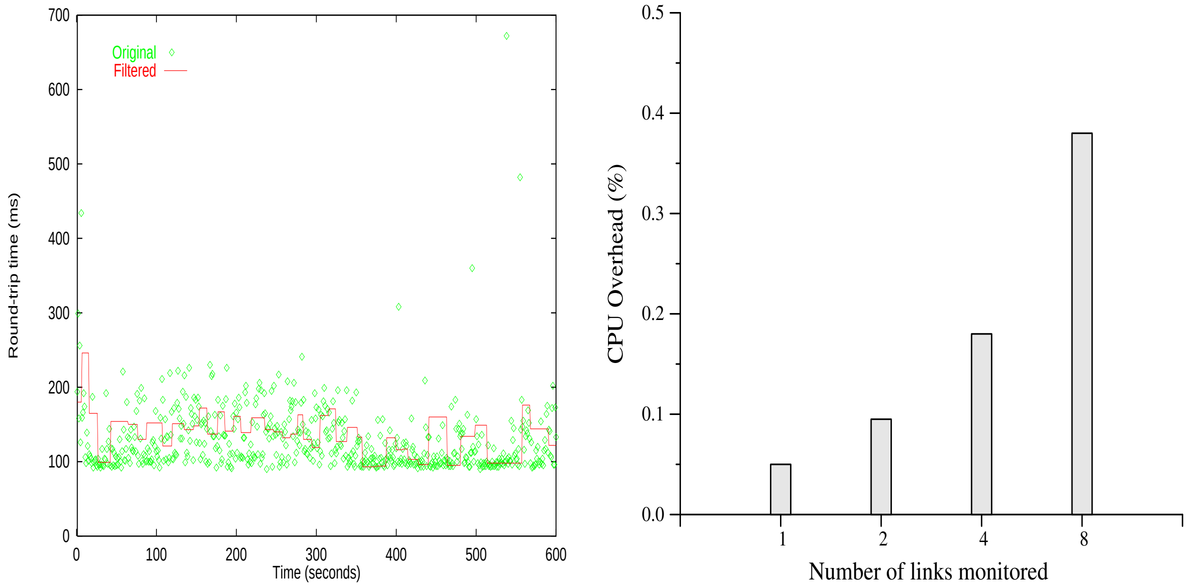
Komodo[2] is a distributed network latency monitor. The design principles of Komodo are: low-cost active monitoring[3] and fault-tolerance. An active monitoring approach is needed for `adaptalk` (described in the next section) as passive monitoring cannot provide information about links that are not used in the current placement but could be used in alternative placements. It is our working hypothesis that effective mobility decisions can be based on medium-term (30sec-few minutes) and long-term (hours) variations. At these resolutions, we believe that active monitoring can be achieved at an acceptable cost. This section briefly describes the design and implementation of Komodo.

Komodo allows applications to initiate monitoring of network latency between any pair of hosts running the monitor. The application need not be resident on one of the hosts in the host-pair being monitored. Komodo is implemented as a user-level daemon that runs on every host. Applications pass monitoring requests to their local Komodo daemon. If the requested link includes the current host, the local daemon handles the request. Otherwise, it forwards the request to the daemon on the appropriate host. Each daemon monitors the UDP-level latency on a network link for which it has received monitoring requests, by sending a 32-byte UDP packet to the daemon on the other end of the link of interest. If an echo is not received within an expected interval, (the maximum of the ping period or five times the current round trip time estimate) the packet is retransmitted. Using UDP for communication may, occasionally, lead to loss of messages. Message loss can lead only to a short-term loss of efficiency. Since we expect monitoring requirements to be coarse-grained, the effect of packet loss should be small.

Applications that initiate a monitoring request can control the frequency with which Komodo *pings* the specified link to a maximum upper bound. Applications need to refresh requests periodically to keep them alive; otherwise, Komodo drops the request after an age out period.

[2] Komodo dragons are a species of *monitor* lizards found on the island of Komodo which is close to both Java and Sumatra.

[3] Active monitoring uses separate messages for monitoring, passive monitoring generates no new messages and piggybacks monitoring information on existing messages.



(a) Operation of the Komodo filter

(b) CPU utilization of Komodo

Figure 2: (a) The input to the filter is a 10-minute trace of one-per-second latency measures between `baekdoo.cs.umd.edu` and `lanl.gov`. Note that the four single-ping impulses towards the right end have been eliminated. (b) The CPU utilization is computed by dividing the (user+system) time by the total running time. Each experiment was run for 1000 seconds with one ping per second for all links.

The latency measures acquired by Komodo are passed through a filter before being provided to the applications. This filter eliminates singleton impulses as well as noise within a jitter threshold (we use a jitter threshold of 10ms, which is the resolution of most Unix timers). If the measure changes rapidly, a moving window average is generated. This filter was designed on the basis of our study of a large number of internet latency traces (see Section 5.1) which revealed that: (1) there is a lot of short-term jitter in the latency measures but in most cases, the jitter is small; (2) there are occasional jumps in latency that appear only for a single ping; and (3) for some traces, the latency measure fluctuates rapidly. Figure 2(a) illustrates the operation of the filter.

Each daemon maintains a cache of current latency estimates for all its currently active monitoring requests. This cache is maintained in a well-known shared memory segment and can be efficiently read by all Sumatra applications executing on the same machine. A latency estimate for a request received from another host is forwarded only when a new filtered estimate (different from the previous filtered estimate) is generated and is piggy-backed onto a ping reply if possible.

To address concerns about the cost of active monitoring, we measured the CPU utilization of Komodo for varying number of links. Results in Figure 2 (b) show that the maximum CPU utilization for up to eight links is less than 0.4 %. The amount of data transferred is 256 bytes per second. Also, up to eight links, the CPU utilization scales linearly. By extrapolation, the load for 20 hosts would be 1% CPU utilization and 640 bytes/sec data transfer.[4]

4 `Adaptalk`: An adaptive internet chat application

`Adaptalk` is a relatively simple network chat application built using Sumatra and Komodo. It allows multiple users to have an online conversation; new participants can join an ongoing conversation at any point; multiple independent conversations can be held. To ensure that all participants see the same conversation and that new participants can join ongoing conversations, a central server is used to serialize and broadcast the contributions.

[4]This assumes that the linear scaling holds; given the low utilization there is no reason to believe that it would not.

Adaptalk has been divided into three components: handling keyboard events, managing the chat screen and coordinating the communication between participants. Each component is implemented by a separate *object-group*. Each host participating in the conversation runs two *execution-engines*, one houses the screen object-group and the other houses the keyboard object-group. The central server is implemented as a separate shared object-group, msgboard, which can (and does) move between hosts, positioning itself within the engine that houses the screen on its current host. Each message on the chat board starts from a keyboard which invokes a remote method on the msgboard. The msgboard serializes incoming messages and broadcasts each message by issuing a set *remote-execution* requests, one per participant, that updates the screens on all participants. In this case, remote execution is preferred to remote method invocation as there is no useful return value and remote execution allows fast one-way communication.

Individual messages in adaptalk, and other chat applications, consist of single lines of characters, usually no more than 50-60 characters. The goal of a chat application is to provide a short response-time to all participants so that a conversation can make quick progress. The response-time for a particular participant depends on the latency between it and the central server. Given the latencies of all the links, the primary knob that adaptalk can turn, to maintain a low response-time for all participants, is the position of the central server.

4.1 Mobility policy

There are two main features of the adaptalk mobility policy. (1) continuous tracking of the instantaneously *most-suitable-site* and (2) deferral of server-motion till the potential for a significant and *stable* performance advantage has been seen. The first feature allows it to quickly take advantage of opportunities for optimization; the seconds helps ensure the gain is greater than the cost.

As mentioned in the previous section, the goal of adaptalk is to minimize the maximum response-time seen by any participant. The suitability of a machine as the location of central server is characterized by the maximum over the network latency measures for all participants. The machine that achieves the lowest measure is voted the *most-suitable-site*. Votes are taken after every new message is posted at msgboard. The voting algorithm runs as part of the post_msg method at the msgboard.

A new site for the central server is selected whenever: (1) one of the sites that does not currently host the server receives more than a threshold number of votes; or (2) the current site receives very few votes over a threshold number of voting opportunities. The first condition is used to move the server to locations that consistently promise better performance; the second condition is used to quickly move away from locations that provide poor performance.

We expect three types of variations in the network characteristics which may be cause for migration: (1) population variations, which represent changes in the distribution of users on the network, as participants join or leave an ongoing conversation. (2) spatial variations, i.e. stable differences between latencies of different links; (3) temporal variations, i.e. changes in the latency of a link over a period of time; and Adaptalk's migration policy, shown in pseudo-code in Figure 3, can adapt to all three types of variations.

Consider the case with a fixed number of participants with significant spatial variation in network latency and little temporal variation. In this case, the migration algorithm rapidly recognizes the best location for the msgboard, but waits until this choice has been ratified over some period of time (votes > win_threshold) before moving msgboard. As shown in Section 5, this policy allows adaptalk to effectively insure itself against poor *initial placement* of the msgboard. Once a good location has been found, the msgboard does not move, unless temporal variations or changes in population distribution cause another node to become a substantially better location (i.e. votes[newHost] > win_threshold) or the current host to become a substantially bad choice (i.e. votes[currentHost] < loss_threshold). In such cases, the msgboard will move during the conversation. After initial experiments with adaptalk, we set the win_threshold to be $25 \times n$, the loss_threshold to be 25 and the voting_cycle to be $50 \times n$. Here, n is the number of participants. The length of the voting_cycle was set large enough to amortize the cost of movement in cases where large temporal variations or fluctuations in population distribution cause frequent repositioning.

```
Class msgboard
int post_msg(String blab)
{
 for (all screens s)
  screenEng[s].rexec("Screen",blab);

 // Find the engine that minimizes max. latency
 for (all engines e ) {
  for (all talkers t) {
   // Get latency data from Komodo
   latency = find_latency(e,t)
   if (max < latency) max = latency;
  }
  if ( max < minmax )
   winner = e, minmax = max;
 }
```

```
// The engine winner won this round of voting.
rounds ++ ;
votes[winner]++;

// Has winner been winning consistently ?
if ( votes[winner] > win_threshold )
 return(winner);

// Voting cycle is over - find the best placement.
else if ( rounds % voting_cycle == 0) {
 // If the current host didn't do too badly, stay.
 if (votes[current] > loss_threshold)
  return (current);
 // Else, move away to engine with max. votes.
 else return (newHost = most_wins());
}
```

Figure 3: `Adaptalk`'s migration policy in pseudo-code.

5 Evaluation

To evaluate the performance impact of network-aware adaptation on the Internet, we performed two sets of experiments. First, we monitored round-trip times for 32-byte ICMP packets sent to a large set of hosts over several days. The goal of these experiments was to study the spatial and temporal variation in network latency on the Internet. Results from this study are presented in section 5.1.

Second, we measured the performance of three versions of `adaptalk` over long-haul networks, using traces collected during the internet study. Our evaluation had two main goals: (1) to determine if network-aware placement of components of an application distributed over multiple hosts on the Internet provides significant performance gains over a network-oblivious placement; and (2) to determine if dynamic placement based on online network monitoring provides significant performance gains over a one-time placement based on initial information. Results from this study are presented in section 5.3.

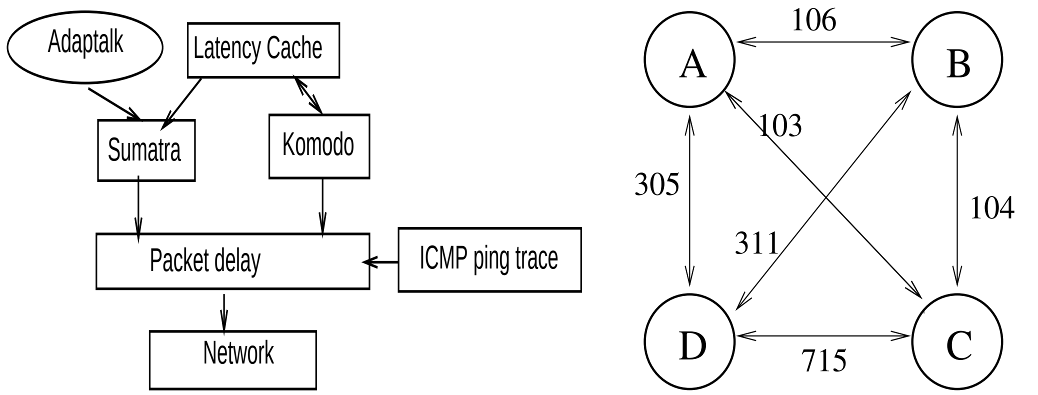
5.1 Variations in Internet latency

We selected 45 hosts: 15 popular `.com` web-sites (US), 15 popular `.edu` web sites (US) and 15 well-known hosts around the world. These host were pinged from four different locations in the US. The study was conducted over several weekdays, each host-pair being monitored for at least 48 hours. We used the commonly available `ping` program and sent one ping per second. This resolution was acceptable as our goal was to discover medium-term (30sec/minutes) and long-term (hours) variations.

The conclusions of our study, briefly, are: (1) there is large spatial variation in internet latency (the per-hour mean latency varied between 15 ms and 863 ms for US hosts and between 84 ms and 4000 ms for non-US hosts); (2) there is a large and stable variation in the latency of a single host-pair over the period of a day (maximum daily variation in per-hour mean latency for US hosts was 550 ms and for non-US hosts was 5750 ms); (3) There is a lot of jitter in the latency measures but in most cases, the jitter is small. (4) There are isolated peaks in latency that appear only for a single time interval.

5.2 Experimental Setup

Having established that there are significant spatial and temporal variations in network latency on the internet, we examined how well `adaptalk` could adapt to these variations.



(a) Organization on each host (b) Avg. Latency (in ms) between hosts

Figure 4: Experimental Setup. Four local machines on a LAN were used to simulate four remote machines on the Internet by adding delays to packets. ICMP ping traces between real Internet hosts were used to generate the delays, so as to capture real-life temporal variations in latencies.

To simulate the characteristics of long-haul networks, we decided to run our experiments over a low-latency LAN and delay all packets based on the ICMP `ping` traces described above (see Figure 4 (a)). This approach also allowed us to perform repeatable experiments. To ensure that delaying packets, instead of using a real network, does not skew the latency measures, we performed a simple test. Free-running Komodo monitors were installed at `bookworm.cs.umd.edu` and `jarlsberg.cs.wisc.edu` and were used to collect UDP latency measures between this host-pair. In parallel, a trace of ICMP ping times between these two hosts over the same period (5000 sec) was collected. This trace was later fed into trace-driven Komodo monitors running on two hosts on our LAN. The latency measures reported by the trace-driven monitors matched quite well with the actual latency measures reported by free-running monitors. The average of the actual latency measures was 128 ms (std dev = 64); the average of the values reported by the trace-driven monitors was 144 ms (std dev = 68).

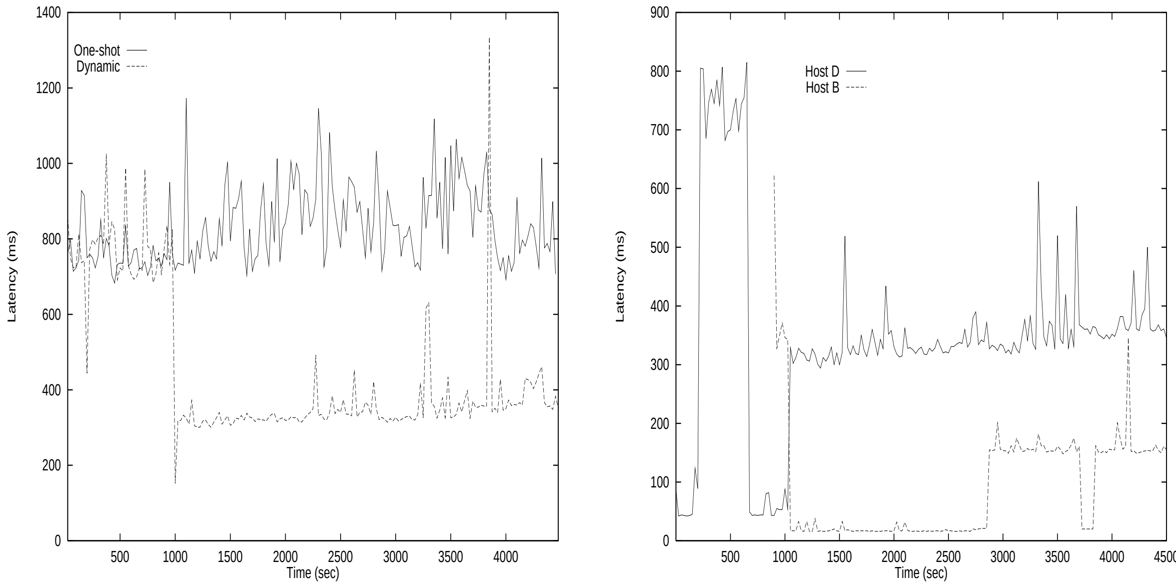
We performed all our experiments on four Solaris machines on our LAN. We picked six trace-segments from the internet study and used them to delay packets between the machines. All these segments were over the noon-2pm EDT period.[5] These traces were selected to approximate the network latency spectrum observed in the internet study. Hosts participating in the selected traces include: `java.sun.com`, `home.netscape.com`, `www.opentext.com`, `cesdis.gsfc.nasa.gov`, `www.monash.edu.au` and `www.ac.il`. This setup makes the four local machines behave like four far-flung machines on the internet. Figure 4 (b) shows the configuration used for the experiments.

5.3 Experiments

We performed a series of experiments to evaluate the benefits of adapting to population variation, spatial variation and temporal variation. The experiments consisted of running three different versions of the chat server. The first version, called *static*, had no migration support and no network-awareness. The location of the `msgboard` was chosen in a network-oblivious fashion. The second version was a stripped-down version of *adaptalk*, called *one-shot*. It used network information from Komodo to find the best initial placement for the `msgboard`, and used mobility support to move it there. After initial placement, migration decisions and network-awareness were turned off. The third version, called *dynamic* was the full-fledged `adaptalk`, as described in section 4. It used on-line monitoring and dynamic placement to position the `msgboard`.

The performance of *static* depends on the location of the `msgboard`. If *static* chooses the same location as *one-shot*, both would have the same performance. On the other hand, since *static* is network-oblivious, it is just as likely to place the `msgboard` at the worst possible location. As the performance of *one-shot* already presents a

[5] 12 noon is the beginning of the daily latency peak for US networks and the end of the daily latency peak for many non-US networks.



(a) one-shot vs. dynamic for population variation. Max latency (over all participants) vs time.

(b) Latency variations for hosts B and D Jumps signify movement of the server.

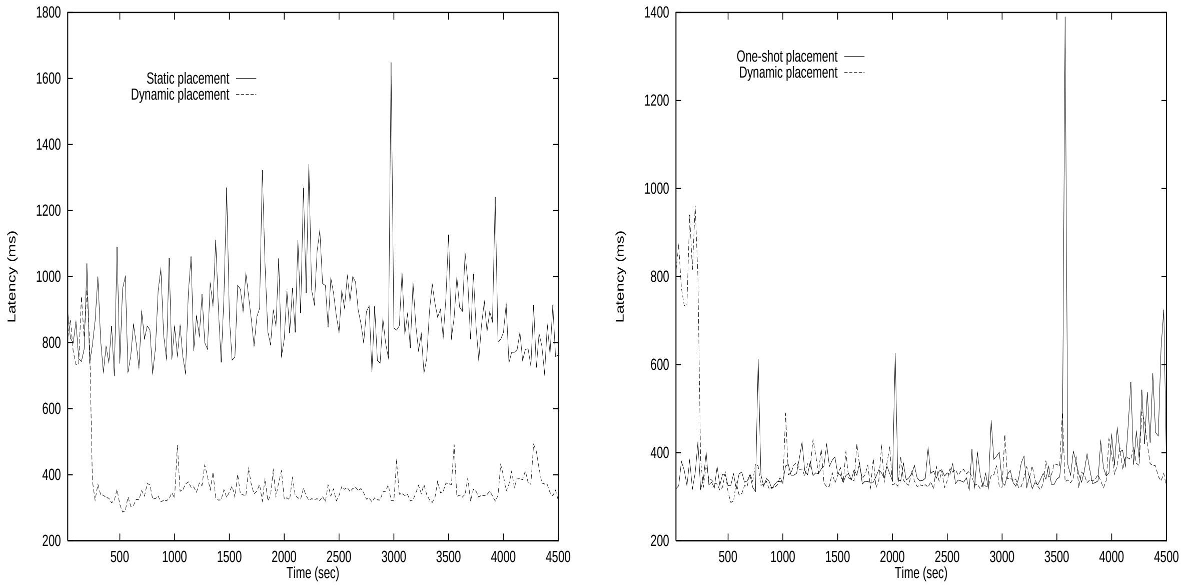
Figure 5: Adaptiation to Population variation. Hosts C and D initiate the conversation. Host B joins after 900 seconds and host A joins after 1800 seconds. The *one-shot* version places the chat server at host D. The *dynamic* version migrates the server when new hosts join.

rough upper-bound of *static's* performance, we deliberately chose the worst initial placement when running *static*.

Adaptation to Population Variation: To evaluate the effect of changing user distribution we used the following workload: A conversation was initiated between hosts C and D. Host B joins the conversation after 15 minutes, and host A joins after another 15 minutes. Each host sends a sequence of 70-character sentences with a 5-second think time between sentences. With only two hosts initiating the conversation, there is no difference between the best and worst initial placement for the `msgboard` and both the *static* and *one-shot* versions perform identically (both place the `msgboard` on host D). Figure 5 (a) plots the maximum latency over all hosts for the *one-shot* version. Note that even after new hosts join the conversation there is no noticeable difference in maximum latency. In contrast, the *dynamic* version adapts to the changing population workload. Soon after host B joins the conversation, the adaptive placement policy moves the `msgboard` there, causing a drop in the maximum latency. After host A joins the conversation, the `msgboard` moves between hosts A and B in response to temporal fluctuations. This can be seen from the variation in latency for host B in Figure 5 (b). These movements help keep the maximum latency steady even in the presence of temporal fluctuations.

Adaptation to Temporal and Spatial Variation: In this case the client population is assumed to be stable. The workload consists of all 4 hosts jointly initiating a conversation which runs for 75 minutes. As before, each host generates a new sentence every 5 seconds. In this case, the network-oblivious (*static*) version places the chat server on host D. The network-aware (*one-shot*) version uses latency information provided by Komodo to determine that host B is a much better placement. For the *dynamic* version, initial placement is less important as it should be able to recover from a bad initial placement. For this version, we place the `msgboard` at host D, the worst-possible location.

To avoid clutter, Figure 6 shows the performance of these three versions in two different graphs. Figure 6 (a) compares the maximum latency (over all participants) for the *dynamic* and *static* versions. As seen from the sharp drop on the left end of the graph, the *dynamic* version is successfully able to move the `msgboard` away from its bad initial placement to more suitable location. Figure 6 (b) compares the average maximum latency (over all



(a) Dynamic vs static placement (b) Dynamic vs one-shot placement

Figure 6: Maximum latency (over all participants) vs time in `adaptalk`. The one-shot and static worst placement are computed based on latency information available when the conversation is initiated. The population of talkers is constant.

participants) for the *dynamic* and *one-shot* versions. It shows that once the *dynamic* version moves the server to a more suitable location, the performance of the two versions is largely equivalent. This implies that adapting to short-term temporal variations in a steady population workload does not provide much performance advantage over one-shot network-aware placement. It may, however, still be advantageous to adapt to long-term temporal variations. We note that at the far right of graph Figure 6 (b), temporal variation in the link latencies do allow the *dynamic* version to do better than the *one-shot* version.

6 Discussion

In the introduction, we had raised three questions with respect to network-aware mobility. First, how should programs be structured to utilize mobility to adapt to variations in network characteristics? Second, is the variation in network characteristics such that adapting to them proves profitable? Finally, can adequate network information be provided to mobile applications at an acceptable cost?

Our experience with Sumatra and `adaptalk` provides some early insights about application structure suitable for adaptive mobile programs. First, the migration policy should be cheap so that applications don't have to analyze the tradeoffs of the migration decision itself. An easy-to-compute policy allows frequent decisions and rapid adaptation to changes in the environment. We believe that an easy-to-compute migration policy was key to `adaptalk`'s ability to quickly find good locations for the chat server. Second, good modularization helps an application take advantage of mobility. Modularization is important for all distributed applications but it is more so for mobile programs as they have to make online decisions about the placements of different components. Third, to be resource-aware, remote accesses should be split-phase; the first phase delivers an *abbreviation*, a small and cheaply computed metric of the data (for example, size, number of data items, thumbnail sketch etc) and the second phase actually accesses the data. This allows the application to change its data access modality for the second phase (retrieve remotely, request filtering, move to data location) based on the value of the abbreviation and knowledge of its own requirements.

To answer the second question, we evaluated the profitability of adapting to changes in the user-distribution as well as spatial and temporal variations in network latency. Adapting to changes in user-distribution led to significant gains allowing `adaptalk` to find better placements as more users came online. Support for mobility allows applications built around a central data-structure to recover from a poor initial placement of this structure by repositioning it to a more suitable location. Adapting to temporal variations alone did not not lead to significant benefits over the period of an hour and a half. In light of this experience, we expect that a simpler migration policy for `adaptalk` for short periods would consider migration only when users join or leave the conversation, rather than on every message as is currently done. Since long-term variation of latency could as large as 550 *ms* (US hosts) and 5750 *ms* (non-US-hosts), longer conversations could still benefit from adapting to temporal variations.

Our experiments with Komodo illustrate that cheap active monitoring can provide network information that can be profitably exploited. Though it would be best to use Komodo as a stand-alone system supplying network information to many distributed applications, its cost is so low that one can contemplate rolling Komodo into individual applications such as `adaptalk` without overloading the network. Active monitoring was needed for `adaptalk` as it needed information about links that are not used in the current placement but could be used in alternative placements. Other applications that change the location of computation but do not change the pattern of communication would not need active monitoring. An example of such an application would be a distributed database query in which the query-plan is fixed but the computation of the joins can be moved closer to or away from the data sources based on network characteristics. Active monitoring, as implemented in Komodo, might not be as cheap for applications that are bandwidth-sensitive and not latency-sensitive. We expect that, in such situations, *on-demand* active monitoring of network characteristics would be preferable to continuous determination as in Komodo.

Finally, we would like to argue the need for mobility as an adaptation mechanism. An alternative adaptation mechanism, which places replicated servers at all suitable points in the network, could adapt to spatial, temporal and population variation by handing off conversations between servers and by using dynamically created hierarchies of servers. It is quite likely that for any particular application, such a strategy would be able to achieve the performance achieved by programs that use program mobility as the adaptation tool. The advantage of mobility-based strategies is that it allows small groups of users to rapidly set up private communities on-demand without requiring extensive server placement. This is facilitated by the fact that mobility-based strategies can automatically determine and utilize suitable server locations.

7 Related work

The notion of moving programs around to achieve better overall performance is a well studied topic [12]. Process migration has been used successfully for load balancing, failure recovery and improved resource utilization on networks of workstations. Process migration suffers from a few drawbacks when implemented in its full generality. For example, it is difficult to deal with IO file descriptors. Further, such systems have generally been geared towards homogeneous networks of workstations. Another motivation for mobility is remote evaluation [9]. Remote evaluation usually means only code transport and no state transport. The important issues here are guaranteeing the integrity of the server while the shipped function is being evaluated.

Much of the design of Sumatra has been based on earlier systems which incorporated mobility into object systems. Notable among these are Emerald [4] and Obliq [3] from which we borrowed several features to incorporate into our system. The Emerald system was one of the earlier mobile object systems which served as a model for several subsequent systems. Emerald incorporated process mobility via active objects, object groupings, distributed stack and distributed garbage collection. Emerald was designed for local area networks. Obliq is a distributed object system that provides facilities for object mobility and state mobility while providing static scope. TeleScript [7] is a commercially available system that supports program mobility. Rus et. al. [11] describe an adaptive mobile application which does intelligent information gathering. They use a modified version of TCL called *AgentTCL* [6] as an agent language. *AgentTCL* does not, however, provide support for mobile distributed objects. Our system combines both distributed objects and agent hopping while providing application level control over all policy decisions thus making it more flexible and efficient. Dag Johansen et. al. [8] describe a system called TACOMA which incorporates mobility and selective transmission of objects with mobile programs. It may be noted that our notion of object group is a generalization of the notion of "briefcase" where the mobile program is able to state what objects get left behind and are remotely referred to on a hop.

Application-transparent or system level adaptation to wide variations in network bandwidth has been used successfully by the designers of the CODA file system [10] to improve the performance of applications.

Sun has recently released an Object Serialization and Remote Method invocation API for Java [2, 1]. This allows objects to be serialized or flattened and shipped over the network and for methods to be invoked on remote objects. However, this does not allow for stack motion while methods are in execution.

8 Conclusions and future work

This paper is a first step in demonstrating that distributed programs can use mobility as a tool to adapt to variations in their operating environment. Our exploration of network-aware mobile programs lead us to the following conclusions. First, network-aware placement of components of a distributed application can provide significant performance gains over a network-oblivious placement. For short term applications (applications that run for an hour or so) exploiting spatial variations as well as variations in the number and location of the clients achieves most of the gains. For longer-running applications, exploiting temporal variations might be worthwhile. Second, effective mobility decisions can be based on coarse-grained monitoring. This allows extremely cheap active monitoring without losing effectiveness. Third, to be resource-aware, remote accesses should be split-phase; the first phase delivers an *abbreviation*, a small and cheaply computed metric of the data and the second phase actually accesses the data. This allows the application to change its data access modality for the second phase based on the abbreviation and knowledge of its own requirements. Finally, there is significant spatial and temporal variation in Internet latency.

We believe that there is a class of long running applications over the Internet for which resource-aware mobility could provide flexibility and performance which would take a lot more effort to achieve by other means. One future direction we would like to pursue is to identify such applications and understand their structure and requirements. Some of the examples we intend to study include resource-aware pre-fetching for web clients, sequence servers and multi-database queries over the Internet. Another direction that we plan to explore is efficient distributed monitoring of other resources, in particular, network bandwidth and server availability.

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