Hybrid Web Service Orchestration

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Abstract

A service orchestration model which distributes the data flow while retaining the control flow centralised is the subject of this paper. More specifically, experiments were devised and executed to determine its applicability as a superior substitute to traditional service orchestration models. The main criterion for superiority has been the completion time for executing workflows of web service operations.

The experiment results indicate that indeed it is possible to have improvements over the traditional orchestration model. However, it is also possible to misconfigure the hybrid model, in which case the benefits may not only vanish, but it might be more costly than the traditional model.

Acknowledgements

I will only acknowledge the mortal souls that have helped me on my way so far. Specifically for this thesis, I would like to acknowledge the help my housemates, Nishad Manerikar and Simone Fulvio Rollini have given me. Their knowledge of gnuplot and LATEX, and more importantly their willingness and eagerness to help, cannot remain unacknowledged. Dr. Chris Brown, though slightly cynical and disbelieving, managed to patch up my symptoms one by one to the extent where I could work on this project. For that I can be nothing but thankful. I would also like to thank Archimandrite Raphael Pavouris and Hieromonk Avraamy Neyman, not for any religious reasons, but because they had always expressed what I interpreted as genuine interest in my progress with the paper. Last, I'd like to thank Jano Van Hemert, Jon Weissman and Adam Barker for not only chosing me for this project, but also for supporting me throughout (though I have to admint Adam's "Good stuff" comments continue to puzzle me).

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I saved thanking my family for last. Not because I wouldn't be here without them. Perhaps I would. Not because they've spent a large sum of money on my education over the year. Not even because they've supported me over the years. I may sound selfish or just immature saying this, but I always took that as a given and an obligation. I want to acknowledge them because it feels unapologetically right.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(*Nikos Kyprianou*)

To Tefkros. I owed you one, and I still do. This is so I don't forget that.

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Chapter 1

Introduction

As applications continue to move away from the desktop and onto the network, the importance of well-performing web applications increases. Whereas many of the migratory desktop applications make their transition as lightweight web applications with few data demands, not all applications are created equal. The applications used by collaborating scientists and academics around the world, in their attempts to cure life's ills and solve problems of unimaginable complexity, are very often data-intensive. And while mankind's will may be strong and the required processing power readily available, the fickle ether that is today's network cloud, is increasingly becoming a bottleneck. This is because traditionally, the data being transferred collapses to a single point, the application coordinator. Successful attempts at eliminating this bottleneck could quite realistically have profound effects on the world as we know it.

Communicating the data required or produced by data-intensive web applications may have a high cost, both in terms of time and the use of network resources. This is especially true in this age of wide-spread deployment of services over the web. Application developers are integrating these services in order to form a logically cohesive, yet loosely coupled, new application, or workflow. And whereas the developers simply coordinate the different services, the system designers are looking at ways of optimising the performance of such workflows.

This paper attempts to evaluate the performance of a proposed alternative to existing workflow execution models. The hybrid orchestration model attempts to eliminate the bottlenecks in today's centrally-coordinated models. It does so my relieving the load of the central bottleneck by keeping data closer to where it is used.

In this paper, we will investigate under which conditions the proposed model achieves its goals, or whether it is inherently a better model. The limitations of this proposed

model are another area to be investigated, as are the environments in which it operates. Underlying the entire paper is the hypothesis being tested: does the hybrid orchestration model have a better performance executing workflows that the traditional centralised orchestration model?

The model itself is described in further detail in Chapter 3, followed by a description of its implementation (Chapter 4) which was used for carrying out this paper's experiments. The purpose of the experiments (Chapter 5), their configuration (Chapter 6) and their results (Chapter 7) follows. The paper concludes with alternative solutions and possible further work. Our first task however is to take a closer look at the domain in which the model is to operate.

Chapter 2

Background

By combining functionality provided by multiple applications new, composite application can be created. The topic of this paper is the analysis of a proposed model for coordinating and executing such composite applications which are distributed over a network. This chapter introduces the domain within which the proposed model operates and describes the alternatives.

2.1 Web services

Service-oriented architecture (SOA) is an architectural paradigm where software applications are built using loosely coupled distributed services. A SOA defines the services of which a system is composed and how they interact in order to accomplish a certain system behaviour. As an example, ordering a travel package online is presented as a single application, but could involve the use of a number of services (e.g., selecting a hotel, an airline, renting a car).

Web services architecture [1] is an attempt at standardising services for SOA for web applications using simple, interoperable standards (XML, WSDL, SOAP, etc). Web services are described as a software system that allows machine-to-machine interaction over a communication network.

The Web Services Description Language (WSDL) [2] is used to describe the web service interface. An XML document written using WSDL for a web service will provide how a web service will be invoked, what input is expected and what output is returned.

Simple Object Access Protocol (SOAP) [3] defines the semantics for the data being exchanged. When a web service request is made, the web service expects the data to be

XML which conforms to the SOAP, as defined in the web service WSDL description. Though the SOAP specification did not place requirements on which transport protocol it should be used with, the Web Services Interoperability organisation has mandated that HTTP always be used [4].

2.2 Web service composition

Whereas a single web service should provide a single service (or a family of related services), an application may need to access different web services in order to provide its solution. Such applications are commonly referred to as composite applications.

A web service used by a composite application satisfies a request for a specific operation (which would be a single step in the application logic). The sequence of tasks executed when following the application logic is the composite application's workflow.

For instance, in an on-line ticket ordering composite application, web services would be used to provide individual tasks of the workflow. A web service operation could be used to check whether a particular seat is available. The workflow of the application however, would include selecting an event, the seat section, the seat itself, repeating the steps in order to select another seat, and purchasing the tickets.

Data-intensive workflows are characterised by communication patterns of high volume of data. In compute-intensive workflows, heavy computing/processing is an important part of the workflow. In data-centric workflows the aim is to route data so that it is available when needed.

2.3 Workflow execution paradigms

An important aspect of web service composition is the approach taken to coordinate its execution. Two differing paradigms have been put forth as possible solutions for this issue: web service orchestration and web service choreography.

2.3.1 Orchestration model

Service orchestration (Figure 2.1) is a centralised approach which discriminates between control and data flow. Control flow are the tasks needed to control/orchestrate the workflow, whereas data flow relates to the the tasks that compose the actual application. In service orchestration, all communication is routed via a central process

(workflow engine) for both the control and data flow.

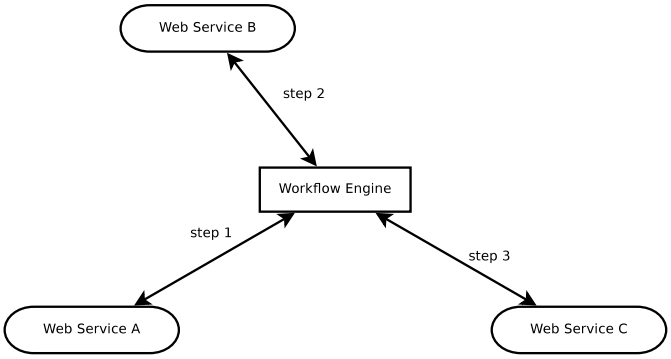


Figure 2.1: Orchestration: The workflow engine orchestrates the workflow by coordinating the invocation of the web services

In the web service world, Web Services Business Process Execution Language (WS-BPEL) [5] has become the de facto standard for orchestration. With WS-BPEL, the workflow can be defined without the need to modify any of the services, with the central process providing the workflow logic.

2.3.2 Choreography model

Service choreography (Figure 2.2) does away with the centralised process and instead each collaborating service is aware of its part in the workflow. In this decentralised approach, the collaborating services exchange messages in order to coordinate execution of the workflow. Note that in order for this collaboration to take place, the web services need to be modified so that they are aware of the workflows they are involved in.

A specification has been put forth for web service choreography in the Web Services Choreography Description Language (WS-CDL) [6]. This approach has so far not been widely used, nor are there many implementations of the specification.

2.3.3 Alternative model: Decentralised orchestration

An alternative to the above two models has been proposed [7]. In the decentralised orchestration (Figure 2.3) model, a centralised workflow is analysed and partitioned into smaller workflows.

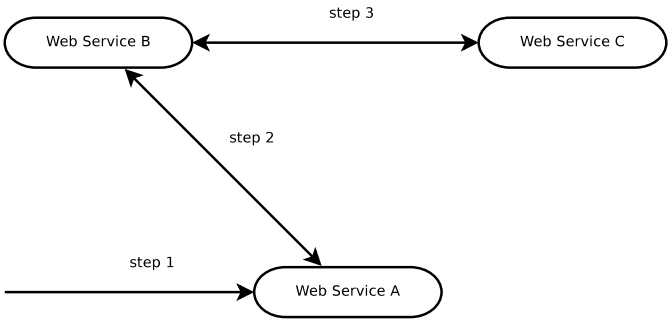


Figure 2.2: Choreography: The web services coordinate each other's invocations in order to complete the workflow

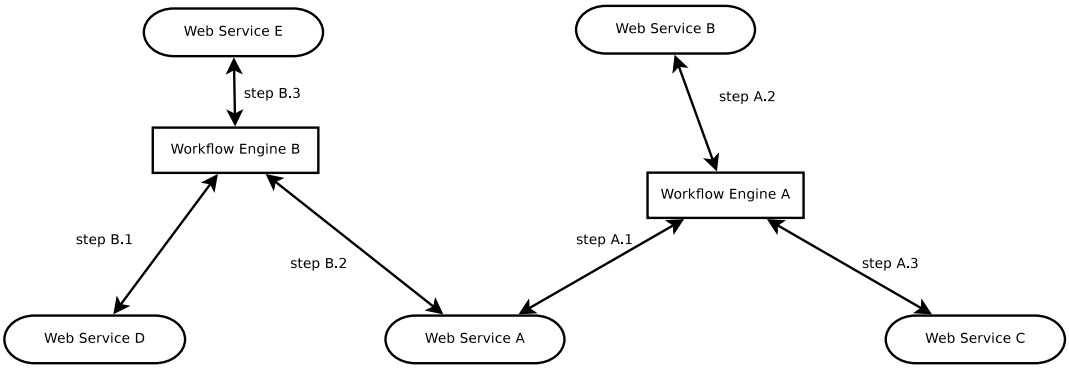


Figure 2.3: Decentralised orchestration: Each workflow engine orchestrates its own partition of the overall workflow.

Multiple workflow engines are used to execute the partitioned workflows (each executing its own partition). This removes potential bottlenecks that would exist had a central workflow engine been used.

Decentralised orchestration was found to minimise the amount of communication in the workflow. This approach increases the complexity of the workflow design and execution, while deadlock can be introduced.

The general approach to this model is similar to that of parallel programming. The program (workflow) is partitioned, and a different processor (workflow engine) executes the workflow.

2.3.4 Alternative model: Service Invocation Triggers

Service Invocation Triggers [8] act as proxies for each service invocation. To do this, the workflow needs to be fragmented into simple (with no loops, no conditionals, sequential) fragments. Triggers are created for each invocation and they are aware of data-dependencies.

By knowing which response is associated with which trigger, the receipt of that response triggers the invocation. Since the requests are handled by the triggers, the intermediate results never reach the web service client. This is an obtrusive solution

2.3.5 Alternative model: Hybrid orchestration

A hybrid orchestration model (Figure 2.4) for workflow execution has been proposed [9]. The examination of this hybrid orchestration model is the subject of this paper.

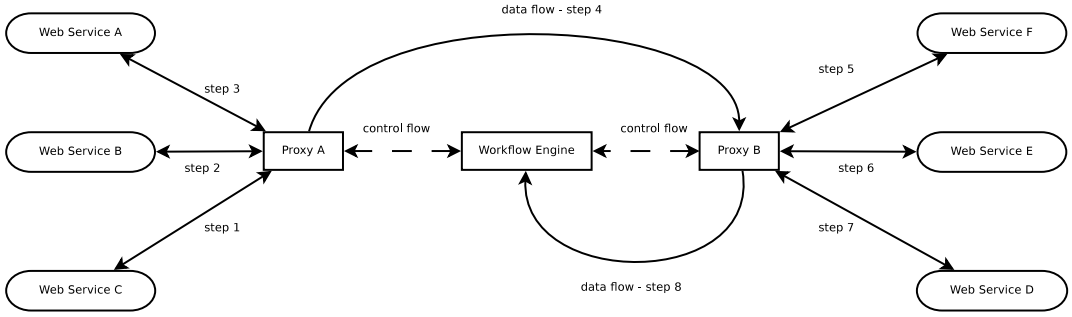


Figure 2.4: Hybrid orchestration: The workflow engine communicates with the proxies using the control flow. The proxies carry out web service invocations on behalf of the workflow engine. The data flow can be used between all actors.

In this model, while the control flow remains centralised, the data flow is decentralised. Applications with these flow characteristics were found to have advantages compared to other variations of centralised/distributed control and data flow [10]. To accomplish this, proxy servers are introduced into the system. The workflow engine sends control flow messages to the proxies, instructing them to make requests on its behalf to the workflow web services. When a workflow web service provides its response to the proxy, it is stored locally. The workflow engine is notified of this event and may send another control flow message to the proxy, informing it what it should do with the response. Possible actions include sending the response as a request to another workflow web service operation or to forward the data to another proxy.

As observed in [11] the placement of the proxies may improve the performance of the hybrid model as compared to the traditional orchestration model. For example, under the traditional model, all data would have to be sent to the workflow engine which may be at a remote location (compared to the web services). In the hybrid model a proxy can be placed closer to the web services (for instance in the same domain), thereby incurring a lower cost for data transfer. Besides locality, proxies may be placed at interesting sites, which are defined as sites which provide some added benefit to the overall workflow.

Chapter 3

Hybrid orchestration model

The contribution of the hybrid model is the introduction of the proxy. The proxy is partnered with the workflow engine, but attempts to be a non-disruptive extension to the traditional orchestration model. This chapter examines how the proxy can be designed in order to satisfy this requirement, since the features made available by the proxy define how a traditional workflow engine can interact with it to execute the worfklow.

3.1 Proxy

Proxies will need to interact with three actors (Figure 3.1): the workflow engine, other proxies and the workflow web services. Examining the interaction proxies may have with each of these actors exposes the desired interface for the proxies. The expectation is that the minimising the cost of data handling and communicating control flow messages is not as beneficial as minimising the cost of communicating the large data flows associated with the workflows.

3.1.1 Proxy-Proxy (P-P) interaction

In the hybrid model, data flow is decentralised. Instead of sending all data back to the workflow engine, data may remain on the proxy. In order for the workflow to continue, the data on a proxy, would have to be sent to other proxies. This requirement implies that a mechanism exists for proxies to exchange data messages.

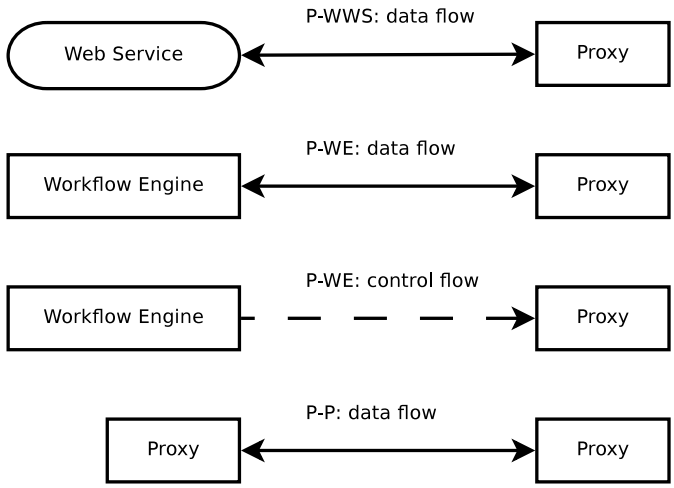


Figure 3.1: The proxy interactions defined by the hybrid model

3.1.2 Proxy-Workflow Web Service (P-WWS) interaction

Proxies make web service requests and receive web service responses. However, proxies neither create web service requests (they may construct them from existin data) nor do they use the responses. Requests are either received from the workflow engine or another proxy, or alternatively, they may be the response from a previous request. Responses on the other hand will either be stored, or forwarded to another proxy or the workflow engine. Therefore a full SOAP protocol stack is not a necessity at the proxy.

3.1.3 Proxy-Workflow Engine (P-WE) interaction

In the hybrid model, the workflow engine remains the centralised orchestrator for the workflow. Whereas traditionally in systems like BPEL, the workflow engine interacts with the workflow web services, this is not require in the hybrid model. Instead, the workflow engine may accomplish the same tasks by delegating workflow web service interaction to the proxies, which would act as pass-through services.

As before, the workflow engine must be able to coordinate the execution of the workflow by using control messages (now directed at proxies). These control messages could be sent directly to the proxy that requires them, or may be forwarded by other proxies. As mentioned earlier, for the purposes of this paper, a decentralised control flow (in the form of control message piggy-backing) is not considered, and so the workflow engine would communicate with proxies directly.

3.1.4 Storage

The proxy will need to store responses from web services. As scientific workflows may deal with large volumes of data, and the proxy may be handling multiple requests concurrently, keeping responses in memory may not be feasible. Whether or not to write responses to permanent storage cannot be determined by the workflow engine, as the proxy may be handling requests from multiple workflow engines. This role will instead be the responsibility of the proxy and will be based on the current state (and available resources) of the machine on which it executes. This introduces a level of non-determinism into the performance evaluation of the hybrid approach since the varying workload of the machine impacts the performance of the proxy. A force-write policy could be enforced so that all data is always written to permanent storage, though this too may hamper performance.

3.1.5 State

Whether or not proxies need to maintain state depends largely on whether a synchronous or asynchronous communication model is implemented for P-WE interaction. With asynchronous communication, the workflow engine would instruct the proxy on what action to execute and then terminate its connection. The proxy would perform the required action and once completed, initiate a new connection with the workflow engine. To accomplish this, it would have to maintain state information for pending requests, possibly by mapping task identifiers to network ports/connections.

If synchronous communication is used, then it is possible to relax the state maintenance requirements. With synchronous communication, the workflow engine keeps its connection (per request) to the proxy open, waiting for its response. This is the approach taken in the paper.

Irrespective of the communication model used, some state will always need to be maintained at the proxy. This is because it will need to store web service responses which may be used for any number of different web service requests. In other words, there is no guarantee that a web service response will be consumed immediately.

The proxy is also in a position to help the workflow engine in optimising the workflow through the use of statistics. Although analysis of the statistics may not be the responsibility of the proxy, the proxies need to record metrics that can be analysed. For example, for each request-response pair, the size of the request and response should be recorded, as should the delay between making the request and when the first bytes of

the response are received. This is especially true for the purposes of this paper, where the performance of the hybrid model needs to be analysed.

3.1.6 Data handling

As web services are developed by multiple organisations, the web services involved in a workflow may not share a common interface. This could extend both to the message and type formats used. Some scenarios where data transformations might be needed:

1. Typed values: One web service may indicate a boolean value with an integer type, another with a text value, and yet another could use boolean value.

2. Headers: One web service may require headers for all its messages, whereas another might not.

3. General transformations: The output of one web service operation cannot be supplied as input to another web service operation unaltered. It might be necessary to drop elements, add new ones or somehow modify the response.

For the purposes of this paper, data transformation will not be used. It is further assumed that a web service response may be used to construct a request for any other web service invocation.

3.2 Workflow Web Service (WWS)

Web services used in existing workflows may not be available inside the experiment test bed for this project. Therefore, web services will have to be otherwise provided. One such way is by introducing a simple web service into the system that can be used to construct new workflows.

Computation costs of the WWS are not an issue for this project, since its purpose is to examine the effect of performance due to communication costs. As existing web services (or data sources) will not be available in the experiment test bed, the web services used should be able to generate data to be included in their responses. To be able to be used as input for other web services, the specification of the input and output data should be compatible (considering data transformations will not be used). To allow for variability in the experiments conducted, the amount of data returned by WWS should be configurable

3.3 Workflow engine

In the traditional model, the workflow engine may maintain state (e.g., for each current workflow execution instance, what are the requests that are pending) of the different WWS in order to determine what to do next in the workflow. The introduction of proxies however, necessitates that state be maintained for them as well. State information in this case could be what data exist on which proxies, with what identifiers are they tagged, etc.

Chapter 4

Implementation

With the basic design of the hybrid model (and its proxy) already defined, this chapter takes a look at a concrete implementation of the entire model. The interface to the WWS and the proxy are explained, and a brief overview of the workflow engine implementation is given. The following sections detail the implementation of the proxy architecture and address the reasons behind taking certain implementation decisions.

4.1 Implementation architecture

The implementation of the hybrid model used in this project consists of two components, the P-WWS bundle and the workflow engine. P-WWS contains an implementation of a basic workflow web service and a proxy. The workflow engine components contains an implementation of a simple traditional workflow engine, a hybrid workflow engine, as well as functionality needed for executing workflow tests.

4.1.1 Workflow Engine

The workflow engine controls the execution of workflows. In the traditional model, the workflow engine interacts directly with the web services by making web service operation requests and processing the responses. In the hybrid workflow architecture, at the very least, the workflow engine must be able to communicate with the proxies. It is also possible that the workflow engine interacts with some web services directly. This could be the case when proxies are not available or when the cost of invoking its operations directly lowers the overall cost of the workflow.

4.1.2 P-WWS bundle

A proxy is used to interact with the WWS (making requests), proxies (forwarding data) and workflow engines (workflow control data). Since it interacts with web services, it should contain a SOAP-capable web service client.

P-WE communication is not bound by this restriction. That is, a non-standard, non-SOAP family of protocols could be used for the interaction of proxies with the workflow engine. It should be noted, that traditional workflow engines have been designed to interact with web services. As the project aims to examine the behaviour of the hybrid model with existing workflow engines, minimal changes to these engines should be made. This would be the case if the proxy was also a web service itself. This would allow the workflow engine to continue to act as a web service client, but instead of interacting with WWS, it would interact with their corresponding proxies.

Similarly, P-P communication need not be based on SOAP. For the purposes of this project this liberty was not taken. Since proxies can act as web services and web service clients, they have been implemented to provide web service operations so that proxies communicate between themselves over SOAP.

The P-WWS bundle also includes a workflow web service, i.e., one that could be used in a workflow. Although existing web services could be used, this bundle includes a simple web service providing a trivial operation. One reason behind this simplification is the need to minimise the processing time of the workflows. Existing web services could introduce a variable processing time which might not be controllable. In addition, the experiment test bed may not lend itself for deployment of real-world web services for building a workflow.

4.2 Implementation details

The following section describes the programming interface for the different components of the software system. Figure 4.1 summarises the programming interface by presenting the system's use cases.

4.2.1 Workflow Engine

The implemented workflow engine provides the functionality of a traditional workflow engine, as well as the ability to interact with proxies of the hybrid workflow architecture. As all interactions with proxies and workflow web services are of the form of

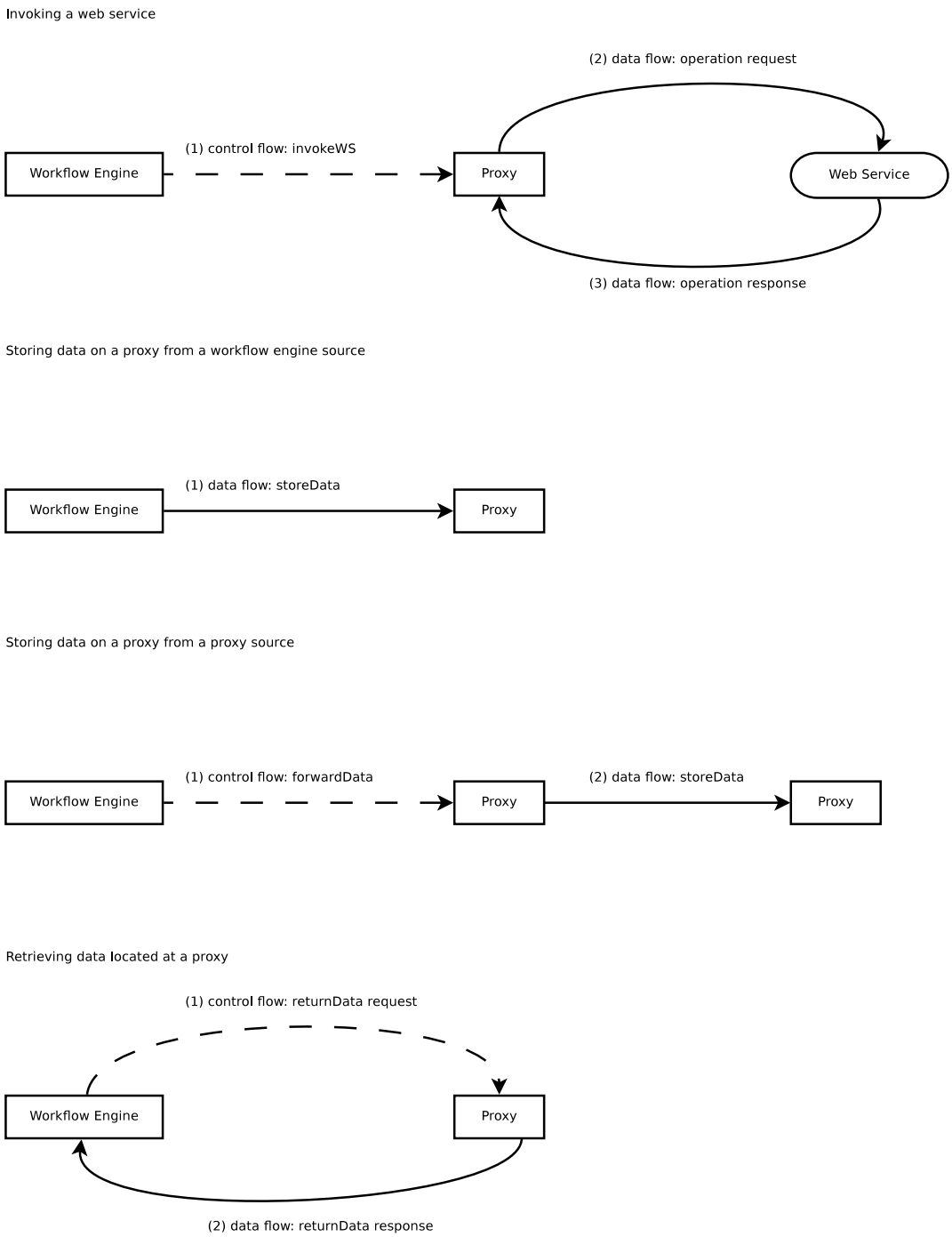


Figure 4.1: Programming interface use cases

web service operations, the workflow engine includes web service clients to interact with both of them.

In addition to controlling the workflow, the workflow engine implementation serves the purpose of logging the results of the workflows. The workflow engine uses the log

results to calculate certain statistical metrics at runtime. These logs and metrics form the basis of the experimental results and their analysis. The workflow engine is also responsible for loading the experiment configurations

4.2.2 WWS

The web services used in the workflows all share the same interface. Only one operation is available as part of the web service implementation.

4.2.2.1 Operation: operation

Listing 4.1: Workflow web service operation: operation

```
/*
Parameters
  input : the input data
  scale : how much of 'input' should be returned
Return value
  byte array based on 'input'
*/
public byte[] operation(byte[] input,
                        float scale)
```

The purpose of *operation* is to provide an efficient way of modifying the amount of data leaving a web service. The contents of byte array *input* are ignored. Instead, the scale factor *scale* is used to determine how much data is to be returned, where $|returnvalue| = |input| * scale$.

operation is intended to be called by the proxies in the hybrid workflow architecture, and by the workflow engine in the traditional workflow architecture. In the hybrid workflow architecture, *operation* may be invoked by the workflow engine.

4.2.3 Proxy

Proxies must provide two basic functions: the ability to invoke web service operations and to allow for the workflow engine to dictate the data flow. Being able to invoke web services has a straightforward solution, by making the proxy be a web service client. Of course, the workflow engine would dictate when and how a proxy would invoke a

web service. The workflow engine would also be responsible for controlling the data flow between proxies and for controlling the data flow between itself and the proxies. These basic functions are provided by the proxy operations *invokeWS*, *forwardData*, *storeData* and *returnData*. These are exposed as web service operations.

4.2.3.1 Operation: invokeWS

Listing 4.2: Proxy operation: invokeWS

```
/*
Parameters
  operationID : the tag for the result of the operation
  endpoint    : the address of the web service to invoke
  scale       : the desired scale factor for the I/O data
  dataIDs     : the tags for the data to include as input
Return value
  a log entry pertaining to the invocation requested
*/
public String invokeWS(String operationID,
                       String endpoint,
                       float scale,
                       List<String> dataIDs)
```

invokeWS invokes a web service operation on behalf of the workflow engine. The assumption made is that the data to be used in the web service request already exists on the proxy. That means that the data will have to have been sent to the proxy by another proxy or the workflow engine, or alternatively, it may be the stored response of a previous web service operation invocation. Another approach would have been to allow the combination of the tags and actual data in the invocation of *invokeWS*. This has the possibility of eliminating control flow messages exchanged between the workflow engine and the proxy.

dataIDs is a list of tags of data that are to be sent in the request of the invocation. With the simplified API for the workflow web services, the assumption is made that the associated data are simply concatenated for use in the web service request. The resulting concatenated data are used as input to *operation*, along with *scale*. The return value of *operation* is tagged with *operationID*.

The tag for the response is provided by the workflow engine. This means that the only information the workflow engine would require would be the log entry for the invocation. The workflow engine is able to determine how long its request takes to be executed, but the proxy provides it with information about how long it takes for it to invoke the workflow web service operation. It is assumed that the difference between the two times is the sum of the communication costs between proxy and the workflow engine, with the processing time of the request at the proxy.

As all web services deployed in the workflow share the same API, *invokeWS* allows for their invocation using a single web service client. *endpoint* is used to direct the invocation to the correct web service.

4.2.3.2 Operation: forwardData

Listing 4.3: Proxy operation: forwardData

```
/*
Parameters
  operationID : the tag for the data to be forwarded
  endpoint    : the address of the proxy to which to send
                data
Return value
  a log entry pertaining to the forwarding request
*/
public String forwardData(String operationID,
                          String endpoint)
```

forwardData forwards data between proxies. The assumption made is that the data to be forwarded already exists on the source proxy. That means that the data will have to have been sent to the proxy by another proxy or the workflow engine, or alternatively, it may be the stored response of a previous web service operation invocation.

operationID is the tag of the data to be forwarded. As all proxies share the same API, *forwardData* allows for their invocation using a single web service client. *endpoint* is used to direct the invocation to the correct proxy.

forwardData provides functionality for the hybrid workflow architecture and it would be used by the hybrid workflow engine. Proxies cannot initiate forwarding on their own.

forwardData can be thought of as the source operation for forwarding, with *storeData* acting as the sink operation. That is, the workflow engine invokes *forwardData* on a proxy, which in turn invokes *storeData* on the proxy defined by *endpoint*.

4.2.3.3 Operation: storeData

Listing 4.4: Proxy operation: storeData

```
/*
Parameters
  operationID : the tag for the data to be stored
  data        : the data to be stored
Return value
  none
*/
public void storeData(String operationID,
                      byte[] data)
```

storeData accepts data from proxies and the hybrid workflow engine for storing on the proxy.

operationID is the tag with which *data* will be stored.

4.2.3.4 Operation: returnData

Listing 4.5: Proxy operation: returnData

```
/*
Parameters
  operationID : the tag for the data to return
Return value
  the data tagged with 'operationID'
*/
public byte[] returnData(String operationID)
```

returnData returns data that is stored on a proxy to the hybrid workflow engine.

operationID is the tag of the data to be returned to the workflow engine. The assumption is that the data to be returned already exists on the proxy.

Chapter 5

Experiment design

In scientific workflows and data-intensive workflows in general, the performance of the workflow is defined by the communication cost associated with its data flow. The hybrid model attempts to minimise the cost of the data flow by placing proxies close to the sources or sinks of the data. Due to the centralised nature of the traditional model, the data flow passes through the workflow engine for each web service operation invocation. The introduction of proxies in the hybrid orchestration model alters the performance by modifying the path of the data flow. The purpose of the experiments carried out is to observe and analyse the behaviour of various workflows (and workflow variables) when using the hybrid model.

5.1 Workflow patterns

As with software design patters, workflow patterns have been identified to solve particular problems [12]. Workflow patterns are general patterns of communication within a workflow. Of particular interest for this project are patterns which affect the data flow.

Three basic workflow pattern families have been identified for inclusion in the experiments. These workflow patterns were chosen because are basic cases which all workflows would include. In addition, they can be linked to make workflows which may mirror realistic distributed composite applications.

In the sequential workflow, one step of the workflow cannot be executed (or alternatively, cannot be completed), until the previous step completes. A sequential workflow could be useful for pipelined applications. Fan-in workflows are those where a number of services feed into another. With fan-out workflows, one service sends data to multiple services.

5.1.1 Sequence

In the context of web service orchestration, the sequence workflow pattern (Figure 5.1) describes the flow of data that moves from web service to web service serially. This can be thought of as a pipeline, where the response of one web service operation invocation, becomes the request for another.

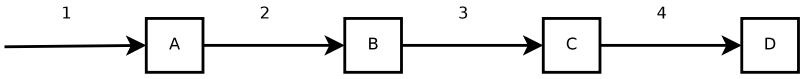


Figure 5.1: Sequence workflow pattern: Each consecutive step cannot complete until its previous step has completed

When thought of as a pipeline, the sequence pattern is an important one to investigate under the hybrid orchestration model. As proxies would ideally be placed close to the web services that they invoke, a pipeline could reduce the cost of the workflow. In a pipeline however, the response from the workflow web service will be sent to the proxy, which can then use it for a subsequent web service invocation, or forward it to another proxy.

The pipeline model also implicitly requires a blocking communication model. If the output of one operation is to be used as input for another operation, then there is little the workflow engine can do to optimise these sequential steps by using parallelism.

5.1.2 Fan-in

Fan-in (Figure 5.2) is a workflow pattern describing data from multiple sources flowing into a single sink.

In the traditional orchestration model, if blocking communication is used, then the fan-in pattern degrades to a sequence pattern. This is because although the individual workflow web services could send data to the final sink when they are ready, they will instead send it to the workflow engine. The workflow engine thus becomes a synchronisation point. It will wait for data from all web services to be received before forwarding it to the final sink. The synchronisation point is necessary because parameters in web service invocations must all be passed at the same time. Therefore the performance for the fan-in pattern depends on the *slowest* web service. The slowest web service is the one from which the workflow engine receives its data last. Only then can the workflow engine send the data to the final sink. If the slowest web service

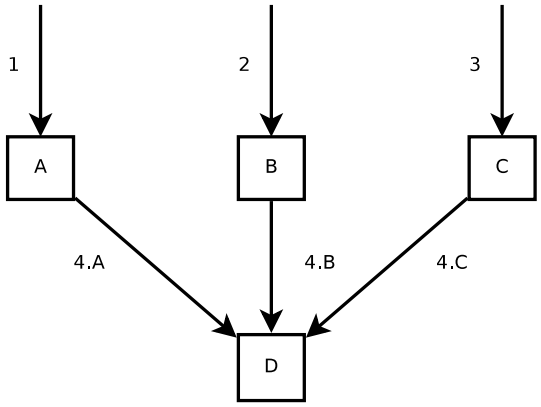


Figure 5.2: Fan-in workflow pattern: Regardless of the order in which steps 1, 2, 3 execute, step 4.x cannot be executed until all three are completed.

happens to be the first web service in the workflow, the remaining web services will all be delayed. With non-blocking communication, the invocations of the web services can occur concurrently, thus hiding some of the cost of the slowest web service.

In the hybrid orchestration model, the choice of proxy which will serve as the proxy for the sink, can affect the performance. As mentioned above, in the traditional orchestration model, data from the different sources would be sent back to the workflow engine, which would then proceed to send the data to the sink web service. By placing a proxy close to the sink or source web services, the overall cost of the workflow may be reduced. This is especially true for the case of using non-blocking communication. As data becomes available, the workflow engine can instruct the proxies to forward it to the appropriate proxy. The tests performed for the fan-in pattern all use non-blocking communication, though data forwarding between proxies occurs after all web services have finished execution of the request.

5.1.3 Fan-out

Fan-out (Figure 5.3) can be thought of as the reverse pattern of fan-in. With fan-out, data from a single source is sent to multiple sinks.

As with the fan-in pattern, using blocking communication degrades this pattern to the sequence pattern. It is expected that as with the fan-in pattern, the placement of the proxy in the fan-out pattern could reduce the overall cost of the workflow.

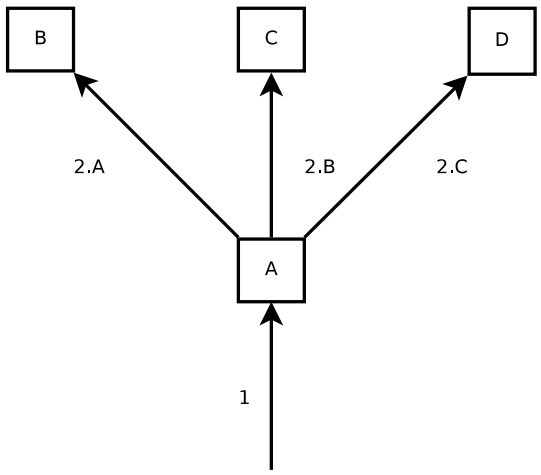


Figure 5.3: Fan-out workflow pattern: Once step 1 completes, steps 2.x can occur (concurrently or sequentially).

5.2 Network characteristics

5.2.1 Network topology

Another factor that could influence the performance of a workflow is the network on which it is executed. As each communication link in the workflow has its own cost, it is necessary to observe how the workflow cost changes when the network topology and proxy placement changes. A network topology change could be the moving of the workflow (or a part of it) from a Wide Area Network to a Local Area Network (or vice versa). Similarly, a proxy could be placed within the same domain of a web service or a set of web services, or it can be placed outside. The relative merits of each approach would have to be analysed.

Moving the web services to a relatively uniform network topology, e.g., a LAN, allows for a simplified analysis of the hybrid model. In a LAN, it is expected that the cost of the communication links would be relatively uniform. In this case the behaviour of the hybrid workflow model with respect to the different workflow patterns may be exposed more readily. In a WAN, the cost of the communication links may vary widely and the network load is difficult to control.

5.2.2 Network load

Another factor worth considering, is the load of the network on which the workflow is executed. This will allow investigation of the relative responsiveness of the hybrid and traditional orchestration models to network load. This investigation may also expose relative merits between the different workflow patterns (e.g., which pattern degrades faster).

5.3 Workflow characteristics

Besides the workflow patterns mentioned above, other parameters characterise workflows. Examining the performance of the hybrid model as these parameters change is the subject of this project, and thus focus is placed on these experiments.

5.3.1 Data size

The overall size of the data flow of a workflow can be used as a good rule of thumb for comparing the traditional and hybrid models. Note that for the same workflow, the two models may need to transfer data flows different sizes. In fact, introducing an arbitrary number of proxies in the workflow means that the difference can be significant.

Data size as a workflow parameter can also be used for scalability analysis. That is, how the performance of the proxies degrades as the data size of the messages increases. Such analysis is also useful at the individual message level and not just at the workflow level. In this case, it is useful to see how large a single message can be considering the proxy performance, and whether any such analysis carries to other network topologies.

5.3.2 Workflow fragments

The hybrid model attempts to eliminate the communication between WWS and the workflow engine by storing intermediate results on the proxies. There are two cases however, where the data flow must utilise the P-WE links.

- **Start of the workflow.** When data needs to be supplied in the first step of the workflow, then the workflow engine will have to supply such data over the P-WE link.
- **End of the workflow.** When the final WWS contains data that will have to be made available at the workflow engine, it will transmitted over the P-WE link.

There are many real world scenarios where it is expected that the communication links between the proxies and the workflow engine would be the most expensive links in the workflow. For example, the workflow engine may be in Europe, whereas the WWS (and in the hybrid model the proxies) may be in North America. The hybrid model in this case is expected to benefit by using the transatlantic links only for the control flow.

This may not be possible for all workflows, but it is useful to consider this situation with respect to workflow fragments. Workflow fragments are arbitrary parts of a workflow examined in isolation. By examining scenarios which do not use the first and last P-WE communication links for the data flow, it should be possible to infer the behaviour of the hybrid model for arbitrary workflow fragments.

5.4 Proxy characteristics

Proxies are an introduced variable into orchestration under the hybrid model. Thus, it must be determined how they affect the performance of the execution of the workflows.

5.4.1 Number of proxies

If we take a workflow to be a static entity, then by moving it to the hybrid model, certain liberties can be taken. One such liberty would be the number of proxies in the execution of the workflow.

For example, one could assign one proxy for the entire workflow. This could be the case if the workflow web services are all close together and the workflow engine is at a distant location (where closeness is defined by the cost of network communication). In this case, it might be preferable to place a single proxy close to the workflow web services. This proxy would then in effect mirror the actions of the workflow engine, but without incurring the cost of the expensive P-WE communication link for its data flow.

Alternatively, multiple proxies could be utilised in the execution of the workflow. This could be useful for distributing the workload of the proxies, or if a workflow-specific routing scheme is desired.

5.4.2 Proxy placement

Where to place a proxy is another issue that needs to be investigated. Regardless of the number of proxies used in a workflow, where they are placed can affect the workflow's performance.

A simple scenario would be the case of using a single proxy for a group of workflow web services. Whether the proxy is placed close to the most heavily used communication link (in terms of data transferred), or whether it is placed close to the most often used communication link, would be something worth investigating.

Chapter 6

Experiment configuration

To be able to provide a useful analysis of the experiment results, certain factors pertaining to the experiments need to be controlled. Besides the experiment execution parameters, the experiment test bed needs to be controlled.

6.1 Results capture

Results capture occurs in proxies and the workflow engines. Although individual results may be logged at the proxies, the logs for each workflow iteration are available only at the worflow engine.

6.1.1 Proxy logging

The basic metric for analysis of the performance of workflows is the time take to complete both the entire workflow and its individual component tasks. The proxies use timers to determine the time needed to communicate with web services and other proxies. The proxies would thus be primarily responsible for recording the time take to complete tasks that they initiate. The actions recorded by proxies are the time taken to forward data to another proxy and the time taken to invoke a web service and receive the result. These recorded events are returned to the workflow engine as the result of the web service operation that triggered them.

As analysis of the recorded logs happens at the workflow engine, any data that it could use for the analysis would have to be supplied by the proxies. The proxies thus return metadata related to the tasks that they log on behalf of the workflow engine. Besides the time taken to complete an operation, the proxies also return the amount of

data sent and received. The proxy or web service being invoked is also identified in the log.

6.1.2 Workflow engine logging

Similar to the proxies, the workflow engine has timers that record the time taken to complete an operation as well as the time needed to execute a single workflow. In the case of the workflow engines, all individual tasks are timed. Tasks in this case would be invocations of the proxies, or when working in the standard orchestration mode, invocations of the individual web services.

Although proxies log the tasks that they initiate, the workflow engine needs to do the same for the tasks that it delegates to the proxies. For example, invoking a web service may take a proxy 1 second to complete, whereas the time elapsed for the workflow engine may be much higher. Any events logged by proxies are inserted in the log in the appropriate positions as nested events. As with the proxies' logging system, metadata are also recorded at the workflow engine.

The workflow engine is in a better position to record results at the workflow level as it has a complete view of the workflows being executed. The workflow engine is aware of the total amount of data to be sent through the system as well as the time needed to complete it. These data are included at the end of each workflow iteration and are a primary source for data analysis.

6.1.2.1 Log processing

The workflow engine has additional responsibilities besides the execution of workflows and capturing the log events for such executions. In fact, it is also responsible for performing basic processing of the log results of the different iterations of the workflow executions. This basic processing involves calculating the average and standard deviation for the recorded times of the different iterations.

6.2 Experiment execution configuration

Many of the tests executed are similar in many aspects and share the same programmatic specification. It is therefore desirable to have a method for configuring their parameters for each different test or for each iteration. The configuration system used in the experiments software system makes use of text-based properties files.

On initiating a specific experiment, its associated properties files are loaded as well. The parameters configurable via the properties files include:

- number of iterations to execute (for each configuration of the experiment)
- the set of nodes to use for the experiment
- the basic data size to use in the experiment

Sample configuration files are listed in Appendix A.

6.3 Software environment

The experiments software system is composed of two parts, the proxy (with its associated web service) and the workflow engine. Both developed systems are based on Java technology. The P-WWS bundle is deployed as a set of two web services, while the workflow engine is a stand-alone application which acts as a web service client. The proxies are deployed on workflow nodes, while workflow engines are deployed on engine nodes.

- **Java Runtime Environment.** The software system is written entirely in the Java programming language. Java [13] is a language which has been designed to write programs that execute on a platform-independent virtual machine. Regardless of the actual virtual machine implementation, the programs executed use the same programming interface. The Java Runtime Environment, JRE, includes such a virtual machine. As the test bed on which the experiments will be executed is not controllable, it is desirable to be able to write the software system in a language that enables portability. New nodes could be added to the workflow by simply copying over the software system to a computer with the JRE.

- **Application container.** An application container hosts web applications. In the case of the experiments software system, these web applications are web services.

  One purpose of the application container is to expose the web services through HTTP. Another is to provide the SOAP stack with which messages sent to web services or sent by the web services are processed correctly.

Jetty [14] is the application container selected for these experiments. The reason for choosing Jetty is its small size. Having a small size, a pre-configured installation of Jetty can be uploaded on new nodes in order to test new configurations.

- **JAX-WS.** The Java API for XML Web Services (JAX-WS) [15] is a specification for developing SOAP web services in Java. A reference implementation is made available from Sun Microsystems through the Metro project [16]. The Java Architecture for XML Binding (JAXB) [17] is a library that comes with JAX-WS and handles the serialisation and deserialisation of SOAP messages.

6.4 Node configuration

6.4.1 Workflow nodes

Each computer participating in a workflow hosts a P-WWS bundle. As these are Java-based, a Java Runtime Environment (JRE) is needed, with a minimum version of 1.5. As libraries needed by the software system (JAXB) were not bundled with all JRE implementations since 1.5, these were added to each system.

In order to be able to host the web services of the experiments software system, an application container (Jetty) is used. Although the required version (jetty6) was not available as an installation option in the deployed environments, a pre-configured instance was copied to each node. The pre-configured instance included the JAX-WS libraries and the P-WWS bundle.

6.4.2 Engine nodes

Each computer acting as a workflow engine contains workflow configurations and web service clients for interacting with the P-WWS bundle. The implementation of the workflow engine and the web service clients is Java-based and requires a JRE. The particular implementation of the web service clients requires a minimum version of 1.5. Similarly to the workflow node machines, additional JAXB libraries are needed in order to use the web service clients. The JAX-WS 2.1 library which includes the appropriate JAXB library was added to each engine node.

6.5 University of Edinburgh configuration

A pool of computers from the University of Edinburgh Distributed Informatics Computing Environment (DICE) [18] LAN were selected as workflow nodes for this configuration. These machines are all located in the same building and are connected to the network via a 100Mb network connection. All these machines share the same hardware environment and operating system.

These machines use a distributed file system. This allowed uploading of a pre-configured Jetty installation on one machine from which all others could also start the installation.

In addition to these similarly matched machines, select servers were chosen to act as the engine nodes. One of these machines was from the pool of workflow nodes, while another was a server located in a geographically isolated location. This server is connected to the LAN through the University's WAN.

6.6 PlanetLab configuration

PlanetLab [19] is a network of computers contributed by various institutions across the world. Currently consisting of over 900 machines, it allows the contributing members to restrict access to these nodes.

Each machine provides a basic Linux environment (Fedora Core 4 - kernel 2.6.12) into which a PlanetLab user can log into remotely. The PlanetLab user can then configure the software environment by installing additional software through the Fedora application environment provided.

The set-up process for a PlanetLab workflow node included:

- install Java 1.70 IcedTea in order to be able to run the software system
- upload the pre-configured Jetty installation
- update the JAXB libraries in the system with those included in the pre-configured Jetty installation

For the engine nodes, the workflow engine was also uploaded, together with the experiment configurations.

The nodes selected were based on their geographical location. A minimum of five nodes were selected from France and Germany, while a minimum of nine were

selected from the US. These sites were selected to simulate plausible collaborations using workflows. The engine nodes were selected to be remote servers for the same reason.

For example, one could imagine a Russian scientist accessing a workflow composed of French and German services in order to study the Arian 5 space simulations. Alternatively, a CERN employee might need to distribute data across several locations in order to parallelise their processing.

It is worth noting that in both configurations, very little control can be exercised over the workload and resource allocations to each node. PlanetLab has a network throttling policy and can modify on the fly the network resources allocated to each user on a specific machine. The DICE nodes used in the University LAN can also experience widely varying workloads, as they may be in use remotely by multiple students.

Chapter 7

Experiment results analysis

The experiments devised and executed for this project fall under two categories. The first is the set of basic experiments which includes a set of tests which simply compare the execution of a workflow using the traditional and the hybrid model. The second is the set of experiments which attempt to isolate a specific parameter in the hybrid model and to examine how it affects the execution of workflows.

7.1 Basic experiments

As it is desirable to examine the hybrid model in real-life workflow conditions, the experiments were devised to simulate some of the conditions that occur in scientific workflows.

A common scenario in which scientific workflows are executed is that of collaborating universities or institutions. It could be the case that these organisations are located in the same network or geographical domain. In other situations, the collaboration may cross both network and geographical boundaries.

Another factor which may be variable in the scientific workflows, is that of the workflow engine placement. The workflow may be served from within a domain, but could also be served from a remote location or organisation.

Local Area Network (LAN) experiments were executed on the the University of Edinburgh network. Two basic configurations of the workflows being tested were executed. In both configurations the P-WWS bundle is deployed on machines that are connected via a network switch. The differentiating factor is the placement of the workflow engine.

7.2 Local LAN configuration

In the first configuration, the workflow engine is deployed on a computer that is also connected to the workflow web services via a network switch. In fact, all the workflow and engine nodes are in the same building.

The reasoning for choosing this configuration for testing is the assumption of communication link equality. All machines are local. The communication cost between any two machines is low.

If we make the assumption that the communication cost is also uniform, then the problem of evaluating the hybrid model performance, is that of comparing the number of links used. If the hybrid model uses more communication links for a workflow than the equivalent traditional model does, then it would be expected that it would be a more expensive model.

Three workflow patterns were executed for this configuration: fan-in, fan-out and sequence. The sequence workflow pattern was executed twice, once using the initial and final communication links and another by avoiding transferring data via these links.

7.2.1 Workflow pattern: seq_if

7.2.1.1 Experiment configuration

For the sequence pattern which uses both the first and last communication links for the data flow (seq_if), three different workflow sizes (4-node, 8-node, 16-node) were tested. The data flows as in a pipeline with no data transformations (i.e., the output of one operation is the input for the next operation). Because no data transformations are performed, and the web service simply replies with the same data it received, this workflow is equivalent to echoing the initial data throughout the workflow.

Taking the 4 node configuration as an example (Figure 7.1), the one can easily see that in the traditional model, there would be 8 communication steps between the proxies and the workflow engine. In the hybrid model, this depends on the number of proxies used. In the base case of sharing a single proxy, then there would be 8 communication steps between the proxy and the 4 web services, and 2 communication steps between the proxy and the workflow engine. Since the workflow engine, the proxy and the workflow web services, are all hosted on different machines of the same LAN, one would expect the cost of the communication steps to be equal. Assuming the message processing and workflow web service operation processing costs are negligible,

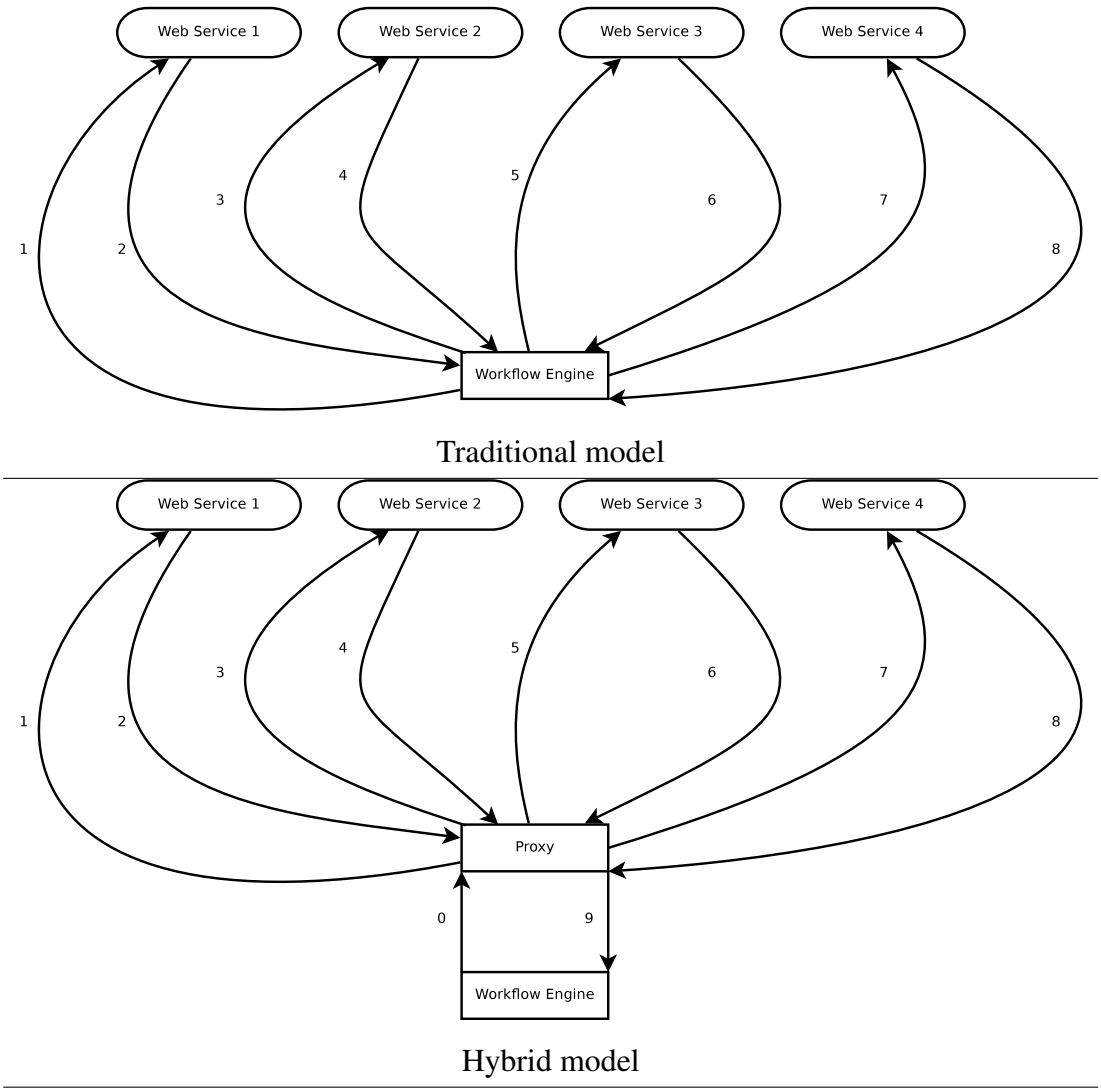


Figure 7.1: seq_if (4-node): Data flow

the performance of the hybrid model would be expected to be 125% slower than the traditional model (10:8 communication steps).

In the 8-node and 16-node configurations, the workflow is slightly altered in the hybrid model. In both configurations, one proxy is assigned to four sequential (in the workflow) nodes. This implies that after the execution of four workflow web service operations, one proxy will need to forward the latest response to the next proxy. This means that one additional data flow link is added for each such forwarding.

7.2.1.2 Results analysis

Table 7.1 presents the performance difference between the hybrid and traditional models for a 4-node configuration of equivalent workflows. The experiment was executed on the localised LAN, and a single shared proxy was used for the hybrid model execution of the workflow. The table shows that the predicted 125% performance change is always within the observed performance range of the hybrid model for the specific workflow model.

When one observes just the average change in performance, a trend is noticeable. As the size of the data flow increases, the hybrid model becomes increasingly slower compared to the traditional model. A possible explanation for this observed result is that as the data flow becomes larger, the processing cost of the data increases. Although the processing cost at the workflow web services should remain the same, the message processing cost does not. The messages are processed both at the proxy and the workflow web services. The processing cost at the proxy is an introduced cost that does not exist in the traditional model and can partly explain the performance degradation.

When the data flow size is 96MB the average performance degradation is lower than 125%. When observing the raw metrics, one can attribute this to a larger standard deviation in the execution times.

As can be seen in the table and Figure 7.2, the hybrid model has a degraded performance when compared to the execution of the equivalent workflow in the traditional model. The figure also illustrates how the standard deviation increases as the data flow size increases.

In the 8-node and 16-node configurations, additional data links were added for the use of forwarding data between proxies. In a localised LAN configuration, these links would have an equivalent cost to the other data flow links, and so it would be expected that the performance of the hybrid approach would further degrade. Using the assumptions made earlier for the 4-node configuration, then the performance degradation for the 8-node configuration would be 118.75%, while for the 16-node configuration it would be 115.63%. This shows that the per-node performance actually increases as the workflow size increases.

Tables 7.2 and 7.3 appear to verify this claim. In the tables, the performance degradation of the hybrid model is similar to the 4-node configuration for the equivalent data flow sizes. Although similar however, as more nodes are added, the performance degradation of the hybrid model is decreased. The small change however could imply

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
2.00	[0.97, 1.33]	1.13
4.00	[1.08, 1.33]	1.20
6.00	[1.19, 1.33]	1.25
8.00	[1.18, 1.30]	1.24
16.00	[1.23, 1.30]	1.26
24.00	[1.20, 1.33]	1.26
32.00	[1.22, 1.38]	1.30
40.00	[1.19, 1.43]	1.30
48.00	[1.08, 1.60]	1.31
64.00	[1.04, 1.75]	1.35
80.00	[1.03, 1.91]	1.40
96.00	[0.79, 1.62]	1.14

Table 7.1: seq_if (4-nodes, 25-runs, local LAN) hybrid model relative perf.

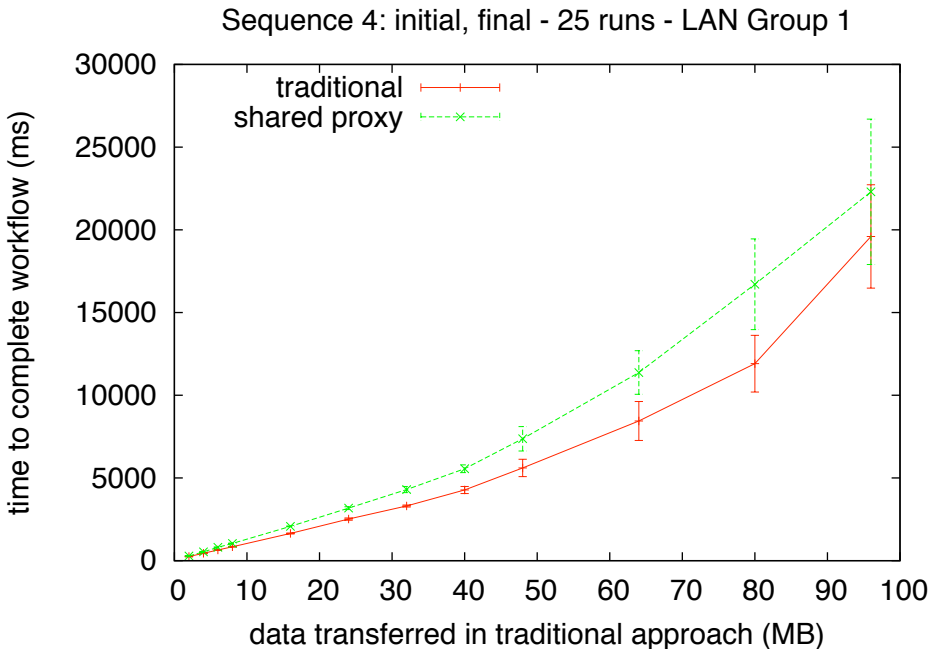


Figure 7.2: seq_if (4-nodes, 25 runs, local LAN) model comparison

that the increase in the message processing costs (more proxies for processing), offset the per-node benefits.

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
4.00	[1.05, 1.29]	1.16
8.00	[1.18, 1.34]	1.26
12.00	[1.20, 1.40]	1.30
16.00	[1.23, 1.33]	1.28
32.00	[1.24, 1.32]	1.28
48.00	[1.25, 1.34]	1.30
64.00	[1.26, 1.38]	1.32
80.00	[1.34, 1.59]	1.46
96.00	[1.27, 1.64]	1.45
128.00	[1.33, 2.01]	1.63

Table 7.2: seq_if (8-nodes, 25 runs, local LAN) hybrid model relative perf.

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
4.00	[1.10, 1.20]	1.14
8.00	[1.15, 1.24]	1.20
12.00	[1.18, 1.30]	1.24
16.00	[1.17, 1.28]	1.23
32.00	[1.19, 1.35]	1.27

Table 7.3: seq_if (16-nodes, 10 runs, local LAN) hybrid model relative perf.

Taking into account the individual message sizes corresponding to the data flow sizes is important in this case. For example, in the 4-node configuration, transferring 8MB translates to 1MB message sizes, while in the 8-node configuration, the individual message size would be 0.5MB. 1MB messages in the 8-node configuration result in a data flow of 16MB. With smaller messages producing the same data flow sizes, one would expect the message processing costs (per node) to decrease. Therefore, there could be a combination of reasons for producing these similar results (e.g., increase in overall message processing costs, decrease of per node message processing costs).

7.2.2 Workflow pattern: seq_ninf

7.2.2.1 Experiment configuration

For the sequence pattern which does not use the first and last communication links for the data flow (seq_ninf), three different workflow sizes (4 nodes, 8 nodes, 16 nodes) were tested. In order to avoid using the first and last communication links for the data flow, a trivial data transformation is required.

Since only a single workflow web service operation exists which requires input to produce output based on a multiplier/scale factor, it is technically impossible in this implementation to avoid using the first and last communication links for the data flow. One way of achieving an equivalent result though is to use a very small input and use the scale factor to produce a large output size. In this experiment, this was achieved by sending one byte as the request and using a large scale factor for producing the response. Although the first communication link is used in the data flow, its cost is minimal (slight overhead for passing in the parameters).

Similarly, the last communication link can be avoided by using the scale factor. In this case, the web service operation will receive input of some size, but the scale factor can be used to reduce the size of the output.

The first and last web services behave as input/output multipliers. The remaining web services simply echo the input. No further data transformations are applied in this workflow.

Taking the 4 node configuration as an example (Figure 7.3), the one can easily see that in the traditional model, there would be 6 communication steps between the proxies and the workflow engine. In the hybrid model, this depends on the number of proxies used. In the base case of sharing a single proxy, then there would be 6 communication steps between the proxy and the 4 web services. Since the workflow engine, the proxy and the workflow web services, are all hosted on different machines of the same LAN, one would expect the cost of the communication steps to be equal. Assuming the message processing and workflow web service operation processing costs are negligible, the performance of the hybrid model would be expected to be the same as that of the traditional model (6:6 communication steps). Obviously, the introduction of the proxies introduces some overhead in the form of additional control flow messages sent to the proxies. The overhead would be in the form of the round-trip times for the additional control flow messages.

In the 8-node and 16-node configurations, the workflow is slightly altered in the

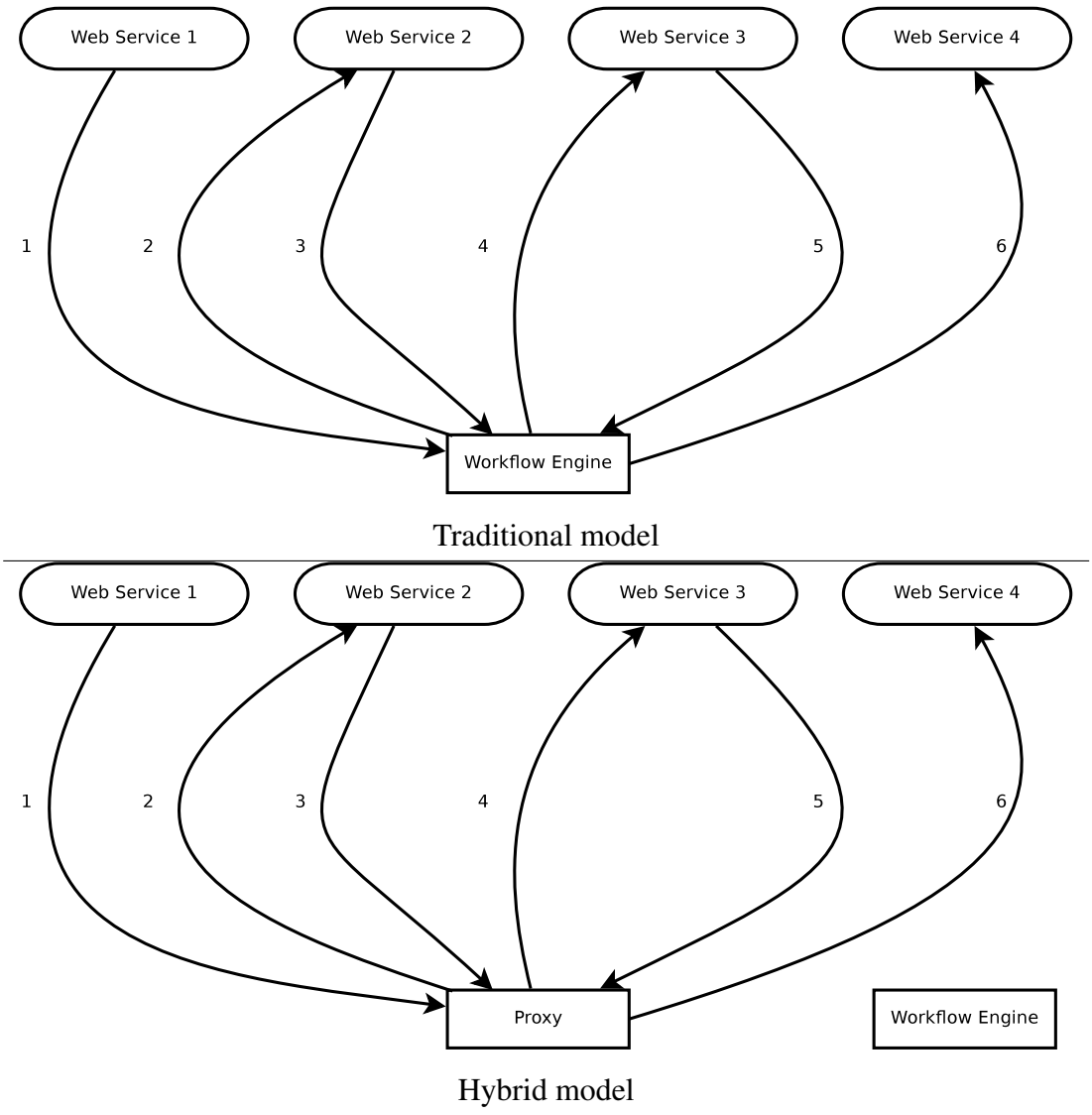


Figure 7.3: seq_ninf (4-node): Data flow

hybrid model. In both configurations, one proxy is assigned to four sequential (in the workflow) nodes. This implies that after the execution of four workflow web service operations, one proxy will need to forward the latest response to the next proxy. This means that one additional data flow link is added for each such forwarding.

7.2.2.2 Results analysis

Table 7.4 presents the performance difference between the hybrid and traditional models for a 4-node configuration of equivalent workflows. The experiment was executed on the localised LAN, and a single shared proxy was used for the hybrid model execu-

tion of the workflow.

The table shows that the when the initial and final communication links are eliminated, then the performance of the hybrid and traditional models for the execution of equivalent workflows is very similar. This is in-line with the expected results.

Slightly unexpected is that the hybrid model was observed to perform better than the traditional model. The performance bounds (lower) in all cases show that the execution of the workflow in the hybrid model may complete before that of the traditional model. When one observes the upper bounds, then the opposite statement also holds, i.e., the execution in the hybrid model may take longer to complete. The observed average performance change shows that up to a data flow size of 12MB, the hybrid model performs faster. With a larger data flow size, the hybrid model's performance worsens with respect to the traditional model.

The results may be partly explained by the relatively small communication costs and the corresponding large deviation. As the data size increases, the communication costs increase faster than the deviation. Thus the traditional model, which has fewer communication steps becomes more efficient. This can also be observed in Figure 7.4.

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
1.5	[0.25, 39.34]	0.84
3	[0.88, 1.09]	0.98
4.5	[0.91, 1.09]	0.99
6	[0.88, 1.06]	0.97
12	[0.93, 1.06]	0.99
18	[0.96, 1.06]	1.01
24	[0.93, 1.13]	1.03
30	[0.83, 1.12]	0.96
36	[0.90, 1.31]	1.09
48	[0.81, 1.43]	1.09
60	[0.72, 1.70]	1.09
72	[0.64, 1.68]	1.06

Table 7.4: seq_ninf (4-nodes, 25 runs, local LAN) hybrid model relative perf.

As more nodes are added to the workflow, one would expect the performance of the hybrid model to drop. This is because additional proxy-to-proxy communication

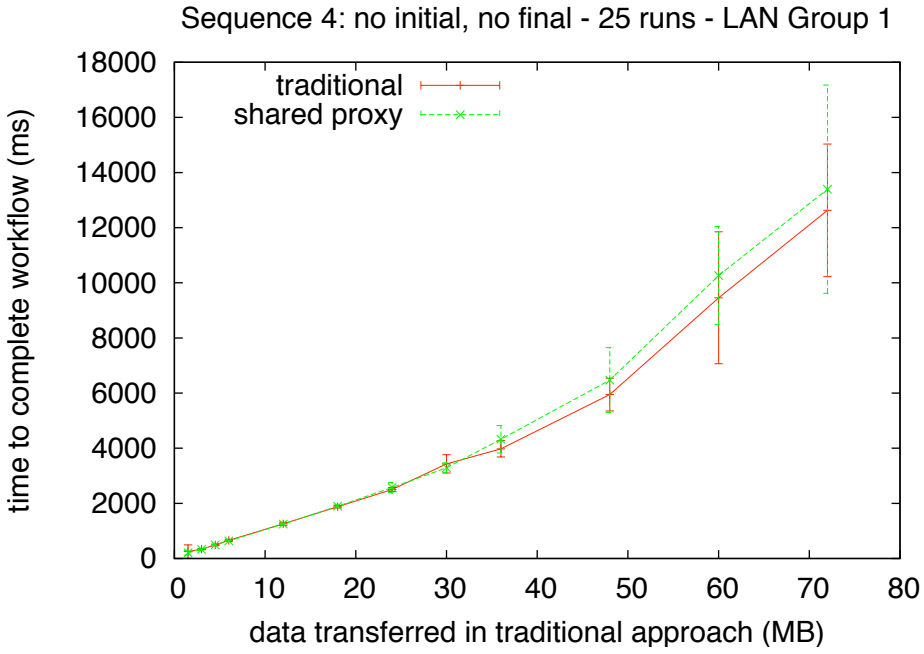


Figure 7.4: seq_ninf (4-nodes, 25 runs, local LAN) model comparison

steps are needed to forward data. For the particular 8-node and 16-node configurations used in the experiments, one proxy is assigned to four sequential web services. That means that in the 8-node configuration one extra communication step is needed, while two additional communication steps are needed in the 16-node configuration. This translates to an expected performance change of 107% and 110% respectively.

Tables 7.5 and 7.6 show that the performance of the hybrid model degrades as the data size increases. The performance drop is to be expected, though it deviates to a large extent from the expected performance drops. An unexpected result is that the performance of the hybrid model does not degrade as the number of additional links increases (i.e., with more nodes). As can be seen by the bounds of the performance change, this may be due to a larger deviation of the running times of the execution of the 8-node configuration. As this was executed 25 times, compared to 10 times for the 16-node configuration, it may be that as more runs are executed, there is a greater chance to have outliers which would affect the average and the datandard deviation.

7.2.3 Comparison of seq_if and seq_ninf

The differences between the seq_if and seq_ninf workflows is the lack of data flows in seq_ninf the for the first and last steps. The general scenario which has the workflow

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
3.5	[0.22, -9.27]	0.95
7	[1.07, 1.25]	1.16
10.5	[1.06, 1.22]	1.14
14	[1.09, 1.25]	1.17
28	[1.12, 1.22]	1.17
42	[1.13, 1.22]	1.18
56	[1.13, 1.29]	1.21
70	[1.14, 1.42]	1.27
84	[1.09, 1.56]	1.31
112	[1.06, 1.97]	1.45

Table 7.5: seq_ninf (8-nodes, 25 runs, local LAN) hybrid model relative perf.

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
7.5	[0.36, 6.04]	1.05
15	[1.13, 1.24]	1.18
22.5	[1.14, 1.24]	1.19
30	[1.12, 1.25]	1.19
60	[1.15, 1.24]	1.20
90	[1.17, 1.28]	1.22
120	[1.18, 1.38]	1.27

Table 7.6: seq_ninf (16-nodes, 10 runs, local LAN) hybrid model relative perf.

engine at a remote location provides a good comparison point for the two workflows. This is because, one could imagine a scenario where the cost of the workflow engine-to-proxy communication is the most expensive communication step. In the localised LAN scenario though, this statement cannot be made. In a localised LAN, all communication links are considered to have the same cost.

More specifically for the seq_if and seq_ninf workflows though, a direct comparison is also difficult due to the different data flow sizes. The metric recorded by the software system is that of the total data transferred in an equivalent workflow under the traditional orchestration model. As seq_ninf lacks two data flow communication steps,

for *equivalent* workflows, less total data is transferred. To overcome this, the data flow sizes (and the corresponding execution times) can be adjusted using an appropriate multiplier.

One hurdle to overcome before adjusting the data flow size however, is the changing network conditions. For a given workflow experiment, multiple runs are executed in sequence. In the case of short-running experiments, this minimises the possibility of changing network conditions between runs. Different workflows however may be executed under wholly different network conditions. One approach for correcting this is to normalise the data based on the observed results. The same message sizes and nodes are used for both seq_if and seq_ninf, so one could use the time taken to complete the communication steps which are active in both workflows and normalise the data based on this result. Ideally, this should be done for all communication steps as individual nodes may suffer different performance degradations. For this analysis however, the assumption is made that the network performance degradation is uniform. To further simplify the situation, a random run is selected from both workflows. These runs are used to normalise the data.

Once the running times have been normalised, and the data flow sizes adjusted, reasonable comparisons can be made for the two workflows. The data from the traditional model is not useful here as a direct comparison of the hybrid model executions is needed.

To examine the relative performance of the two workflows, one needs to examine the communication steps involved in each. Again, only the data flow communication steps need to be taken into account. The differences between the number of communication steps in each workflow should reveal the expected performance difference.

Taking the 4-node configuration as an example, seq_if uses 10 data flow communication steps while seq_ninf uses 6. This gives seq_ninf an expected performance difference of 60% compared to seq_if. For the 8-node configuration the expected performance difference is 79% (15:19 data flow communication steps), while for the 16-node configuration, the expected performance difference is 89% (33:37 data flow communication steps).

The normalised data do not seem to be in agreement with the expected results. Although seq_ninf does perform better than seq_if, the improvements are not as high as predicted. Table 7.7 show that for the 4-node configuration, the performance difference is at 80%, and not 60% as predicted. Tables 7.8 and 7.9 reveal that for the 8-node and 16-node configurations, the performance differences again are not as high as predicted.

For the 8-node configuration, the actual difference is 92% (79%), and for the 16-node configuration it is 98% (89%).

One interesing result from the observed data that is worth pointing out, is that as the number of nodes increases, the performance of the two workflows becomes more similar. This is to be expected as the number of data flow communication steps in which the two workflows differ is fixed at four. Therefore any benefit of seq_ninf of having four fewer communication steps ends up being amortised over more nodes as the number of nodes increases.

It should be noted that although the performance differences differ from the predicted ones, they nonetheless become smaller as the number of nodes increases. As more nodes are added, the difference of the predicted performance difference to the observed performance difference is at 25% (4-nodes), 14% (8-nodes), and 9% (16-nodes). Therefore as the number of nodes increases, the predicted performance difference becomes a good evaluator of the actual performance difference.

data transferred in traditional model (MB)	av. running time of seq_if (ms)	normalised av. running time of seq_ninf (ms)	running time change for seq_ninf (%)
2	284.6	279.84	98
4	531.76	440.75	83
6	807	655.04	81
8	1041.44	850.29	82
16	2071.76	1664.64	80
24	3173.72	2528.43	80
32	4294.6	3430.56	80
40	5558.4	4387.57	79
48	7368.92	5769.6	78
64	11374.48	8628.48	76
80	16708.8	13681.71	82
96	22298.56	17859.36	80

Table 7.7: seq_if and seq_ninf perf. comparison (4-nodes, local LAN)

data transferred in traditional model (MB)	av. running time of seq_if (ms)	normalised av. running time of seq_ninf (ms)	running time change for seq_ninf (%)
4	611.2	684.3	112
8	1157.6	1075.43	93
12	1762.28	1584.55	90
16	2264.04	2086.49	92
32	4501.04	4167.63	93
48	6957.2	6401.92	92
64	9235.8	8530.15	92
80	12938.24	11470.86	89
96	16288.52	15321.23	94
128	28406.08	24552.78	86

Table 7.8: seq_if and seq_ninf perf. comparison (8-nodes, local LAN)

data transferred in traditional model (MB)	av. running time of seq_if (ms)	normalised av. running time of seq_ninf (ms)	running time change for seq_ninf (%)
8	1177.4	1341.35	114
16	2207.5	2168.75	98
24	3328.1	3253.59	98
32	4395	4312.19	98
64	9086	8675.24	95

Table 7.9: seq_if and seq_ninf perf. comparison (16-nodes, local LAN)

7.2.4 Workflow pattern: fan-in

7.2.4.1 Experiment configuration

The fan-in pattern is a more complicated pattern than the sequence workflow patterns described above. The experiments constructed to test this pattern use, as previously, 4-node, 8-node and 16-node configurations. However, with the fan-in pattern, the cost of the communication links is no longer uniform.

The basic workflow for these experiments is that data is received (in parallel) from all but one workflow web service. The responses are then combined and sent to the remaining workflow web service. This final request is therefore equal to the sum of all the previous communication steps. This gives the overall communication costs for the pattern in the hybrid model as 6 data flow steps (4-nodes), 22 data flow steps (8-nodes), and 54 data flow steps (16-nodes).

The increase in the communication steps of the 8-node and 16-node configurations is due to the fact that the introduction of proxies necessitates additional communication steps. Once a response is received by a proxy from a workflow web service, if that proxy is not the proxy responsible for the final workflow web service operation invocation, then it must forward the data to that proxy.

As with seq_ninf, the initial and final communication links are not used. In fact, as can be seen in Figure 7.5, the communication between workflow engine and the proxies does not involve any data flow communication.

Taking the 4-node configuration as an example (Figure 7.5), and assuming the message size for all but the last workflow web service are the same, there would be 6 communication steps between the proxies and the workflow engine. (3 for the first 3 workflow web services, and a cumulative cost of 3 steps for the final workflow web service).

In the hybrid model, this depends on the number of proxies used. As in the previous workflow pattern experiments, a single shared proxy is used. With this proxy configuration, there would be 6 communication steps between the proxy and the 4 web services.

With a single proxy, there is no need to forward data, and thus no more data flow communication steps are needed. Since the workflow engine, the proxy and the workflow web services, are all hosted on different machines of the same LAN, one would expect the cost of the communication steps to be equal. Assuming the message processing and workflow web service operation processing costs are negligible, the performance of the hybrid model would be expected to be the same as the traditional model. However, this does not take into account the additional control flow messages needed to coordinate the proxies. When the additional control flow messages are taken into account, one would expect the performance of the hybrid model to be lower than that of the traditional model.

In the case of the 8-node and 16-node configurations, then the expected performance is more easily determined. All data at proxies will need to make their way to

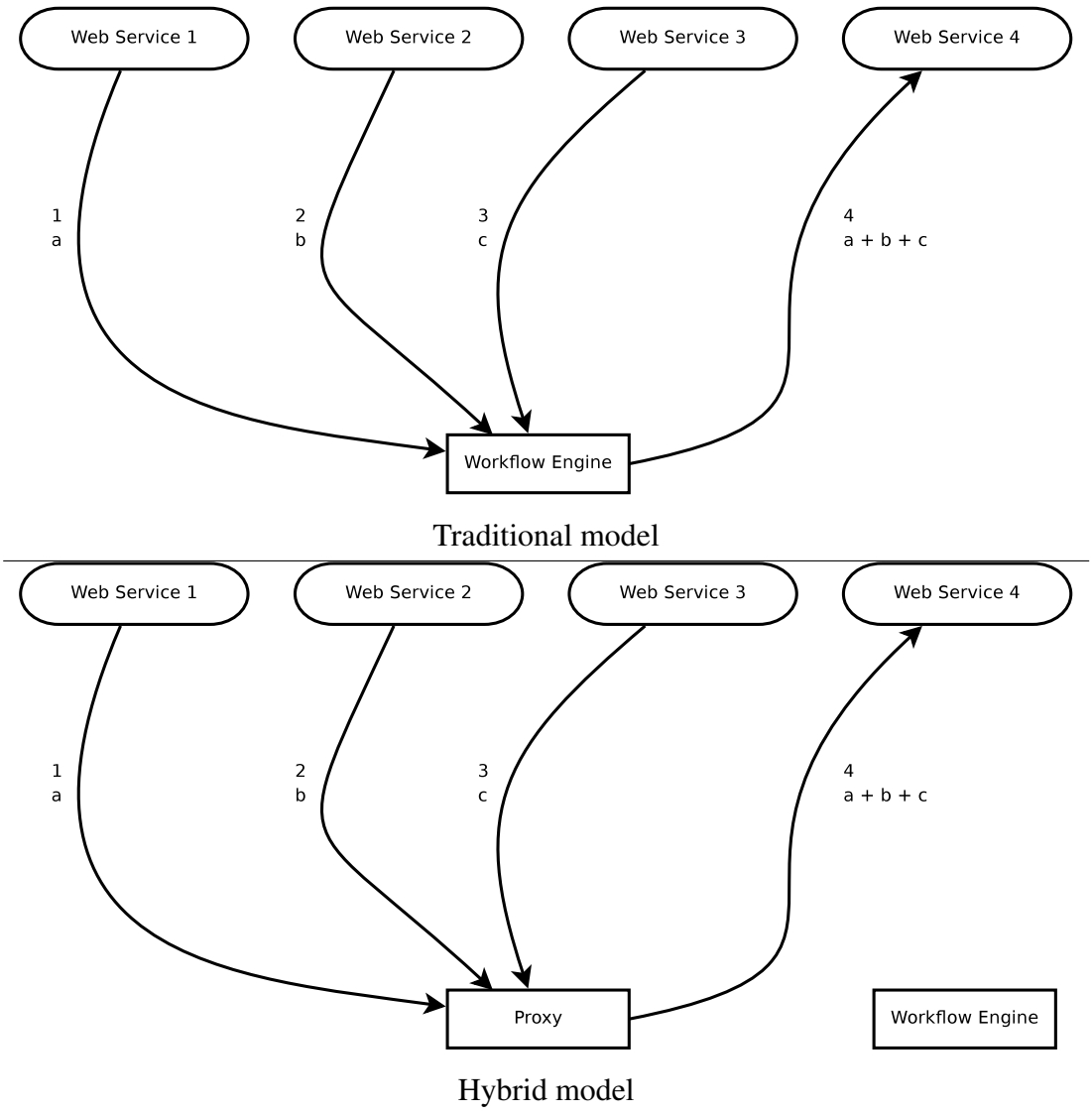


Figure 7.5: fan-in (4-node): Data flow

the proxy responsible for the final workflow web service. The configurations tested in this experiment use four web services per proxy. Therefore in the 8-node configuration, four additional data flow messages are needed for proxy forwarding (18+4), while in the 16-node configuration twelve data flow messages will be added (42+12). This translates to an expected increase in running time of 122% for the 8-node configuration and 129% for the 16-node configuration. If one takes into account the additional control flow messages, then the expected increases should be greater.

It should be noted that the workflow execution is not optimised. More specifically, the proxy forwarding does not happen as soon as data is available for forwarding. Instead, after all proxies have received all expected responses, a forwarding step is

initiated for all proxies. This is not expected to be an issue for the localised (and remote) LAN configurations since it is expected that all communication links have the same cost. However in a network environment with variable communication costs, this implementation will not be optimised. Instead of the proxy forwarding already available data, it will idle waiting for all of its workflow web services to respond. This is not an issue for the 4-node configuration (no proxy forwarding needed), but this would translate to non-optimal performance in the 8-node and 16-node configurations.

7.2.4.2 Results analysis: fan-in

Table 7.10 presents the performance difference between the hybrid and traditional models for a 4-node configuration of equivalent workflows. The experiment was executed on the localised LAN, and a single shared proxy was used for the hybrid model execution of the workflow. The table shows that the expected behaviour is closely followed. The performance hovers at the same levels in both models. The additional control flow messages in the hybrid model lowers its performance. No general trend can be observed as far as any possible correlation between data flow size and performance change.

As can be seen in the table and Figure 7.6, the hybrid model has a degraded performance when compared to the execution of the equivalent workflow in the traditional model. The figure also illustrates how the standard deviation increases as the data flow size increases. This increase affects both the hybrid and traditional workflow models.

In the 8-node and 16-node configurations, additional data links were added for the use of forwarding data between proxies. In a localised LAN configuration, these links would have an equivalent cost to the other data flow links, and so it would be expected that the performance of the hybrid approach would further degrade. Based on the expected performance changes described above, the per-node performance is expected to decrease as the workflow size increases.

Tables 7.11 and 7.12 verify the claim of degraded performance. However the observed performance drop is lower than the predicted one. For the 8-node configuration, the predicted performance drop is within the performance bounds defined by the average and the standard deviation. The observed average performance drop is lower than the expected one. This may be because of the fact that the requests are performed in parallel.

The completion of batch (parallel) communication steps may require less time than the equivalent sequential communication steps. This would be due to better scheduling

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
1.5	[0.63, 1.29]	0.90
3	[0.87, 1.53]	1.19
4.5	[0.84, 1.11]	0.96
6	[0.92, 1.08]	0.99
12	[0.99, 1.07]	1.03
18	[1.00, 1.06]	1.03
24	[0.97, 1.08]	1.02
30	[0.96, 1.12]	1.04
36	[0.99, 1.10]	1.04
48	[0.91, 1.20]	1.05
60	[0.92, 1.15]	1.03
72	[0.87, 1.25]	1.04

Table 7.10: fan-in (4-nodes, 25 runs, local LAN) hybrid model relative perf.

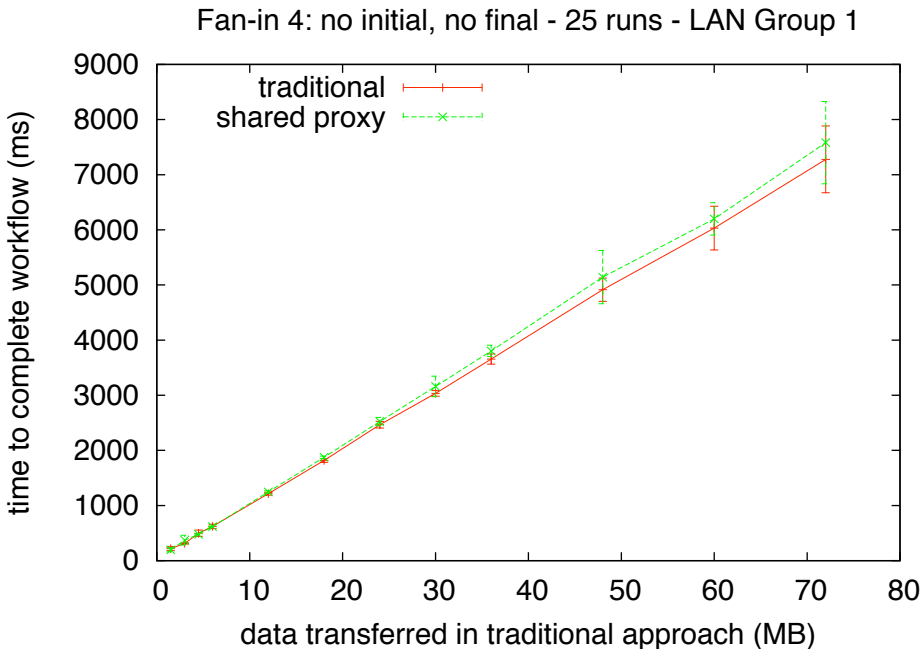


Figure 7.6: fan-in (4-nodes, 25 runs, local LAN) model comparison

of the tasks and a better allocation of network resources.

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
3.5	[0.80, 1.67]	1.12
7	[1.02, 1.26]	1.13
10.5	[1.10. 1.29]	1.19
14	[1.08, 1.19]	1.14
28	[1.09. 1.20]	1.14
42	[1.12, 1.23]	1.17
56	[0.99, 1.31]	1.13

Table 7.11: fan-in (8-nodes, 25 runs, local LAN) hybrid model relative perf.

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
7.5	[0.40, 2.69]	1.47
15	[0.76, 1.39]	1.06
22.5	[0.97, 1.04]	1.00
30	[0.85, 1.57]	1.20
60	[0.94, 1.24]	1.09

Table 7.12: fan-in (16-nodes, 10 runs, local LAN) hybrid model relative perf.

7.2.5 Workflow pattern: fan-out

7.2.5.1 Experiment configuration

The fan-out pattern is a more complicated pattern than the sequence workflow patterns described above, and its behaviour is similar to that of fan-in. The experiments constructed to test this pattern use, as previously, 4-node, 8-node and 16-node configurations. In this experiment each four workflow web services are associated with a single proxy instance. As with the sequence workflows, the cost of the communication links is uniform.

The basic workflow for these experiments is that the first workflow web service will provide the data that will then be sent to all remaining workflow web services. As with seq_ninf and fan-in, the initial and final communication links are not used. This means that there is one communication step per workflow web service, and so for the traditional model the number of involved web services is equal to the number of communication steps involved with the data flow. For the hybrid model, the commu-

nication costs for the pattern as used in the experiment, are 4 data flow steps (4-node configuration).

With a single proxy, there is no need to forward data, and thus no more data flow communication steps are needed. Since the workflow engine, the proxy and the workflow web services, are all hosted on different machines of the same LAN, one would expect the cost of the communication steps to be equal. Assuming the message processing and workflow web service operation processing costs are negligible, the performance of the hybrid model would be expected to be the same as the traditional model. However, this does not take into account the additional control flow messages needed to coordinate the proxies. When the additional control flow messages are taken into account, one would expect the performance of the hybrid model to be lower than that of the traditional model.

In the case of the 8-node and 16-node configurations, then the expected performance is more easily determined. All data at proxies will need to make their way to the proxy responsible for the final workflow web service. Therefore in the 8-node configuration, one additional data flow message is needed for proxy forwarding (8+1), while in the 16-node configuration three data flow messages will be added (16+3). This translates to an expected increase in running time of 113% for the 8-node configuration and 119% for the 16-node configuration. If one takes into account the additional control flow messages, then the expected increases should be greater.

The increase in the communication steps of the 8-node and 16-node configurations is due to the fact that the introduction of proxies necessitates additional communication steps. When the first workflow web service provides its response to its associated proxy, that proxy will be notified by the workflow engine to forward the data to the proxies responsible for the invocation of the remaining workflow web services (with the exception of the workflow web services it is responsible for). The number of times the original data will need to be forwarded is one less than the number of proxies in the workflow.

As with fan-in, the communication between workflow engine and the proxies does not involve any data flow communication (Figure 7.7).

7.2.5.2 Results analysis

Table 7.13 presents the performance difference between the hybrid and traditional models for a 4-node configuration of equivalent workflows. The experiment was executed on the localised LAN, and a single shared proxy was used for the hybrid model

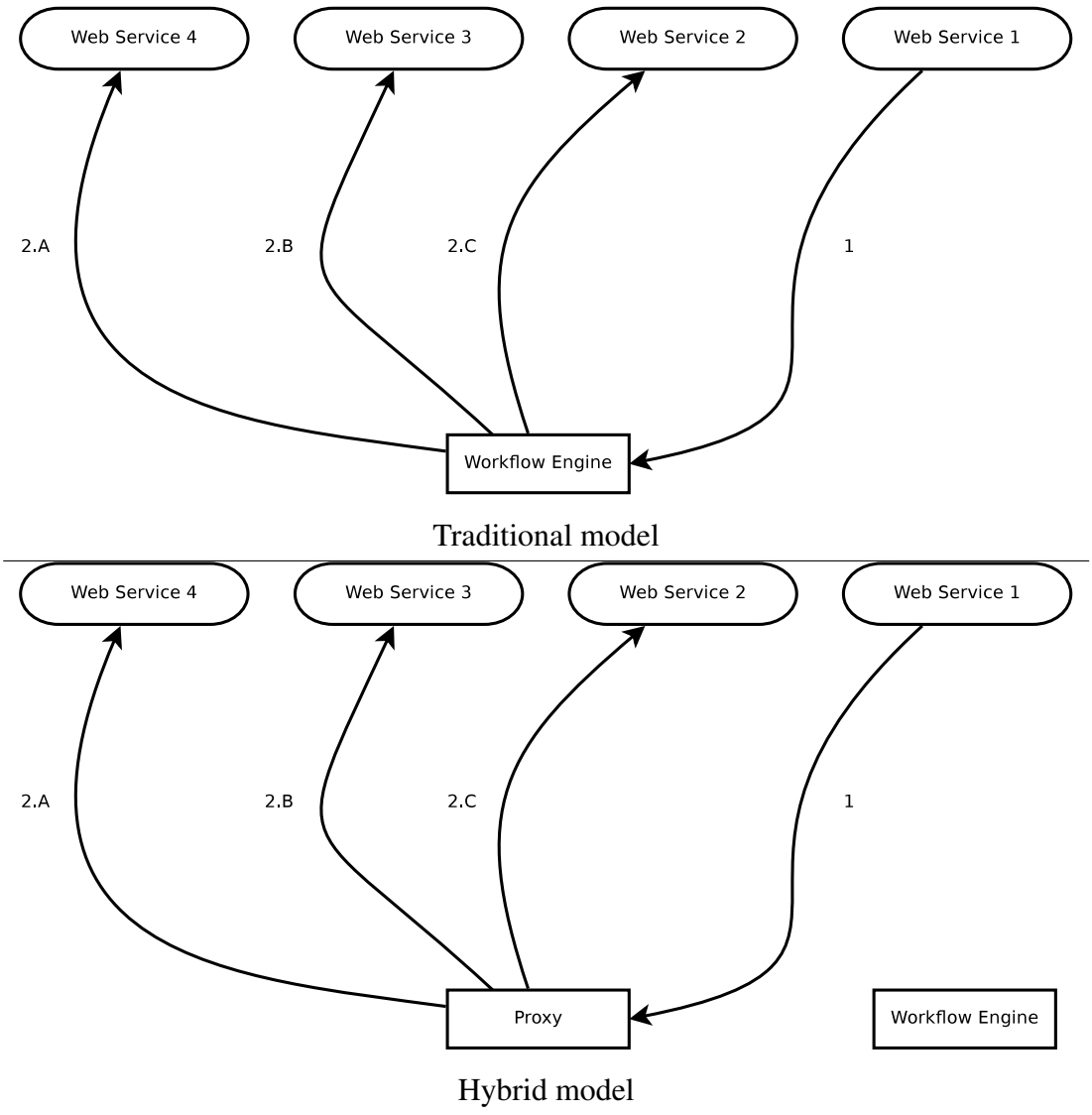


Figure 7.7: fan-out (4-node): Data flow

execution of the workflow. The table shows that the expected behaviour is closely followed. The performance hovers at the same levels in both models. The additional control flow messages in the hybrid model lowers its performance. Unlike the results of the fan-in pattern though, there does seem to be a trend for performance to degrade as the message size (and data flow size) is increased.

As can be seen in the table and Figure 7.8, the hybrid model has a degraded performance when compared to the execution of the equivalent workflow in the traditional model. Note however that at small message sizes, the hybrid model slightly outperforms the traditional model. This difference however is within the error margin (using standard deviation). The figure also illustrates how the standard deviation increases

as the data flow size increases. This increase affects both the hybrid and traditional workflow models.

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
1	[0.67, 1.30]	0.91
2	[0.82, 1.15]	0.97
3	[0.95, 1.13]	1.04
4	[0.90, 1.13]	1.01
8	[0.97, 1.07]	1.02
12	[0.99, 1.08]	1.04
16	[0.96, 1.13]	1.04
20	[0.98, 1.18]	1.08
24	[0.78, 1.46]	1.07
32	[0.71, 1.71]	1.11
40	[0.68, 1.96]	1.16
48	[0.57, 1.97]	1.08

Table 7.13: fan-out (4-nodes, 25 runs, local LAN) hybrid model relative perf.

In the 8-node and 16-node configurations, additional data links were added for the use of forwarding data between proxies. In a localised LAN configuration, these links would have an equivalent cost to the other data flow links, and so it would be expected that the performance of the hybrid approach would further degrade. Based on the expected performance changes described above, the per-node performance is expected to decrease as the workflow size increases.

Tables 7.14 and 7.15 verify the claim of degraded performance. However the observed performance drop is higher than the predicted one.

For the 8-node configuration, the predicted performance drop is actuallyt outside the performance bounds observed. Whereas the expected performance was at 113%, the lower performance bounds are almost always larger (the exception being at the smallest data size). A closer examination of the individual results reveals that the initial proxy (i.e., the proxy that will forward the initial response) may be the cause. The initial proxy took 2-4 times as long to invoke certain web services and to forward data to the next proxy as it did to invoke come of the other web services. An increased workload cannot be used to explain this as its connection speed to some web services

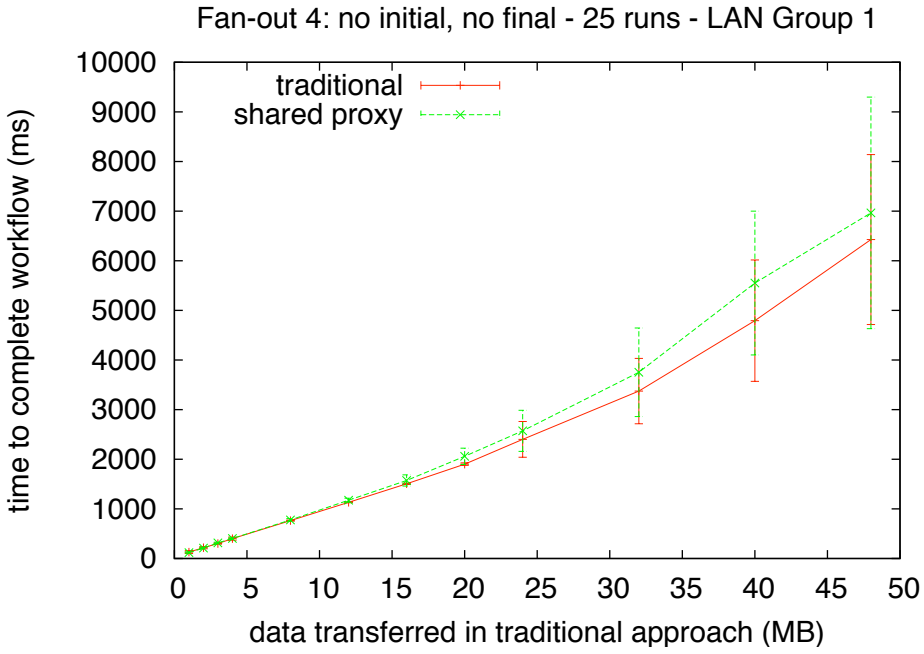


Figure 7.8: fan-out (4-nodes, 25 runs, local LAN) model comparison

remains unaffected. The most probable explanation is a changing network load. The invocation times for the second proxy deviated less.

For the 16-node configuration, the predicted performance is within the observed bounds, though the averages are larger. One of the factors for this is that whereas the standard deviation for the traditional model execution ranged from 1-5%, the hybrid model execution ranged from 3-91%.

7.3 Remote LAN configuration

A variation to the localised LAN configuration is increasing the cost of the workflow engine-to-proxy communication. This can be accomplished by moving the workflow engine outside of the LAN.

A real world scenario of this would be when an organisation provides all the workflow web services used by a workflow. For example, NASA may provide services for retrieving satellite images and processing the images. A company like Google could construct a workflow for these services in order to identify landmarks visible from different altitudes in space. The workflow (via the workflow engine) would be accessible through Google's servers, whereas all workflow web service requests would be handle

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
2	[0.74, 2.53]	1.31
4	[1.28, 1.64]	1.45
6	[1.22, 1.47]	1.34
8	[1.26, 1.54]	1.40
16	[1.26, 1.47]	1.37
24	[1.30, 1.56]	1.43
32	[1.29, 1.57]	1.43
40	[1.35, 1.67]	1.50
48	[1.22, 1.80]	1.50
64	[1.34, 2.09]	1.68

Table 7.14: fan-out (8-nodes, 25 runs, local LAN) hybrid model relative perf.

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
4	[0.13, 3.12]	1.55
8	[1.12, 1.29]	1.20
12	[1.16, 1.32]	1.24
16	[0.79, 1.91]	1.34
32	[1.15, 1.26]	1.21
48	[1.07, 1.48]	1.27
64	[1.14, 1.24]	1.19

Table 7.15: fan-out (16-nodes, 10 runs, local LAN) hybrid model relative perf.

on NASA's network.

For the purposes of this experiment, the configuration used moves the workflow engine to a remote machine which accesses the LAN via a WAN. The workflow web services and proxies remain as in the localised LAN configuration.

The reasoning for choosing this configuration for testing is to break the assumption of communication link equality by introducing a slow link. What the proxy architecture does, is introduce additional link (proxy-to-proxy, workflow engine-to-proxy), while eliminating some other ones (workflow engine-to-workflow web services). This configuration allows the testing of what happens when a slow link is introduced.

Introducing a slow link would have the expected result of degrading the performance of the hybrid and traditional models. One needs to consider however, to what extent each model degrades.

The same workflow patterns as with the localised LAN configuration were tested. In fact, the only difference in the experiments is the location of the workflow engine.

7.3.1 Workflow pattern: seq_if

Table 7.16 presents the performance difference between the hybrid and traditional models for a 4-node configuration of equivalent workflows. As links are no longer uniform, an expected performance improvement is difficult to determine. What is clear though is that by simply replacing the workflow engine with one with a higher cost, the hybrid model outperforms the traditional model.

The table shows that on average, the hybrid model always outperforms the traditional mode. An exception exists with a data flow size of 8MB, but even in that case the performances are comparable.

At small data flow sizes (2MB-8MB), the two models have similar performance. As the data flow size increases, the performance of the traditional model degrades faster. At the high values of data flow size, the performance of the traditional approach is actually twice as bad as that of the hybrid model. This trend can be seen in Figure 7.9. The graph and table also show that even when taking into account standard deviation of both models, at large data flow sizes, the hybrid model always performs better.

The explanation for the results is straight-forward. In the traditional model all data flow communication occurs over the expensive workflow engine-to-proxy communication link. The hybrid model however, needs to use that link only for the first and last communication steps. In the first step, data needs to be available at the proxy to invoke the first workflow web service. In the last step, the final response needs to be made available at the workflow engine.

The hybrid model is able to take advantage of the nature of the workflow pattern. The sequence pattern used in the experiment acts as a pipeline. Therefore the intermediate results are always used up in subsequent steps. Since all intermediate steps occurs within the LAN, these steps are cheaper than sending the data back to the workflow engine.

In the 8-node and 16-node configurations, additional data links were added for the use of forwarding data between proxies. These links would have an equivalent cost

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
2	[0.72, 1.28]	0.97
4	[0.70, 1.52]	0.99
6	[0.77, 1.24]	0.97
8	[0.90, 1.17]	1.02
16	[0.69, 1.06]	0.85
24	[0.54, 1.02]	0.73
32	[0.47, 0.84]	0.63
40	[0.46, 0.73]	0.58
48	[0.43, 0.68]	0.54
64	[0.42, 0.64]	0.52
80	[0.37, 0.61]	0.48
96	[0.40, 0.61]	0.50

Table 7.16: seq_if (4-nodes, 25 runs, remote LAN) hybrid model relative perf.

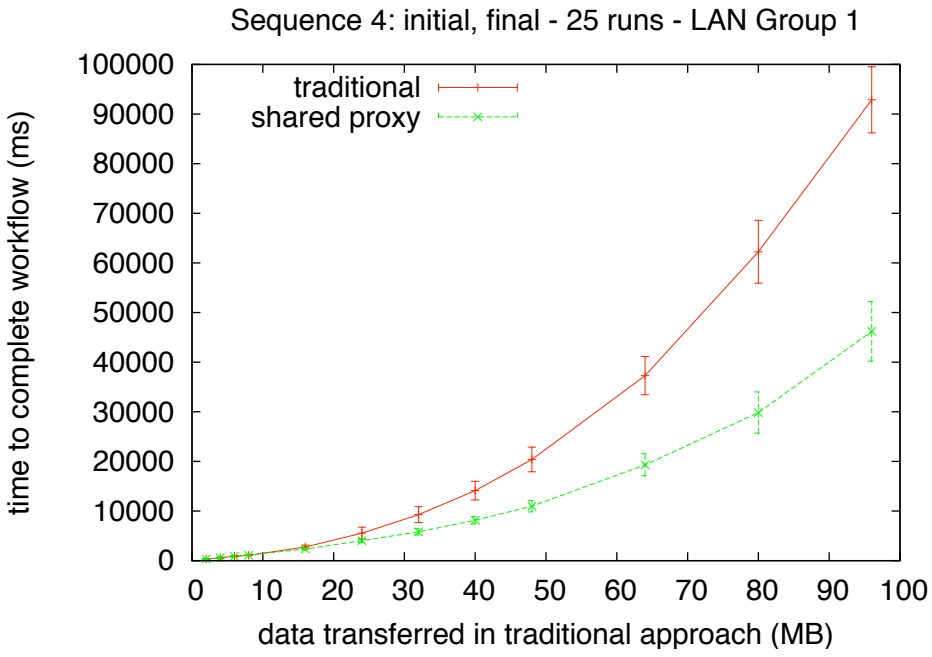


Figure 7.9: seq_if (4-nodes, 25 runs, remote LAN) model comparison

to the other data flow links, and so it would be expected that the performance of the hybrid approach would degrade, as compared to the 4-node configuration.

Tables 7.17 and 7.18 verify this claim. The 8-node configuration uses only a single additional proxy, and continues to experience improvements when compared to the traditional model. Similarly, the difference increases as the data flow size increases, though the relative difference is smaller. In the 16-node configuration, the two models behave similarly. The 16-node configuration uses three additional proxies, and the intercommunication between the proxies cancels the benefits of not using the workflow engine-to-proxy links.

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
4	[0.63, 1.23]	0.86
8	[0.90, 1.21]	1.04
12	[0.94, 1.17]	1.05
16	[0.95, 1.24]	1.08
32	[0.84, 1.12]	0.97
48	[0.67, 0.97]	0.80
64	[0.53, 0.76]	0.63
80	[0.45, 0.71]	0.56
96	[0.44, 0.66]	0.54
128	[0.40, 0.58]	0.48

Table 7.17: seq_if (8-nodes, 25 runs, remote LAN) hybrid model relative perf.

data x-ferred in trad. model (MB)	perf. ratio range	av. perf. ratio
8	[0.63, 1.23]	0.86
16	[0.90, 1.21]	1.04
24	[0.94, 1.17]	1.05
32	[0.95, 1.24]	1.08
64	[0.84, 1.12]	0.97

Table 7.18: seq_if (16-nodes, 25 runs, remote LAN) hybrid model relative perf.

7.3.2 Workflow pattern: seq_ninf

Table 7.19 presents the performance difference between the hybrid and traditional models for the three different node configurations (and their respective workflows). The experiment was executed on the remote LAN, and a single shared proxy per group of four consecutive workflow web services. The table shows that for each configuration, the hybrid model execution of the workflows outperforms the equivalent traditional workflow model at all data flow sizes.

Two trends are observed for the three configurations.

As the data flow size increases, the observed performance benefits of the hybrid model increase. This is to be expected because as more data circulates in the workflow, the traditional model will increase the load on the workflow engine-to-proxy communication link, whereas the hybrid model will never use it. These observed benefits decreases as the number of configurations increase. This can be explained by the fact that with more nodes, more proxies are used, and therefore additional communication links are introduced to the workflow. Although the cost of these links is lower than than the workflow engine-to-proxy links, it is nonetheless non-zero. In addition, the workflow engine sends more control messages to coordinate the forwarding of data between the proxies.

The other trend is harder to explain. At the smallest data flow sizes of each of the configurations, the hybrid model outperforms the traditional model to a greater extent than with higher data flow sizes. The order of execution of the tests offers a possible explanation for this trend. As tests are performed using increasing data flow sizes, the system would have its lightest load at the beginning of the experiments. This may have provided a performance boost to the hybrid model.

7.3.3 Workflow pattern: fan-in

Figure 7.10 presents the performance difference between the hybrid and traditional models for the three different node configurations (and their respective workflows). The experiment was executed on the remote LAN, and a single shared proxy per group of four consecutive workflow web services. 25 runs were executed for the 4-node and 8-node configurations and 10 runs for the 16-node configuration.

The figure shows that for each configuration, the hybrid model execution of the workflows outperforms the equivalent traditional workflow model at all data flow sizes. The only exception being the smallest data flow size test for the 8-node configuration.

data flow size (MB)	av. perf. ratio 4-nodes	av. perf. ratio 8-nodes	av. perf. ratio 16-nodes
1.5	0.61		
3	0.66		
3.5		0.71	
4.5	0.63		
6	0.7		
7		0.95	
7.5			0.77
10.5		0.91	
12	0.52		
14		0.93	
15			0.92
18	0.42		
22.5			0.95
24	0.31		
28		0.86	
30	0.28		0.97
36	0.26		
42		0.7	
48	0.23		
56		0.49	
60	0.18		0.85
70		0.43	
72	0.18		
84		0.41	
90			0.66
112		0.32	
120			0.54

Table 7.19: seq_ninf (25 runs, remote LAN) hybrid model relative perf.

Even in that case the performance of the two models were comparable (the hybrid model took 111% more time to complete).

The general trends observed in the seq_ninf are noticeable in the results for this experiment as well.

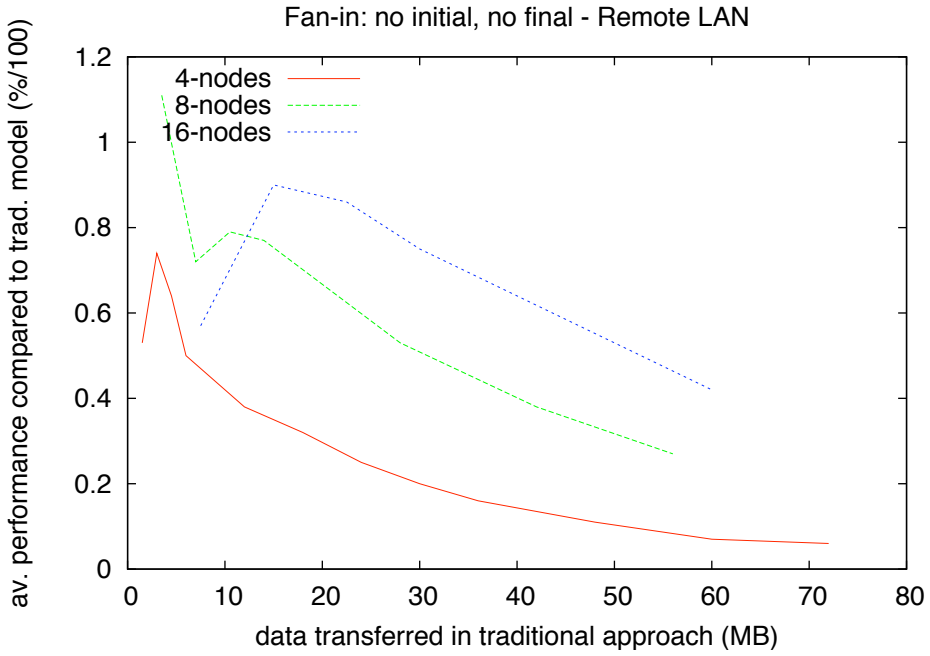


Figure 7.10: Relative performance of hybrid models on a remote LAN, for fan-in

7.3.4 Workflow pattern: fan-out

Figure 7.11 presents the performance difference between the hybrid and traditional models for the three different node configurations (and their respective workflows). The experiment was executed on the remote LAN, and a single shared proxy per group of four consecutive workflow web services. 25 runs were executed for the 4-node and 8-node configurations and 10 runs for the 16-node configuration.

The figure shows that for the 4-node configuration, the hybrid model always outperforms the traditional model in execution of the workflows. Again, this can be explained by the introduction of the slower workflow engine-to-proxy communication link which the hybrid model always avoids.

For the other two configurations however, an unexpected result is observed. With the exception of the smaller data flow sizes, the hybrid model is outperformed by the traditional model. The only possible explanation for this is that the use of the additional proxies not only reduces any benefits of using the hybrid model, but that the additional communication cost is higher than the sum of the workflow engine-to-proxy

communication links. A closer inspection of individual test runs reveals that one of the proxies experienced considerable delays in forwarding data. Due to the increased cost of data forwarding from this proxy, the overall execution time of the hybrid model was higher than that of the traditional model which did not need to interact with the proxy.

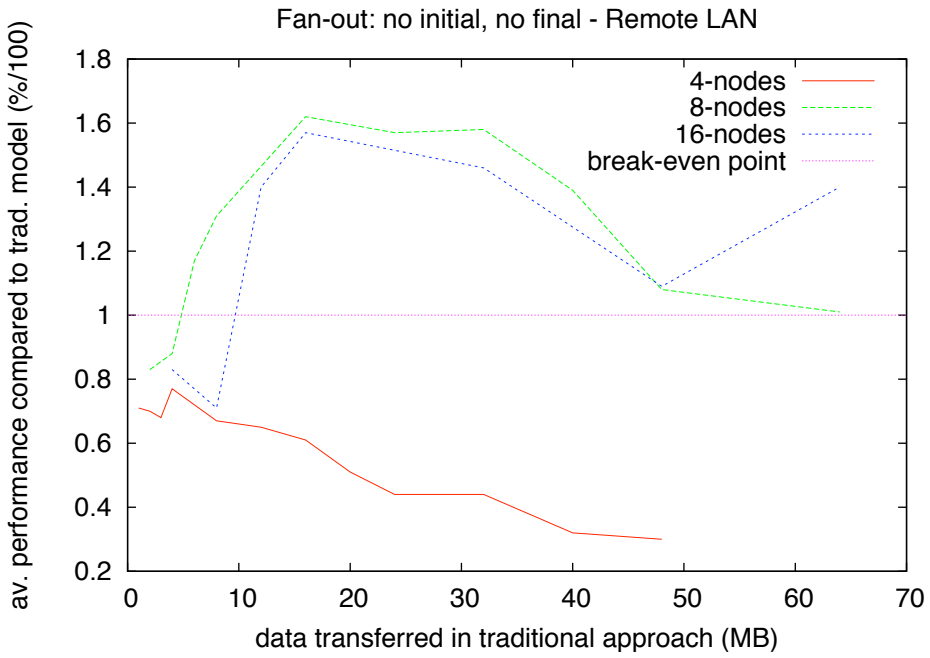


Figure 7.11: Relative performance of hybrid models on a remote LAN, for fan-out

7.4 PlanetLab configuration

The LAN configurations present a good environment for analysing the capabilities of the hybrid model. With the LAN configurations, the assumption that all communication links are equal is not unreasonable. Although difference between communication links do exist, the experiments have shown that unless the network or processing load is high, the communications links are within a factor of one from each other. This relative uniformity is what allows certain conclusions to be made both about the workflow patterns and the hybrid model in general.

Moving the experiments to the PlanetLab configurations allows for more realistic environments to be tested. The PlanetLab experiment configurations are based on geographical locations of the nodes. The geographical location of nodes is used as an indicator of communication link cost.

By grouping the nodes, certain realistic scenarios can be constructed for the experiments. For example, by using a group of nodes all located in France, one experiment can execute a workflow simulating the interactions between collaborating French universities. Such scenarios are common in scientific workflows.

Due to the many different factors involved in mashing up different components into groups, analysis of the performance of the hybrid model is not straightforward. Instead of looking at trends in the averages of multiple runs, it may be necessary to take into account subtasks of individual runs of an experiment.

The workflow engine was similarly placed in a remote geographic location. This is also a common feature of scientific workflows as one can imagine a scientist in a remote location having to access resources from different collaborating institutions.

7.4.1 4-node configurations

A number of different 4-node configurations were used to run the four basic workflow patterns that were executed on the LAN configurations. All configurations were based on geographical locations of their nodes. One configuration uses four nodes in France, with another French node acting as a proxy. A similar set-up uses German nodes, while two other configurations use nodes located in the US.

7.4.1.1 France

The results for this configuration are shown in Figure 7.12. For all patterns, the hybrid model outerforms the traditional model. Table 7.20 shows that the seq_ninf has the best performance difference compared to its execution in the traditional model. Fan-in has the worst performance difference.

Pattern	best perf. ratio	worst perf. ratio	av. perf ratio
seq_ninf	0.51	0.72	0.62
fan-in	0.64	0.93	0.79
fan-out	0.62	0.78	0.70
seq_if	0.67	0.79	0.72
Overall			0.71

Table 7.20: Performance change of hybrid model compared to traditional model for all patterns (France)

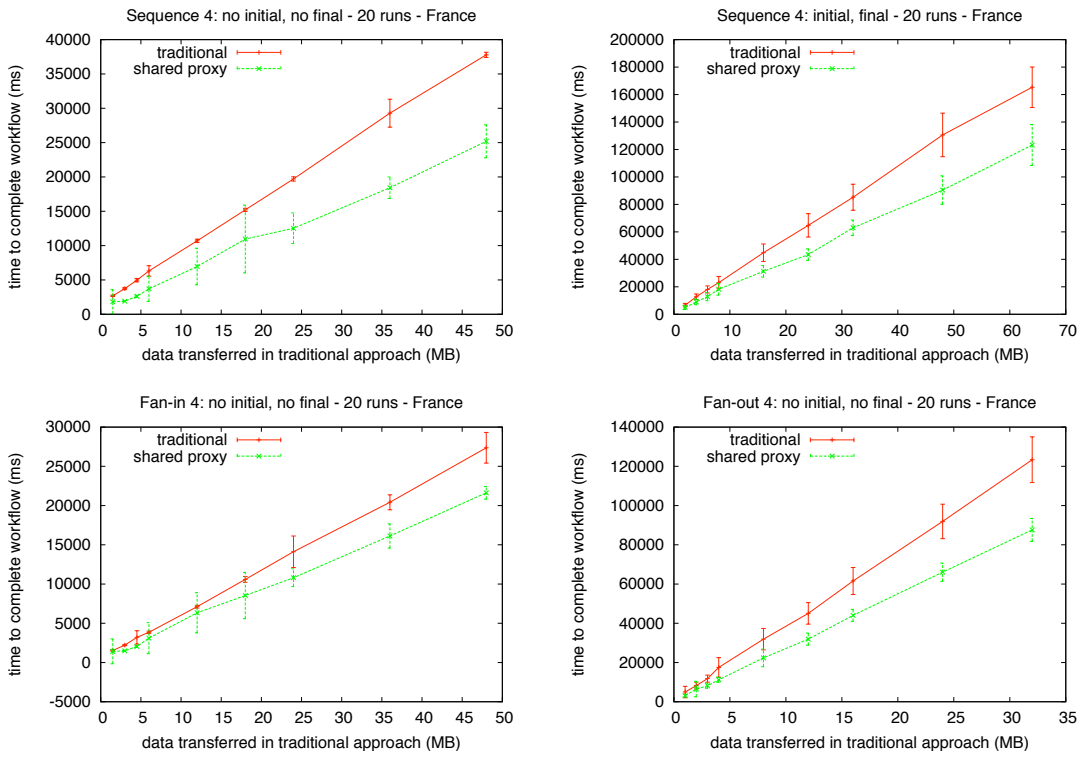


Figure 7.12: 4-node configuration (France) performance of hybrid and traditional model for the basic workflow patterns

7.4.1.2 Germany

The results for this configuration are shown in Figure 7.13. For all patterns, the hybrid model outerforms the traditional model. Table 7.21 shows that the seq_ninf is still the best performing pattern (with respect to the equivalent execution in the traditional workflow). Seq_if is the worst performing pattern. Note that the overall improvement in the German nodes (0.45) is higher than in the French nodes (0.71). Checking against individual runs, it is found that the German nodes had a higher communication cost to the workflow, and thus the better improvement when moving to the hybrid model.

The large improvement with fan-in is due to one outlier run. In the traditional model, one node took approximately 200 times longer to respond than expected (249 seconds as opposed to the expected 1.25 seconds). It's effect on the performance however cannote be explained by the hybrid model. Subsequent (and previous) requests to the same node completed with the expected running time. It is logical therefore to conclude that the outlier run was due to some node-specific performance degradation at that instance.

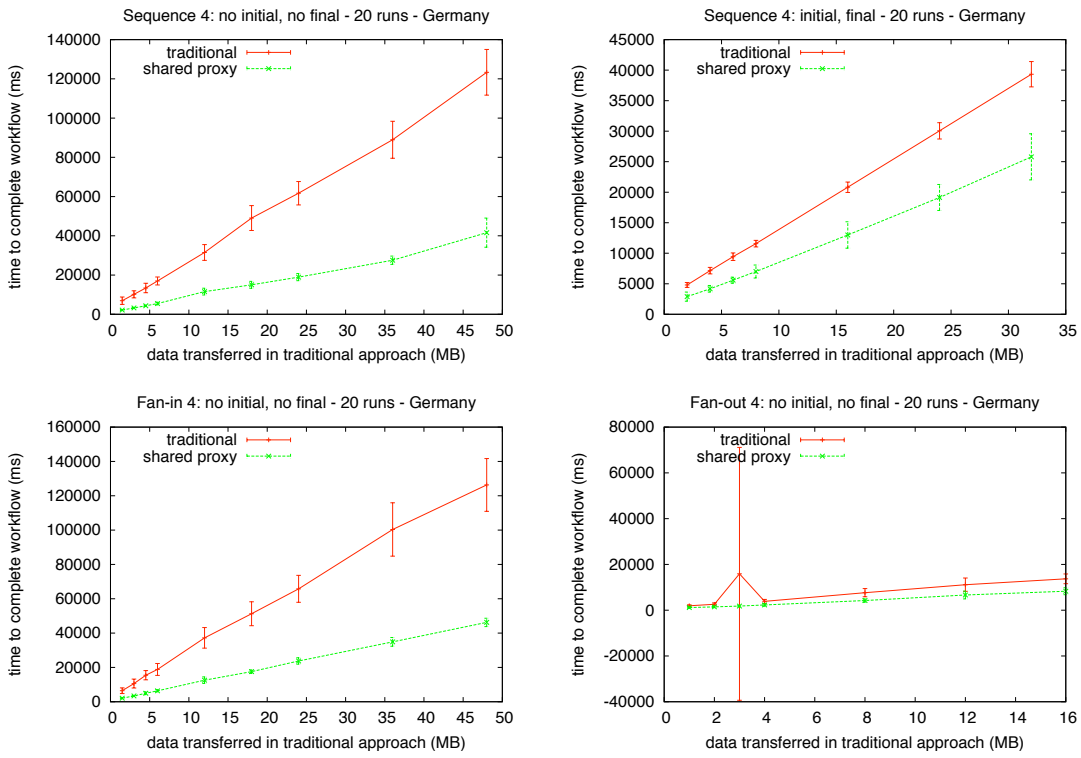


Figure 7.13: 4-node configuration (Germany) performance of hybrid and traditional model for the basic workflow patterns

7.4.1.3 USA

The results for the first 4-node grouping of nodes are shown in Figure 7.14. For all patterns, the hybrid model outerforms the traditional model and the general execution time reduction is similar (approximately 0.60). Table 7.22 shows the performance

Pattern	best perf. ratio	worst perf. ratio	av. perf ratio
seq_ninf	0.31	0.37	0.32
fan-in	0.32	0.37	0.34
fan-out	0.11	0.60	0.52
seq_if	0.58	0.66	0.61
Overall			0.45

Table 7.21: Performance change of hybrid model compared to traditional model for all patterns (Germany)

boost for each pattern using the hybrid model.

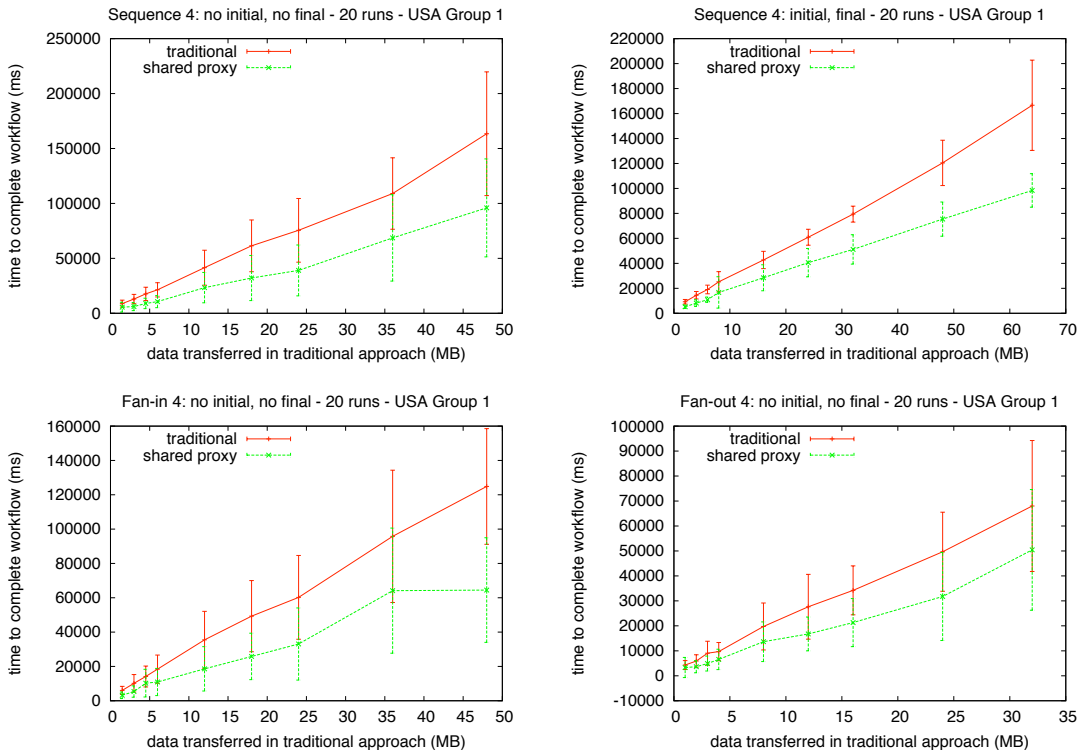


Figure 7.14: 4-node configuration (USA Group 1) performance of hybrid and traditional model for the basic workflow patterns

Pattern	best perf. ratio	worst perf. ratio	av. perf ratio
seq_ninf	0.47	0.63	0.55
fan-in	0.52	0.72	0.57
fan-out	0.54	0.77	0.66
seq_if	0.57	0.67	0.62
Overall			0.60

Table 7.22: Performance change of hybrid model compared to traditional model for all patterns (USA group 1)

The results for the second 4-node grouping of nodes are shown in Figure 7.15. For all patterns, the hybrid model outerforms the traditional model. Table 7.23 shows the performance boost for each pattern using the hybrid model.

For fan-out, the minimum performance change of 0.92 is troubling. This is because at 0.92, the hybrid and traditional model have similar behaviour. When observing the individual runs of the experiment, certain patterns can be used to explain this behaviour.

The communication links to the first web service from both the worklow engine and the proxy was observed to be 5-15 times slower than the other links. The speed of this link was variable. In certain runs, it was faster to communicate with the workflow engine, whereas other times its link to the proxy was faster. This variability alone cannot be used to explain the near similar performance of the hybrid and traditional models. A closer look at the individual runs shows that during one period, while executing the test with the second highest data flow, the proxy link to one other web service increased its cost approximately 10-fold. This spike was not observed with smaller data flow sizes or with the highest. The cost of the workflow engine communication link to that same web service remained the same during this period. This negatively affected the recorded performance of the hybrid model.

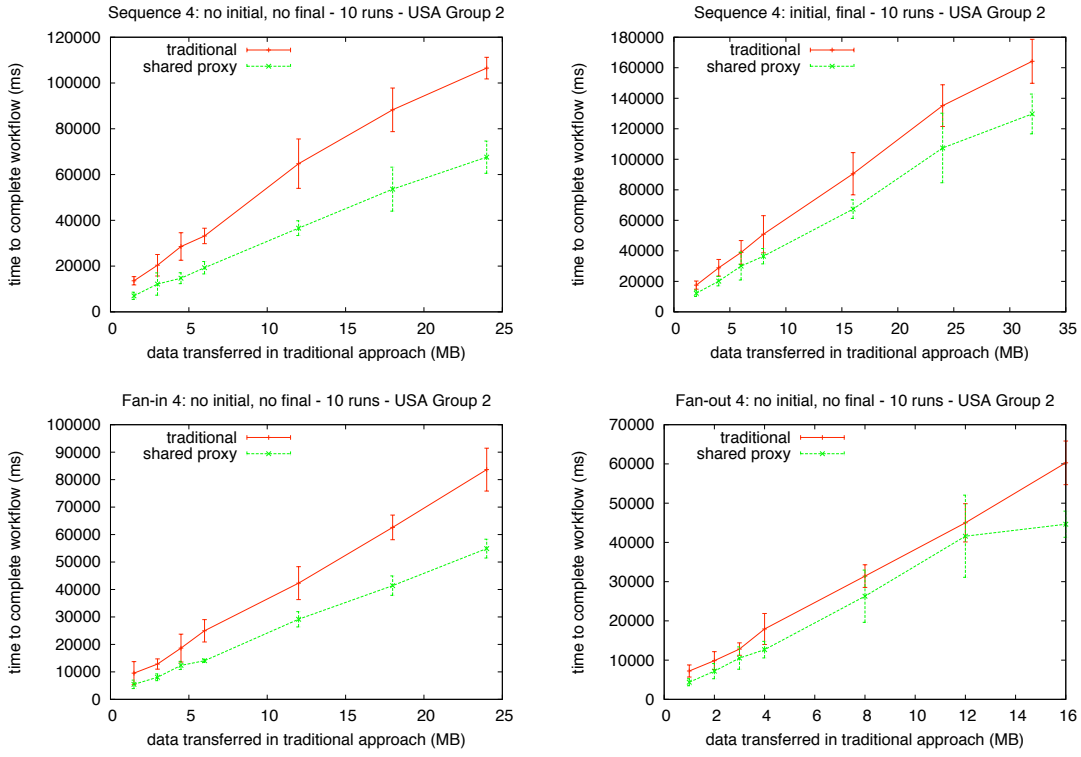


Figure 7.15: 4-node configuration (USA Group 2) performance of hybrid and traditional model for the basic workflow patterns

7.4.2 8-node configurations

Two 8-node configurations were used. Both configurations were used to run the four basic workflow patterns that were executed on the LAN configurations.

The two configurations were based on geographical locations of their nodes. The first configuration was composed of nodes from both Germany and France, with one local proxy for each subgroup.

The second configuration was US-based. As some nodes became unavailable before execution of this experiment, some modifications were made to the general set-up. Two sub-groups were of 2 and 4 nodes composed this 8-node configuration. The first sub-group's two nodes in effect simulate the missing two nodes. A separate US-based proxy was assigned to all nodes. This means that proxy forwarding was not used in this experiment since the data was always available on the proxy.

7.4.2.1 Europe

The results for the tests are shown in Figure 7.16. For all patterns, the hybrid model outerforms the traditional model. Table 7.24 shows the performance boost for each pattern using the hybrid model. In these tests, there was little variability in the performance change (between max. and min.).

7.4.2.2 USA

The results for the tests are shown in Figure 7.17. For all patterns, the hybrid model outerforms the traditional model. Table 7.25 shows the performance boost for each pattern using the hybrid model. The general trend, with the exception of the fan-out

Pattern	best perf. ratio	worst perf. ratio	av. perf ratio
seq_ninf	0.51	0.63	0.57
fan-in	0.56	0.69	0.63
fan-out	0.60	0.92	0.77
seq_if	0.70	0.79	0.74
Overall			0.68

Table 7.23: Performance change of hybrid model compared to traditional model for all patterns (USA group 2)

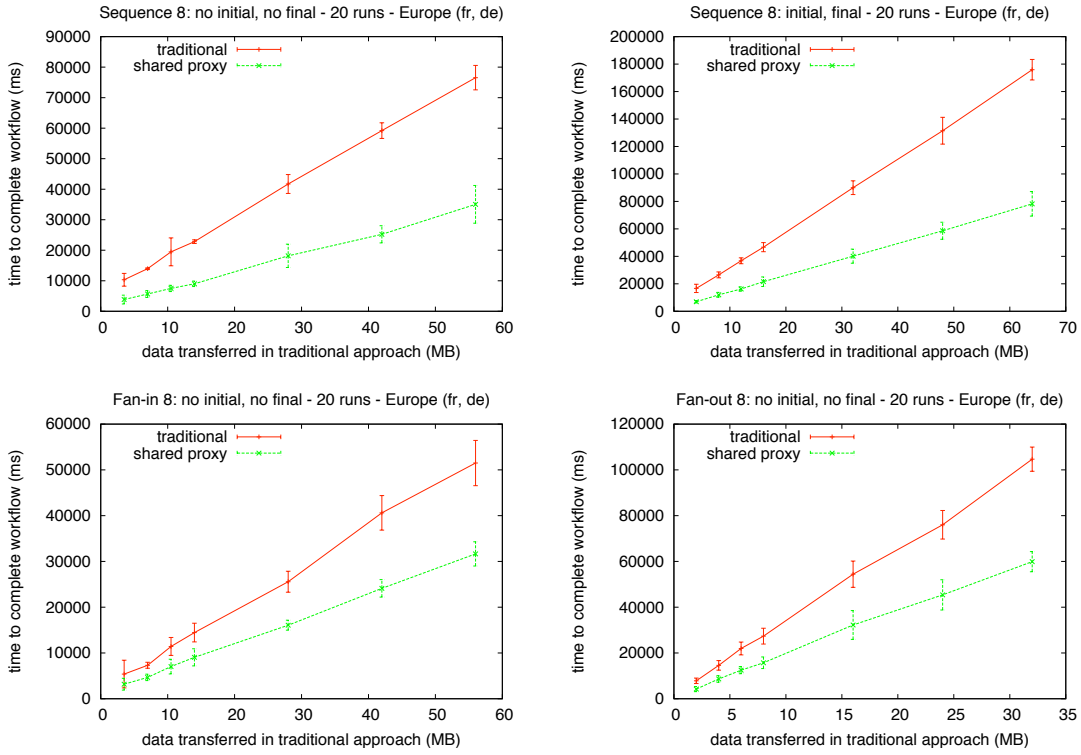


Figure 7.16: 8-node configuration (Europe) performance of hybrid and traditional model for the basic workflow patterns

pattern, is that the hybrid model completes the workflow execution in approximately half the time needed by the traditional model.

Having a single proxy allows analysing the data by ignoring any forwarding delays. Looking at the fan-out pattern, there seems to be little improvement in using the hybrid model. On average, the hybrid model executes the workflow in 0.85 of the time needed

Pattern	best perf. ratio	worst perf. ratio	av. perf ratio
seq_ninf	0.37	0.46	0.41
fan-in	0.59	0.64	0.62
fan-out	0.54	0.60	0.58
seq_if	0.41	0.46	0.44
Overall			0.51

Table 7.24: Performance change of hybrid model compared to traditional model for all patterns (Europe)

by the traditional model. One needs to consider however, that only a single proxy is used, and thus no forwarding costs are incurred.

In order to determine the reason for this unexpected behaviour, the individual runs need to be analysed. From the individual runs, no clear trend was found. Most proxy-to-workflow web service communication links were less expensive than the equivalent workflow engine-to-workflow web service communication link. A few however were more expensive and so some of the performance gains were lost.

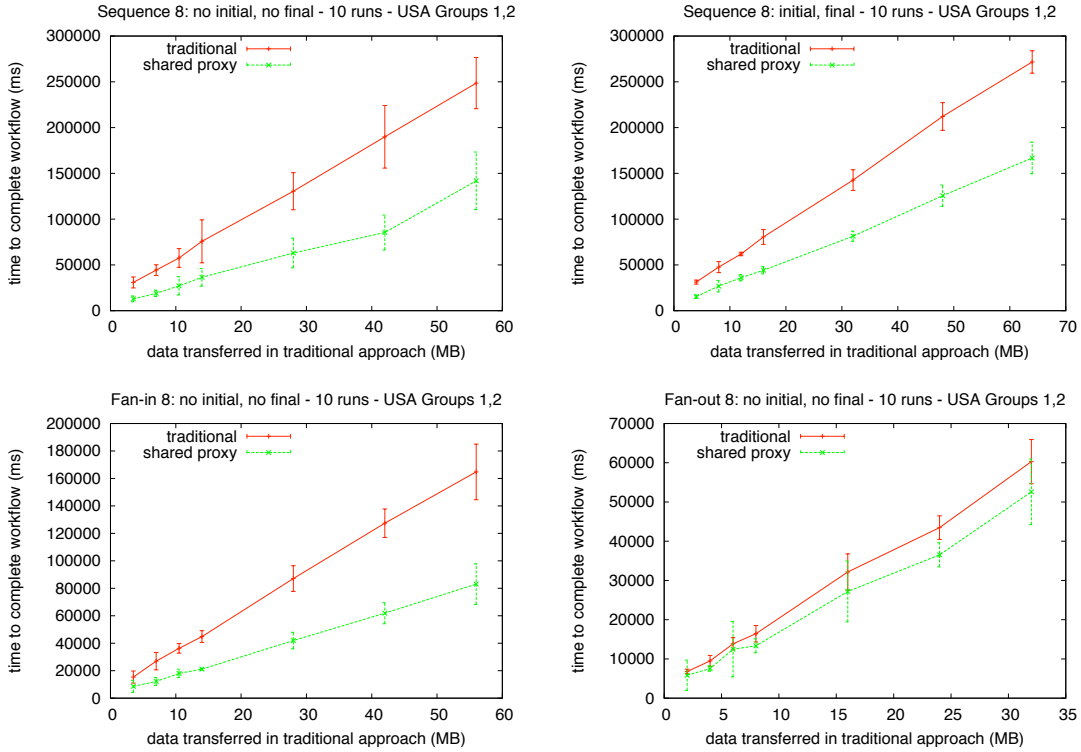


Figure 7.17: 8-node configuration (USA) performance of hybrid and traditional model for the basic workflow patterns

7.4.3 16-node configuration: World

One set of experiments was executed across all available PlanetLab nodes involved in the other experiments. The nodes were grouped based on their geographical location and the proxies used mirror the set-up of the previous experiments.

The results for the tests are shown in Figure 7.18. As can be seen in the figures, the seq_if is the only configuration in which the traditional approach outperformed the hybrid approach. When one examines the results presented in table 7.26, then one

can also see that with the exception of fan-in, the other workflow patterns had similar performance under both models.

For fan-out, the culprit for the performance degradation appears to be the proxy forwarding. As each proxy is located close to its workflow web services, the proxy-to-workflow web service communication may offer advantages to the hybrid model. However, proxies will eventually have to share data between themselves through forwarding. This forwarding may end up being costlier than any benefits gained.

7.5 Targeted tests

7.5.1 Node location

The Local and Remote LAN experiments examined the behaviour of the workflow patterns under each configuration. It would be useful to also compare the two configuration directly. Figure 7.19 presents two tests which differ only in the location of

Pattern	best perf. ratio	worst perf. ratio	av. perf ratio
seq_ninf	0.41	0.46	0.44
fan-in	0.45	0.56	0.49
fan-out	0.79	0.90	0.85
seq_if	0.49	0.61	0.57
Overall			0.59

Table 7.25: Performance change of hybrid model compared to traditional model for all patterns (USA)

Pattern	best perf. ratio	worst perf. ratio	av. perf ratio
seq_ninf	0.69	0.90	0.77
fan-in	0.38	0.52	0.43
fan-out	0.53	0.96	0.82
seq_if	0.96	1.26	1.11
Overall			0.78

Table 7.26: Performance change of hybrid model compared to traditional model for all patterns (World)

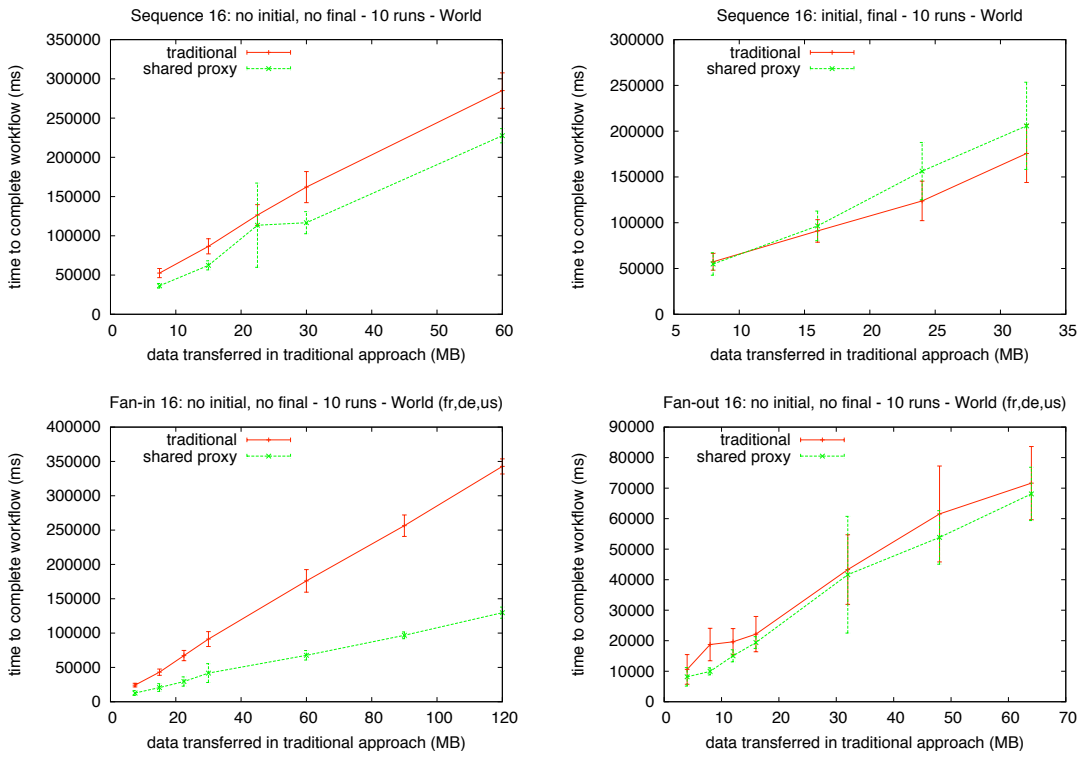


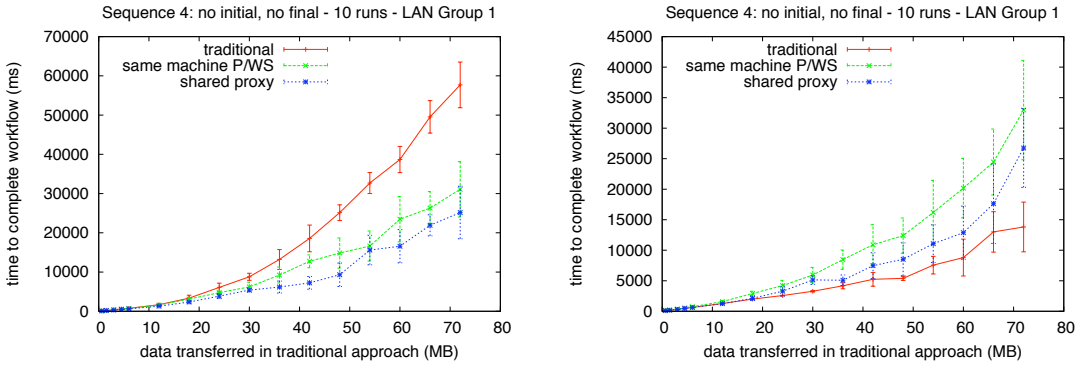
Figure 7.18: 16-node configuration (World) performance of hybrid and traditional model for the basic workflow patterns

the workflow engine. As can be seen, changing the location of the workflow engine manages to invert the order of best performing workflow executions. Without examining the specific network topology one cannot determine where to place nodes, whether those nodes are proxy nodes or workflow engine nodes. Note that these test also tested the number of WWS per proxy assignments. A targeted experiment for this variable follows.

7.5.2 Web services per proxy

Although some of the previous test used either 4 or 8 WWS per proxy, those experiments were not repeated using a different assignment. For that purpose another set of tests was executed using more extreme WWS to proxy assignments.

The seq_ninf experiment was repeated with 1 WWS assigned to 1 proxy (on the same machine), and compared both to the equivalent traditional model workflow and another instance of the hybrid workflow employing 4 WWS per proxy. The results of these tests are presented in Figure 7.20. In these set of results, one can see that both



Remote LAN Local LAN

Figure 7.19: seq_ninf (4-nodes, 20 runs) under different LAN configurations

proxy assignments produce near identical results. In all three tests, the two hybrid model workflows execute faster than the traditional model workflow. Although these results seem to indicate that fewer WWS per proxy are more effective, one can easily construct scenarios where the two hybrid model workflows do not have similar results.

7.6 General comments

In many of the experiments, one will observe a large standard deviation of values. This could be a distressing indicator, as any potential gains could be argued to be not significant. One needs to look at individual runs in order to determine whether this is due to network conditions, or an instability in the models. When looking at the individual runs, whenever an increase in the running time is observed, it was consistent throughout the run. This implies that the issue in the performance degradation may have something to do with a gradual change in network conditions rather than anything else.

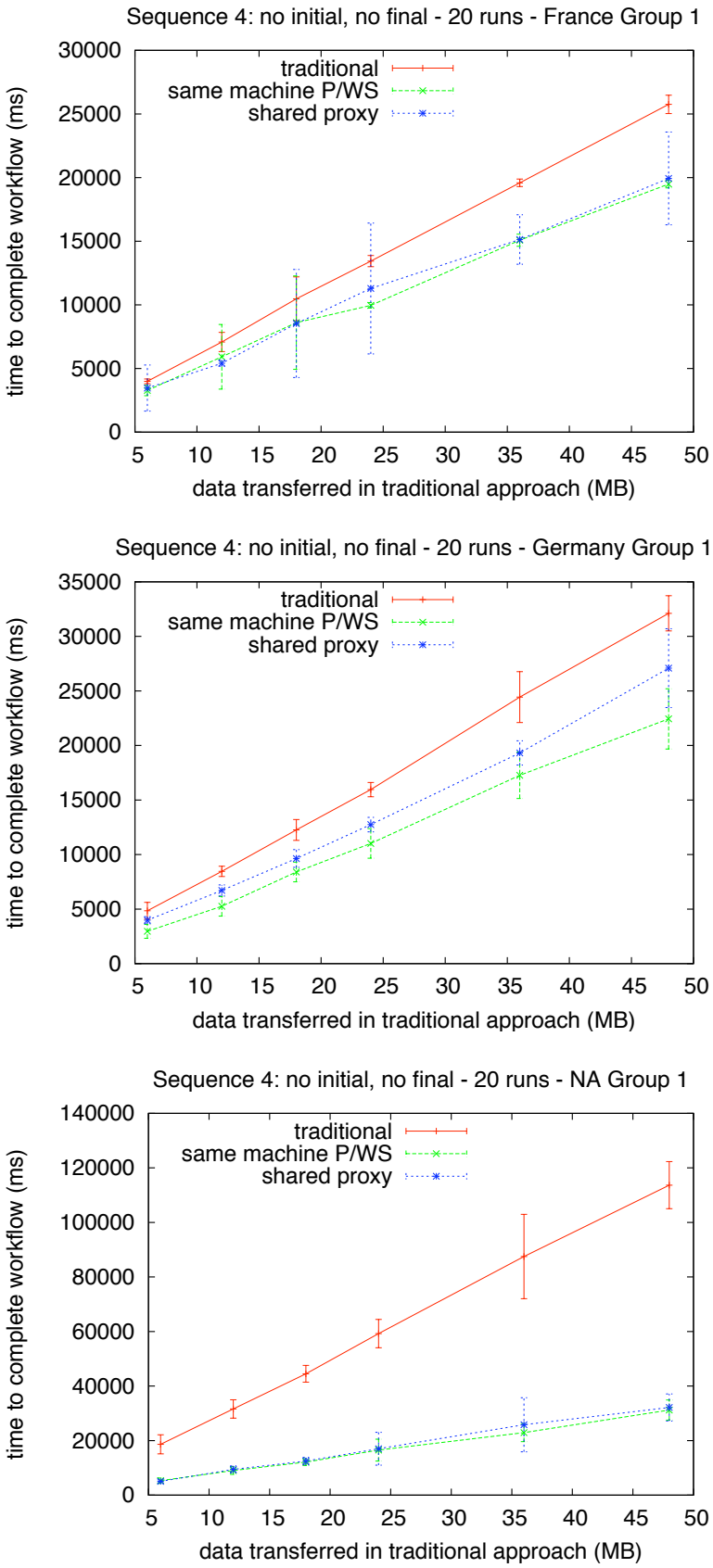


Figure 7.20: seq_ninf (4-nodes, 20 runs) with different proxy assignments

Chapter 8

Discussion

Would a statement concerning a potential performance vantage the hybrid model may have over the traditional model be conclusive or elusive? Previous results [11] indicate that beyond some message data size, the hybrid model outperforms the traditional model. This chapter attempts to address this issue by identify the relevant results and analyses produced by this project.

8.1 Conclusions

When one talks of whether or not the hybrid model has met its goals, it is important to establish the constraints within which this is judged. For example, the local LAN experiments have shown that this is not an environment where a proxy architecture would be beneficial. This of course would be a logical conclusion. If all links in a workflow have the same cost, and new links are added, then the cost would be higher.

Once the workflow engine was moved most workflows became 2-5 times faster than their equivalent traditional model ones. A LAN workflow with an external workflow engine is a reasonable configuration, though the PlanetLab testing would obviously be the most representative of real-world collaboration environments.

When executing experiments on PlanetLab encouraging results were observed. With the exception of one experiment which had a degraded performance when compared to the traditional model, all others saw improvements, with a 9-fold improvement also being observed. Most promising however was that in all cases, when all the workflow patterns were taken into account, the overall change was always beneficial and ranged from 128% to 222% improvement. This is important as it implies that even if one pattern is misbehaving, a workflow, which will probably be composed of an ar-

ray of patterns, will still experience improvements with the hybrid model. This result is especially useful since that enables end-to-end workflow to be executed while still obtaining an improvement (and not just workflow patterns).

One observation is that no single parameter can be used as a reliable predictor for the performance of the hybrid model. Using message data size without taking into account network topology is useless, as is taking into account network topology without taking into account network load. Nevertheless, one can use reasonable indicators to make predictions about the performance. For example, one could reasonably use relative distance or network speed as an indicator as to whether introducing the hybrid model (and its proxies) would improve the workflow execution time.

It would be safe to say that the hybrid model has met its goals, though its static configuration diminishes some of its potential benefits.

8.2 Future work

Having discussed the benefits of the hybrid model, our attention can turn at what else may be done in the future.

Although the overall results were promising, their unpredicability should dictate the direction taken in the future. One problem with the approach taken in this project is that the software system was static. The proxy assignments were determined prior to the begining of each experiment and they were not modified during testing.

Being able to dynamic change the overlay workflow (overlay being the set of proxies used), would allow the system to better tolerate unpredictable system behaviour. The current approach is beneficial if the proxies are chosen after examinint historical flow data. It would still be unable to overcome unpredictable behaviour, but in a stable network, this may not be an issue. Injecting dynamic choices into the workflow adds complexity to the system, but may improve its tolerance to unexpected network conditions.

A dynamic optimiser could also decide when a proxy should be avoided, so that the workflow engine invokes a web service directly. Experiments which combine the traditional and hybrid model have not yet been performed.

Another area that could be improved is the API for the proxy. The workflow engine, as implemented (with the proxy) for this project, needed to send additional control flow messages in order to achieve certain tasks. For example, it first had to invoke storeData on a proxy and then send a control message to instruct it to invokeWS with

the stored data. Although as the message size increases the cost of the control message is absorbed into the cost of sending the data, such delays could be avoided.

In addition, it may be worth investigating whether some choreography features could be added to the proxy. For example, the proxy could be informed of the next x operations in the workflow, and it would be able to determine whether it needs to do anything in the meantime (e.g., forward data).

Appendix A

Experiment configuration properties

This section includes samples of the configuration files used by the workflows engine.

- *machines.properties* contains a mapping of symbolic names (as used in the testing system) and actual machine names.
- *execution.properties* lists which experiments should be executed and using what parameters.
- *test.properties* is one such experiment which contains assignments of experiment machines to the actual machines

```
################################################

# test.properties

proxy.0=proxy.01
proxy.1=proxy.01
proxy.2=proxy.01
proxy.3=proxy.01
webservice.0=lan.01
webservice.1=lan.02
webservice.2=lan.03
webservice.3=lan.04

################################################
```

```
################################################

# machines.properties

# University of Edinburgh - AT 4.12 lab
lan.01=rosberg.inf.ed.ac.uk:18181
lan.02=wurz.inf.ed.ac.uk:18181
lan.03=brundle.inf.ed.ac.uk:18181
lan.04=hakkinen.inf.ed.ac.uk:18181
proxy.01=piquet.inf.ed.ac.uk:18181

# University of Edinburgh - AT 5 North lab
lan.05=axna.inf.ed.ac.uk:18181
lan.06=langraw.inf.ed.ac.uk:18181
lan.07=crane.inf.ed.ac.uk:18181
lan.08=rode.inf.ed.ac.uk:18181
proxy.02=ain.inf.ed.ac.uk:18181

# University of Edinburgh - AT 5 North lab
lan.09=turbitail.inf.ed.ac.uk:18181
lan.10=monotreme.inf.ed.ac.uk:18181
lan.11=yarpha.inf.ed.ac.uk:18181
lan.12=tapley.inf.ed.ac.uk:18181
proxy.03=farsorr.inf.ed.ac.uk:18181

# University of Edinburgh - AT 5 West lab
lan.13=nannup.inf.ed.ac.uk:18181
lan.14=yallingup.inf.ed.ac.uk:18181
lan.15=busselton.inf.ed.ac.uk:18181
lan.16=vasse.inf.ed.ac.uk:18181
proxy.04=jak.inf.ed.ac.uk:18181

################################################
```

```
################################################

# execution.properties

# experimentName is the name by which the project is referred to
# testName is the name by which an experiment can be loaded
# iterations is the number of times to repeat the test
# config is the name of the properties files with the node assignment
# values are comma separated numbers representing the basic data unit
#     size for the experiment

experimentName=testName%iterations%config%values

################################################
```

Appendix B

Possible optimisations

The hybrid model was expected to be a non-intrusive substitute to the existing centralised orchestration model. As such, it has been designed so that it make minimal requirements of its environment or it's interacting peers. This has meant that certain features which may have improved its performance had to be excluded.

If one were to do away with the existing traditional orchestration model, then it's possible that some of these conditions would be relaxed. Alternatively, one could consider employing these ideas for the proxy-proxy communication or perhaps even P-WE communication. Such a solution would be non-disruptive to the workflow web services.

B.1 Data handling

Although ignored in this project, data transformation may be necessary in workflows and it may be worth considering how the proxy could be change to accommodate for this.

One approach is to extend the proxy so that it performs data transformations and processing. If the proxy performed the data transformations independently, then the hybrid model would no longer be flexible (i.e., changing the web service interface requires altering the proxies). As the workflow engine has global knowledge about the workflow web services it supports, it can inform the appropriate proxy of how to manipulate the data. This would increase the size (and possibly number) of control messages exchanged, but would avoid transferring the data to the workflow engine for processing.

Another approach would be to provide web services which can process messages

between web service operation invocations, i.e., introduce additional flows in the workflow. As the hybrid model is considered to be non-disruptive, this approach would not be suitable.

The final approach would be to allow the workflow engine to perform the data transformations locally. That is, whenever the data needs to be transformed before it is used by some workflow web service, the proxy which contains the data would be instructed to send the data back to the workflow engine.

Which approach should be used is debatable and may very well depend on the existing workflow. If in the current workflow the workflow engine and transforms the data, it would be beneficial to delegate such tasks to the proxies (and incurring additional control flow costs). If the current workflow already uses web services for its transformations, then the issue is mute as the transformation is considered to be part of the workflow. Note that in scientific workflows (moreso than in business workflows), the web services might already be tightly coupled, so such issues might not arise.

If the proxies are able to transform the data, further optimisations to the workflow might be possible. For example, if a transformation increases the size of a message, then unaltered message can be sent to the proxy handling the next invocation and let it transform the data.

B.2 Web service extensions support

The web services considered in this project are those for which synchronous communication would not create problems (e.g., TCP connection timeouts). There are many cases where asynchronous communication would be beneficial. An example of this would be the invocation of a long-running web service operation. The time between invocation and return of the response (i.e., propagation, processing and computation), may exceed any connection timeouts used. Asynchronous communication would allow for the connection to be closed and for the web service to initiate a new connection when it has the data ready. A solution to this issue is provided by WS-Addressing, a web service extension which allows the invoker to provide the address to which the response should be sent.

WS-Addressing and other web service extensions are not considered in this project, though they have been identified as useful to scientific workflows [20]. This is because there is no guarantee that the web services used in a workflow would employ or support web service extensions. One could argue that the introduction of proxies (if imple-

mented as web services) into the orchestration model would allow for the use of web service extensions, at least for the proxy-proxy communication. However, one needs to also consider the deployment of the proxy. If implemented as web services, then the web services would be deployed in an application container. The optimal deployment for proxies would be to be deployed in the same container as the web services it will be invoking. Since no guarantees can be made that all involved web containers would support the relevant web service extensions, this situation is also not considered.

This conforms to the general notion of scope described above. If an existing workflow employed web service extensions, then the hybrid workflow will continue to use the extensions. The caveat in this case is that the workflow semantics (and web services) may need to be altered to incorporate the proxies. This may be necessary for example with security extensions that restrict who may invoke web service operations.

B.3 Message optimisation

A number of different approach could be used to improve the SOAP message processing of the proxy architecture. Currently the project exchanged base64 binary messages, which are converted from binary to text in order to be sent over the SOAP message.

- Encode the message. This could be a custom encoding or some other binary encoding.
- Modify the message fragmentation. It may not always be possible to process the largest of messages. Message fragmentation for web services makes this possible,
- XML Infoset + SOAP Message Transmission Optimization Mechanism (MTOM). When dealing with binary data, the MTOM solution (which uses XML Infoset) stored binary data separately.
- Abandon the SOAP stack. Message exchange could continue using just TCP.
- Single control connection. Control flow messages could always be directed to a well-known server. Having an open control flow connection would avoid the overhead of opening a new connection.
- HTTP-gzip. HTTP allows for data to be posted in a zip format. As SOAP will use the HTTP, then it may be useful to compress the payload.

B.4 Simpified proxy stack

The proxy acts as a passthrough for all its actions. Data is provided by the workflow engine (or the workflow web services) as are control messages to be acted upon. The SOAP overhead however is imposed on all interactions of the proxy, as it continues to behave as a web application.

The proxy could be simplified by letting it assume that anything received from another proxy, workflow engine or workflow web service, is valid. It could operate at a lower level protocol (e.g., TCP) and avoid much of the message processing costs.

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