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Scalable Online Simulation for Modeling Grid Dynamics

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by

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PUBLICATIONS

X. Liu and A. Chien, *Realistic Large Scale Online Network Simulation*, the ACM Conference on High Performance Computing and Networking, SC2004, Pittsburgh , Pennsylvania, November 2004.

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ABSTRACT OF THE DISSERTATION

Scalable Online Simulation for Modeling Grid Dynamics

by
Xin Liu
Doctor of Philosophy in Computer Science
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Professor Andrew A. Chien, Chair

Large-scale grids and other federations of distributed resources that aggregate and share resources over wide-area networks present major new challenges because they couple the behavior of resources and networks. These infrastructures support a new breed of applications which interact dynamically with their resource environment, making it critical to understand dynamic application and resource behavior to design for performance, stability, and reliability. Coupled use means that accurate study of dynamic applications, middleware, resource, and network behavior depends on coordinated, accurate, and simultaneous simulation of all four of these elements. Thus, the long-term challenge is to support scalable, high-fidelity, online simulation of applications, middleware, resources, and networks to support enable scientific and systematic study of grid applications and environments. That challenge is the focus of this dissertation.

We define the problems in performing large-scale, high-fidelity, online simulation. We consider a number of approaches, and then present our approach in detail. Our approach includes a set of techniques which enable the use of real application and middleware software, and modeling of essentially arbitrary network and resource properties. These techniques include resource virtualization via application interception, computation resource simulation

based on soft real-time scheduling, and packet-level online network simulation. Our studies and experiments show that these techniques can support simulation experiments with complex software packages as well as resource and network structures.

While most of the techniques in our approach are inherently scalable, one major challenge is online network simulation – which we implement as a parallel distributed discrete-event simulation, well-known to be challenging to scale. A range of techniques for scaling our online network are studied. Exploiting advanced graph partitioners, we explore a range of edge and node weighting schemes based on a variety of static network and dynamic application information. While simple approaches do not achieve acceptable load balance, our studies show that detailed network structure and behavior can be combined with the graph partitioners to achieve both good load balance and parallel efficiency. For example, our improvements increase efficiency and scalability by over 100 times, achieving a parallel efficiency of over 40% on 90-node clusters for a range of experiments.

Our online simulation techniques are embedded in a working simulation tool, the MicroGrid, which enables accurate and comprehensive study of the dynamic interaction of applications, middleware, resource, and networks. We present experimental results with applications which validate the implementation of the MicroGrid, showing that it not only runs real grid applications and middleware, but also accurately models underlying resource and network behavior. Our scalability experiments show that our load balance algorithms are effective, and the best of them, hierarchical profile-driven load balance, scales well, enabling simulation networks of 20,000 routers with 90 cluster nodes. This is the largest detailed network simulation ever performed, and corresponds in size to a large ISP's network. Realistic packet level network simulation with tens of thousands of routers enables accurate study of grid and network dynamics at unprecedented scale, and we believe great opportunities for new insights.

Chapter 1 Introduction

1.1 Emergence of Grid Computing

Increasing network performance, computation power, maturing distributed software structures, and the growth of the Internet are enabling the emergence of novel types of computation, communication, and resource sharing. These technical changes mirror an increasing trend, in the scientific and commercial worlds towards collaboration and sharing in larger and larger communities. Based on the growth and abundance of network connected systems and bandwidth, these pools of shared resources, grids, allow geographically distributed organizations to share applications, data and computing resources. Within a grid, networked resources -- desktops, servers, storage, databases, even scientific instruments -- can be combined to deploy massive computing power wherever and whenever it is needed most. Grids can also enable dynamic and flexible sharing of data (and thereby information) across diverse organizations, with controlled access. Users can find resources quickly, use them seamlessly, and allow resource providers to manage them efficiently. These emerging grid systems already comprise thousands of hosts and terabytes of data, and continue to grow in scale.

The growth of both deployment and use of grid environments (EuroGrid [1], TeraGrid [2], Grid2003 [3], and PlanetLab [4]) is rapid – driven by business pressures to reduce management cost and increase resource efficiency, as well as to accelerate the process of designing and deploying information technology solutions. A number of grid middleware projects have been developed to enable access to grid resources, such as Globus [5], Legion [6], Condor [7], NetSolve [8], and GrADS [9]. Moreover, ranging from a computational project which searches

for extraterrestrial intelligence (SETI@home [10]) and other desktop computing examples (GIMPS [11], Entropia [12], Folding@Home [13], etc.) to more recent molecular modeling for drug design, brain activity analysis, and high energy physics [3], academic researchers have been using Grid technology to solve large complex problems that require collaboration of multiple organization, including scientific disciplines ranging from high-energy physics to the life sciences.

Today, an increasing number of commercial enterprises are deploying grid technologies developed in the scientific research community to improve their utilization of computing resources, as well as to provide new capabilities. Essentially, all major computer software and service provider companies, including IBM [14], HP [15], Sun [16] and Oracle [17], have adopted grid technologies, and have begun to address the wide range of technology and business issues. Their products offer a range of software toolkits for creating and hosting grid services, federating data, describing applications, and mean to provide grid solutions for enterprise computing and e-commerce. In fact, grid computing has become a widely adopted technology in a number of industries, including life sciences, financial services, energy, and aerospace [18].

While grid technologies aggregate and share resources over wide-area networks to support applications at unprecedented levels of scale and performance, they also raise the critical issue of grid dynamics. First, grid applications couple network behavior with computation and storage devices (end resources). As a result, understanding the behavior of even single applications or resources requires integrated study of both networks and end resources. Second, because grids are based on sharing resources, a natural competition for these resources does exist among users. With uncontrolled application behavior, computation and network load in the system may vary dramatically. In open grid systems, where users and applications can enter without admission control, this competition may be extreme, producing unstable resources and effective denial-of-

service for applications. Even at modest load factors, large applications or even malicious users may compete for shared resources, affecting the performance of each other greatly. In fact, each application may act dynamically in an attempt to improve its performance, but the aggregation of these actions may have dramatic adverse impact on overall grid behavior.

1.2 The Problem

Understanding grid dynamics and their effect on application performance and grid resources is a critical problem. To support grid applications and large-scale grid environments running a broad variety of critical commercial, scientific, and societal functions, we must be able to engineer resource stability, application performance stability, application quality of service, and also efficient resource utilization. As a community, our current capabilities for such design are limited, both in the context of grids and in the larger context of distributed systems. It is no exaggeration to say that our understanding of Internet, distributed application, end resource, and grid dynamics is quite limited.

While research continues apace, current grid middleware systems and environments provide only the basic mechanisms needed for execution in a grid. We have little understanding of how to combine dynamic resource allocation, quality of service provisioning, and application performance models to achieve a desired design goal of resource stability, application stability, predictable behavior, guaranteed quality of service, etc., in an open, shared, efficiently utilized grid environment. Current practice is to evaluate the middleware and applications in a handful of small scale grid environments before being released for use in large production grids. Only after some time, based on ad hoc testing and use, is their dynamic behavior under typical circumstances understood. However, even at this point, we have limited understanding of their dynamic properties in novel circumstances, such as different resource environments, competitive resource demands, or failure modes. In fact, as evidenced by the 2003 electrical

power grid failure [19], understanding of such circumstances is a critical element of risk assessment. Further, we lack the tools to perform such studies either analytically or empirically.

Low-end pervasive or ubiquitous computing systems (i.e. Jini, Windows CE, Cell phone, etc.) systems have similar needs. These applications often depend on open shared resource environments, which strive to ensure application quality of service, and are subject to large fluctuations in load (which may arise from crowds of devices!). While the structure of solutions for pervasive computing and grid systems may ultimately differ, the simulation and modeling needs for coupled network and resource modeling are remarkably similar.

In brief, understanding the dynamic behavior of grid environments (applications, middleware, resources, and networks) remains an open research challenge, and the subsequent engineering need to ensure resource stability, application performance stability, application quality of service, and also efficient resource utilization remains daunting. This problem motivates us to build empirical tools for characterization described in this dissertation.

1.3 Insufficiency of Previous Approaches

Traditionally, distributed applications and networks have been studied separately – each community employing relative simple models for the other domain. For example, distributed systems researchers often use simple latency, bandwidth, and reliability models for networks, while networking researchers use application models based on basic web-browsing or other simple models of application workloads. These methodologies have produced significant advances, but we are increasingly faced with the reality that a broad range of distributed applications are now strongly network dependent, and that their performance depends directly on detailed dynamic network properties, such as packet loss, protocol behavior, latency, bandwidth, etc. While significant advances have been made in aggregate modeling of network

behavior [20, 21], at present, only detailed packet-level studies, or close analogs, can accurately model protocol dynamics, particularly in more extreme cases [22, 23]. At the same time, increasingly complex and dynamic applications can have a dramatic impact on networks performance; some examples include, peer-to-peer file sharing, viruses such as MyDoom, and multi-gigabit stream transfers for scientific applications. In particular, peer-to-peer file sharing and multi-gigabit scientific applications are exemplary of a future generation of applications which are highly network performance aware, and subsequently, adapt their behavior--and thereby network use--rapidly and drastically, in response to the experienced network performance. These concurrent changes motivate a strong need for integrated simulation and modeling of distributed networks. Further, the increasing complexity and adaptive behavior of applications and middleware motivate the use of integrated simulation tools, which enables these complex software systems to be used directly – accurate modeling is difficult.

In summary, traditional approaches are insufficient for accurate modeling of grid applications. Using simple network modeling is often inaccurate, and building application performance model may be infeasible and may elide subtle, yet critical, performance details. We believe that integrated simulation tools, which allow direct use of complex system and detailed network modeling, are a most promising practical solution. Real testbeds have a range of advantages, but any single real grid is inflexible and limited in scalability, when compared to simulation tools. Furthermore, real testbeds are far more expensive than simulation-based approaches. Thus, the rapidly evolving needs of application, middleware, grid, and network designers as well as users and operators demand integrated simulation tools. Without tools that integrate resource, network, and software system modeling, accurate study of grid application and system dynamics is impossible.

1.4 Approach: Online Simulation

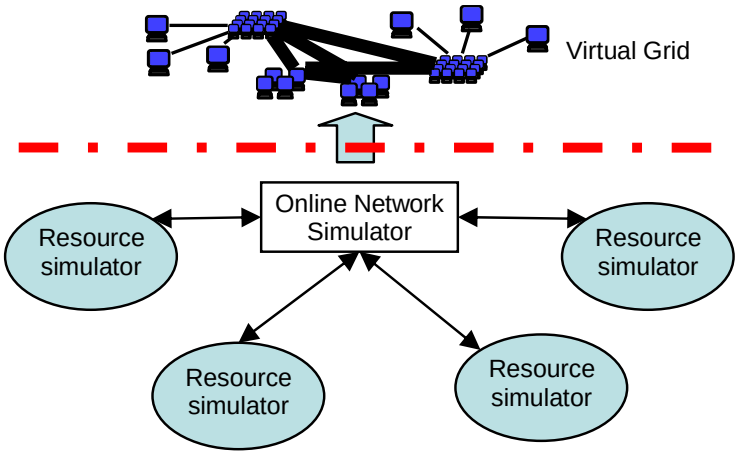


Figure 1.1 Integrated Online Simulation

Our approach is to develop and design an integrated online simulation system (see Figure 1.1), which supports direct execution of real applications within a simulated grid environment. This system will enable scientific and systematic study of dynamic applications, middleware, resources, and network behavior. Furthermore, it should provide a vehicle for observable, repeatable study and systematic exploration of design spaces for a wealth of application and middleware design problems, exploration of rare or extreme situations, rational choices in application deployment, grid resource allocation, and network design.

To achieve the goal of integrated online simulation, critical sub-problems include resource virtualization, resource modeling, online network simulation, and global coordination, which combines the resource modeling modules. There are many challenges and open questions in the area. The critical questions are:

1) How do we support a virtual (simulated) grid environment? How do we provide information services within the virtual grid?

2) How do we provide this illusion of a virtual grid efficiently?

3) How do we provide accurate resource modeling for computation, storage, and network? How much fidelity is enough?

4) How do we provide a scalable online simulation of networks, given large networks with bursts of traffic loads, highly distributed applications, and complex dynamic interactions between applications, networks and resources?

5) How do we support multiple simulation modules in a single experiment?

As we will show in this dissertation, accurate and comprehensive study of the dynamic interaction of applications, middleware, resource, and networks is possible with scaled real-time online network simulator, and can as well be used to simulate and understand complex grid behavior

For computational modeling, efficiency is a critical issue, as we need to construct virtual grid environments with large numbers of resources in order to run large numbers of complex grid applications. Accuracy is a second priority, but the level of accuracy must remain steady enough to support direct execution of applications. In our approach, this is achieved through the use of soft real-time process scheduling, combined with resource virtualization based on virtual host identity.

The network model provides the communication and coordination which couples the resource simulation modules. It is addressed by using detailed packet-level simulation and realistic network routing protocols, which makes scalability the major remaining challenge for network modeling. To address scalability, we use parallel discrete-event simulation enhanced by sophisticated load balancing algorithms which exploits a range of static network and dynamic application information, distributed network simulation. Our experiments demonstrate that our approaches can achieve scalable parallel discrete event simulation, while supporting high fidelity simulation of a large grid system.

An important concept in our approach is scaled real-time execution. To guarantee correct interaction between different simulation components, the components should make progress at the same pace. Scaled real-time execution achieves the desirable effect of global coordination while providing more flexibility, when simulating larger or faster virtual resources with limited physical resources.

1.5 Contributions

The primary contribution of our work is to introduce a scientific instrument for study of Grid dynamics, the MicroGrid. This system enables a novel approach to the study of the interaction between applications, middleware, resources, and networks via online simulation at full scale. Individual contributions are summarized below:

1) A Simulation Framework which enables flexible and accurate virtual grid modeling.

We proposed a scaled real-time online simulation mechanism to study application performance directly. Its capabilities include instrumentation needed to capture real application detail, flexible network modeling and configuration. Coupled with our soft real-time process scheduling mechanism, it can provide a high fidelity virtual grid modeling environment.

2) A Formulation that maps the critical load balancing problem of network simulation to a graph partitioning problem, and solves it with graph partitioners, to improve the scalability of network simulation.

Exploring a range of edge and node weighting schemes based on a variety of static network and dynamic application information, we designed and evaluated three weighting mechanisms, and demonstrated that, compared to topology-based techniques (TOP), adding application placement information (PLACE) improves load-balance significantly, while adding profile information (PROFILE) enables improvements of 50-66%.

3) Load-balancing mechanisms which improve the simulation efficiency and scalability for large-scale network simulation.

While this mechanism can be integrated with the three former algorithms, the hierarchical profile-based load balance approach (HPROF) demonstrates the best performance in simulating large scale network. It is shown that HPROF can increase efficiency and scalability by over 100 times, achieving a parallel efficiency of over 40% on 90-node clusters, for a range of experiments.

4) Large-scale detailed packet level network simulation, with realistic network topology and network routing structures (100 AS with 200 routers in each AS, BGP4 and OSPF routing).

In addition to detailed modeling of OSPF and BGP routing protocols, we developed a set of heuristics for automatic realistic BGP routing configuration as an improvement to Internet-like topology generation.

5) A System which achieves accurate grid dynamic study at unprecedented scale.

We implemented and validated the MicroGrid toolkit prototype. Simulation experiments of different large-scale network topologies and applications on Linux clusters show that our implementation is scalable. Using a 128 node cluster, we are able to accurately simulate a network with 20,000 routers, which is comparable to a large ISP network.

1.6 Dissertation Roadmap

The rest of this dissertation is organized as follows. Chapter 2 provides a simple introduction on current approaches for application performance modeling, and some background on parallel and distributed discrete event simulation and graph partition algorithms. Chapter 3 presents the specific context of our work, defines the problem we address, and provides our dissertation statement and criteria for success. We introduce our approach to the

problem, scaled real-time online simulation, in Chapter 4. Chapter 5 presents the details of our MicroGrid design and implementation, which includes the soft real-time process scheduling, online network simulation, and the load balancing algorithms for larger scalability. The MicroGrid system is validated in Chapter 6, and experiments on different network topologies and applications are used to show the scalability of the MicroGrid systems in Chapter 7, focusing on the effect of our load balancing algorithms. After that, the MicroGrid is used on two real network related research experiments in Chapter 8. We discuss related work in Chapter 9 and conclude in Chapter 10 by summarizing and discussing future research directions.

Chapter 2 Background

In Section 2.1, we give a simple introduction of current approaches for application performance modeling. After that, we present some background for understanding the reminder of the dissertation. Section 2.2 introduces some basics of parallel and distributed discrete-event simulation, which is a key base of our network simulator. Then Section 2.3 introduces the graph partitioning algorithms used in our load balance studies of network simulation.

2.1 Application Performance Modeling

In this section we introduce four methods that have been used for network distributed system and Grid experiments to evaluate dynamic behavior: network simulation, Grid modeling, emulation, and real testbeds.

2.1.1 Grid Modeling Toolkits

A wide range of software tools [24] provide general-purpose discrete-event simulation or even more focused Grid simulation libraries. The notable ones are Bricks[25], MONARC[26], GridSim[27] [28], and SimGrid[29].

The Bricks simulation system [25], developed at the Tokyo Institute of Technology in Japan, helps in simulating client-server global computing systems that provide remote access to scientific libraries and packages running on high-performance computers. Bricks is designed using an object-oriented discrete-event simulation framework and implemented in Java. Bricks provides a Brick script language that enables the user to setup configuration and parameters of

the Global Computing Environment. The user resorts to building “bricks” within the script to build and evaluate a variety of simulations.

The MONARC (Models of Networked Analysis at Regional Centers) [26] simulation framework is a design and modeling tool for large-scale distributed systems applied to High Energy Physics experiments. It is an object-oriented discrete event simulator, written in Java. The tool employs a process-oriented approach for flexible simulation, and consists of threaded objects or “Active Objects”. The framework provides a complete set of basic components (processing nodes, data servers, network component) for easily building complex computing model simulation.

The GridSim [27], developed at University of Melbourne in Australia, supports modeling and simulation of heterogeneous Grid resources, users, applications, brokers and schedulers in a Grid computing environments. It provides primitives for creation of application tasks, mapping of tasks to resources and their management so that resource schedulers can be simulated to study the scheduling algorithms involved. GridSim is based on the event-driven discrete event simulation engine SimJava [28].

The SimGrid[29] toolkit, developed at UCSD, is a C language based toolkit for the simulation of application scheduling. SimGrid aims at providing the right model and level of abstraction for studying Grid-based scheduling algorithms. It supports modeling of resources that are time-shared, and the load can be injected as constants, or from real traces. Using SimGrid API, tasks can be assigned to resources, depending on the scheduling policy being simulated.

The primary limitations with all of these grid modeling tools is that they do not allow easy use of existing applications and grid middleware, and thus, the results achieved are only as good as the models which are developed for these complex pieces of software. In addition, these tools typically have simple models of networks and protocols – known to be inaccurate. Most

important, no direct experimentation with applications, middleware, networks, and grid resources is supported.

2.1.2 Network Simulation

Many research efforts explore network and computation simulation systems and techniques in order to model a wide range of distributed systems and networks. However, in early systems, distributed applications and networks have been studied largely separately – each community employing relative simple models for the other domain. These separate tools cannot be easily composed. For example, many network simulators based on packet-level discrete-event simulation that have been built which provide accurate network environment (e.g. NS-2[30], GloMoSim [31]，and PDNS [32]).

NS-2 [30] is a sequential discrete-event simulator that enables the simulation of Transport Control Protocol (TCP), routing and multicast protocols over wired or wireless networks. NS-2 allows network researchers to study and evaluate specific network protocols under various network conditions, an essential step to understand their behavior and performance.

PDNS[32] is an extension of NS-2 with improvement in capacity by using distributed hardware. In order to achieve the goal of limited modifications to the base NS software, we chose to use a federated simulation approach where separate instantiations of NS modeling different sub-networks are executed on different processors.

GloMoSim[31] is designed to support simulation of very large wireless mobile networks with thousands of nodes. It is developed based on the Parsec parallel simulation language. GloMoSim can be used to simulate specific wireless communication protocols in the protocol stack.

In terms of grid environment, a common issue of these tools is that they can only capture part of what is relevant to future distributed systems which couple resources and networks, and

have adaptive applications. They do not model other resources and they do not enable the network simulations to be coupled directly to applications. While it is possible to write application module for the simulators, the process is labor-intensive, since the applications may evolve rapidly. Furthermore, the abstraction and approximation can lose subtle details which may be important to application behaviors and performance, since the users may not understand the application well.

2.1.3 Network Emulation

Emulation refers to the ability to introduce the simulator into a live network; it can be used to study the application performance directly. Usually, network emulation supports direct application execution and intercepts the live application traffic transparently. However, instead of using network simulator, it usually uses software routers or simulated routers to approximate the network behavior.

The dummynet[33] is the most popular of this category. As a flexible bandwidth manager and delay emulator, dummynet permits the control of network traffic going through the various network interfaces, by applying bandwidth and queue size limitations, and simulating delays and losses. In its current implementation, packet selection is done with the *ipfw* program, by means of "pipe" rules. A dummynet *pipe* is characterized by a bandwidth, delay, queue size, and loss rate, which can be configured with the *ipfw* program. Pipes are numbered from 1 to 65534, and packets can be passed through multiple pipes, depending on the *ipfw* configuration.

NSE [34], an adaptation of NS-2, also has an emulation facility. When using the emulation mode, a soft real-time scheduler is used, which ties event execution within the simulator to real time. Provided sufficient CPU horsepower is available to keep up with arriving packets, the simulator virtual time should closely track real-time. If the simulator becomes too slow to keep

up with elapsing real time, a warning is continually produced, if the skew exceeds a pre-specified constant threshold.

The benefit of emulation approach is the speed, since it is required to be fast enough for real-time execution. However, it is either limited by scalability, or by the accuracy of network modeling. For example, the dummynet cannot capture the congestion of multiple flows on a single path, since every flow behavior is modeled independently, and there is no global coordination. The NSE uses detailed network modeling based on a sequential simulator; its capability is limited for large network emulation. To address these issues, there are many other on-going research projects on advanced emulation, such as ModelNet [35] and Emulab [36]. However, as we will show in related work in Chapter 9, they have major difference with our online simulation approach, and they are not sufficient for our virtual grid modeling target.

2.1.4 Real Testbeds

Real testbeds use a specific set of real resources for experiments, such as PlanetLab [37] [37], TeraGrid [2], and GrADS testbed [9]. Real testbeds have the advantage of providing high speed execution and, of course, realistic execution. However, actual testbeds have a number of limitations, including: (i) limited experimental configurations (cannot run experiments for a wide range of platform scenarios, or for platforms or networks that do not exist); (ii) non-observability – phenomena occur which are not observable in routers, systems, networks, etc., and (iii) reproducibility – phenomena occur which cannot be repeated to be understood. These barriers are a real limitation to understanding important behaviors, and thereby, deeper understating of the dynamics behaviors. We believe that simulation tools such as the MicroGrid are an essential complement to the use of real testbeds.

2.2 Parallel and Distributed Discrete-Event Simulation

The foundation of the Microgrid, online network simulation, is at parallel and distributed discrete-event simulation at the packet level.

2.2.1 Discrete-Event Simulation

Simulation is the imitation of the operation of a real-world process or system over time. Some real-world systems are so complex that models of these systems are virtually impossible to solve mathematically. Numerical computer-based simulation can be used to mimic the behavior of the system overtime. Data can be collected from the simulation as if a real system were being observed.

A simulation should contain (1) state variables to represent the state of the physical system, (2) some logic and rules on state variable update to model the evolution of the physical system, and (3) some representation of time.

Usually a simulation consists of two layers. The first layer is the simulation engine, which provides the basic components of time, entity, event, channel, and process. The second layer, simulation model, builds upon the simulation engine and provides the virtual representation of real world systems.

2.2.1.1. Simulation Time

Time, in particular simulation time, is a very important concept in the simulation. There are several different notions of time that are important when discussing a simulation.

Physical Time: the time in the real-world system.

Simulation Time: an abstraction used to model physical time. It is defined as a totally ordered set of values where each value represents an instant of time in the physical system being modeled. Sometime it is also referred as virtual time.

Wall-clock Time: the time during the execution of the simulation program

The progression of simulation time during the execution of the simulation may or my not have a direct relationship with the progression of wall-clock time. Simulations can be classified according to their relationship:

1) Real-time Simulation: the simulation time advances as fast as the wall-clock time. This kind of simulation usually involves interaction between simulated and physical systems (like human participants in a training exercise).

2) Scaled Real-time Simulation: the simulation time advances faster or slower than wall-clock time by some constant factor. For example, the simulation may be paced to advance 1 second of simulation time for each four seconds of wall-clock time, making the simulation appear to run four times slower than the real world. This technique is often used when the simulation cannot keep up with the speed of the real system with available physical resources, such as in our online network simulation at Chapter 4.

3) Non-constraint Simulation: there is no relationship between the simulation time and wall-clock time. It can make progress as fast as possible. This approach is usually used in pure simulation.

2.2.1.2. Discrete-Event Simulation

Simulations that utilize a discrete event system are called discrete-event simulations. Most simulation systems can be categorized as either discrete or continuous though, “Few systems in practice are wholly discrete or continuous, but since one type of change predominates for most systems, it will usually be possible to classify a system as being either discrete or continuous” [38]. A discrete system is one in which the state variable(s) change only at a discrete set of points in time. For example, the computer network can be treated as a discrete system by setting appropriate state variables. If we treat a network packet as the minimal unit of the

network model, then system events (packet send, packet arrival, and packet dropping) only happen at a discrete set of points in time. So the system state variables, such as packets number in a queue, only change at discrete points.

```
While (simulation is going) {
    Remove the event with smallest time stamp from event list
    Set the simulation time to the time stamp of this event
    Execute the event handler, it may put new events to the event list
}
```

Figure 2.1 Main Loop in an Event-driven Execution

Discrete event simulation can work in an event-driven execution mode. In discrete event simulation system, the simulation time is a set of totally ordered values, representing state variables that are updated when “something interesting” occurs. The “something interesting” is referred to as an event, where an event is an abstraction to model some instantaneous action in the physical system. An event may change state variables and create new events. Each event has an associated time stamp indicating the simulation time that the event occurs. So the simulation time jumps from one event to the next event. The simulator maintains a priority queue of events following the timestamp order, and always handles the next event with the smallest timestamp (Figure 2.1).

Event-driven execution can be combined with real-time or with scaled real-time modes by preventing the simulation from advancing to the time stamp of the next event until wall-clock time has advanced to the time of this event.

2.2.2 Parallel and Distributed Simulation

When the simulated system becomes too complex to be simulated by a single computer node, it can exploit parallel and distributed simulation. The complex physical system can be viewed as being composed of some number of subsystems and each subsystem can be simulated

by a logical process (LP), and interactions between physical subsystems can be modeled by exchanging time-stamped messages between the corresponding logical processes (Figure 2.2).

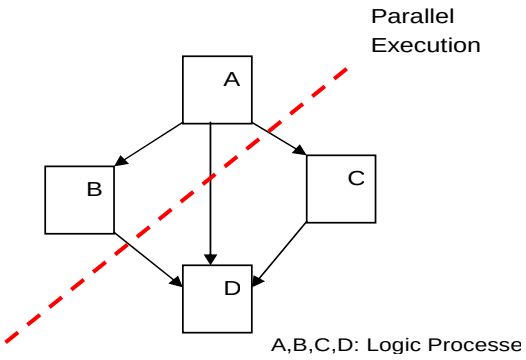


Figure 2.2 Parallel Executions of Multiple Logic Processes

While this paradigm would seem to be ideally suited for parallel/distributed execution, synchronization must be used to avoid causality errors. That is, each logical process must process all of its events, both those generated locally and those generated by other LPs, in time stamp order. Otherwise, it is possible that the computation for one event may affect another event in its past. It is easy to maintain the event order in a sequential simulation by using a central event queue. In parallel/distributed simulation, however, it is not enough to use local event queues alone. As shown in Figure 2.3, the LP D cannot process the event E_{14} from LP B until it can be sure that no other LPs may send it events with a timestamp smaller than 14. For example, LP A may generate an event E_{12} , which may be physically delivered to LP D later than E_{14}. If E_{14} is processed earlier than E_{12} in LP D, this is called a causality error. The general problem of ensuring that events are processed in time stamp order is referred to as the synchronization problem.

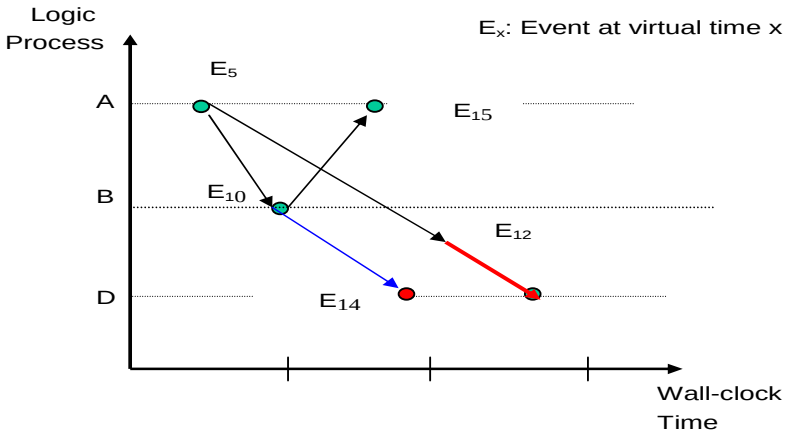


Figure 2.3 Causality Errors

Two major approaches to synchronization algorithms are *conservative synchronization* and *optimistic synchronization*, different in how to move the simulation time. Here we will introduce the details of conservative synchronization, since it will be used in our network simulator.

2.2.2.1. Conservative Synchronization

To prevent causality errors, simulation using conservative synchronization does not process an event T until it is sure that no new events will have a timestamp smaller than T. To achieve this, some mechanism is required for an LP to indicate to other LPs the current lower bound on the timestamp of events it may send out in the future. Null messages can be used for this purpose, which are used only for synchronization and do not represent any physical events in the simulated systems. As shown in Figure 2.4, a null message with timestamp T_1 from LP C to LP B promises that no events with timestamp smaller than T_1 will be sent from LP C. After LP B receives all null messages from all other LPs, LP B can figure out what the upper bound of the timestamp is, and all events with smaller timestamps can be processed safely. In this case, all events with timestamp less than Min(T_1, T_2) can be processed safely.

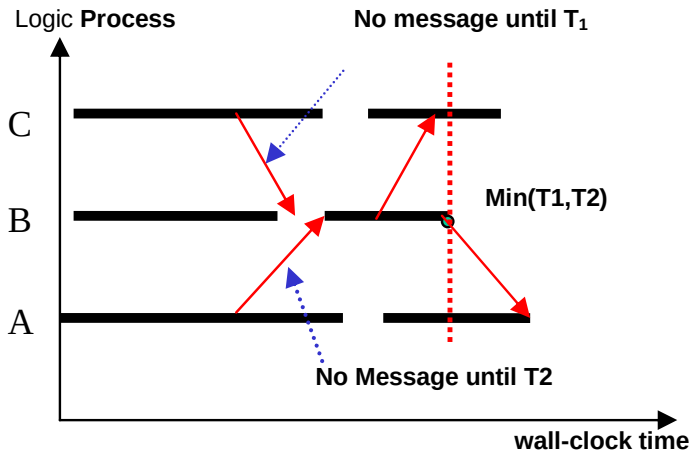


Figure 2.4 The Null Message Algorithm

Then the problem that remains is how to set the timestamp in a null message. Here comes one important concept in this Null Message algorithm: *Look-ahead*, which can be defined as the following:

Look-ahead: If a logical process at simulation time T can only schedule new events for another LP with time stamp of at least T+L, then L is referred to as the look-ahead for the logical process.

In reality, the look-ahead represents the physical limitations on how quickly one physical process can interact with each other. For example, in network simulation, it could be the link latency between two routers; in air traffic simulation, it can be the time required from an airplane to fly from one airport to another airport.

So the time stamp of a null message can be set to the current time of the LP plus its look-ahead.

A major issue in the Null Message algorithm is that its performance depends critically on the look-ahead value, which decides how frequently the LPs are required to exchange null

messages. As we know, null messages do not represent any useful activity in the simulated systems and are pure simulation overhead.

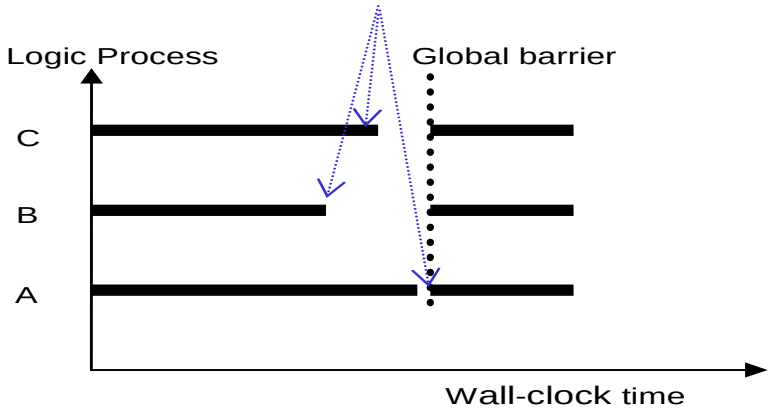


Figure 2.5 Synchronous using Barrier Synchronization Protocols

The Null Message algorithm can be implemented efficiently using a mechanism called *barrier synchronizations*. A barrier is a general parallel programming construct that defines a point in time when all the processors participating in the computation must stop. As shown in Figure 2.5, before a LP process enters the barrier, it sends null messages to other LPs; then it blocks and waits until it receives all null messages from the other LPs. The barrier operation is completed when all LPs have received all null messages, and then the LP is allowed to resume execution until the next barrier point, which is the current time plus look-ahead.

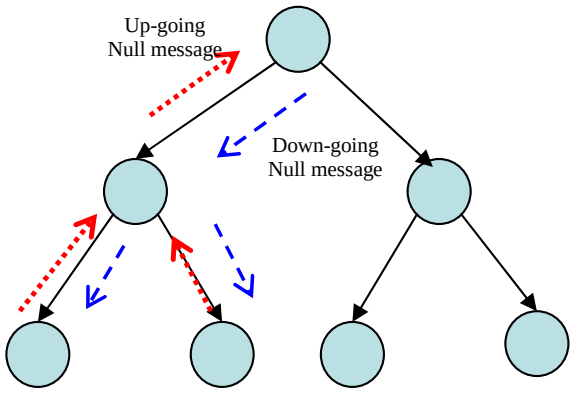


Figure 2.6 Global Barrier using a Tree Structure

The benefit of using a barrier is that we do not have to send null messages between all pairs of logical processes. Instead, we can organize the logical processes efficiently and reduce the number of null messages greatly. If, the logical processes are on a shared-memory multiprocessor, the barrier can be easily achieved by using a global synchronization variable. If the logical processes are on a distributed system like a cluster, all LPs in a machine can synchronize locally and then use a representative to synchronize with other machines. The machines can be organized as a balanced tree with each node of the tree representing a different machine (Figure 2.6). When a leaf machine reaches the barrier points, it sends a null message to its parents. Each machine will wait until it gets all null messages from its children and then send a null message to its own parent. After the root receives all outstanding null messages, it knows every machine has entered the barrier. And this information can be propagated back to all machines following the revert tree.

2.3 Graph Partitioning

Our work exploits graph partitioning algorithms as a key tool in solving critical load balance problems, necessary to provide scalability for our network simulator

2.3.1 Single-Objective Single-Constraint Graph Partitioning Problem

Typical graph partitioning algorithms generally solve single objective partition problems such as:

Given an input graph G = (V, E) with weighted vertices and edges, we want to partition it into k parts such that,

- each part has roughly the same number of vertex weight (**constraint**)
- the edge-cut (the number of edges) that straddles partitions is minimized (**objective**)

The task of minimizing the edge-cut is considered as the objective and the requirement that the partitions will be of the same size is considered as the constraint. This single-objective single-constraint graph partitioning problem is can be efficiently solved with multi-level k-way graph partitioning algorithms[39], and it is widely used for static partitioning in scientific simulation.

2.3.2 Multi-Constraint Graph Partitioning Problem

However, this single constraint graph partitioning problem is not sufficient to model many of the underlying computational requirements, found in today's large scale applications. For example, in a large distributed application, we need to balance both the computation load, as well as the memory consumption, across multiple physical nodes. Both memory and computation are two distinguished constraints, and if the partitioner fails to balance both requirements, it is hard to achieve good overall application performance. This problem can be solved by modeling it as a graph in which every vertex has an associated weight vector w of size m, every weight represent an balance requirement, every edge has a scalar weight, for which we find a partitioning such that each partition has roughly equal vertex weight with respect to each of m weights and the edge-cut is optimized. This problem is usually referred to as the multi-constraint graph partitioning problem, and there are many efficient algorithms available [40, 41].

2.3.3 Multi-Object Graph Partitioning Problem

Beside multiple balance requirements, a complex distributed application may have multiple optimization requirements. For example, a multi-phase application can consist of multiple phases; each phase has quite different communication patterns. If we want to minimize the communication traffic across the network, we should put multiple phases together, and balance the requirement of different phases. This problem can be solved by modeling it as a graph in

which every edge has an associated weight vector w of size m, each weight represents an optimization requirement, every vertex has a scalar weight, and for which we find a partitioning such each partition has a roughly equal amount of vertex weight and the edge-cut with respect to each of m weight and the edge-cut is optimized. This problem is usually referred to as a multi-objective problem, and there are some efficient algorithms to solve it [42].

There have been a large number of graph partitioning packages targeted at parallel computing since the early 90's, including METIS[42], Chaco[43], Jostle[44], PARTY[39], and Zoltan[45]. As a well studied problem, we expect that any high quality graph partitioning package (in this case METIS[42]) should produce results of comparable partition quality to other graph packages. Our choice of METIS is mainly due to its performance and the flexibility in supporting multiple constraints, as well as multiple objectives.

Chapter 3 Dissertation Statement

The focus of our research is to enable the study of dynamic interaction between applications, middleware, resources, and networks in a controlled environment. We first describe the hardware and software context for this dissertation in Section 3.1, and then we define the simulation problem in this context in Section 3.2. Our dissertation statement is given in Section 3.3, while Section 3.4 discusses the way to evaluate our approach.

3.1 Context

First, we introduce applications which are the subjects of our performance study. And then we describe the software and hardware resources to be used for the study.

3.1.1 Target Applications, Networks, and Resources

In the last few decades, the prospects of large-scale distributed applications deployed across the Internet have grown phenomenally. Examples of those applications include distributed supercomputing applications, peer-to-peer file sharing application, distributed interactive simulation (DIS) for training and planning in the military, and real-time widely distributed instrumentation systems[5]. These applications often involve thousands of geographically distributed endpoints (including computers, storages, and instruments) connected through wide area networks with latency ranging from a few milliseconds to a few hundreds milliseconds. They are sufficiently coarse-grained that they can run on the Grid, but their performance greatly depends on network conditions, such as traffic congestion and routing stability. When compared to traditional parallel and distributed computation in a local area network, the conditions of

wide area network show much larger variability and therefore lead to much more unstable and unpredictable performance. Moreover, resource hungry large applications can not only affect the network performance with their multi-gigabit traffic streams, but may also be network aware and respond to current network performance. Therefore, it is critical to study the application behavior under different network conditions.

These applications often have complex logic, coupling large computation and storage resources. They can also be built above grid middleware, such as Globus[5], Legion[6], and Condor[7]. Furthermore, with help from emerging grid software tools, such as the Network Weather Service (NWS)[23] and GrADS developing framework[9], more applications can adapt to the available network and resource conditions for better performance. All these components together make a complex system which may exhibit non-linear dynamic behavior, and depend on some subtle interactions between multiple components.

It is very important to understand the performance and behaviors of these applications under grid environments. It can be used to predict the application performance before deployment, decide the resource requirement for predicted performance, diagnose the system abnormality after deployment, and detect the system performance bottleneck for upgrading.

3.1.2 Execution Platform

In order to understand these applications, we need an execution platform for simulation experiments. First of all, the platform hardware and available software should be scalable in order to support large scale simulation. Second, the cost effective is also an important criterion, since it decides whether or not the platform will be widely available. In our study, we choose the cluster platform, based on the following considerations.

First, clusters have become a cost effective and popular way to build large-scale systems. The low latency cluster communication hardware and software (like Myrinet and MPICH-GM)

have improved their performance greatly. These days, most supercomputers are built on cluster technology, and small clusters are widely available in research communities. Large scale SMP machines are too expensive for most researchers.

Second, also for cost reasons, cluster systems usually have more memory than SMP machines. It is normal for a 64-node cluster to be equipped with 256GB memory, which is comparable to the 288GB memory of the high end Sun Fire 12K Enterprise Server [46]. Since most simulations require a great deal of memory, cluster systems present a big advantage over SMP based parallel simulation.

Third, using flexible cluster technology is often easy to achieve large network throughput. For online network simulation, the simulation engine needs to exchange network traffic with applications running on other machines. An SMP machine usually has very high inter-processor bandwidth, but the external network I/O is usually quite limited, since only a few I/O processors can process external network traffic. This may quickly become a bottleneck for the whole simulation system. Cluster systems, on the other hand, are quite different. With current network switches, the application traffic can be easily handled by every simulation node and efficiently distributed to different nodes for better load balance.

Our target cluster is one that can fit in a single room and is entirely connected by at least one high performance network, such as switched Fast Ethernet or Myrinet. Bandwidths of the network range from 100Mbps up to 10Gbps, and the network latency for small message should be around a few microseconds. In addition, our target cluster should have TCP/IP protocols and a high performance MPI implementation available, such as MPICH-GM. The MPI is primarily used for the communication within the distributed network simulation.

3.2 Problem

To meet the challenge outlined above, integrated simulation tools are required for modeling virtual grid systems. The questions are how to do it, how to do it accurately, and how to do it efficiently with high scalability.

3.2.1 How to Provide a Virtual Gird Environment

A virtual grid environment should be fully virtualized, which means applications can be executed on the virtual grid without any modification, they should use all virtual resources, storage, and networks transparently. This is important to maximize the range of experiments and their realism. Compared to traditional emulation systems, which also support directly execution of real applications, a virtual grid environment is more complex because it must support virtual resource identification, virtual resource discovery, and virtual resource interaction. It is critical to use real applications and middleware transparently; it is also required in order to enable the direct study of dynamic interactions between applications, middleware, resources, and networks.

For example, in a typical Globus application, one may use the GIS system to discovery suitable resources first, and then submit the job to multiple gatekeepers, which launch jobs on local resources through job-managers. There are many open questions with regards to supporting Globus application transparently, they include: How do we describe and discover virtual resource in the GIS system; how do we associate virtual resources with gatekeepers; and how are applications launched from job-managers on virtual resources.

3.2.2 How to Simulate Efficiently and Accurately

Although highly accurate simulations are always desirable, with limited physical resources one must make tradeoffs between accuracy and efficiency. For example, there are accurate

simulators for processor, memory, and disks. But if those simulators were used for grid modeling, they would take too much time to yield any results, despite their accuracy. On the other hand, the resource simulation must be accurate enough in capturing the underlying details for it to be useful. For example, in a peer-to-peer application, it requires hundreds of endpoints to build a representative overlay network structure.

So the first question to ask is how much accuracy is required for a specific resource simulation, or could we reduce the accuracy requirement without hurting the overall accuracy of the whole simulated system. For example, do we need packet level detail for network simulation, and do we need the instruction level simulation for computation resource modeling. After this, we should determine how to simulate it efficiently. Our choices may include how to simplify the routing protocol in simulation without affecting the final routing decisions, or how to aggregate the simulation of a large number of idle virtual resources with a single physical resource. This decision making is critical to achieve accurate modeling of a virtual grid, in a timely manner, given the bounds of physical resource constraints.

3.2.3 How to Simulate with High Scalability

Another challenge in modeling grid dynamics is the scalability of the simulation tools. Essentially this means, can the simulation tool use physical resources efficiently and also, can it support simulation of larger networks or applications when more resources are available. This challenge is decided by both the scale of the Internet itself, which includes millions of hosts and routers, and the scale of grid applications, which usually consist of hundreds and thousands of processes distributed across a wide area network. To make a meaningful grid simulation, it should be able to support a network comparable to a significant part of the real Internet, with reasonable background traffic; it should also be able to support real applications with thousands of endpoints.

In Grid simulation, the scalability issue is particularly critical for the network simulation. The other components, such as computing nodes and storage systems, can be simulated in parallel given enough computing resource. However, these components need communication and coordination to function correctly, which in a distributed simulation happens through the network system. Due to small network delay and fast interaction among network routers and endpoint hosts, the whole network systems must be simulated with enough concurrency and tight synchronization.

Beside the implementation efficiency we mentioned above, there are two major factors affecting the scalability of a distributed simulation system. First, scalability depends on available parallelism, and thus, the problem is whether and how to find large parallelism for a given network simulation. There is significant on-going research on parallel and distributed network simulation. Some of these solutions exploit the parallelism in network simulation on SMP machines, but they suffer from limited internal hardware scalability. Only a few recent simulators support exploiting scalable message passing systems, such as a cluster system. However, none of them have demonstrated good scalability when challenged with irregular network simulation problems. This is due, mainly, to the fact that the communication overhead on cluster systems is much larger than that of SMP machines, and thus, it requires more parallelism in the simulation problem itself, in order to achieve good performance.

Second, scalability depends on the achieved load balance. Load balance is important because it directly affects the simulation performance: the speed of the parallel/distributed simulation is limited by the speed of the node with the most loads. How to achieve load balance across simulation engine nodes is still an open research problem. Since the simulation engine load depends predominately on the amount of simulated traffic, which may change dramatically during the simulation, balancing the simulation load is a big challenge. Our choice of cluster

platform also makes load balance more difficult, since it basically rules out the possibility of dynamic load balance, due to the high overhead of task migration across machines.

3.3 Dissertation Statement

My thesis is:

Accurate and comprehensive study of the dynamic interaction of applications, middleware, resources, and networks is important and is possible with scaled real-time online network simulator. Using sophisticated load balance algorithms by exploiting a range of static network and dynamic application information, distributed network simulation based on discrete-event simulation engine can be scalable and support high fidelity simulation of a large grid system.

Scaled real-time simulation is our approach to enable hybrid simulation of multiple simulation modules. As we argued in the last section, it is essential to model multiple resources and network together for modeling dynamic interaction of applications, middleware, resource, and networks. Scaled real-time simulation is a special kind of simulation in which simulation time advances with constant rate, usually slower than real-time. It is different from traditional simulation and emulation approaches in the way the simulation time advances: in traditional simulation, the simulation time advances as fast as possible, and in emulation approaches, the simulation time advances just as real time. Our approach relaxes this real-time requirement of emulation and allows more flexible resource speeds and ratio. Scaled real-time simulation is the base of coordinating multiple hybrid simulation modules without complex synchronization mechanism.

Online network simulation is our approach to improve the simulation accuracy. It is an enhanced network simulation technology, which can pass live traffic from application through the simulated network to its destination, and support direct application execution. Thus, online

network simulation allows the study of real, temporal and feedback behavior of network and application protocols, as well as their interaction with other network traffics. The scaled real-time online network simulation technique, plus other resource modeling and virtualization methods, can provide accurate simulation of virtual gird environments.

To support large-scale simulation, the key speed limits are the simulation efficiency and the load balance of distributed network simulation. The load balance problem is known to be hard, since simulation workload is proportional to network traffic packet number, which changes dramatically with bursts of traffic loads in large network. The characteristics of grid environment with highly distributed applications and complex dynamic interactions between applications, networks and resources make the problem even harder. Our sophisticated load balance algorithms exploit a range of static network and dynamic application information to improve the load balance. Good load balance is important for the performance of the network simulation and therefore for the scalability of the entire virtual grid model.

3.4 Success Criteria

To demonstrate that our scaled real-time online simulation technique can successfully enable hybrid simulation of multiples resources and application together, we need to present our design and implementation. Success will be demonstrated by providing a simulation toolkit which can provides modeling of virtual grid environment. Using this simulation toolkit, we will construct a range of grid environments and execute a batch of real applications directly on the simulated grids.

In addition to the support of direct application execution on virtual grids, fidelity is also an important success criterion. For fidelity, the basic question is whether we have developed a simulation mechanism that can provide detailed and accurate modeling of the virtual grid. Success will be demonstrated by a range of validation experiments. We will first provide

validation on the accuracy of single resource modeling, including network and computation resource. The validation experiments will show that the network simulator achieves correct network latency and bandwidth under multiple network configurations and that the computation resource simulation enforces the correct resource usage under multiple resources and application configurations. Then we will validate that for a given real application, the modeling is still accurate. The basic methodology is to use the MicroGrid to simulate a few real systems, and then, compare the application performance on real systems directly to that on the simulated systems. The application execution time between the real systems and the simulated systems should match.

Using advanced load balance algorithms to achieve good scalability is also a critical claim in our dissertation statement. Success will be demonstrated by designing and implementing those load balancing algorithms, applying them on experiments with a range of network topologies and application configurations, and improving the scalability of the whole simulation systems in the term of load imbalance, application simulation time, and parallel efficiency (see Section 7.1.3 for detailed metrics definition).

We will also show that the scalability we achieve is good enough for detailed grid modeling. Success will be demonstrated by executing simulations of Grid applications over large network systems, including a simulation of a large ISP network with 20,000 routers and hosts, a simulation of the real Internet BGP simulation of more than 16000 Autonomous Systems, and a simulation of a large scale Denial of Service attack on an 200-node overlay network with 200 users and 10Gbps of attacking traffic. We set these scale thresholds (network size, application number, traffic volume, etc.) because we think they are large enough to keep the major feature of a large grid environment and that the simulation results are applicable to real grid environments.

Chapter 4 Approach

In this chapter, we discuss high level concepts behind our approach to virtual grid modeling, and discuss and justify major design decisions in the MicroGrid.

4.1 Overview

Using scalable physical resources, the basic objective of the MicroGrid is to provide a virtual grid environment for real grid applications and middleware, enabling direct execution on a large number of virtual resources with arbitrary performance ratios (Figure 4.1).

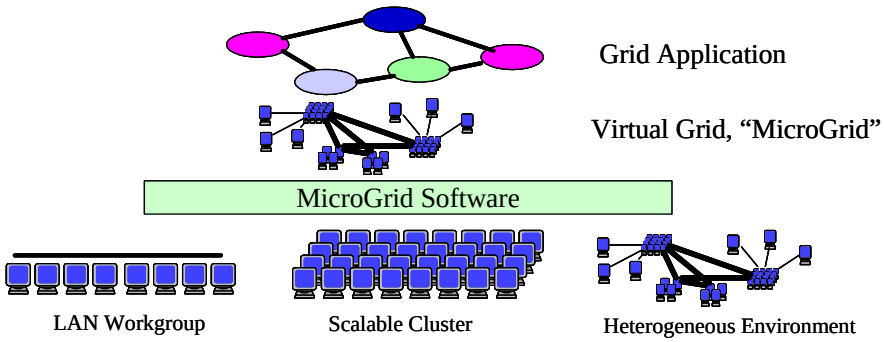


Figure 4.1 The Approach in the MicroGrid

Addressing the problems of constructing such a high-fidelity virtual grid, as listed in Section 3.2, our approach to integrated online simulation of virtual grid environments is as follows.

1) **Resource Virtualization using Live Application Interception.** The application perceives only the virtual grid resources (host names, networks), independent of the physical resources being utilized. Using live application interception, we can also

virtualize the grid information services and virtualize/simulate the appropriate operating system resources.

2) **Computation Resource Simulation using Soft Real-time Scheduling.** The target is to achieve accurate computation resource modeling with less overhead and less prerequisites. Based on direct application execution and user level process scheduling, the soft real-time scheduling approach can efficiently model a large number of virtual resources on a single physical host.

3) **Network Modeling using Scalable Online Simulation.** To improve the scalability of virtual grid modeling, the traffic-based load balance for distributed conservative discrete-event network simulation is used. The distributed simulation can exploit parallelism in the network simulation problem, and our sophisticated load balance algorithms can use a range of network and application information to achieve good load balance and performance of the entire simulation.

4) **Coordination of Multiple Simulation Modules using Scaled Real-time Execution.** To provide a coherent global simulation of multiple virtual resources, we need to coordinate the simulation speed of different virtual resources. This can be achieved through scaled real-time execution of all simulation modules. Based on the desired virtual resources and physical resources employed (CPU capacity and network bandwidth/latency), the virtual time module determines the *maximum feasible simulation rate*, under which all resource simulation can be run in a functionally correct manner.

We will discuss these approaches in detail in the following sub-sections.

4.2 Resource Virtualization using Live Application Interception

To virtualize a grid environment, the MicroGrid intercepts all direct uses of resources or information services made by the application. In particular, it is necessary to mediate over all operations which identify resources by name, either to use or retrieve information about them. We first consider general mediation, and then we consider the specific issue of information service.

4.2.1 Virtualizing Resources

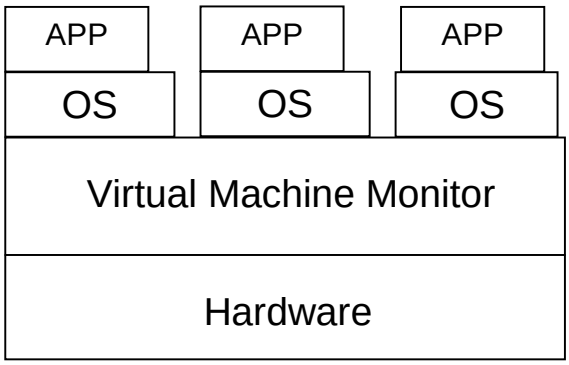


Figure 4.2 Virtualization based on VMM

Virtualization, in a rather loose definition, is a framework that devides the resources of a computer into multiple execution environments. More specifically, it is a layer of software that provides the illusion of a real machine to multiple instances of virtual machines. In general, there are two possible ways to virtualize resources. The first approach is the virtual machine monitor (VMM) approach (Figure 4.2), including VMWare[47], Denali[48], Entropia[12], and Xen[49]. VMMs usually provide full virtualization, while a guest operating system instance is required to provide a virtual machine on which traditional applications can be directly executed. However, the complexity and overhead of VMMs is so large that it is infeasible to create many instances on a single physical machine. For example, the CPU performance loss of VMWare is

between 9-15%. Also, VMMs have little support for virtual network performance modeling, which we will discuss in Section 4.3.

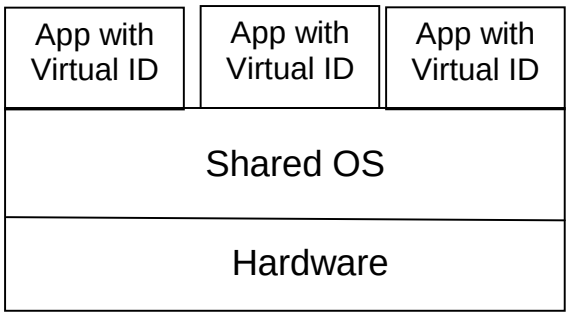


Figure 4.3 Virtualization based on Virtual Host ID

Another approach is to just virtualize the host identity (Figure 4.3). In general, we need to virtualize processing, memory, networks, disks, and any other resources being used in the system. However, since operating systems effectively virtualize each of these resources -- providing unique namespaces for each process and sharing of CPU, disk, etc-- the major challenge is to virtualize host identity. The benefits of this approach are the simplicity and efficiency; consequentially, it can be naturally used for virtual network performance modeling. This approach is especially good if one wants to create a large number of virtual hosts, but maybe only a small part of them are active at the same time. The idle virtual machines basically introduce no overhead to the physical machine, a feature quite different from that of the VMM approach. Of course, this requires added resource modeling to guarantee correct virtual resource performance.

In the MicroGrid, we choose the virtual host identity approach, since we intend to simulate a very large number of virtual hosts. Each virtual host is mapped to a physical machine using a mapping table of virtual IP address to physical IP address. All relevant library calls are intercepted and mapped from virtual to physical space using this table. These library calls include:

gethostname()

bind, send, receive (e.g. socket libraries)

process creation

By intercepting these calls, a program can run transparently on a virtual host with the appearance of the virtual hostname and IP address. The interception ensures that the program can communicate with processes running on other virtual Grid hosts. Many program actions which utilize resources (such as memory allocation) only name hosts implicitly, and thus, do not need to be changed. Any socket-based application can be run on the virtual Grid as the MicroGrid completely virtualizes the socket interface.

4.2.2 Virtualizing Information Services

Information services are critical for resource discovery and intelligent use of resources in Computational Grids. To provide a fully virtualized Grid environment, we also need to provide information services for virtual resources. For example, when it comes to supporting the Globus middleware, this problem amounts to virtualization of the Globus Grid Information Service (GIS)[50].

One key problem is how to get application to look at the virtual information service. One straightforward solution is to run an information service in the virtual world, and store and retrieve all virtual resource information directly. This is a simple solution in logic, but it introduces a large overhead in experiments. For example, in Globus, this requires a GIS server for every experiment, it takes significant time to initialize the GIS server, and makes it hard to add simulation-related information.

Instead, our approach is to use a real information server --- no additional servers or daemons are needed. In this approach, an application running in the simulation environment needs to talk to a server in the real world, and it requires special support from the network virtualization module. The network virtualization module should intercept all access to network,

identify all access to virtual information services, and forward them to the real information server directly, instead of routing through the network simulator.

Beside this transparent access issue, desirable attributes of a virtualized information services include:

1) Compatibility: virtualized information should be used as before by all programs

2) Identification and Grouping: easy identification and organization of virtual Grid entries should be provided

3) Use of identical information servers: there should be no incompatible change in the entries

Our approach achieves all of these attributes by extending the standard GIS LDAP records with fields containing virtualization-specific information. Specifically, we extend records for compute and network resources. Extension by addition ensures subtype compatibility of the extended records (a la Pascal, Modula-3, or C++). The added fields are designed to support easy identification and grouping of the virtual Grid entries (there may be information on many virtual Grids in a single GIS server). Figure 4.4 and Figure 4.5 show examples of the extensions to the basic host and network GIS records.

```
hn=vm.ucsd.edu, ou=CSAG, ...
Is_Virtual_Resource=Yes
Configuration_Name=Slow_CPU_Configuration
Mapped_Physical_Resource=csag-226-67.ucsd.edu
CpuSpeed=10
```

Figure 4.4 Virtual Host MDS Records

```
nn=1.11.11.0, nn=1.11.0.0, ou=CSAG
Is_Virtual_Resource=Yes
Configuration_Name=Slow_CPU_Configuration
nwType=LAN
speed=100Mbps 50ms
```

Figure 4.5 Virtual Network MDS Records

4.3 Computation Resource Simulation using Soft Real-time Scheduling

To provide accurate virtual grid modeling, the MicroGrid need to simulate every computation resource as a component of the overall simulation, providing real-time performance feedback to the simulation and regulating the rate at which virtual time is allowed to progress. The major challenge in computation resource simulation is that we need to simulate a large number of resources efficiently, due to the fact that a typical grid environment usually includes thousands or more resources which need to be simulated in a much smaller cluster system.

One possible solution to the above challenge is using the VMMs in Section 4.2, which also provide computation modeling for virtual machines. This approach is accurate but involves more overhead. Another possible approach is to use real-time operating systems to schedule the execution of virtual machines, which can be more accurate, but less flexible, since real-time operating systems are not widely deployed.

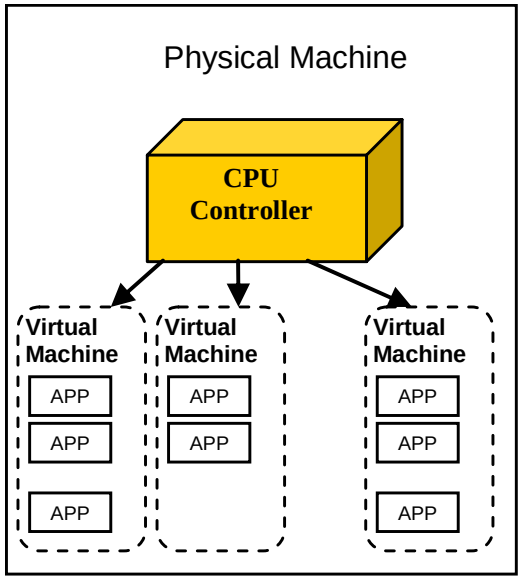


Figure 4.6 Computation Resource Simulation using Soft Real-time Scheduling

Based on the direct execution of application and resource virtualization, computation resource simulation is to provide appropriate performance for the processes running on a virtual compute resources. As shown in Figure 4.6, the MicroGrid uses a CPU controller, a soft real-time process scheduler, on each physical host to control resource utilization of the processes resident with each virtual machine. Periodically, the controller checks the CPU usage of every application process on the physical machine, and then calculates the latest CPU usage of each virtual host. If the amount of effective cycles exceeds the speed of the virtual hosts, the controller stops all processes of that virtual host; otherwise, the controller wakes up the processes and lets them proceed.

In theory, this approach can accurately simulate an arbitrary number of virtual computation resources by tuning the simulation speed. However, due to the limitation of non-real-time operating systems and minimal OS scheduling unit, the CPU controller can neither accurately monitor the real resource usage of every application process, nor stop and wakeup a special process at the exact points it should. We will discuss in more detail how to address this issue in Section 5.2.

To summarize, our computation resource simulation approach is to use direct execution on original operating system, and control the overall CPU time allocated to a specific virtual machine. This light-weight approach is efficient and can support a large number of virtual machines on a physical machine. Moreover, it is flexible, and can be used on any target operating system of the real application. One major short-coming to this approach is low accuracy, since it does not guarantee resource usage from the bottom line. However, as you will see from the validation experiments in Section 6.1, the accuracy is sufficient for most application simulation.

4.4 Network Modeling using Scalable Online Simulation

There are critical challenging requirements for network simulation in the MicroGrid: accuracy, scalability, and support for direct application execution, and they are addressed in Section 4.4.1, Section 4.4.2, and Section 4.4.3, respectively.

4.4.1 Packet Level Detailed Simulation

While significant advances have been made in aggregate modeling of network behavior[20, 21], at present only detailed packet-level or close analogs can model protocol dynamics accurately, particularly in extreme cases[23]. This is especially true when we target our study on application performance. Extreme cases are important. Since while they rarely happen in normal operation, their consequence may be critical. For examples, for a distributed application, what is the performance with routers in link saturation as happens under malicious Denial-of-Service attacks? How could the routing system respond if there is temporary network partition due to attacks?

Remember that we want to understand the behavior of individual applications, we want to understand and diagnose anomalies, and we also want to understand behavior of collections of applications and resources in ordinary and extreme circumstances. For all these purposes, the

details matter. Since network and application behavior depends on detailed packet behavior, and feedback effects on network protocols and resource management are critical, the simulation must use closed-loop feedback.

To capture as many as possible network protocol details, packet level simulation is required to provide accurate modeling. For example, it is known that most applications use the TCP protocol for network communication and their performance directly depends on the behavior of TCP. However, TCP performance is sensitive to individual packet behavior. For instance, whenever a TCP sender detects packet loss, it will reduce the congestion window size by half, thus reducing the TCP bandwidth dramatically. Congestion window increase, which is additive, takes a longer time to recover. Another example is the Nagel Algorithm[51] in TCP, which is used to delay the sending of small data until more data are available, because sending large packets has less overhead. However, this optimization may raise major performance issue for interactive or RPC-based applications.

4.4.2 Online Network Simulation

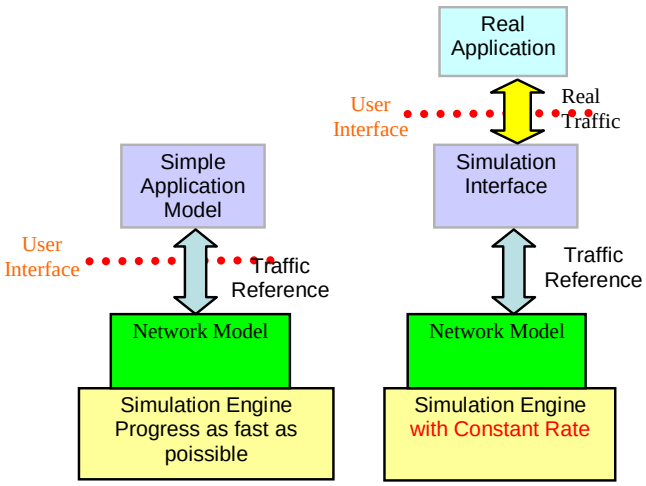


Figure 4.7 Online Network Simulation vs. Network Simulation

Network simulators, such as the NS-2, have been widely used to study network protocol and network performance for a long time. Usually these tools focus on the network itself, and

they cannot be used to study application directly. The user must write a simulation module to abstract and mimic the behavior of the application. It requires deep understanding of the application to write such a performance module effectively, and it invariably introduces unknown inaccuracy through this approximation and abstraction. With the coming of complex distributed and Grid application, it becomes less and less feasible to write accurate application modules for simulation. Instead, people want to study applications directly using an online network simulation, an enhanced network simulation technology which can support direct application execution by passing and modeling the behavior of live traffic from application through the simulated network to its destination.

The MicroGrid supports direct execution of real applications to exercise complex applications and to capture the subtle interaction between applications, middleware, and operating systems. Just like the virtualization of network identity, the MicroGrid intercepts all network related function calls in a given application, and redirects the traffic into the network simulator. The packet movement and timing are modeled by the network simulator and the data are feed back to real application at the other endpoint at the correct time (Figure 4.7). Here the MicroGrid provides a virtual Grid environment and the user can use it as a real Grid testbed transparently. We call this approach online network simulation.

The benefit of online network simulation is that the user can study application performance directly, rather than building another application module for the simulation. This reduces the overhead of simulation greatly, and since it catches all the details of the application implementation as well as interactions between the application and the real system, it provides more accurate and direct results to the users.

There are two major challenges in online network simulation. First, we need to intercept the network traffic transparently; second, the delay between the application and simulator must be

negligible when compared to the simulated network delay, since this delay is not modeled by the simulator. We will discuss this in more detail in Section 5.3.

There is another technique that has an objective similar to online network simulation, but uses a different approach, called network emulation. Like online network simulation, network emulation also supports direct application execution and intercepts the live application traffic transparently. However, instead of using a network simulator, it usually uses software or simulated routers to approximate the network behavior. The benefit of this approach is the raw speed it offers. This approach often allows for emulation that is fast enough for real-time execution. However, accuracy and flexibility are usually limited when compared with online simulation.

4.4.3 Distributed Conservative Discrete Event Network Simulation

Here we describe and justify some of our design choices in network simulation.

4.4.3.1. Parallel vs. Distributed Simulation

To provide scalable large-scale simulation, we can use parallel discrete-event simulation. Over the last two decades, parallel discrete-event simulation, or PDES for short, has been recognized as an important and challenging research area. PDES is used when executing a single discrete-event simulation program on a parallel computer, which can be either a shared-memory multi-processor or a distributed-memory cluster of computers. By exploiting the parallelism inside a simulation problem, parallel simulation overcomes the limitation of memory and execution speed of sequential simulation. We can find in-depth review of the state of art of PDES in the Fujimoto book[52].

In general, parallel simulation on shared memory machine is a much mature approach and is expected to provide good performance, which is due primarily to simple programming model and small communication overhead. However, distributed simulation on clusters using message

passing communication could be a better choice for large scale network simulation, based on the following consideration.

First, clusters have become a cost effective and popular way to build large-scale systems. As we mentioned in Section 3.1.2, clusters are widely available for researchers. Second, clusters are more scalable than SMP systems. Currently all the largest supercomputers are based on the clustering technology and some of them are available for public accesses in national computer center, such as NCSA and SDSC. This provides the opportunity for extreme large-scale network simulation. Third, the coming of advanced distributed simulation technology, including DaSSF, enables a chance to build large scale network simulators based on distributed simulation.

4.4.3.2. Conservative vs. Optimistic Simulation

Conservative algorithms try to avoid any possible causality errors. In practice, they are usually overly pessimistic, and force sequential execution when it is not necessary. This reduces the achievable parallelism in the simulation and requires good look-ahead (see Section 2.1) for concurrent execution and scalability. Optimistic algorithms, on the other hand, allow violation to occur but provide a mechanism to recover, which can achieve greater parallelism and has no limit on the look-ahead. However, optimistic algorithms usually have more complex control and need special mechanisms for state saving, roll back, and dynamic memory allocation.

The preference for different synchronization methods depend on the structure of simulation events and interaction between simulation entities, which in turn depends on the systems being modeled. For online network simulation, we prefer the conservative algorithm for the following reasons.

1) Easier to implement. From our experiments, we can also tell that the look-ahead in network simulation is sufficient (with good partition algorithms) to achieve good speedup, even

when the absolute look-ahead is not very large: the network delay of a physical link (1-10 milliseconds).

2) Smaller memory footprint. In a large network simulation, we need to simulate thousands of hosts and routers, and an even larger number of network packets. The memory requirements are critical to the scalability of the whole system. Due to the property of optimistic simulation, the simulator must keep the un-commit events for possible roll-back. Because of the nature of high speed network traffic, this memory consumption can easily go out of control and degrade the benefit of optimistic simulation.

3) More stable progress for real-time execution, which is critical for online network simulation. The rollback of optimistic simulation may halt the simulation and affect the real time simulation accuracy.

4.4.3.3. Automatic Load Balance for Scalability

As we discussed in Section 3.2, scalability is an open research challenge for network simulation. The detailed packet level simulation requirements in the MicroGrid present an even greater scalability challenge. In a large network consisting of thousands of routers and hosts, there are a large number of traffic flows. It is a serious challenge to simulate such a large network, which requires such a huge number of computation and memory resources. There is already a lot of research going on to improve the scalability of network simulation. But much of this research uses approximation, for example, reducing the network size by removing non-bottleneck routers and links[53], relaxing the synchronization requirement[35], or even using fluid flow to represent traffic[54]. As we have shown in Section 4.3.2.1, details matter and none of these approximations are suitable for our purpose.

With the constraints above, we want to exploit the parallelism in the original network simulation problem to improve scalability. Based on the specification of the virtual and the

physical resources, the MicroGrid needs to map virtual machines to physical hosts. To achieve scalable performance, we must use automatic mapping to balance the compute and memory load across physical machines and thus reduce the network traffic between them.

To achieve the optimal load balance is an NP-Hard problem[55], and this is impossible without the network traffic information; in practice, a network mapping problem can be naturally modeled as a graph partitioning problem and solved with the classical graph partitioning algorithms with approximation. With detailed traffic information, we can estimate the number of simulation events on each single link and use it to calculate the edge weight. We will discuss this approach in more details in Section 5.4.

4.5 Scaled Real-time Execution

To maintain the correct execution timing relationship between the application and the network, we must coordinate the pacing of the network simulator and the execution rate of real application. The easiest way is to let both make progress in real-time mode. However, this approach is not flexible and sometime infeasible, since the simulator might not powerful enough to keep up with real-time execution. In this case the simulation must be slow down. For example, if we want to simulate two 4GHz machines using a 1GHz machine, the application has to be slowed down by a factor of 8, which means the simulation will require 8 times more than a real system to complete. As shown in Figure 4.8, for an application taking 15 minutes of real time, the simulation will take 2 hours (8 times) to complete.

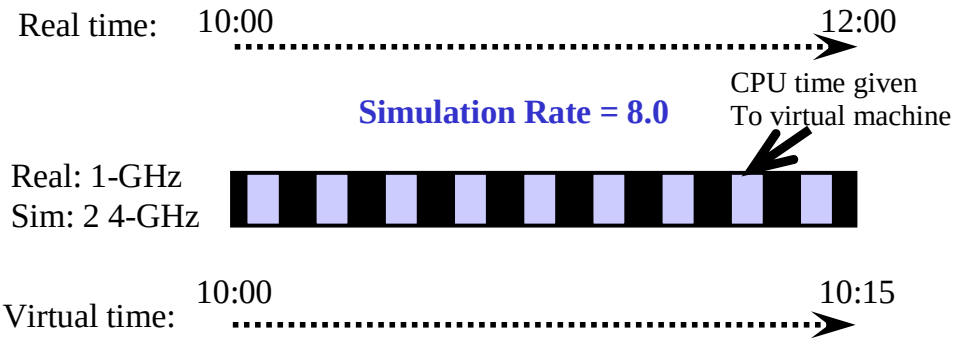


Figure 4.8 Simulation Rate

To maintain the correct interaction between the network and the application, the network simulator must be slowed down by the same simulation rate as all other simulation modules. For example, if an application should spend 15 seconds on computation and then 5 seconds on communicate, if we only slow down the computation by a factor 2, then the computation and computation ratio becomes 6:1, instead of the real 3:1. Such distortion of the real scenarios can introduce large inaccuracy in simulation results. Our approach avoids that problem.

There is also a good side-effect of slow down, it improves the accuracy of the whole simulation; since it makes the delay between application and simulator much smaller when compared to the simulated network delay.

To achieve scaled real-time simulation, the simulator must first decide the scale factor (Scale) and then make progress according to this scale factor. The pseudo code of the simulation control is listed in Figure 4.9.

```
T_start_wall_clock_time = wallclock();
While ( simulation ) {
        Wait until ( scaled_virtual_time() >= simulation_time);
        Processes all events at the end of this time step
        Advance simulationtime to the next time step
}
```

Figure 4.9 Pseudo Code of the Scaled Real-time Simulation Control

This capability can be used to simulate future networks or processors which are much faster connected to slow 100Mbit networks, future 100Gbit networks, and every speed in between. For example, by slowing the simulated speed of computing resources, the effect of future high speed transparent optical networks can be studied.

4.6 Summary

In this chapter, we introduced the MicroGrid approach to modeling the dynamic interaction between applications, middleware, resources, and networks. To address the challenge of modeling complex grid applications, Section 4.2 and Section 4.3 present possible solutions based on live application interception and controlled direct execution. Section 4.4 focuses mainly on how to achieve accurate and scalable online network simulation. Accuracy is guaranteed through packet level detailed simulation. To address scalability issues, the basic approach is to use a distributed conservative discrete event simulation engine to exploit the parallelism available in the network simulation problem. Section 4.5 addresses the issue of scaled real-time execution. This is the base of coordination between multiple simulation modules. And the ability to control resource and network speeds in an online simulation (as opposed to emulation) enables the MicroGrid to support arbitrary performance ratios between elements in a simulation.

Chapter 5 System Design

The main capability of the MicroGrid is to allow grid experimenters to directly execute their applications in a virtual grid environment. The MicroGrid can exploit either homogeneous or heterogeneous physical resources. This chapter describes the MicroGrid 2.4.5 implementation, released in June 2004 and available from http://www-csag.ucsd.edu/. The MicroGrid 2.4.5, the latest in a series of MicroGrid implementations which stretch back as far as October 2000, supports Grid applications that use the Globus Toolkit 2 middleware infrastructure.

This chapter is organized as follows. Section 5.1 provides an overview of the MicroGrid system design. Implementation of the CPU controller for computation resource modeling is introduced in Section 5.2. Following that, Section 5.3 presents the details of network modeling, and Section 5.4 focuses on improving the scalability of network simulation using traffic based load balance.

5.1 The MicroGrid Overview

We have designed and implemented a tool called the MicroGrid which enables accurate and comprehensive study of the dynamic interaction of applications, middleware, resource, and networks. The MicroGrid creates a virtual grid environment – accurately modeling networks, resources, the information services (resource and network metadata). Thus, the MicroGrid enables users, grid researchers, or grid operators to study arbitrary collections of resources and networks. Further, the MicroGrid provides transparent virtualization, allowing the direct study of complex applications or middleware whose internal dynamics are difficult to model

accurately. That is, real application software and middleware can be used unchanged and be executed on arbitrary virtual grid structures. In short, the MicroGrid provides a virtual grid infrastructure that enables scientific and systematic experimentation with dynamic resource management techniques and adaptive applications by supporting controllable, repeatable, observable experiments.

5.1.1 The MicroGrid System View

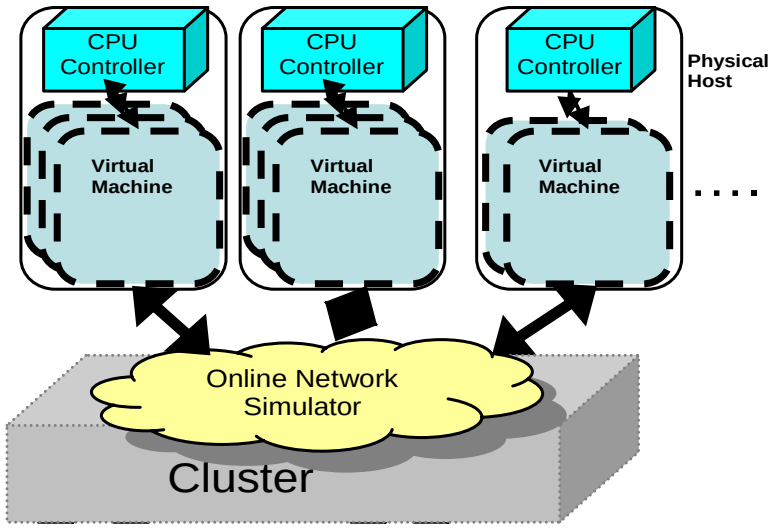


Figure 5.1 the MicroGrid System View

The MicroGrid provides an online simulation of virtual grid environments transparently, allowing applications to be run unchanged. At launch, the MicroGrid reads a virtual grid configuration, and then builds corresponding simulation objects so as to provide the experience of running on a virtual grid. These simulation objects implement models of network elements, compute resources, or grid information services. The MicroGrid can implement the virtual grid simulation using essentially any physical resources, including homogeneous clusters, heterogeneous grid resources, or even on a single computer. Usually the network simulator uses a set of cluster nodes and each node is in charge of simulating a section of the virtual network.

The application processes run in different virtual machines which can be hosted by another set of physical resources.

High speed resource simulation is achieved by direct execution of applications and middleware on virtual machines. A physical machine can host a few virtual machines and uses a CPU scheduler to control the speed and capacity of the virtual machine (Figure 5.1). Direct execution allows experiments to proceed at near real-time. The MicroGrid uses a wrapper library which automatically intercepts library functions in user applications, thereby creating hooks for the virtual grid simulation system. Thus MicroGrid users can run any application on the MicroGrid by simply re-linking the applications to the "wrapper" libraries; neither changes to the application and middleware source codes, nor understanding of them are needed.

The network traffic from the applications is redirected to an online network simulator by the wrapper libraries. Data movement is accurately simulated by the network simulator and delivered back to the application at the appropriate time to reflect 'actual' network behavior.

5.1.2 The MicroGrid User View

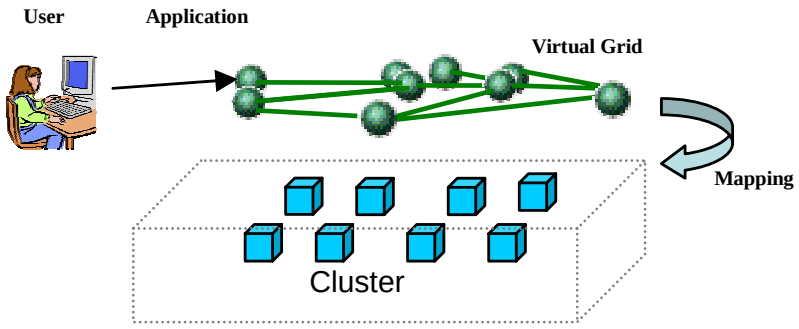


Figure 5.2 The MicroGrid User View

To use the MicroGrid, a user must:

1) Specify a set of virtual resources, including network connectivity and protocols.
    a. Network topology (Nodes, including routers and hosts and Network links, link capacity and link latency)

b. Network protocol (Transport protocols -- TCP or UDP and Routing protocols – OSPF, BGP)

c. Node properties related to communication protocols (e.g. TCP buffer, send window, receive window, segment size, etc.)

d. Compute (relative CPU speed)

e. Compute Node Connections into the network

2) Specify a set of physical resources to be used for the compute and online network simulation, which in turn are used to control the deployment of virtual resources to physical resources.

3) Submit a Grid application as a job on the virtual grid, just like on a real Grid environment

4) Observe the execution of the application, and collect results and performance data

5.2 CPU Controller

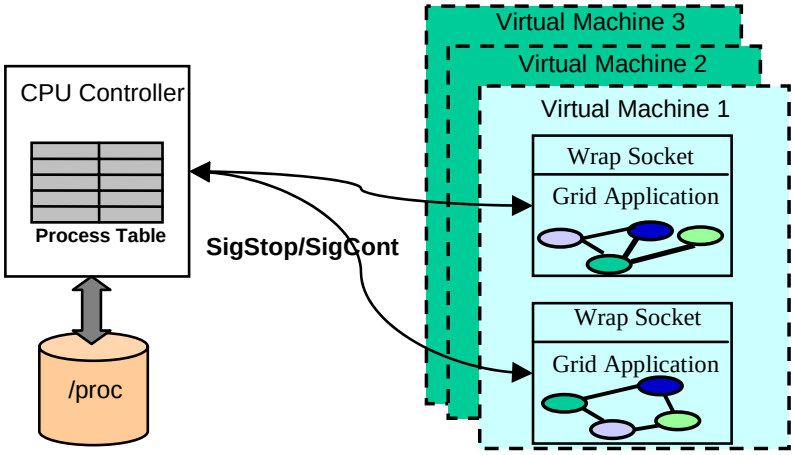


Figure 5.3 CPU Controller

As mentioned in Section 4.2 the MicroGrid uses one CPU controller on each physical host to monitor the per process resource utilization of the processes on each virtual machine, and preemptively schedules them using SIGSTOP and SIGCONT signals (Figure 5.3). Here we

provide more implementation details on how to guarantee accurate CPU quotas for every virtual machine in the controller.

5.2.1 The Challenge

Although the idea of the CPU controller appears simple, there are two factors that make it complex. First, the POSIX.5 thread scheduling mechanism used in Linux is not a real time scheduler. Specifically, it has a 10 milliseconds scheduling unit; that is, when ever a process is scheduled to run, it can use up 10 milliseconds. Second, an application can be a mix of computation and communication; its running time depends on both the CPU speed and the network speed. Ideally, the CPU controller and the network simulator can collaborate to make for a more accurate simulation. However, this would make both the network simulator and the controller more complex. For simplicity and scalability, it is desired that they operate independently, while the CPU controller can make scheduling decisions based on the observations of how much CPU time the application has used.

A naïve implementation, which was used in the first release of the MicroGrid toolkit, demonstrates the effect of these two factors. The original scheduler starts/stops application processes periodically. The period is calculated from the CPU speed of a virtual machine and the number of processes loaded on the virtual machine. For example, if the scheduler is to control a virtual machine which has allocated 25% of real CPU on which two processes are running, it will assign each process 10 milliseconds every 80 milliseconds.

This mechanism works fine if the application is computation intensive, but has the following weakness:

First, it is not suitable for communication intensive applications, which use little CPU resource and spend most of their time waiting for network messages. If the simulation process is stopped by the controller just before the arrival of network data, it is not able to respond until 70

milliseconds later. This 70 milliseconds latency is purely a simulation artifact and hurts the simulation accuracy tremendously. Similarly, if a virtual machine has both communication-intensive and computation-intensive processes, the computation process can easily use up all allocated CPU slots and leave the communication process hungry. This will also introduce large communication delay and, potentially, skew message inter-arrival time.

Second, it allocates CPU resource uniformly to every process on a virtual machine, which is unlikely to happen in the real world. If some processes are waiting for disk I/O or network data, they will not use much CPU time, while other computation-intensive processes should be able to take their quotas.

5.2.2 CPU Controller with Sliding Window

From the example above, we can see two key issues for good CPU scheduling. First, to prevent unwanted communication delay, an application process should always be ready to run if it has not used up its available CPU slots. Second, a computation-intensive process should be able to use all of the CPU quota allocated to its virtual machine; other given processes on the same virtual machine do not take their own slices.

```
decides the sliding window size for every virtual machine
while (simulation is running) {
    polls the CPU usage information from the /proc
    for (every virtual machine) {
        calculates the CPU usage percentage during recent sliding window
        if exceeds the CPU quota, then
            stops all processes on it
    }//end of for
   sleeps until next scheduling point
} //end of while
```

Figure 5.4 Slide Window CPU Controller

To address these two issues, we design the sliding window scheduling mechanism. Instead of proactively starting/stopping processes periodically, the controller lets the OS schedule all processes on a given virtual machine freely, and simply monitors their CPU usage in the background. The scheduler will only stop processes on a virtual machine when they have used up all the CPU time allocated to them. If the virtual machine has been idle for a while, it can accumulate some “credits” that allow for quick response following network data arrival or I/O event completion. To prevent a machine from accumulating too many credits, the controller uses a sliding window algorithm to track its recent CPU usage. The pseudo code of the CPU controller is presented in Figure 5.4.

Because Linux schedules processes in 10ms units, called “jiffy”s, the controller uses a window size measured in the units of jiffies. In order to minimize simulation error, we try to keep the sliding window as small as possible. Since communication latency may be masked by scheduling granularity, we determine the minimal sliding window size as follows:

Suppose *E* is the design accuracy error and *p* is the scaled virtual machine speed (fraction of physical CPU), the sliding window size (*w* jiffies), and the available jiffies in a sliding window *n* should satisfy:

$$w = \text{round}(n/p) \text{ and } | 1 - n/(p*w) | < E$$

For every virtual machine with a given *E* and *p*, we can first find the smallest *n* that satisfies the

$$| 1 - (n/p)/\text{round}(n/p) | < E$$

Then we can calculate the sliding window size *w*, which is the smallest sliding window to satisfy the accuracy error *E* (set to 5% in our implementation). For example, if we have a 1GHz machine, and we want to simulate a 600MHz machine with simulation rate 2, then this virtual machine should take *p*=(600/1000)/2 = 30% CPU of this physical machine. So we need to find the smallest n that satisfies:

$$| 1 - (10n/3) / \text{round}(10n/3) | < 0.05$$

In practice, since *n* is usually a small integer, we can just try 1,2,3 ,… in sequence, and stop at the first number that satisfy the inequation above. Here we can get *n* equal to 2, and then set the sliding window size *w* to round(n/p) = 7.

5.2.3 Discussion

The sliding window mechanism allows simulation of large numbers of machines (100's to thousands) on a small number of machines. Further, since each virtual machine has its own window size, grids with extremes of heterogeneous performance from slow to fast machines can be modeled accurately on the same physical machine.

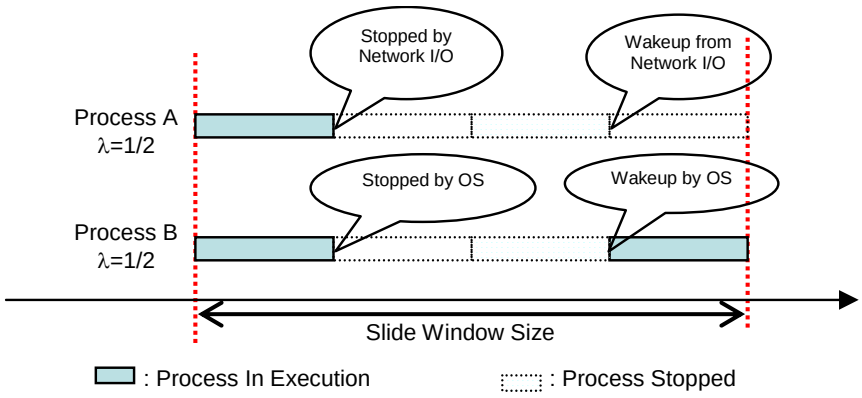


Figure 5.5 Possible Inaccuracy from Large Sliding Window Size

However, reducing *E* often leads to larger sliding window size, which may lead to simulation error for applications which have mixed computation and communication. The major reason for this is that the CPU controller has no idea whether a waiting process is waiting for network delay, or is just scheduled out by the operating system. For example, Process A and Process B are supposed to use half of the real CPU on two physical machines. Both of them stop after using ¼ of the sliding window size time, one due to the network I/O and the other due to the host OS scheduling. At the ¾ sliding window point, process B is re-scheduled to run by the OS, and the CPU controller should let it use up the rest of the sliding window. Process A is also woken-up by the completion of network I/O at the same time, and it should be stopped by the CPU controller, since it should only use ¼ of the real CPU time due. Currently the CPU controller cannot distinguish these two cases, and it will always grant another ¼ sliding window time to Process A.

So under some conditions, we may still have large inaccuracies: such is the case when an application has mixed computation and communication with some special structures, and the sliding window size is large in comparison to communication latency. As we will show in our validation experiments, with reasonable design accuracy error *E*, this situation rarely happens and has little effect on overall application performance.

5.3 Scaled Real-time Online Network Simulation

Network modeling is achieved by MaSSF. MaSSF (pronounced “massive”) is a scalable packet-level network simulator that supports direct execution of unmodified applications. MaSSF consists of four parts.

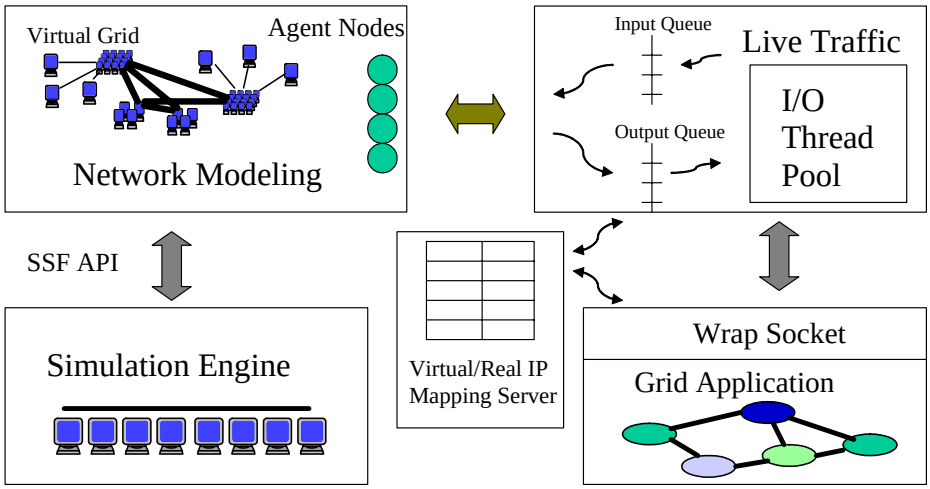


Figure 5.6 The MaSSF Scalable Network Simulation System

1) Simulation Engine: MaSSF uses a distributed simulation engine based on DaSSF [56]. It utilizes an MPI-connected cluster system to achieve scalable performance. The original simulation engine, executable only in pure simulation mode, has been modified to operate in a scaled real-time mode (as discussed in Section 2.3). This simulator can run in a scaled-down mode when the simulated system is too large to be executed in real time on the available hardware. With the global coordination of the MicroGrid, this feature provides extreme flexibility to accurately simulate a wide range of networks accurately.

2) Network Modeling: MaSSF provides necessary protocol modules for detailed network modeling, such as IP, TCP/UDP, OSPF, and BGP4. We have built simplified implementations of these protocols which maintain their behavior characteristics. We also use a network configuration interface similar to a popular Java network simulator implementation, SSFNet[57], for user convenience.

3) Online Simulation Capability: To support simulation of traffic from live applications, we employ an *Agent* module which accepts and dispatches live traffic from the application wrapper to the online network simulation. Traffic is also delivered to application through the Agent module.

4) Live Traffic Interception: Application processes use a wrapper library called *WrapSocket* to intercept live network streams at the socket level. The *WrapSocket* then talks to the *Agent* module to redirect traffic into the network simulator and vice versa. *WrapSocket* can be either statically or dynamically linked to application processes and requires no application modification.

These components and their relationship are illustrated in Figure 5.6. In the following sections we will present a more detailed description and rationale for our design choices.

5.3.1 Network Modeling

MaSSF's goal is to enable detailed modeling and simulation of Internet protocols and networks. It uses object-oriented simulation components to construct a network, setup network protocols running on various hosts and routers, and create/accept traffic to be simulated. Traffic can be created using traffic generation modules or can be imported from live applications. Network traffic is simulated at the IP packet level and every network packet movement is represented by a simulation event. MaSSF models the hop by hop movement of IP packets through the network, including link transfer delay, queuing delay in router queues, and packet drop. The simulation engine has a scaled real-time scheduler that delivers events at the exact time specified by the event timestamp. In this way, we can capture link congestion and network dynamics in the real world.

5.3.1.1. Network Protocol Stack

Like the Click Modular Router[58] and SSFNet[57], MaSSF provides a batch of protocols, such as IP, TCP, UDP, OSPF, and BGP, and some network elements, like hosts, routers, links, and switches, that can be used to construct a network. For example, a host can be configured with *IP*, *TCP*, and *Socket* protocols, plus an *httpClient* traffic generation module or a live traffic *Agent* module. A router can be configured with *IP*, *TCP*, *OSPF* modules as an internal Autonomous System (AS) router and it can also be configured with *IP*, *TCP*, *BGP* modules to be used as a BGP router. With these basic components provided by MaSSF, users can construct a network entity using any reasonable module combination. Moreover, users can also write their own protocol modules for new applications or network protocols.

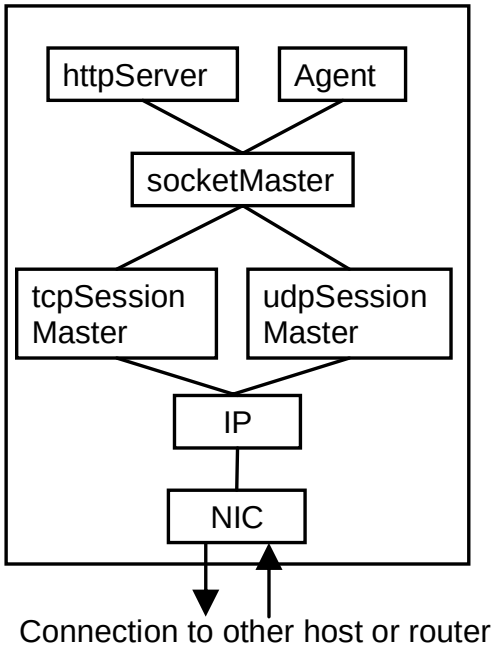


Figure 5.7 Protocol Stack for a Host with *httpServer* and *Agent*

All protocols running on a host or router are constructed as a protocol stack with well-defined interfaces to facilitate the data movement along the stack. Figure 5.7 illustrates the major network elements and protocol sessions that are used in a host model. This host is equipped with one network interface card (NIC), which is connected to another host or router.

The host has an *httpServer* application running, which uses a socket interface, just like in a real operating system, to communicate with the TCP protocol session masters at the transport layer. A TCP or UDP session is created when a request arrives from the application, and is torn down when the session is finished. An IP layer is required to manage packet sending, receiving, and forwarding by the NIC. This host also has an Agent protocol module, which means it can accept real traffic from live applications. Figure 5.8 is a router equipped with two NICs, with both BGP and OSPF routing protocols.

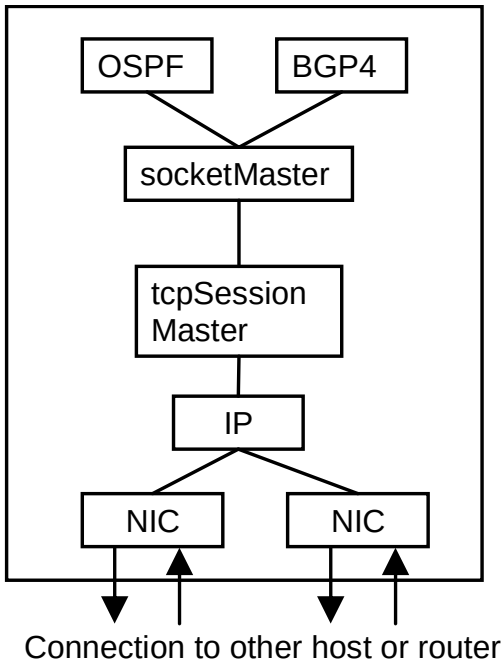


Figure 5.8 Protocol Stack for a Router Running BGP and OSPF

5.3.1.2. Network Topology and Configuration

The first step in network simulation is to provide the topology and configuration of the network to be simulated. In MaSSF, the input network is described by the Domain Modeling Language (DML). MaSSF models are self-configuring - that is, each MaSSF class instance can autonomously configure itself from a configuration file in DML format [59].

DML has a simple syntax: it is a list of attributes. The key of the attribute is an identity and the value of the attribute can be a number, a string, or another attribute list enclosed in brackets. DML is a recursively defined list of key-values. Logically, a DML file can be viewed as a tree. The root and all internal nodes represent a list of attributes and all leaf nodes represent attributes with simple values. All nodes can be identified by a key path starting from the root, like the hierarchical Java module name.

An input DML file specifies the network topologies, including network entities (host/router) and links between entities. The link latency and bandwidth are also specified in the DML file. For each entity, the user can also decide the protocol stack. Figure 5.9 and Figure 5.10 are example DMLs corresponding to the entities in Figure 5.7 and Figure 5.8 respectively. Figure 5.11 is a simple network with 2 hosts and 1 router. The *Net, host, router, link, attach, interface,* and *graph* are reserved attribute keys for network specification. The *graph* attribute represents the protocol stack installed on an entity, and the *link* attribute is used to represent a network connection. The *attach* attributes are the NICs connected to a link.

```
host [   id 0
         route [ dest default interface 0 ]
         interface [ id 0 bitrate 100000000 latency 0.0001 ]
         graph [
              ProtocolSession [ name agent use Agent]
              ProtocolSession [ name httpserver use httpServer ]
              ProtocolSession [ name socket use socketMaster ]
              ProtocolSession [ name tcp    use tcpSessionMaster ]
              ProtocolSession [ name ip     use IP ]
         ]
    ]
```

Figure 5.9 A Host with Agent and *httpServer*

```
router [id 1
        interface [ id 0 bitrate 100000000 latency 0.0001 ]
        interface [ id 1 bitrate 100000000 latency 0.0001 ]
        graph [
            ProtocolSession [ name bgp use BGP4]
            ProtocolSession [ name ospf use sOSPF ]
            ProtocolSession [ name socket use socketMaster ]
            ProtocolSession [ name tcp    use tcpSessionMaster ]
            ProtocolSession [ name ip     use IP ]
        ]
    ]
```

Figure 5.10 A Router with OSPF and BGP Routing Protocols

```
Net [   id 0
        host [ id 0 interface [ id 0]
        host [ id 1 interface [ id 0]
        router [ id 2
                interface [ id 0 ]
                interface [ id 1 ]
        ]
        link [attach 0(0) attach 1(0) attach 2(1) ]
    ]
```

Figure 5.11 A Simplified DML for a Network with 2 Hosts and 1 Router

The DML file has all information regarding the network. This information is parsed and stored in a database by MaSSF at initialization phase. MaSSF uses this database to create the virtual hosts and routers, setup network connections, and build the forwarding table. After initialization, the DML file and the database are no longer necessary, all simulated network elements work independently, just like in the real world network.

5.3.1.3. Addressing in DML

As in the DML examples, every host or router is identified with an *id* attribute and every NIC can also be identified an interface *id* attribute. The link attribute is used to represent a network connection, and it uses the NIC identities to represent which NICs are connected to this link. For example, the

link [attach 0(0) attach 1(0) attach 2(1)]

represents that there is a switch connecting host 0, host 1, and router 2, using interface 0, 0, and 1 respectively.

The *Net* is also identified by the *id*. MaSSF supports hierarchical networks with nested *Net* attributes. And each *Net* attribute can have multiple sub *Net* attributes, identified with different *id* attributes. The *Net*, *router*, *host*, and *interfaces* defined in such a manner can be uniquely addressed using the NHI scheme, where NHI represents the Network-Host-Interface. The network address of *Net* attributes is formed by concatenating the id of the network definition at each level starting from the DML root, separated by colons. Similarly, the NHI address of a host or router is the encompassing *Net* addressing concatenated with the *id* of the host, separated by colons. The NHI address of a NIC is the concatenation of *Net* and *host* address, followed by the NIC *id*, enclosed in parentheses. For example, an NHI of 4:2:12(3) represents the third NIC of host 12 in the network 4:2.

The NHI scheme can be used to globally address any host, router, or interface, uniquely. However, when used in a DML file, the network address essentially starts from the root of the DML Net; typically a local address is sufficient. For example, when we define a link in Net 4, only the local address is used

Link [attach 2:12(3) …]

In this way, a sub-network can be defined without knowing the upper-level network, and a single definition can be used multiple times by different networks. This makes the DML quite flexible when defining a hierarchical network.

NHI addressing is only used inside the DML file, and external users require IP addresses. The user can specify an IP address for every NIC of the hosts and routers in the DML file or MaSSF can automatically assign IP addresses according to CIDR address mechanism [60].

After assigning an IP address, the forwarding table will be setup automatically, according to the configured routing protocols.

5.3.1.4. Routing in MaSSF

As in a real world router, packet forwarding in the MaSSF router is decided by a local forwarding table, which is calculated by the routing protocols. We have implemented the OSPF protocol for intra-domain routing and BGP4 protocol for inter-domain routing. As we already see in the examples, these protocols can be installed in the router protocol stack.

Two versions of OSPF are implemented in MaSSF. The first is the static OSPF, which only calculates the shortest-path routing of an AS at the beginning of simulation and it will not respond to network changes during the simulation. However, it can still accept dynamic routing information from BGP protocols. The second fully implements the specification of OSPFv2 [61] and recalculates the routing table dynamically when experiencing router failure, link failure, or heavy traffic congestion. Compared to the dynamic version, static OSPF is much simpler, and requires less memory. Since all routers in an AS has the same view of the network, we can just keep a single network database in an AS, and calculate forwarding tables for every router together. The network topology database can be released after initialization. Dynamic OSPF, on the other hand, has to keep the AS network topology information and calculate the forwarding table by itself. In practice, we only use the static OSPF for large scale simulation, and use the dynamic OSPF only when we really care about the routing dynamic inside an AS.

The BGP protocol in MaSSF is based on the SSF.OS.BGP4 model from SSFNet. The focus of porting the BGP4 model from SSFNet to MaSSF, is not on to develop novel BGP simulation technology, instead, the focus is to exploit the scalability offered by the MaSSF simulation framework So, functionally the MaSSF implementation is fully compliant with the BGP-4 specification in the RFC1771[62], just like the original SSFNet BGP model. And it is also fully

validated with the test suits in SSFNet, covering functionality such as basic peering session maintenance, route advertisement and withdrawal, route selection, route reflection, and internal BGP.

One major consideration in our BGP implementation is the reduction of memory consumption for better scalability. For a large network simulation, one big memory consumer is the BGP routing table, since it grows exponentially with the number of ASes. To alleviate this memory problem, we fully reuse routing entries among the three parts of BGP Routing Information Base (RIB) [63]: Adj-RIBs-In, Loc-RIB, and Adj-RIBs-Out . Unlike the Java automatic memory management of SSFNet, MaSSF manages all objects using reference counters which reduce the memory consumption by 60%. The other big memory consumer is the local forwarding table. In MaSSF, the BGP routers can work with OSPF routers insider an AS and only broadcast default routing to external networks, instead of the whole routing table in the BGP router. This is can greatly reduce the memory consumption and computation overhead for a large AS with hundreds of internal routers. Of course the user can disable this feature if they want to manually control the routing policy inside the AS.

5.3.2 Online Network Simulation

Online network simulation is to enhance traditional network simulation with supports for direct execution of applications. Two major issues are discussed here, one is how to intercept live application traffic and the other is how to inject the traffic to the traditional network simulation.

5.3.2.1. Socket Level Interception

In order is to support direct execution of real applications in MaSSF, we need to intercept live traffic from applications and present it to the network simulator. It can be achieved either at the socket level by intercepting the *send(), recv()* network related system calls or at the IP

packet level by manipulating the IP packet directly. The difference between these two approaches is whether or not the operating system's TCP stack (see Figure 5.12) is used in the data movement path. The advantage of the second approach is that it does not model the TCP stack, leading to a much simpler implementation. However, using the original TCP stack requires running the simulation in real time, since the OS TCP stack observes the real packet RTT (round trip time) and adjusts its send rate according the RTT it observed. This is a big constraint, since in many situations the physical resources are not fast enough to achieve real time simulation. So MaSSF takes the first approach, intercepting the live traffic at socket level for scaled-real time simulation.

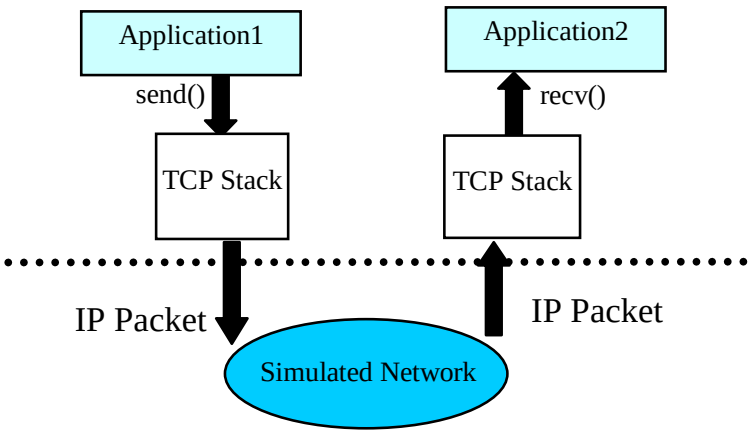


Figure 5.12 Traffic Flow in a Real Operating System

As shown in Figure 5.13, MaSSF intercepts all network related system calls using a library called *WrapSocket*, which can be either statically or dynamically linked to application programs. Every virtual host has a corresponding Agent inside the simulator, and *WrapSocket* sends the Agent a logical reference for each intercepted network operation. A detailed TCP stack is implemented inside MaSSF and packet movement and timing are accurately simulated. Only packet references are routed in the simulated network, while the real data stays in *WrapSocket* and is delivered directly to the destination processes' *WrapSocket*. There are no extra data copies, and minimal real network traffic is incurred. When all required data arrive at the

destination *Agent*, it allows *WrapSocket* to successfully return calls to *recv()*. At this point, we expect that all real data is already waiting in *WrapSocket*, since it is transferred directly through the fast local network. The application then returns from the call to *recv()* with the real data.

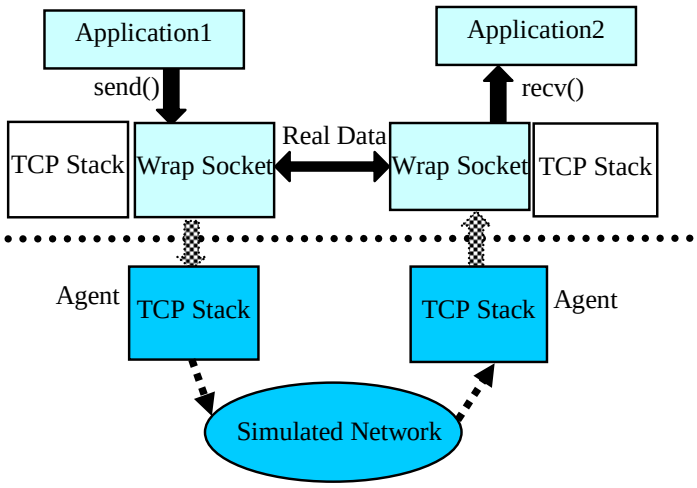


Figure 5.13 Traffic Flow in MaSSF

In our approach, all network behaviors (including TCP sliding window management, link congestion, and packet drop, etc.) are precisely modeled inside the simulator, and the only source of distortion is the delay for transferring a logical reference from *WrapSocket* to the *Agent*. Since this is a small amount of data (~60 bytes), moving across a fast local link, its impact on the simulation of wide-area network delay is negligible.

5.3.2.2. Efficient Request Handling

Every network operation is translated into a request to the simulator and after processing the result will be sent back to the wrapper. Since the delay between the wrapper and the Agent module is not modeled by the simulator, it must be handled as fast as possible. And the most important factor is that no pending request blocks subsequent requests even if its own semantics describe it as a blocking operation; these operation include blocking *connect*, *recv*, and *send* operation. The reason for this is that a simulation engine node may support many virtual hosts,

with many application processes connected to it. If the request handler blocks on one request, it cannot handle requests from other processes or from other virtual machines.

Based on these considerations, the simulation module is implemented with the following features.

1) Non-blocking Request Handling: All event handling must be non-blocking. For those blocking operations, the block happens only in the wrapper; all operation within the simulator is non-blocking. To achieve this, we exploit callback mechanisms in the simulator, implemented through the Continuation construct.

```
Continuation {
        int success();
        int failure(int err_no);
};
```

For every blocking request, a continuation object is created and registered in the simulator. For example, a blocking read operation can create and register a continuation on the corresponding TCP session. When new data arrives, the simulator will check whether any pending read continuation is registered and whether it is satisfied, if so, the success() function will be called and the read result is sent back to the wrapper.

2) Event-based Request Dispatch: Every simulation node has a thread pool to accept requests. Requests form the wrapper are first put into an event queue, and then handled by a thread pool in FIFO model. The event handling is non-blocking, so only a small number of threads are needed to handle a large number of clients (application processes).

3) Optimization for Select and Poll: All function calls are handled in a RPC-like approach, except the select and poll calls. These calls are different. They have timeout mechanism with the timeout values can be quite small and called very frequently. If they are implemented in a straight forward fashion, that is, one request for per call and timeout in the simulator, the

overhead for some applications could be so large that it would affect the accuracy of the simulation. Hence, these calls are handled separately. We do not send out a request for every call, instead, we only send out a request when it is different from the last request, such as when selecting on different socket sets. Timeouts only happen in the wrapper, and the simulator is not involved. An old selection request will register a continuation, and it will either result in success or be overwritten by a new selection on that socket. An invalid selection result must be sent back to the wrapper when that selection has timeout. The wrapper can use sequence numbers to distinguish invalid results.

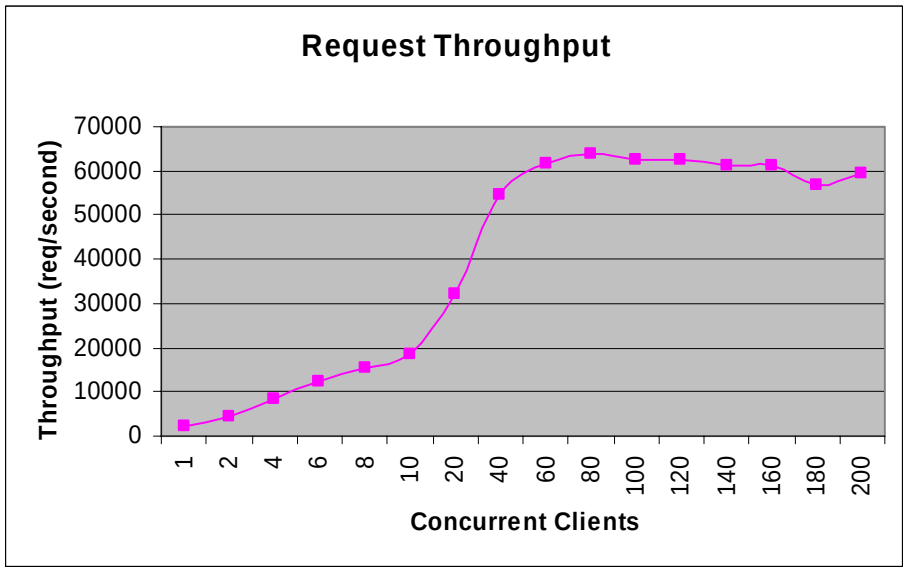


Figure 5.14 Request Throughput for a Single Simulation Engine

Figure 5.14 shows the request throughput of a single simulation engine node, versus concurrent number of clients. For a single client, the throughput is about 2200 requests per second, and the total throughput can reach 65K requests per second. This throughput seems small, but it can support quite a fast network, since every request can correspond to a send operation, which can be much larger than a network packet. Also, all simulation engine nodes provide fully parallelized on requests handling, we can increase simulation engine nodes numbers if necessary.

Figure 5.15 shows the request delay, versus the concurrent client number. The minimal request delay is about 0.47 milliseconds, which is quite small, when considering the wide area network delay (more than 10 milliseconds) plus the possible slowdown rate. The delay increases slowly until it reaches the throughput bottleneck with 60 full speed clients.

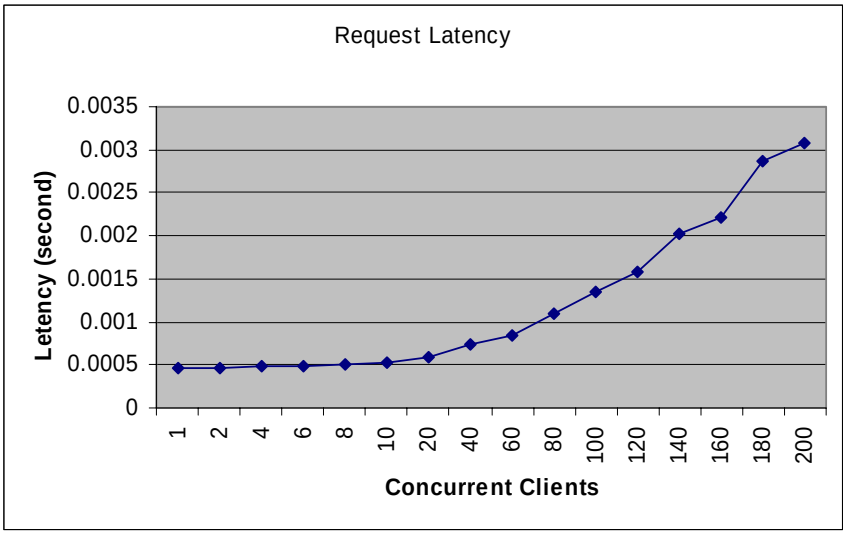


Figure 5.15 Request Latency of a Single Simulation Engine Node

5.4 Traffic Based Load Balance for Scalable Simulation

In this section, we discuss the details of our automatic load balancing for scalable network simulation.

5.4.1 Elements of Network Mapping Problem

To achieve scalable performance, MaSSF uses a distributed simulation engine running on a cluster. Given a network topology and available cluster nodes, the MaSSF partitions the virtual network to multiple blocks, assigns each block to a cluster node, and simulates in parallel, as shown in Figure 5.16. Every cluster node runs a discrete event simulation engine and events are exchanged among cluster nodes. To maintain the simulation accuracy, these cluster nodes also need to synchronize periodically.

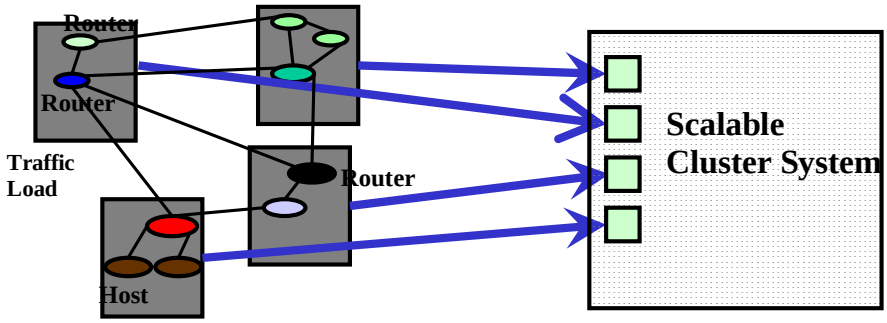


Figure 5.16 Mapping Routers to Physical Resources

For large simulations, the network mapping cannot be done manually or casually. Instead, the mapping is a critical and demanding challenge, since we need to achieve load balance across all cluster nodes. This is difficult because the workload on each physical node varies greatly, depending both on the virtual mapping and network traffic in that subset of virtual network (Figure 5.17). Furthermore, two more optimization goals should be considered. One is to maximize link latency across partitions to reduce the frequency of synchronization among simulation engines and maximize concurrency, a critical element of scalability for large scale simulation. This feature is an attribute of our MaSSF system and all other network simulators based on conservative discrete event simulation engines. The other optimization goal is to minimize the communication of simulation events between simulation engine nodes. It is expensive to transfer a simulation event across physical nodes both in terms of computation overhead and communication latency. Also, the physical network of the simulation engine nodes is often a performance bottleneck for the whole simulation. Hence, it is important to minimize this communication.

The problem above is called the network mapping problem. To achieve the optimal load balance even with known traffic is a NP-Hard problem[55]. However, in practice, a network mapping problem can be naturally modeled as a graph partitioning problem and solved with the classical graph partitioning algorithms.

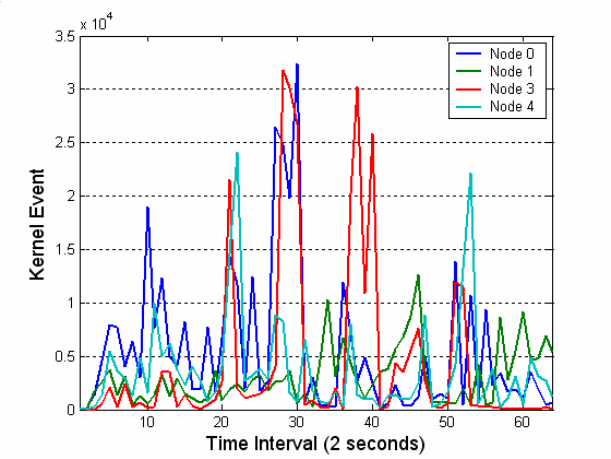


Figure 5.17 Load Variation over the Lifetime of Simulation

5.4.2 Modeling Network Mapping as a Graph Partitioning Problem

Given an input graph G = (V, E) with weighted vertices and edges, typical graph partitioning algorithms can partition it into k parts such that, each part has roughly the same number of vertex weight and the edge-cut (the number of edges) that straddles partitions is minimized. By setting the vertex and edge weights appropriately, mapping a simulated network to a set of physical simulation resources can be modeled as a graph partitioning problem and solved using a generic graph partitioning algorithm.

As a well studied problem, we expect that any high quality graph partitioning package (in this case METIS[64]) should produce results comparable to other graph packages. So our challenge is how to apply the graph partitioning algorithm in METIS to solve the mapping problem by defining the suitable input graph G, constraint conditions, and optimization objectives for the graph partitioning algorithm. Our choices are discussed in the following subsections.

5.4.2.1. Input Graph

The input graph G is defined by two categories of parameters: network structure and traffic information. The network structure includes detailed network topology, link latency, and link bandwidth. In MaSSF, this information is stored in the network description file and can be easily translated to a vertex and adjacent edge graph. Network traffic information is used to define edge weights in the graph, and it may also affect vertex weights. In general, network traffic information includes background traffic and foreground applications traffic, derived from trace, model, or even live applications. How we approximate and model the expected traffic for the simulation is the distinguishing key characteristic of our three different load balance approaches. We will further focus on how to get that information in Section 5.4.3.

5.4.2.2. Constraints

In a graph partitioning problem, the constraint is the vertex weight to be balanced among multiple vertices. In the network mapping problem, the vertex weight can be defined as weighted sum of computation and memory requirement on each simulation engine node. In the MaSSF implementation, the computation requirement mainly comes from the logic for packet processing, which depends on network connection, routes, and traffic intensity. It is calculated based on the maximal bipartition flow of all traffic flowing through a network node. The memory requirement is mainly based on the routing table size. The routing table size is in the order of $O(n^2)$, where n is the number of routers in an AS (Autonomous System). We also use multiple constraints to balance different kinds of vertex weights together.

5.4.2.3. Objectives

In a graph partitioning problem, the objective is the edge-cut to be minimized. In the network mapping problem, the optimization can use two objectives, which means two different

ways to weight the edges. The first one is to maximize link latency across partitions. This can reduce the frequency of synchronization among simulation engines and maximize concurrency in the simulation, which is very important for scalability for large scale simulation. This feature is an attribute of our MaSSF system and all other network simulators based on conservative discrete event simulation engines.

The second objective is to minimize the communication of simulation events across simulation engine nodes, since it is expensive to transfer a simulation event across physical nodes both in terms of computation overhead and communication latency. Also, the physical network of the simulation engine nodes is often a performance bottleneck for the whole simulation; hence, it is important to minimize this communication. With detailed traffic information, we can estimate the number of simulation events on each single link and use it to calculate the edge weight. How to get such traffic information is the major topic of Section 5.4.3.

5.4.2.4. Multi-Objective Graph Partitioning

In last subsection, two objectives are described. Both of them are important and sometimes in opposition.

1) Apply the single objective algorithm for maximal link latency across partitions, get the optimization edge-cut $C_{latency}$.
2) Apply the single objective algorithm for minimal network traffic across partitions, get the optimization edge-cut $C_{bandwidth}$.
3) Assign each edge weight to

$$w_{conbined} = p\frac{w_{latency}}{C_{latency}} + (1-p)\frac{w_{bandwidth}}{C_{bandwidth}}$$

where p is the user controllable weight of the latency objective.
4) Apply the single objective algorithm with the new normalized edge weights.

Figure 5.18 The Multi-Objective Graph Partitioning Algorithm

The challenge is to figure out how to set edge weights to represent the requirement of both objectives, and still provide the user predictable control on tradeoff. A simple combination-based approach (e.g. simply add two weights to a single weight) does not make sense. Applying the algorithm presented in [42], we can combine two dissimilar weights in a predictable way and use the available single objective METIS partitioning package. This algorithm is based on the intuitive notion of what constitutes a good multi-objective partition. That is, a good solution should be close to the optimization solution for each single objective. Applying this approach on our network mapping problem, we get the algorithm in Figure 5.18:

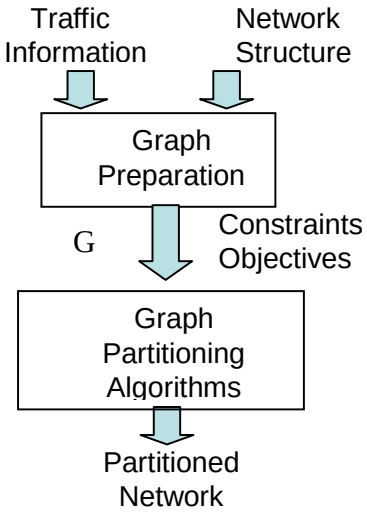


Figure 5.19 Process of Network Mapping

In summary, the mapping process can be modeled as shown in Figure 5.19. First, it takes the network structure and traffic information as input, creates a graph G, and builds objectives and constraints of graph partitioning algorithms. Then it applies partitioning algorithms to get the partitioned network. The partitioned network incapacitates the mapping of emulated network nodes to physical resources. We may have different abstraction of network mapping problems and use different constraints and objectives in the graph partitioning algorithm; however, we believe what we present above is straightforward and should have reasonable

results with small overhead. The problem left is how to collect and use the traffic information, which will be discussed in the following section.

5.4.3 Traffic Based Network Mapping

Three different approaches are explored for network mapping. These approaches vary in how network topology, background traffic, and application traffic are represented and used in the partition. The ability to predict the simulation workload (i.e. network traffic) accurately enables better partitioning and therefore better load balance. However, there are tradeoffs between the specificity of the information used and the generality of the partition produced.

5.4.3.1. Network Topology-Based Mapping (TOP)

Our first approach only considers the simulated network topology, link bandwidth, and latency, in which each virtual node is weighted with the total bandwidth in and out of it. The optimization objective is to maximize the link latency between simulation engine nodes, as discussed in Section 5.4.1. This maximizes decoupling, supporting efficient parallel simulation.

This basic approach is simple and fast, and represented the state of art as we began. Therefore, it forms a performance baseline for our experiments. It should work well for well-engineered networks with evenly distributed traffic. In such networks, the link bandwidth usually determines the routes that are placed over the links, and since networks are typically engineered to match the demand, link bandwidth is closely related to real traffic. For example, this model is expected to be effective when we want to study the web traffic on Internet, which is composed of lots of small web browsing flows.

5.4.3.2. Application Placement-Based Mapping (PLACE)

With precise traffic information, we can do a better mapping. The second approach is based on the observation that simulated network traffic typically consists of a background and a

foreground load. Foreground traffic is created by the target application that the user wants to study, and background traffic is used to provide realistic network conditions. Both traffic loads are estimated separately, and then combined to predicate the aggregated traffic data for better network mapping. We call this approach PLACE.

The background traffic is generated using simple traffic models based on the network topology, and can be explicitly controlled by the user of the network simulator. In this case, it is reasonable that all traffic generators can provide some prediction of their generated traffic load, for example, specifying the average traffic bandwidth between two endpoints. Because the background traffic represents an aggregate of traffic, such a gross characterization can be reasonably accurate.

Due to the nature of configuring application, the foreground load is typically the live traffic from a small set of application programs. Unlike background traffic prediction, it is difficult for users to predict the traffic of the real application. First, the live traffic has complex dynamic behavior that is hard to model (that is why we need a network emulator to study it). Second, users may not have the required knowledge to describe this information (lacking either application knowledge or the computer systems knowledge). As an approximation, we determine the traffic injection points of the application, where its processes attach to the simulated network, assuming that the application fully utilizes the network link at each injection point and every node talks to all other nodes with evenly distributed bandwidth. While this approximation may seem coarse at first glance, it is acceptable when considering that most target applications in simulation are complex and network intensive.

With the source/destination pairs of all traffic flows, the aggregated traffic on each link can be computed by summing the contribution from each flow. To identify the routes used in the simulated network, we instantiate the simulated network and detect the actual routes used (based on dynamically generated routing tables and routing protocols). To get the routing

information, we implement the ICMP protocol inside MaSSF, and use the real Linux *traceroute* tool to discovery the routing paths between each source-destination pair. To reduce the number of *traceroute* execution required, we could use one representative endpoint for each sub-network and only discover the route paths between those sub-network representatives.

With this predicted traffic information, the approach in Section 5.4.3.1 can be improved by recalculating vertex/edge weights. This extra information also enables another objective, which is to minimize the traffic across partitions. In the approach, the multi-objective graph partitioning algorithm described in Section 5.4.2.4 is used.

5.4.3.3. Profile-Based Mapping (PROFILE)

The third approach uses profiling techniques to obtain traffic information automatically from simulation experiments. The profiles are then used to estimate future network use, and to improve the network mapping. Typically this involves an initial simulation experiment using an initial partition and traffic monitoring. The simulation yields detailed traffic information and the network can be repartitioned based on this information.

The critical challenge for this approach is the efficient collection and representation of traffic information during profiling, and the use of this information to repartition the network. In MaSSF, we implement the Cisco NetFlow-like [65] function on each simulated router. This functionality is used to record every traffic flow on each router to a local file. The dump files record the average bandwidth and duration of every flow on every router. Parsing the dump files allows computation of the aggregated traffic on every router and link in the network. By tuning the granularity of the NetFlow, we can get detailed network traffic information with small overhead.

In our implementation, the real network traffic data does not actually travel through the simulator; only packet references are processed by it. Instead of using the real network

bandwidth (MB/s) as the bandwidth measurement, the number of packets in a flow is used, since the real load in the simulator depends on the number of packets it processes. The live traffic injection overhead is also measured by the number of requests coming from the application.

With much more accurate traffic information about the virtual network from the profile data, the same multi-objective graph partitioning algorithm described in Section 5.3.2.4 is applied to get better load balance.

5.4.3.4. Preliminary Results

We implemented these three partition algorithms in the MaSSF and applied them to the network simulations, with different network topologies and different applications. The network topologies are in range of 60-300 hosts and routers, simulated with less than 10 physical nodes (Table 5.1). These studies show that exploiting static topology and application placement information can achieve reasonable load balance, but a profile-based approach further improves load balance for even large scale network simulation. In our experiments, PROFILE improves load balance by 50% to 66% and simulation time is reduced up to 50% compared to purely static topology-based approaches. More details are reported in [66].

Table 5.1 Network Topology Setup in Premier Study

Network Topology	Router	Host	Simulation Engine Node
Campus	20	40	3
TeraGrid	27	150	5
Brite	160	132	8

5.4.4 Hierarchical Load Balance Approach

5.4.4.1. The Small Achieved MLL Problem

When we apply the TOP and PROF approaches to larger networks (e.g. 10,000 routers running on 100 nodes), neither of them gets satisfactory results. Checking the partition output manually reveals that the common reason for poor performance is that the achieved Minimal Link Latency (MLL) across partitions is insignificant when compared to the synchronization cost. This produces an overall simulation efficiency that is quite low. For example, for one network of 10,000 routers, the achieved MLL was only 0.1ms; far less than the synchronization cost of ~0.58ms for 100 simulation engine nodes (see Figure 5.20). Synchronization cost is the time used by the simulation engine nodes for global synchronization, which need to be executed every MLL time. In such a situation, the majority of the time will be spent in synchronization – even perfect load balance would only moderate efficiency. This situation is quite different from the 1ms MLL for a 160 router network and 0.9ms synchronization cost for 8 simulation engine nodes in our previous experiments[66].

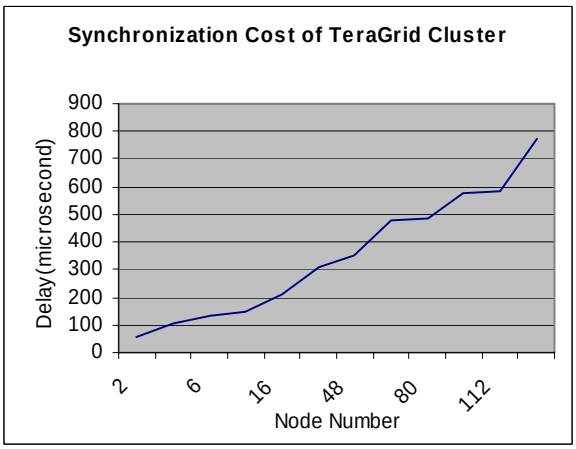


Figure 5.20 Synchronization Cost of the TeraGrid NCSA Cluster

5.4.4.2. Understanding Achieved MLL

The example above exposes a major problem with the existing load balance approaches. In TOP and PROF mappings, the link latency is converted to edge weight of the graph G, and smaller link latency leads to a larger edge weight. When the graph partitioner archives minimal edge-cut across partitions, it is less likely to partition across the link with small link latency, since it corresponds to a large edge weight. However, the optimization goal is the not the MLL, but the minimum edge-cut (the sum of all edge weights that cross partitions). When we have a large graph, the partitioner becomes less sensitive to the MLL, since even the large edge weight from a link with MLL may only be a small part of the final edge-cut.

We may tune the converting algorithm to make the edge weights of small link latencies large enough that it is unlikely they will across partitions, but this depends highly on the network topology, number of the simulation engine nodes, and the physical synchronization cost.

5.4.4.3. Optimizing MLL

To address the issue of small achieved MLL, a new hierarchical partition algorithm is designed. To avoid partitioning across edges with small link latencies, edges with latencies smaller than a threshold, LL, are removed from the input graph (by merging nodes) to the partitioner and are added back to the partitioned output later. In this way, we can guarantee the worst-case of MLL. However, this produces a new problem —how do we choose the latency threshold, LL. If the threshold is too large, it will damage load balance, while if it is too small it will achieve a smaller MLL than possible. Instead of guessing the threshold, our approach is to simply try all reasonable thresholds, create a partition for each, evaluate these partitions, and then pick up the best partition. This is feasible because the partition can be done fast, even for

large networks, and different partition outputs can be evaluated without running the simulation. The pseudo code for hierarchical partitioning is present in Figure 5.21.

```
Input: graph G, partition N, and synchronization cost C
Output: the best partition P of graph G
Hierarchical Partition:
    Set the initial Threshold of MLL (T_mll)
    Loop through all reasonable T_mll:
        Get the dumped graph G_d(T_mll)
        Partition the G_d(T_mll) using an existing partitioner, and get P(T_mll)
        Evaluate the partition result P_d(T_mll)
    Pickup the best partition P_d(T_mll)
    Get the best partition P of original G
```

Figure 5.21 Hierarchical Graph Partitioning Algorithm

This algorithm requires the graph, G, the partition number, N, and the synchronization cost of the simulation engine nodes, C. Figure 5.20 shows the synchronization cost of the TeraGrid SDSC cluster, which is used for all simulations in this paper. We use the synchronization cost to set the initial threshold of MLL (T_{mll}) based on knowledge of the desired number of simulation engines. A T_{mll} is required to be larger than the synchronization cost; otherwise all time will be spent on synchronization, giving poor efficiency. Given the T_{mll}, the original graph G is reduced to a dumped graph G_d by collapsing nodes with link latency less then T_{mll} into a single node. Then any existing partition can be applied to the dumped graph G_d and get the partitioner output. By increasing the T_{mll} step by step (0.1ms in our experiments), we can get a sequence of partitions, and the remaining question is how to select amongst them.

To evaluate the candidate partitions, we use an efficiency metric *Efficiency* (E), which consists of two factors, Es and Ec. The first factor (Es) represents the efficiency decided by the achieved MLL and is calculated:

$$Es = (MLL - C_N)/MLL,$$

where C_N is the synchronization cost of N simulation engine nodes. The latter (Ec) represents the result of computational load balance and is calculated by:

$$Ec = C_{average}/C_{max,}$$

where $C_{average}$ is the estimated average load (simulation event rate) on all nodes, and C_{max} is the max load of all nodes. The final efficiency E is Es * Ec, where larger values of E correspond to better partitions. Maximizing Es and Ec separately does not work because they represent the tradeoff between simulation efficiency and available parallelism. Larger Es means better simulation efficiency, but it also means less parallelism available, since smaller MLL leads to a more coarse-grained partition graph.

In summary, our hierarchical partitioning approach balances the parallelism and decoupling concerns in generating a good network partition. To do so, it generates and evaluates many possible partitions. Because we can create graph partitions and evaluate graph partitions quickly, the METIS graph partitioner[64] used in MaSSF can partition a graph with 10,000 vertexes in about 10 seconds, we can consider thousands of possible T_{mll}.

5.5 Summary

In this chapter, we presented the system design and implementation of the MicroGrid toolkit. We first introduced the soft real-time process scheduler for computation resource simulation, and then the scaled real-time online network simulator MaSSF. These two components together can provide accurate and efficient virtual grid modeling. After that, we introduced the traffic based load balance algorithms to improve the scalability of the network simulator, which is critical to support large scale virtual grid simulation.

Chapter 6 Validation

So far, we have presented our approaches and system design for accurate large-scale virtual grid modeling. However, a design with these approaches and techniques alone is insufficient to enable the systematic study of dynamic behavior. As any simulation tools, before it can be used in any real research studies, it must be validated that the simulation results are accurate comparing the real system behaviors; otherwise, it is useless. In this chapter, we provide validation of the constituent models and the entire MicroGrid system on applications.

6.1 Methodology and Experimental Environment

To validate the MicroGrid system design and implementation, we first provide validation of constituent models, including validation of the CPU resource model on one and several virtual resources per physical resource and validation of the online network simulation models exercised by real transport protocol stacks. Based on validation of different simulation models, we provide validation of the whole MicroGrid system on a range of grid application programs ranging from kernels to full-blown applications on two grid resource configurations.

The basic methodology for validation is to run applications, either real applications or benchmarks written by ourselves, on physical resources and collect the performance data, such as the execution time. Then we use the MicroGrid to simulate the physical resources and execute the same applications on simulated environments. Thanks to the capability of direct application execution on MicroGrid, the simulated application performance results are directly comparable to what we get from the execution on physical resources.

All experiments are executed on a 16-node dual 2.4GHz Xeon Linux cluster with 1G main memory each, connected by a 1Gbps Ethernet switch. The major metric for validation is the percentage of application execution time difference between the simulated environment and real environment. Different application and benchmarks are reported in each experiment.

6.2 Validation of the Computation Resource Simulation

To test the accuracy of the CPU Controller, a few simple benchmark programs are used. We first run them directly on a physical machine, get the real running time T. Then we run them on a virtual machine, which is given different fraction λ of CPU by the CPU Controller, to get a real running time T_λ. So the virtual running time on the virtual machine is $\lambda * T_\lambda$. If CPU controller is accurate, the virtual running time should equal to the real running time T and the value $\lambda * T_\lambda / T$ should equal to 1.

Two different benchmarks are used in this validation, one is computation intensive and the other is a mix of computation and communication, since the accuracy of both kinds of applications depends on the behavior of the CPU Controllers. The communication intensive applications are left to the validation of network simulation (Section 6.3), since their performance mainly depends on the network behaviors.

6.2.1 Computation Intensive Applications

This experiment is used to validate that the CPU controller can accurately allocate CPU resources to computation intensive jobs. The *cpuhog*, which only does computation without any input/output operations, takes 10 seconds to complete without CPU controller. Recall that the sliding window algorithm in the CPU controller can adjust to the design accuracy error *E*. In all experiments, we set the *E* to 5%, which means we expect 5% error margin for all validation results (see Section 5.2).

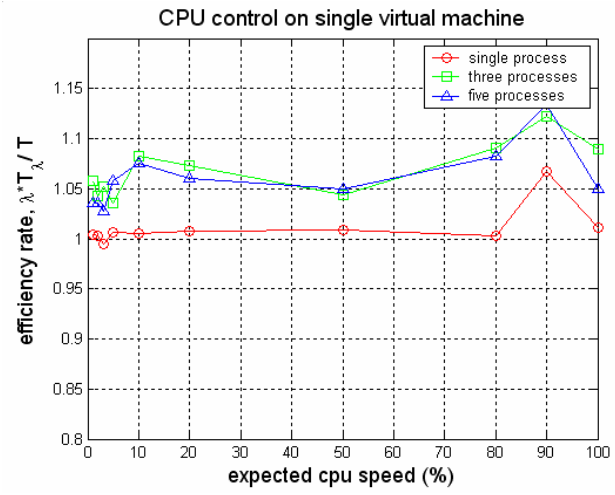


Figure 6.1 The *cpuhog* for Single Virtual Resource

Figure 6.1 are the results for single virtual resource, which show that when there is only one process, the error is almost always in 2%, except when it is near full utilization of the underlying physical resource. At 90% CPU, we observe a 6.7% error. When there are multiple processes, the running time becomes about 6-8% longer.

To understand the performance of CPU controller with multiple virtual resources on a single physical machine, two groups of experiments are executed with three virtual resources and five virtual resources on a physical machine respectively. Each time, the virtual resources are created, and one *cpuhog* is launched on each virtual resource. Then the average completion time is used as the virtual running time to calculate the efficiency rate $\lambda*T_\lambda/T$. The results are shown in Figure 6.2. The "aggregated CPU speed" is the sum of speeds of all the virtual machines. Most of the tests have an error of less than 4%, with the one exception of a 9% error when total CPU is 78%.

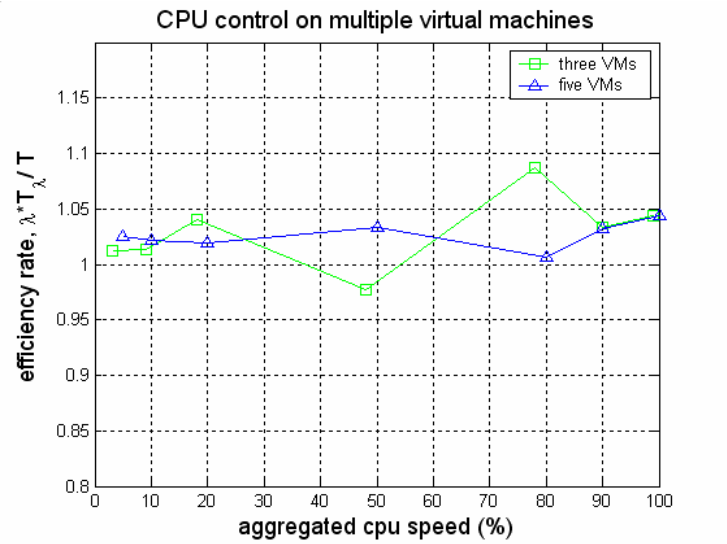


Figure 6.2 The *cpuhog* for Multiple Virtual Resources

The inaccuracy for 90% CPU in Figure 6.1 and for 78% CPU in Figure 6.2 comes mainly from the 5% design accuracy error in the sliding window algorithm: Since we allow 5% error and we always choose the window size as small as possible, when the virtual machine speed is 90%, we would schedule the application for six of seven jiffies rather than nine of ten, which causes a equivalent speed of 85.7% CPU with 4.8% error from 90% CPU; in the multiple-virtual resource experiments, each virtual machines has 26% CPU and is scheduled for one jiffy every four jiffies, which leads to 25% actually speed with about 4% error for 26% CPU.

These experiments show that the CPU controllers can efficiently simulate multiple virtual resources on a single physical resource and still provide accurate computation resource modeling for computation intensive applications.

6.2.2 Applications with Mixed Computation and Communication

This experiment is designed to demonstrate that the CPU controller can achieve accurate performance for application with mixed computation and communication. As discussed in Section 5.2, these applications represent much larger challenge than computation intensive applications, because the CPU controller has no idea whether a waiting process is waiting for

network delay or is just scheduled out by the operating system. The *mixhog* executes computation and communication combination in loop. We can control the length and ratio of computation and communication to check how the CPU controller behaves for different application patterns. The CPU controller design still uses a 5% design accuracy error (see Section 5.2).

Figure 6.3 shows the accuracy of the CPU controller under different communication granularity. The communication and computation ratio in the *mixhog* is fixed (1:1, 1:2, and 1:3) and the communication time (network delay) changes from 10ms to 100ms in these experiments. The errors are always within 10%, except when the communication delay is so small that it is comparable to the OS scheduling granularity (10ms).

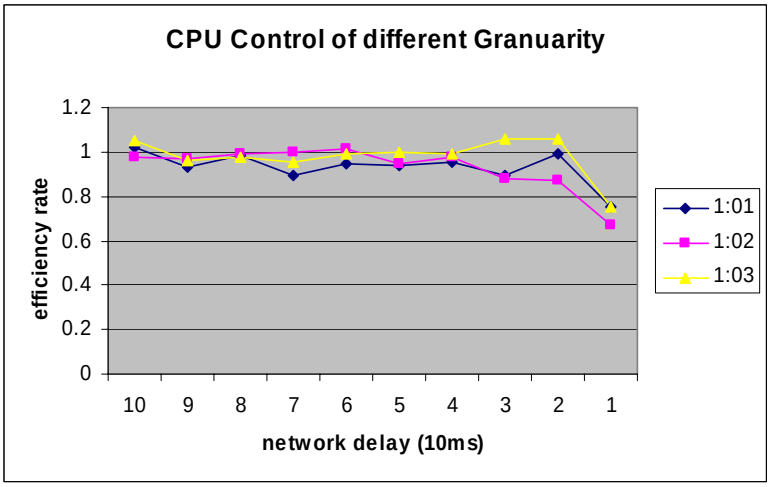


Figure 6.3 The *mixhog* with Different Communication Granularity

Figure 6.4 and Figure 6.5 are the results of CPU controller accuracy against different virtual CPU speed. We can see that the accuracy changes according to the virtual CPU speed, due to the fact that the sliding window size. As we have discussed in Section 5.2, larger sliding window size can lead to larger error. When most time the error is less than 10%, the error can reach 20% when the virtual CPU speed is at 30%, 40% and 60%.

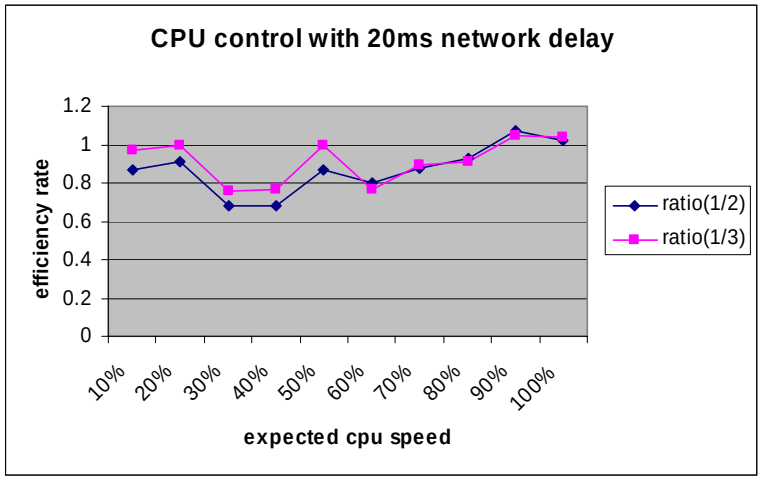


Figure 6.4 The *mixhog* with 20ms Network Delay

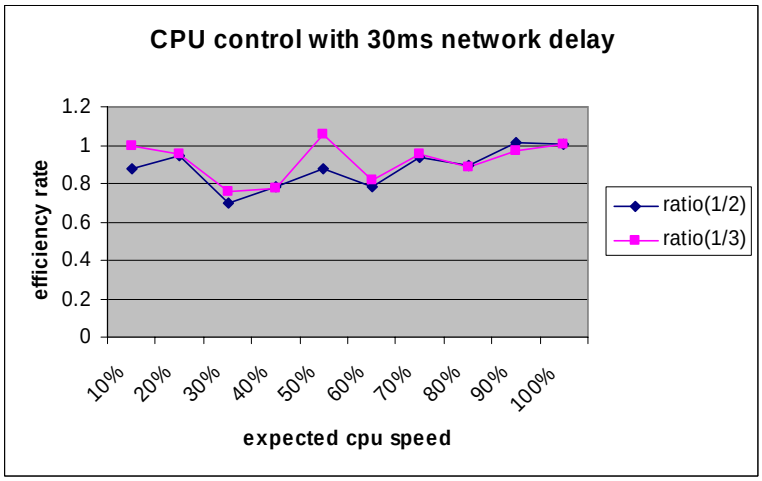


Figure 6.5 The *mixhog* with 30ms Network Delay

In summary, our experiments show that the CPU controller can model CPU speed accurately. The multiple virtual resources experiments also demonstrate its capability to model multiple virtual CPUs on one physical machine accurately.

6.3 Validation of Network Simulation

To test the accuracy of the network simulation, the main focus is on checking the correctness of simple TCP application, since this simple test involves the most important and complex part of the network simulation, the TCP protocol implementation. A majority of

network application performance depends on the TCP protocol behaviors. This simple test can also validate if the CPU controller can guarantee quick response time (Section 5.2), and if the traffic interception and requests handling is quick enough with negligible overhead (Section 5.3).

We use a client/server program *tcpSender/tcpRecver* which sends and receives packets using TCP/IP between two nodes. In each iteration, the sender sends a message to the receiver then wait for a one-byte reply from the receiver. The *tcpSender* can report the latency for each message and the achieved network throughput, under different message sizes. We want to compare results from simulated networks to those from real networks. If no real data available, we use the theoretical values as metrics.

When message size is small, the latency for each iteration is close to the half of network round trip time (RTT); when message size is large enough, the throughput approximates the maximum bandwidth between the two nodes. The TCP throughput is affected by network latency (L), TCP window size (W), network capacity (C), and packet loss[67]. If there is no packet loss, the maximum throughput should be close to:

$$\text{Throughput} = \min(C, W/(2*L))$$

6.3.1 Validation of Local Area Network

Our experiments first test the real network performance between two nodes on a cluster. The nodes are dual Xeon 2.4GHz machines connected by GigE, configured with 128KB TCP window. Experiments show that real network has latency 0.222ms and bandwidth 782.87Mbps. On the MicroGrid, we simulate the two nodes with 128K TCP window and 0.2ms wire latency. The simulated results of different virtual CPU speeds are shown in Figure 6.6 and Figure 6.7.

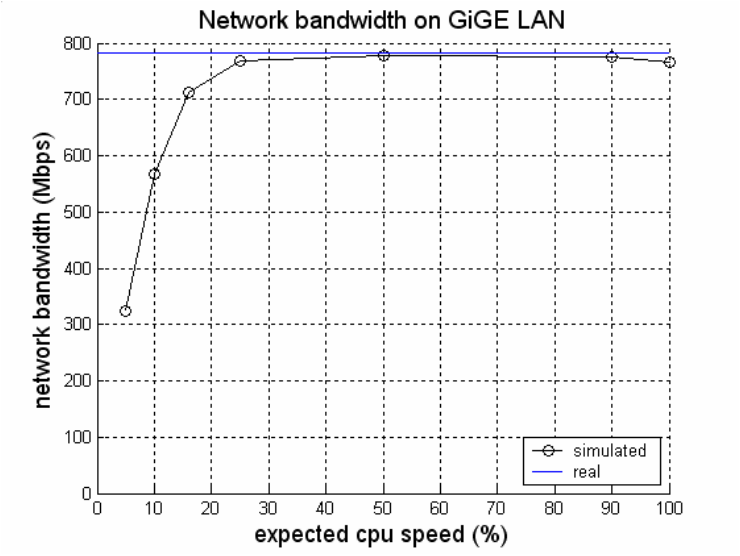


Figure 6.6 Network Throughput on GigE LAN

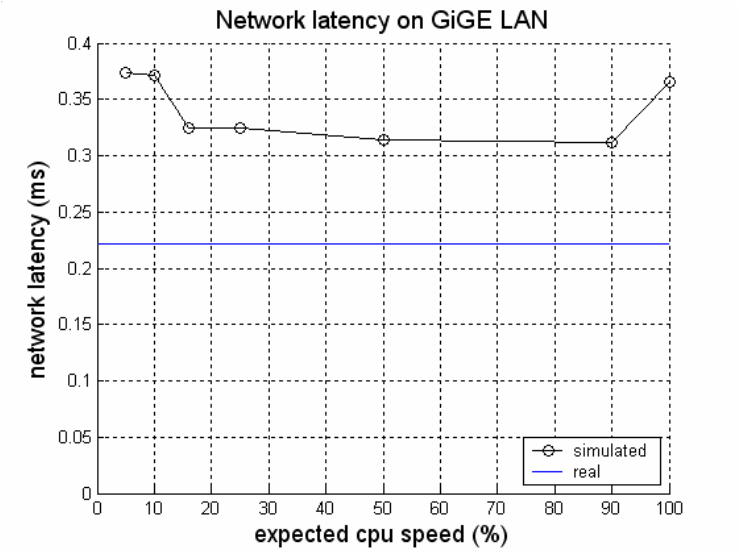


Figure 6.7 Network Latency on GigE LAN

The figures show that the virtual bandwidth (simulated) is close to the target bandwidth when virtual CPU speed is faster than 25% of 2.4GHz Xeon. When virtual CPU speed is not fast enough to support the memory and I/O operations, the bandwidth falls off.

The network latency is about 0.15ms longer than the configured wire latency. This is presumed to be due to *Agent* overhead, overhead through TCP/IP stacks, and the overhead of the MaSSF simulator.

6.3.2 Validation of Metro Area Network

The next set of tests use a network topology with a 1ms latency between the two nodes, and varies the TCP window size from 32KB to 128KB. The results of different CPU speeds are shown in Figure 6.8 and Figure 6.9.

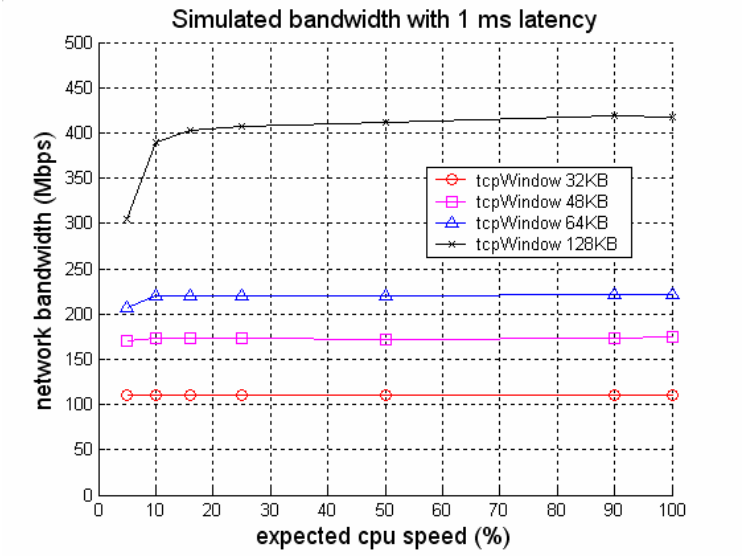


Figure 6.8 Network Throughput on MAN

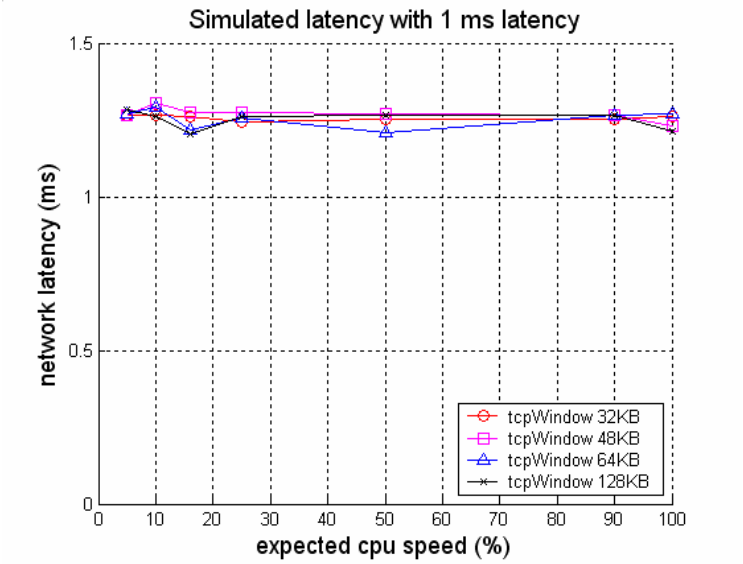


Figure 6.9 Network Latency on MAN

In this case, the network capacity is not the bottleneck any more, so the TCP throughput is mainly decided by latency and TCP window size. We calculate the throughput upper bound in theory, as shown in Table 6.1.

From Figure 6.8 and Table 6.1 we see that our simulator achieves 82-90% of the theoretical maximum bandwidth. Considering the overheads on TCP stacks and application's memory operations, these are excellent results.

As for latency, the simulated value, as shown in Figure 6.9, is about 0.25ms higher than the configured wire latency. Still, this is due to overheads on TCP stacks, application memory operations, and MaSSF overhead.

Table 6.1 Theoretical Maximum Throughput on a Network Channel

	32KB	48KB	64KB	128KB
1 ms	128Mbps	192Mbps	256Mbps	512Mbps
5ms	25.6Mbps	38.4Mbps	51.2Mbps	102.4Mbps
10ms	12.8Mbps	19.2Mbps	25.6Mbps	51.2Mbps

6.3.3 Validation of Wide Area Network

The following figures in Figure 6.10 show the bandwidth on network channel with latency 5 ms and 10ms respectively. The results are consistent with the theoretical bounds in Table 6.1.

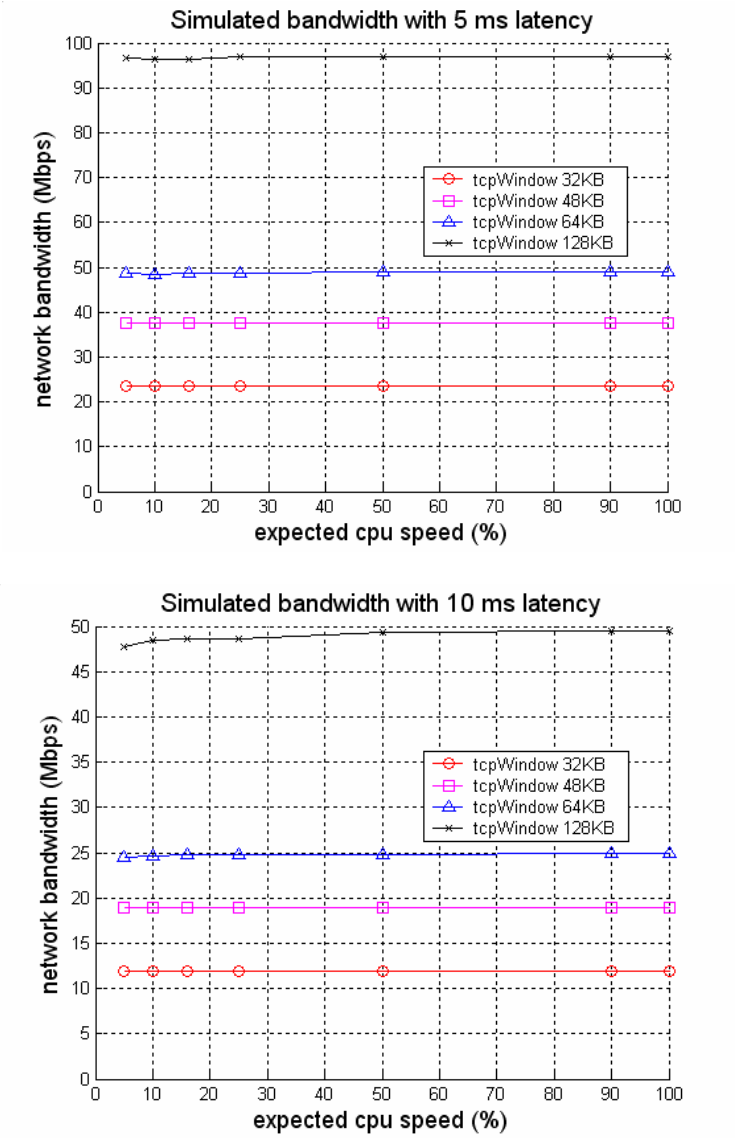


Figure 6.10 Network Throughputs on WAN

Based on these experimental results, we conclude that the MaSSF network simulator can model TCP communications accurately. With no network congestion, the modeled maximum bandwidth approximates real results in local, metro, and wide area networks. The network latency is also modeled accurately, excluding overhead which takes about 0.15-0.25ms per message.

We did not evaluate the simulator with network congestion, although our simulator supports the capability to model competitive traffic (background traffic). Performance with congestion is not easy to evaluate since it depends on the competitive traffic model. Here we also provide no validation on routing protocols such as OSPF and BGP4, instead, there are validation test suites coming with the software package.

6.4 Validation of the MicroGrid on Applications

We have provided validation on each individual simulation module. But this is not enough, since what we really care is if these simulation modules together can provide accurate modeling of a virtual grid environment. More specifically, does the scaled real-time mechanism effectively coordinate multiple resources simulation modules and create correct simulation results? Can the CPU controller handle mix computation and communication well for real applications? To answer these questions, the best approach is to validate the MicroGrid on real applications which can exercise most components together with large traffic and computation loads.

6.4.1 Applications

In this section, we run five classic applications on both real environment and virtual environment simulated using the MicroGrid. Before the results, we first introduce the five applications briefly. These applications are used in the GrADS project[9].

All five applications are SPMD MPI applications and have been previously tested on the GrADS testbed in various real-world experiments. These applications were integrated into the GrADS framework and tested in various experiments as part of the following efforts: ScaLAPACK [68], Jacobi [69], Game of Life [69], Fish [70], and FASTA [71].

ScaLAPACK is a popular software package for parallel linear algebra, including the solution of linear systems based on LU and QR factorizations. We use the ScaLAPACK right-

looking LU factorization code based on 1-D block cyclic data distribution. The application is implemented in Fortran with a C wrapper. The data-dependent and iteration-dependent computation and communication requirements of ScaLAPACK provide an important test for the MicroGrid simulation. In our experiments we used a matrix size of 6000x6000.

FASTA The search for similarity between protein or nucleic acid sequences is an important and common operation in bio-informatics. Sequence databases have grown immensely and continue to grow at a very fast rate; due to the magnitude of the problems, sequence comparison approaches must be optimized. FASTA is a sequence alignment technique that uses heuristics to provide faster search times than more exact approaches, which are based on dynamic programming techniques. Given the size of the databases, it is often undesirable to transport and replicate all databases at all compute sites in a distributed grid. We use an implementation of FASTA that uses remote, distributed databases that are partially replicated on some of the grid nodes. FASTA is structured as a master-worker and is implemented in C. For MicroGrid validation purposes, an important aspect of FASTA is that each processor is assigned a different database (or portion of a database) so the MicroGrid must properly handle input files and provide proper ordering of data assignments onto processors. In our experiments the sizes of the databases are 8.5MB, 1.7MB and 0.8MB respectively. The query sequence is 44KB.

The **Jacobi** method is a simple linear system solver. A portion of the unknown vector x is assigned to each processor. During each iteration, every processor computes new results for its portion of x and then broadcasts its updated portion of x to every other processor. Jacobi is a memory-intensive application with a communication phase involving lots of small messages. In our experiments we used a matrix size of 9600x9600.

The **Fish** application models the behavior and interactions of fish and is indicative of many particle physics applications. The application calculates Van der Waals forces between particles in a two-dimensional field. Each computing process is responsible for a number of particles that

move about the field. The amount of computation depends on the location and proximity of particles, so Fish exhibits a dynamic amount of work per processor. In our experiments we used 6,000 particles.

Conway's **Game of Life** is a well-known binary cellular automaton. A two-dimensional mesh of pixels is used to represent an environment of cells. In each iteration every cell is updated with a 9-point stencil and then processors send data from their edges (ghost cells) to their neighbors in the mesh. Game of Life has significant memory requirements compared to its computation and communication needs. In our experiments we used a matrix size of 9600x9600.

6.4.2 Experiment Environment

We use a subset of the multi-site testbed for the GrADS project as our testbed. The 11 machines used are as following:

UCSD cluster: four 2100+ XP Athlon AMD (1.73 GHz) with 512 MB RAM each. These systems run Debian Linux 3.0 and are connected by Fast Ethernet.

UIUC cluster: three 450 MHz PII machines with 256MB memory connected via TCP/IP over 1Gbps Myrinet LAN. These systems run RedHat Linux 7.2.

UTK cluster: four PIII 550 MHz machines with 512MB memory, running RedHat Linux 7.2, and connected with Fast Ethernet.

The three sites are connected by the Internet2 network with 2.4Gbps backbone links. During our experiments, we observed NWS latency and bandwidth values over a period of 12 hours and obtained ranges as shown in Table 6.2.

In our simulation, we configure all the machines to have 64KB TCP window. The wide area latency is as shown in Table 6.2; the LAN latency is 0.2 ms. We have to remind the audience that, the simulated LAN latency might higher than real latency due to simulation

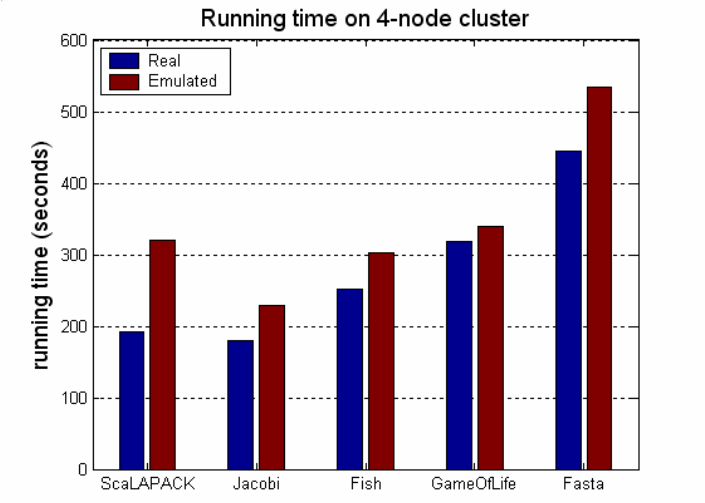
overhead as shown in Section 6.3; while the simulated WAN bandwidth will higher than real bandwidth due to lack of contention.

Table 6.2 Network performance of the testbed, reported by NWS

	UCSD machine	UIUC machine	UTK machine
UCSD machine	60-80Mbps, 0.2 ms	3-7Mbps 31 ms	4-6Mbps 30 ms
UIUC machine	3-7Mbps 31 ms	115-220Mbps 0.2 ms	7-17Mbps 11 ms
UTK machine	7-8Mbps 30 ms	12-18Mbps 11 ms	82-87Mbps 0.2ms

6.4.3 Simulation Results

Two groups of experiments are conducted on those sites: “Cluster” group uses four UTK machines to do clustering computation; “Grid” group uses three machines from each of the three sites. Both groups use a separate UCSD machine to run Globus gatekeeper. The results are shown in Figure 6.11.



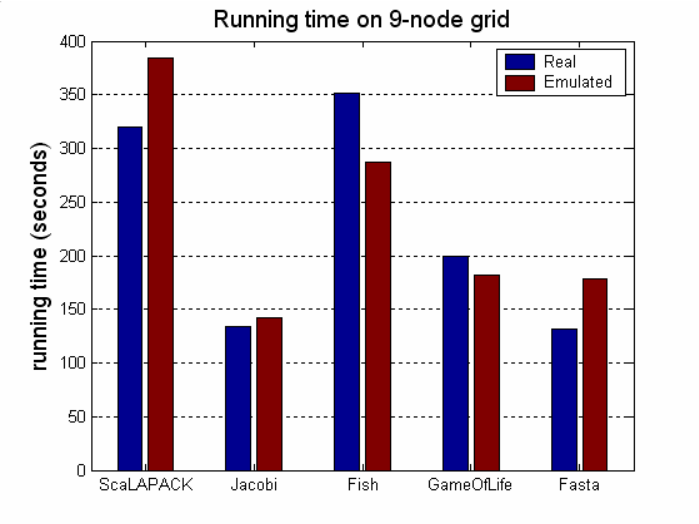


Figure 6.11 Running Time of Applications

For the cluster, all applications run slower on the MicroGrid than on real testbed; most of them have error in 6%-27%, except 66% for ScaLAPACK. The extra overhead comes from two major sources: 1) The MaSSF has some overhead which increases network latency. 2) *WrapSocket* wraps many system functions for simulation, which will cause some overhead.

For the grid environment, the simulated time has about 5% - 35% errors. We can see several interesting differences from the cluster results. ScaLAPACK still runs slower on the MicroGrid than on real testbed, but much closer than on cluster, because ScaLAPACK uses a lot of small communications and the simulation overhead will have more impact on simulated LAN latency than on simulated WAN latency (as shown in Section 6.3). Fish and GameOfLife run faster on the MicroGrid than on real grid. A possible reason is that they both use many large communications, and the simulated network bandwidth is higher than real system due to lack of contention.

6.5 Summary

In this chapter we provide the validation on the MicroGrid system and therefore on our approaches for virtual grid modeling. Specifically, we provide:

1）Validation of computation resource simulation. Experiments with the MicroGrid on simulating multiple virtual resources per physical resource match closely within 2%-9%, even for applications with mix of computation and communication.

2）Validation of the online network simulation. Latency results reported by the TCP client/server benchmark vary only 0.15-0.22ms for different networks, and the throughput results vary from 5% to 18%.

3）Validation of the whole MicroGrid system on a range of grid application programs on two grid resource configurations. Most application execution times match within 65% to 95%.

With a solid validation of the MicroGrid toolkit, a range of interesting experiments for grid applications and middleware is virtually unbounded.

Chapter 7 Scalability Studies

In this chapter two large network simulations, one single AS network of 20,000 routers and one multi-AS network of 100 ASes with 200 routers each, are used to demonstrate the scalability of the MicroGrid system. This scale of network is quite large, even comparing to the largest real grid project testbeds. For example, the Grid2003 [3] has 27 sites across US and Korea which collectively provides more than 2000 CPUs. At the same time, hierarchical traffic-based partitioning and mapping approaches in Section 5.4 are used in these experiments to show the scalability improvement. Practically, now it is possible to do realistic full grid simulation with the MicroGrid in a cluster.

7.1 Experimental Setup

7.1.1 Improve Scalability through Load Balance

The MicroGrid must be scalable to support the study of large networks, resources, middleware, and applications. While most resources can be naturally simulated in parallel with enough physical resources, all the coordination, synchronization and dynamic interaction amongst resources must go through network communication. This means the network must be simulated as a single system with global coordination, and thus the scalability of network simulation is a critical challenge for the entire MicroGrid system. In particular, the challenge is scalable detailed packet-level simulation combined with online simulation. We require packet-level simulation to ensure fidelity in simulation of network, protocol, and application behavior. Higher level simulation approaches, such as flow level simulation and approximation through

network aggregation provide insufficient fidelity for our problems if interest in dynamic distributed systems.

As mentioned in Section 5.4, our network simulator MaSSF uses distributed discrete-event simulation engine to achieve scalable performance. But only this is not enough to provide a scalable simulation. Like all other distributed or parallel applications, MaSSF must have good load balance for good speedup, and such load balance is challenging for network simulation. We have presented three traffic-based mapping approaches and hierarchical load balance enhancement for large scale network in Section 5.4. In this chapter, we want to study the performance of hierarchical load balance technique on traffic-based mapping approaches.

Two traffic-based mapping approaches are chosen as the baseline, topology-based mapping (TOP) and profile-based mapping (PROF). And then the hierarchical load balance technique are applied on them and got topology-based mapping (HTOP) and hierarchical profile-based mapping (HPROF), respectively. Here the PLACE mapping approach is skipped since it is expected to get the performance in the middle of HTOP and HPROF, based on the fact that the traffic information accuracy in PLACE is in the middle of TOP and PROF.

In our experiments, the TOP and PROF partitioners achieve such small MLL that their performance is extremely poor and the simulations cannot be completed in a reasonable time limit. So we adjusted the link latency to edge weight converting algorithm for the large scale network simulation, so partitions are less likely to across edges with small link latency. This tuning is not a general solution and has to be done according different topologies manually. Their results are labeled as TOP2 and PROF2.

7.1.2 Evaluation Methodology

The ultimate goal for scalability is to enable simulation of larger networks with limited physical resources and to enable faster simulation of a specific network with given traffic load.

So our basic evaluation methodology is to simulate a large network with representative traffic load as fast as possible. The network must be large enough to represent a realistic grid environment, and the traffic load should also be intensive enough with dynamic characteristics similar to what are shown on the real Internet.

In this study, we chose two large networks topologies, one single AS network of 20,000 routers and one multi-AS network of 100 ASes with 200 routers each. We will give more details about these networks and justify our choices in the following sections.

Two kinds of traffic loads are used in our experiments; the background traffic and the traffic from real applications. The background traffic are used to provide the realistic Internet network conditions and dynamics, and the real applications are used to represent the simulation targets that we want to simulate it as fast as possible.

For background traffic, there are 8,000 clients continuously sending HTTP file requests to 2,000 servers. The average time gap between two successive requests of a client is 5 seconds and average file size is 50KB. Foreground traffic is created live from Grid applications, including ScaLapack[68] and GridNPB3.0[72]. ScaLapack is introduced in Section 6.4.1. GridNPB3.0 is a set of grid benchmarks in a workflow style composition in data flow graphs encapsulating an instance of a slightly modified NPB task in each graph node, which communicates with other nodes by sending/receiving initialization data. GridNPB includes a range of computation types and problem sizes, and in our experiments we use the combination of Helical Chain (HC), Visualization Pipeline (VP), Mixed Bag (MB) applications, all run at class S size. These programs run for about 30 minutes on our platform.

The experiments use the TeraGrid Itanium-2 cluster for simulation engine nodes. The cluster nodes are dual 1.3GHz Itanium-2 processors with 2Gigabytes of memory, linked with Myrinet 2000 using MPICH-GM. We use 90 nodes as the simulation engines, and 7 nodes for application execution.

7.1.3 Evaluation Metrics

The first metric is the ***application simulation time T,*** which is the time taken to simulate an application in a specific network simulation. As faster simulation is the ultimate goal of our scalability studies, it is the most important metric.

To get deeper insight into the efficacy of our partition and load balance techniques, we also use three other metrics: achieved MLL, load imbalance, and parallel efficiency.

The second metric ***achieved MLL*** shows the effect of the hierarchical load balance approaches in increasing parallelism and is reported directly by the partitioner.

For the third metric ***load imbalance***, we define the load of a simulation engine node as the event rate of the simulation kernel (essentially one per network packet). Using these counters, we calculate the overall *load imbalance* across all the physical nodes in the actual simulation. Assuming the simulation kernel event rates are k_1, k_2, …, k_n, for n nodes used by the simulation engine, the load imbalance is normalized by the standard deviation of {k}.

The last metric is the ***parallel efficiency***, PE(N, L) for a problem of size L on N nodes is defined in the usual way[73] by $PE(N,L) = \frac{Tseq(L)}{N * T(L,N)}$,

where T(L, N) is the runtime of the parallel algorithm, and Tseq(L) is the runtime of the best sequential algorithm. Tseq(L) cannot be measured directly since the network is too large to be simulated on a single machine, thus, we approximate the Tseq(L) by

$$Tseq(L) = \frac{TotalEventNumber}{MaximalEventRateOnEachNode}.$$

7.2 Flat Network Simulation

7.2.1 Single-AS Network Topology

We generate network topologies for our experiments with an adapted BRITE tool [74], a degree-based Internet topology generator following the Power-Law[75]. The flat network topology includes 20,000 routers and 10,000 hosts, which are spread over a geographic area of 5000miles by 5000miles (roughly the size of North American continent, with maximal network latency about 50ms). The routing is decided by the OSPF shortest-path routing protocol.

We chose this network single-AS topology for mainly two reasons. First, with the simple shortest-path routing, simulation of this network demonstrates the capability baseline of our network simulator, including the scale of network entities it can simulate and the number of traffic it can handle. Second, this network has a router count comparable to the size of a large Tier-1 ISP, such as the AT&T network [76]. So the simulation result is valid for many applications that exist in a single ISP network.

7.2.2 Flat Network Simulation Results

In this study, application workloads are executed on the single-AS network with moderate background traffic, and we study the performance of four mapping approaches: TOP2, PROF2, HTOP, and HPROF. As we discussed above, both TOP2 and PROF2 mappings are tuned for the large scale network simulation.

Simulation results are reported following four metrics introduced in Section 7.1.3.

7.2.2.1. Application Simulation Time

The application simulation time of both applications is shown in Figure 7.1. For ScaLapack, the use of PROF2 mapping reduces overall simulation time of TOP mapping by 14%, and the use of the hierarchical mapping (HPROF) further reduces the simulation time up to 40%.

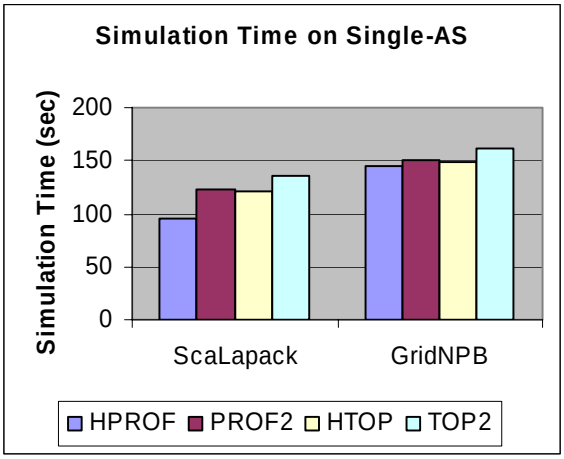


Figure 7.1 Simulation Time on the Single-AS Network

7.2.2.2. Achieved MLL

The achieved MLL is shown in Figure 7.2, and we can see both TOP2 and PROF2 still have much smaller MLL (about 0.6ms) comparing to HTOP and HPROF. It is clear that the hierarchical approaches can significantly increase the MLL, producing enough parallelism for large-scale simulation. These MLL values show that there is enough parallelism achievable for networks of ~20,000 routers in 5000miles by 5000miles area using 90 simulation nodes. These simulations will provide good efficiency with slowdown of 8 times.

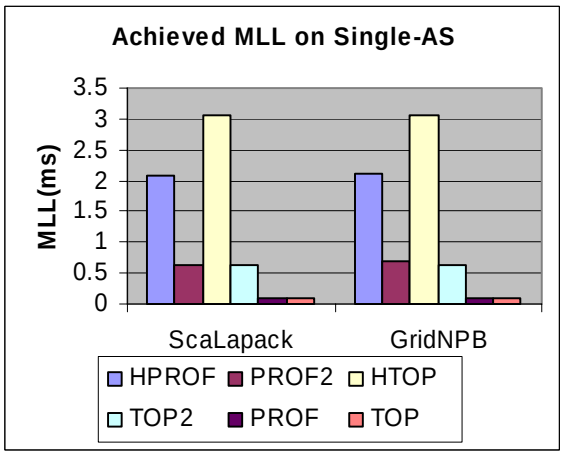


Figure 7.2 Achieved MLL on the Single-AS Network

Despite the fact that it produces the largest MLL (3ms), HTOP does not work very well compared to HPROF. The inaccurate load prediction in HTOP produces a much larger load imbalance which hurts performance.

7.2.2.3. Load Imbalance

The measured load imbalance for both applications is shown in Figure 7.3. The figure reports the normalized load imbalance across the physical simulation engine nodes for each combination of mapping approach and network topology. Each mapping approach produces significantly different results. Compared to TOP2, PROF2 improves load imbalance by about 7%. The HPROF mapping also improves the load imbalance by 11% over HTOP. It is clear that the use of detailed traffic information from a previous simulation execution provides a critical advantage in achieving effective network partitions.

It is also shown that the HPROF mapping produces better load balance than TOP2 and PROF2. This improvement is surprising because the hierarchical approaches use a simpler graph with coarse-grained node weights. So they should have less chance to achieve better load balance. We believe the explanation is that the underlying graph partitioner METIS does a better job for smaller graphs, since reduced graphs have many fewer vertexes.

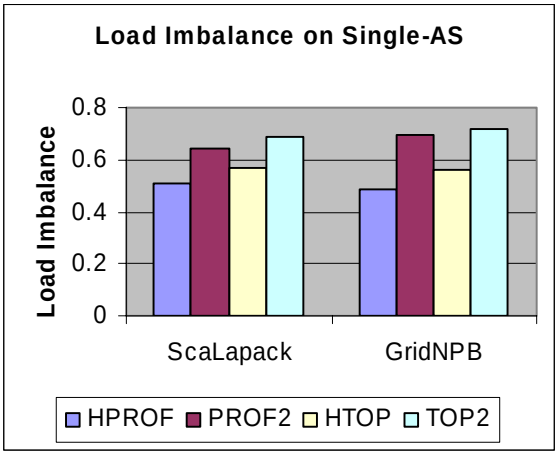


Figure 7.3 Load Imbalance on the Single-AS Network

7.2.2.4. Parallel Efficiency

The parallel efficiency of both applications is shown in Figure 7.4. While the overall efficiency of network simulation at this scale does not reach 100%, these values are excellent for parallel discrete event simulations on irregular loads. The HPROF for ScaLapack achieves about 40% parallel efficiency, a dramatic 64% improvement over TOP2. These levels of parallel efficiency enable effective large-scale network simulations.

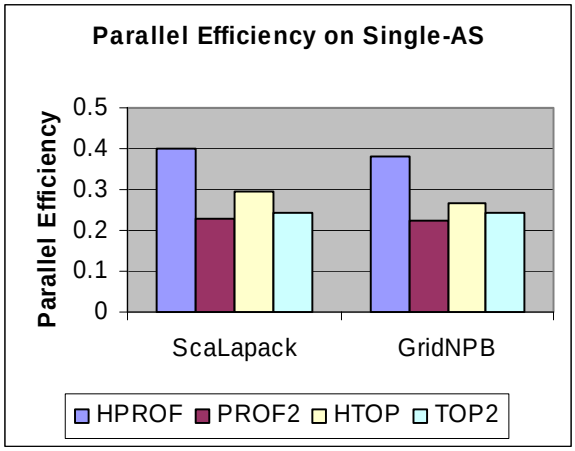


Figure 7.4 Parallel Efficiency on Single-AS Network

7.3 Multi-AS Network Simulation

The Internet is not a flat network with shortest-path routing. Instead, it is organized as a collection of ASes with traffic shaped by BGP policy routing. In such networks, connectivity does not mean reachability and the real dynamics are quite different from a single-AS network. Such networks present greater challenges to achieving load balance because the traffic load is less coupled to network topologies. Despite its importance, to our knowledge multi-AS networks have never been simulated in large-scale because of the complexity involved.

Although there is much research on Internet-like topology generation [74, 77, 78], these studies focus on physical connectivity and pay little attention to routing configuration (particularly BGP). There are two major reasons for this situation. First of all, prior to our

MaSSF simulator, no existing network simulator supported large scale simulation with detailed BGP routing. Simulators either have no support for BGP routing (DaSSFNet[79], ModelNet[35]), or they are limited by scalability to such a degree that BGP policy routing is less relevant (NS2[30], SSFNet[22]). Second, real Internet BGP routing configurations are not publicly available, since routing policy are closely tied to commercial contract terms that are considered highly confidential by ISPs. Fortunately, recent research has explored inferring AS relationships and BGP routing policy from publicly available information, such as BGP routing tables. Several of these efforts have made significant progress [80], making it possible for us to automatically generate realistic BGP routing policies into our network generator.

7.3.1 Multi-AS Network Topology

The network topology is created by our maBrite topology generator with BGP routing configuration as described above. It includes 100 ASes, each containing 200 routers. In addition, 10,000 hosts are randomly attached to Stub ASes for background traffic generation and live traffic agent. All these routers and hosts are spread to a geographic area of 5000miles x 5000miles.

The routing inside each AS is decided by the OSPF routing protocol and inter-AS routing is decided by BGP4 routing protocols. The BGP routing policy configuration is set up by our automatic BGP routing configuration procedure, listed in the Appendix A.

7.3.2 Multi-AS Network Simulation Results

Application workloads are executed on the multi-AS network with moderate background traffic, and we evaluate the performance of four mapping approaches: TOP2, PROF2, HTOP, and HPROF. Again, both TOP2 and PROF2 mappings are tuned for the large scale network simulation.

Simulation results are reported following four metrics introduced in Section 7.1.3.

7.3.2.1. Application Simulation Time

The simulation time of both applications is shown in Figure 7.5. For ScaLapack, the use of PROF2 mapping reduces overall simulation time of TOP2 mapping by 21%, and the use of the hierarchical mapping (HPROF) further reduces the simulation time up to 41%. The GridNPB has less improvement, since it has less communication compared to ScaLapack.

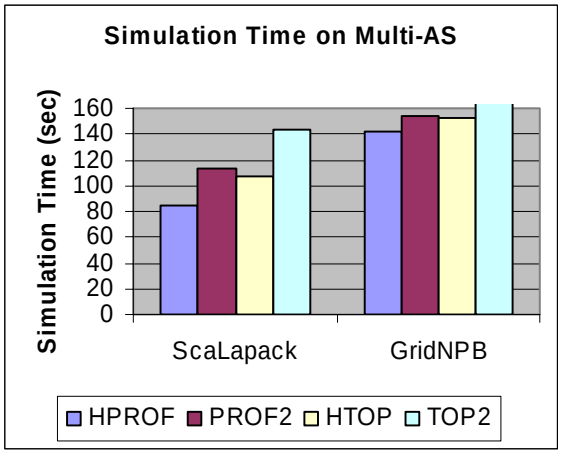


Figure 7.5 Simulation Time on the Multi-AS Network

7.3.2.2. Achieved Minimal Link Latency

The achieved MLL is shown in Figure 7.6. Like on the Single-AS network, the original TOP and PROF produce small MLL's and our data reflects the resulting poor simulation efficiency. The hierarchical approaches achieve much larger MLL's, in some cases ten times larger. MLL's of this size support good simulation efficiency.

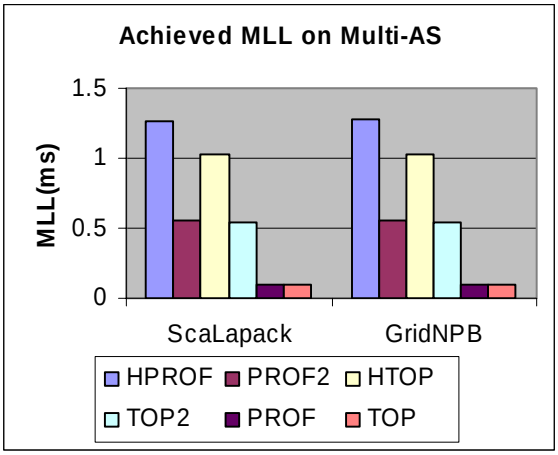


Figure 7.6 Achieved MLL on the Multi-AS Network

7.3.2.3. Load Imbalance

The measured load imbalance for ScaLapack and GridNPB is shown in Figure 7.7. The figure reports the normalized load imbalance across the physical simulation engine nodes for each combination of mapping approach and network topology. Each mapping approach produces significantly different results. Compared to the TOP2 mapping, the PROF2 mapping improves the load imbalance by about 15%. The HPROF mapping improves the load imbalance over HTOP by 31%.

As we anticipated, the load imbalance for this multi-AS network is much larger than the single-AS network due to the use of BGP routing, and it makes the improvement from profile-based techniques significant compared to that of the single-AS network in Section 7.2.

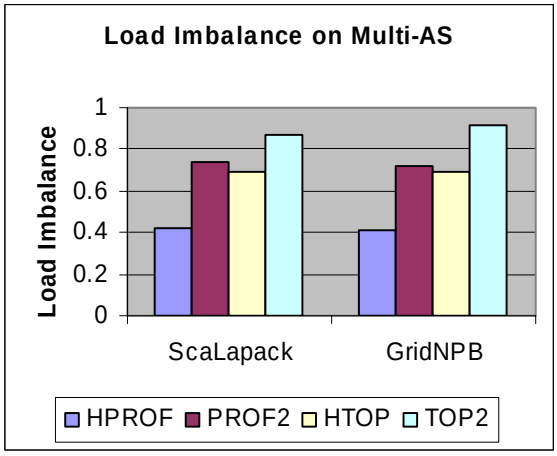


Figure 7.7 Load Imbalance on the Multi-AS Network

7.3.2.4. Parallel Efficiency

The parallel efficiency of the simulation of both applications is shown in Figure 7.8. While the overall efficiency of network simulation does not approach 100%, HPROF for ScaLapack can achieve about 40% parallel efficiency, about a 64% improvement from TOP2. This level of parallel efficiency enables simulation of large-scale Multi-AS networks.

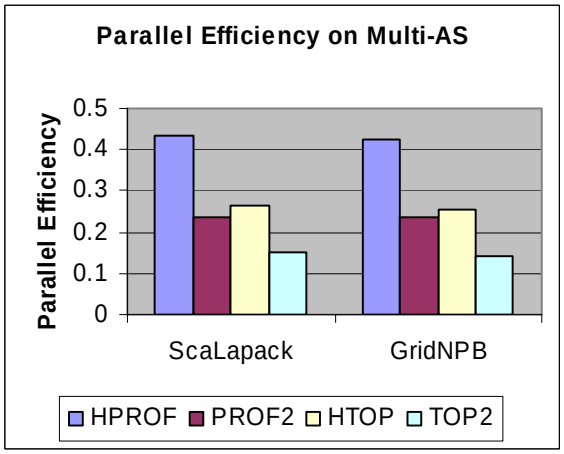


Figure 7.8 Parallel Efficiency on Multi-AS

In summary, these experiments show that our hierarchical load balance approaches still work well for large multi-AS networks with realistic BGP routing configuration.

7.4 Summary

Large-scale and realism are two critical requirements for network simulation for Grid application studies. In this paper, we first study a large flat network with 20,000 routers. Then, at this scale, we study realistic network structures (100 AS's, BGP4 and OSPF routing) versus flat OSPF routing. Multiple load balance approaches are evaluated against these networks. The best of them, hierarchical profile-based load balance (HPROF), can improve the load imbalance by 40% and reduces the simulation time by about 50%. Combining with our packet-level hop-by-hop network simulator and detailed BGP4 protocol support, we demonstrate that we can provide realistic large-scale network simulation for networks including about 20,000 routers.

Based on the generality of these topologies and traffic loads, we can expect similar scalability results for simulation with comparable network size. We believe that it is fair to say the MicroGrid, therefore our integrated online simulation approach, has achieved the scalability enough for accurately modeling a virtual grid environment. Its capability is larger than the simulation requirements of most existing grids and it is large enough to model future grids.

Chapter 8 Case Studies

Two case studies are used to demonstrate the capability of the MicroGrid for network and grid related research. The first is a study of BGP simulation configuration, the second is the study of tolerating Denial-of-Service attacks with a proxy network. As we will show in the experiments details, neither of them is possible without the MicroGrid toolkit, due to the large network size, detailed simulation, and/or online simulation.

8.1 A Study of BGP Simulation Configuration

Border Gateway Protocol (BGP) is used to exchange routing information between different computer networks. It is commonly agreed that we lack clear understanding of this key element of Internet infrastructure. To address this problem, simulation is one of the tools used most by researchers. However, current BGP simulation tools are limited on scalability and BGP routing policy support, and thus, it is hard to evaluate the realistic of current BGP simulation practice.

The unique capability of the MicroGrid toolkit provides new opportunity on this. Given the capability to simulate large topology, given the full support for BGP routing policy and inferred AS relationship form real BGP routing table, and given the capability to compare the simulation results and real data, how close will the simulation data be compared to the real data? In this study, a real Internet AS-level topology is constructed with the most realistic routing configuration ever achieved; then the MicroGrid is used to simulate this network topology, and simulation data are compared directly to real data to check how closely the simulation matches the reality.

Results show 1/4 match. Actually, it is not so bad, as we will show through analysis presented later. It means the simulator does catch something real. We could trust BGP simulation for some studies, such as convergence time, dampening effects, etc. Of course, ideal simulation generates 100% match, but this is hard to achieve. So the next question is how to improve simulation to reality as much as possible.

8.1.1 Problem Definition and Approach

The Internet is composed of a large number of different networks, each of which is administrated by a different organization – Theses are called Autonomous Systems (AS). To route data packets from one network to the other, the Internet uses an Inter-domain routing infrastructure. Border Gateway Protocol (BGP) [62] is the current de-facto inter-domain routing protocol, which is widely deployed with the global Internet since 1996. As a protocol, ideally, we should have a clear understanding about BGP, such as its performance, behavior, vulnerabilities, reaction to stressful events, scalability issue, and so on. However, due to its large-scale and distributed nature, it is commonly agreed that such understanding remains a major research challenge.

Simulation technique is one tool widely used by BGP research community to help improving our understanding [81, 82] of the complexity of this large-scale routing system. It is important to revisit the issue of how BGP simulations are configured since different configurations yield different simulation results. Since BGP is more regarded as a policy-based routing protocol, policy configuration in simulation plays a critical role on the simulation results. In reality, the BGP configuration and routing policy vary on network topologies and business decisions. So one key problem of the BGP simulation is not clear; that is, how closely does the current BGP simulation practice, especially the policy configuration, match to the reality?

One straightforward way to evaluate the reality of BGP simulation is to run simulations with the real Internet topology, then compare the simulation results with real routing data. However, the use of this approach faces two major challenges.

First, such approach requires a network simulator to support large-scale simulation with detailed BGP routing. Current simulators either have no support for BGP routing (DaSSFNet[79], ModelNet[35]), or are limited by scalability to such a degree that BGP policy routing is less relevant (NS-2[30], SSFNet[22]). The scalability coming with the MaSSF provides the opportunity to solve this problem. It can simulate a large network with about ~20,000 ASes on a 100-node cluster, which is large enough for real Internet study.

Second, real Internet BGP routing configurations are not publicly available, since the routing policy is closely tied to commercial contract terms that are considered highly confidential by ISPs. Fortunately, recent research has explored inferring AS relationships and BGP routing policy from publicly available information, such as BGP routing tables. In [83], researchers examined the routing policies in the Internet and classified them into several categories. Such result is well accepted and used in simulations. The maBrite topology generator coming with MaSSF can import real network topology and convert AS relationship to BGP routing configuration.

In our experiment, the MicroGrid toolkit is used to simulate real Internet AS-level topology. First, a real Internet AS-level topology is obtained from BGP routing tables, which are publicly available at various observation points [84, 85]. After that, BGP routers are configured with routing policies based on AS relationships inferred from [83] and some extra information available from the routing table data (see more details in Section 8.1.2). Without shrinking the Internet topology, it is now possible for us to compare the simulation results with real routing data for the purpose of checking if such configuration matches the reality. With the real Internet topology and the routing policy inferred from exiting BGP routing table, we claim that our BGP

simulation is the most realistic that has ever been done. And our results represent the state-of-the-arts of current BGP simulation practice.

8.1.2 Construct the Realistic Internet BGP Simulation Configuration

8.1.2.1. Convert AS Relationship to BGP Routing Policy

BGP4 is the most widely used inter-AS routing protocol used to exchange reachability information between ASes, in the form of route announcements. Each route announcement contains attributes, such AS path, multi-exit-discriminator (MED), and next hop. The most important attribute, AS path, is a list of AS numbers associated to a network. Other attributes are used to define routing policies. One of the key features of the BGP protocol is its capability to support policy routing, which allows each AS to choose its own policy in accepting routes, selecting the best route, and announcing routes to its neighbors. Two kinds of routing policies are: Import Policy and Export Policy.

1) Import Routing Policy: When receiving a route announcement from its neighbor, a router applies its import policies to the route, which include denying, or permitting a route, and assigning a local preference to indicate how favorable the route is. Local preference is used to differentiate routes received from different neighbors, since a BGP router may receive routes to the same destination from different neighbors and it must choose the best route to be used in its local routing table. BGP incorporates a sequential decision process to pickup the best route from a set of candidates to a given prefix. For example, the highest local preference, the shortest AS path, the lowest origin type, and the smallest MED for routes with the same next hop AS. There is a long list of criteria to set the preferential order of routes, and the first and the most important rule is the local preference. In practice, network administrators usually use local

preference to enforce their import routing policies. According to [80], there are two general rules:

Route Preference between Provider, Customers, and Peers: Network operators usually assign different local preferences to routes learned from providers, customers, and peers. Customer routes have the highest local preference, and peer routes have higher local preference than providers.

Consistency of Local Preference with Next Hop ASes: Operators may set local preference configuration based on prefix level or next hop AS level. Since it is easier to maintain provider, customer, and peer preferences based on next hop AS level, most ISPs use this approach in practice.

2) Export Routing Policy: BGP routers use export policies to decide which routes are to be propagated to their neighbors. The policies are usually transformed directly from AS relationships.

Exporting to a Provider: An AS can export its local routes and routes of its customers, but can not export routes learned from its peers or providers

Exporting to a Peer: An AS can export its local routes and routes of its customers, but can not export routes learned from its peers or other providers

Exporting to a Customer: An AS should export all routes it knows to its customers

These basic export policy rules are the direct requirement of commercial agreements. For example, the first rule guarantees that a provider will not use its customer network to transit traffic, and the last rule guarantees that the customer can get full Internet access through its provider.

1) Generate AS level topology based on the BGP routing table
2) Decide AS relationships from the inferring
3) Setup Import Routing Policy
    a. Accept all incoming routes
    b. Set Local Preference according to Next Hop AS, which prefer routes from Customer, over routes from Peer, and over routes from Provider
4) Setup Export Routing Policy
    a. To Provider: Export local and Customer routes
    b. To Peer: Export local and Customer routes
    c. To Customer: Export all routes
5) Pickup default/backup routers for multi-homed Ases

Figure 8.1 Procedure for Internet AS-level Topology Generation

With these heuristic rules, we can convert the inferred AS relationship to routing policies in maBrite topology generator (Figure 8.1).

8.1.2.2. Improve the Routing Configuration with Real Routing Tables

So far, we capture the major routing policy based on AS relationship. However, AS relationship is not the only factor for routing decisions. There are a few others details may affect the final routing decisions, such as the multi-homed stubs AS [63] and selective Announcement [80]. With the help of real routing tables, we can polish our topology to incorporate this information.

Multi-home is a popular practice to provide routing redundancy and higher network bandwidth. A multi-homed AS can have 2 or more providers, but it may prefer to use one provide for most of the traffic, and use the other provider as a backup, in case the routing to the first provider fails or is congested. This decision is not derivable from AS relationships; however, it can be estimated from the real routing table data. We can get its preference by checking all routing entries to that stub AS at observation points. We compare total number of

routing entries to AS S that uses the provider M and that using the provider N, and then set the export preference of AS S.

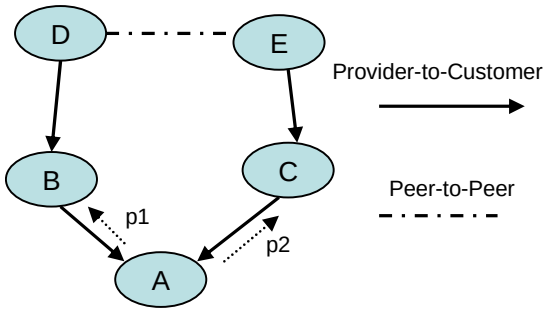


Figure 8.2 Selective Announcement

Selective Announcement is used when the AS wants to treat parts of its network differently. For example, as shown in Figure 8.2, the Stub AS A has two sub-networks with prefixes p1 and p2. The AS A wants to use the provider AS B for incoming traffic of sub-network p1, and use provider C for incoming traffic of sub-network p2. In order to achieve this effect, AS A announces two prefixes separately; it announces only the prefix p1 to provider B, and announces only the prefix p2 to provider C. This routing configuration is not used in our Internet simulation, since currently the maBrite cannot create the AS configuration to generate multiple prefixes automatically. Instead, we just pick the largest prefix and calculate its preference as the multi-homed case above. This is the major source of error in our network topology setup.

8.1.2.3. Scalable Routing Policy Enforcement

From the BGP routing table dumped at May 11, 2004, current Internet has about 17,000 ASes. It is still a big challenge to simulate a network of this scale, in the term of both memory requirement and computation overhead of BGP protocols. The major memory requirement is used to store BGP routing tables on each BGP router, and the computation overhead mainly comes from the enforcement of routing policy.

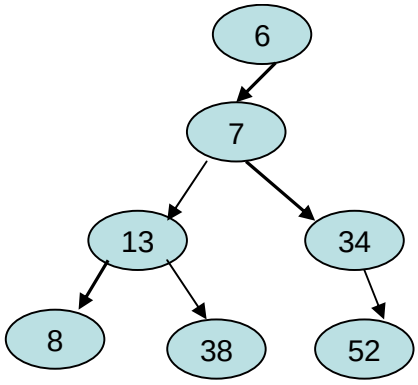


Figure 8.3 An Example of AS relationships

The routing policy is enforced through filter operation using regular expression match, similar to the real commercial router interface. However, this approach is not very efficient and hard to optimize for performance. For example, one AS has a routing policy that only exports routing information of its customers to its peer. Originally this is implemented by putting a list of all customers in the filter definition, and the filter will check the customer list one by one when exporting a routing entry. As shown in Figure 8.3, AS 7 has a provider AS 6 and 2 direct customers AS 13 and AS 34. However, it must list all of its customers, direct or indirect, in its export filters (Figure 8.4). The overhead is large, for a backbone ISP with thousands of customers, in the term of both memory consumption and computation.

```
Export Filter of AS 7:
    clause [  precedence 1
       predicate [
           atom [ attribute nhi_path matcher (.*)(8|13|34|38|52)$]
       ]
     action [ primary permit ]
```

Figure 8.4 The Export Filter using the AS list

In practice, the routing policy is enforced through the community attribute. A provider AS assigns a special community value to all of its customers, which will be associated with all routing entries created by the customers. Then the provider can check the community valued in

export filters and may assign. To mimic this approach, MaSSF implements the community attributed and add the automatic community check/setup in the maBrite generator.

```
Export Filter for AS 7:
    clause [ precedence 1
        predicate [
                atom [ attribute community matcher 7]
         ]
        action [ primary permit
                atom [ attribute community type set value 6]
         ]
```

Figure 8.5 Export Filter using Community Attribute

The Figure 8.5 is the new export filter configuration of AS 7. The *predicate* matches all routing entries with community value 7, which means they are created by its customer ASes. All matched routing entries can be exported to AS 7's neighbors, and the community value is re-set to 6, which is the provider of AS 7. Similarly, AS 6 will use this community value to enforce its own exporting policies.

Summarizing our Internet BGP simulation, we first exploit the scalability of MaSSF to directly simulate the real Internet AS-level topology. This enables the direct comparison of simulation results to real Internet, which is never conducted before. Then we convert the inferred AS relationship to BGP routing configuration and enhance it with real BGP routing table.

8.1.3 Simulation Results

From the BGP routing table dumped at May 11, 2004, current Internet has about 17,000 ASes and this generated network is simulated on a cluster with 60 Itinum-2 nodes.

There are many metrics can be used to evaluate how close is the simulated network to the real Internet. For examples:

1) Routing paths of single-prefix-origination AS:

For a given studied prefix, we compare the routing paths generated by simulation and paths observed at various BGP routers. Routing paths are influenced largely by routing decision algorithm and policy. So by comparing paths, we can do reality check on the simulation code and policy configuration. We will first study prefixes which are originated by single-prefix-origination ASes. In real Internet, we can get the routing paths to these prefixes from multiple BGP observe pointers. These paths are directly comparable to simulation results. By calculating the percentage of simulated routing paths which are exactly the same, one hop difference, and two hops difference, we can evaluate the reality of our routing configuration and simulation.

2) Routing paths of multiple-prefix-origination AS:

ASes which are originating multiple prefixes are not considered in the previous case. Because for those prefixes, there may be different policies applied to them. Those policies are purely a local decision which is not available to us. Thus it is much harder to compare simulation results and observed behavior of those prefixes.

3) Routing Dynamics:

In real world, researchers have set Beacon prefixes, which are brought up and down periodically. For each routing change of Beacon prefixes, we can observe and collect a set of triggered updates. We also simulate Beacon prefixes then compare the simulated routing updates with observed routing updates. More precisely, we compare a) # of updates; b) path changes; c) convergence time; d) inter-arrival time distribution.

We check the routing paths to all single-prefix-origination ASes at the BGP observation points. We use totally 44 observation points. The Cumulative Dense Function (CDF) of the match percentage is shown in Figure 8.6, with the average of 24%. This result is much lower than our expectation, and now it is meaningless to continue the second and third checks until we can improve this match percentage.

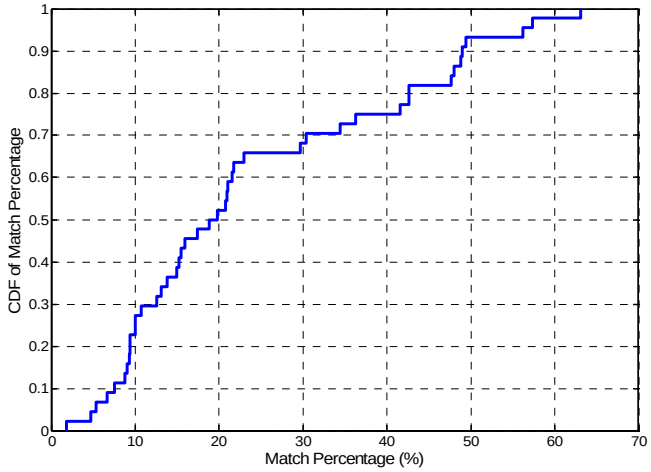


Figure 8.6 CDF of BGP Routing Table Match Percentage

Checking the simulation result, we find two major reasons for the large gap between the simulation output and the real Internet routing table.

First, the routing error in BGP is accumulative. Due to the distributed nature of the BGP protocol, routing decisions are made locally and then propagated to other ASes. Since every BGP routers only export the best routing chosen by themselves, BGP routers have no global view of the network. Any decision different to real Internet will be propagated and introduce a large number of different routes for the other routers.

Second, the selective announcement is the major source of the error, especially in the medium size ISP networks. Those ISP usually have a few customers AS and multiple providers, they usually use selective announcement for traffic engineering. As we mentioned above, we only calculate the preference of the largest prefix and use it to represent the whole AS. This can lead to a large number of routing decision errors and then propagated to the whole Internet. To really improve the simulation result, we must figure out how to create multiple prefixes in a single AS and how to do selective announce automatically in maBrite.

8.1.4 Summary

In this study, we exploit the power of scalable network simulation in MaSSF to simulate real AS-level Internet topology. We also construct the most realistic BGP configuration that has ever been achieved using inferred AS relationship. This network is simulated by the MaSSF on a 60-node cluster. We report our experimental results by comparing the simulation results directly to real routing data. Results show there is a significant gap between simulation results and real data, which warrants further investigation. Results show 1/4 match. As we show above, this is mainly due the accumulative error of BGP and selective announcement. While we cannot do much on the first issue, the later can be mitigate by supporting multiple prefixes in an AS and advanced routing configuration support in maBrite.

8.2 Empirical Study of Tolerating DOS Attacks with a Proxy Network

Denial-of-Service (DoS) attacks are a continuing key threat to Internet applications. In such attacks, especially distributed DoS attacks, a set of attackers generates a huge amount of traffic, saturating the victim's network and causing significant damage. Proxy networks have been proposed to protect applications from Denial-of-Service (DoS) attacks. However because large-scale study in real networks is infeasible and most previous simulations have failed to capture detailed network behavior, the DoS resilience and performance implications of such use are not well understood in large networks. While post-mortems of actual large-scale attacks are useful, only limited dynamic behavior can be understood from these single instances.

Our work exploits the unique capability of the MicroGrid, a detailed large-scale online network simulator, to study proxy networks with real applications and real DoS attacks. MicroGrid supports detailed packet-level simulation of large networks and use of unmodified applications. With MicroGrid, we are able to make detailed performance studies in large

networks environment with complex, typical application packages and real attack software. Our studies include networks with up to 10,000 routers and 40 Autonomous Systems (ASes) with a physical extent comparable to the North American continent. We believe this is the first empirical study of proxy networks for DoS resilience at large-scale, using real attacks, and in a realistic environment.

8.2.1 Background

8.2.1.1. Distributed Denial-of-Service Attacks

Denial-of-Service (DoS) attacks have been a major security threat to typical Internet applications[86-88], in which a central server provide services to a large number of users widely distributed in the Internet. In a DoS attack, attackers consume scarce resource which applications depend on, making the applications unavailable to their users.

There are two classes of DoS attacks: *infrastructure-level* and *application-level* attacks. Infrastructure-level attacks directly attack the service infrastructure, such as the network and the hosts of the application services, for example, by sending floods of network traffic to saturate the network of the application services. On the other hand, application-level attacks denial-of-service applications by exploiting weakness in application-level protocols, for example, by overloading application services with abusive workload or by sending malicious requests causing application services to crash.

Infrastructure-level attacks only require the knowledge of applications' network address, i.e. IP address. Meanwhile, application-level attacks are tightly-coupled with application-level protocols and do not require applications' IP addresses.

Distributed Denial-of-Service (DDoS) attacks are large scale DoS attacks, which typically involves a large number of "zombies". There are two stages in such attacks. First, attackers build zombie networks by compromising Internet hosts and installing zombie programs.

Second, attackers control the zombies to DoS the victim. Both infrastructure and application-level DoS attacks can be used in the second stage. Automated DDoS toolkits, such as Trinoo[89], TFN2k and mstream [90], and worms, such as CodeRed [91, 92], have been used for automation, enabling large scale attacks.

Our study focuses on distributed infrastructure-level DoS attacks.

8.2.1.2. Proxy Network Approach

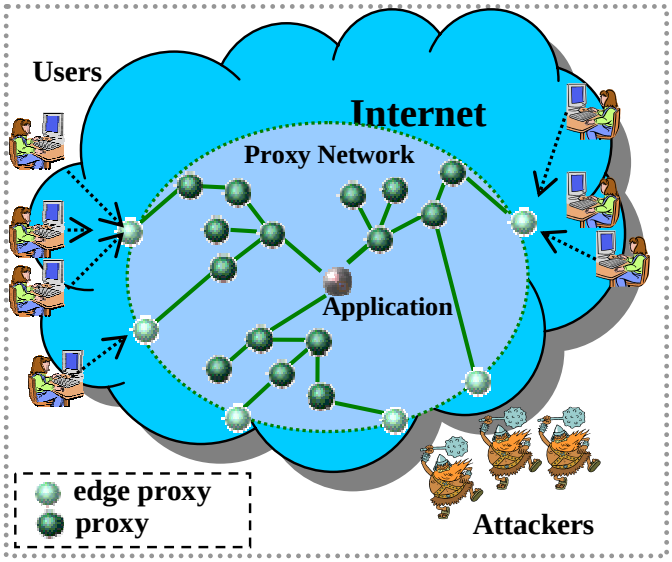


Figure 8.7 DoS-Tolerant Proxy Network

Overlay networks have been used to protect applications from DoS attacks [93-97]. Figure 8.7 shows a generic proxy network encompassing most of the proposed approaches. It shows a conceptual view of the proxy network from two perspectives. Proxies run on a resource pool with a large number of interconnected hosts, e.g. Internet hosts; proxies and applications form an overlay network by having logical connections tunneling application-level traffic among proxy nodes. The essence of the proxy network approach is to allow communication between users and applications without revealing the applications' low-level network address, e.g. IP address. Applications do not publish their own IP addresses. Instead the addresses of a number

of edge proxies are published, and these proxies are used to communicate (via other proxies) with the application.

Since only application level traffic is delivered inside the proxy network, once an application's low-level network address is hidden from attackers, direct infrastructure DoS attacks on the application are avoided. Furthermore, the proxy network is widely distributed in the network and highly redundant, so that it is DoS-resilient and it can shield the applications from DoS attacks.

8.2.2 Problem Definition and Approach

8.2.2.1. Problem

We have little understanding of the performance or effectiveness of proxy networks to provide DoS resilience in large-scale realistic networks. To date, studies of these problems have been limited to theoretical analysis and small-scale experiments. They cannot capture real complex network structures, real temporal and feedback behavior of network and application protocols, and detailed network dynamics, such as router queuing and individual packet drops. All these have important impact on system performance.

Thus, we still do not have answers to many key questions about the viability and properties of these proxy approaches.

1) With real complex network structures and protocol behavior, can proxy networks tolerate DoS attacks? In particular, in large realistic networks, under various attack scenarios, how much can proxy networks mitigate the impact of DoS attacks on users' experienced performance? What are the key parameters to achieve effective and efficient resilience? How does this capability scale up when proxy networks grow in size?

2) What are the basic performance implications of proxy networks? How do they affect users' experienced performance for real applications in large-scale realistic networks?

8.2.2.2. Challenges

To answer these questions, network simulation is necessary, since you cannot do large-scale DOS experiments on real Internet and or a small testbed. However, simulation for DOS attacks presents large challenges on the capability of network simulator.

First, the network simulator must be scalable to support simulation of large network with huge DOS traffic. To make the study results applicable to real Internet environment, the proxy network should be large enough. Also, this proxy network should be widely distributed in the network, and it presents a requirement on number of routers in the simulated network. Besides the large network size, we also expect the large DOS traffic from the attacking module. Since the basic approach for DOS attack is to saturate the network link, we expect the traffic of a few Gbps attacking traffic in the simulated network.

Second, it requires low level details to understand the attacking effect on applications performance. For example, the slow-start effect of TCP congestion window control, the AIMD policy on packet drop, and even the jitter due to the router queuing delays will greatly affect the proxy network and application's performance. Without this packet level detailed network simulation, it is impossible to study these behaviors. Because DoS attacks exercise extreme points of network behavior, correct modeling of such detail is important for realistic studies. In this context, we study the performance and DoS resilience of the generic proxy network approach.

Third, it is important to model real temporal and feedback behavior of network and application protocols and their interaction with other network traffic. This is difficult without online network simulation capability. Online network simulation can also help to capture the subtle details in the proxy network implementation, which is quite important to the final performance of the application.

Due to these challenges, there are no solid answers to the questions above. Existing network simulator are either limited in scalability or in the simulation details.

8.2.2.3. Approach

MicroGrid enables us to study these problems in a straightforward way, which cannot be easily achieved before. MicroGrid creates an Internet-like large-scale virtual network environment, and allows unmodified applications running on it. We built a proxy network prototype and deployed it along with a real application and real user programs into the MicroGrid virtual environment. We build a large zombie network in the virtual environment running a real DDoS toolkit to generate attack traffic. This allows us to do controlled experiments with different proxy network configurations and different attack scenarios, and study the questions above.

Details of our approach include:

1) Use of a large-scale, high-fidelity packet-level online network simulator – MicroGrid – to simulate large-scale realistic network environment, which include up to 10,000 routers and 40 ASes comparable to the size of large ISPs.
2) A real proxy network implementation and real applications deployed together in the MicroGrid virtual environment.
3) A large zombie network of 100 zombies and a real distributed DoS toolkit to generate attack traffic. It supports controlled experiments with various attack scenarios.
4) A tree proxy network topology, rooted at the application with edge proxies at the leaves providing user access. The number of edge proxies is the width of the tree, and the number of hops from root to leaves is the height. For a localized

application implementation, the tree corresponds to subset of links that would be exercised in all proxy networks.

5) Systematic study of a range of attacks, proxy network configurations, application, and resilience strategies.

We systematically study users' experienced performance using a range of proxy network topologies to understand the basic performance impacts of proxy networks; then we generate a range of attack scenarios with different attack magnitude and distribution, and systematically study their impact on users' experienced performance with proxy networks of different sizes to understand proxy networks' DoS-resilience capabilities and scalability.

8.2.3 Experimental Environment

8.2.3.1. Software Environment

There are four software components used in the experiments: a proxy network prototype implementation, apache web server as the application, a web testing tool "siege" to simulate user access, and a DDoS attack tool "Trinoo".

1) Proxy Network Prototype Implementation

The proxy network is a generic overlay network composed of proxy nodes. It can be configured to support any topology and extended to support any routing algorithm. Proxy nodes have unique identifiers, and act as routers. Each pair of neighboring proxies maintains a TCP connection. When a proxy starts, it connects to its neighboring proxies according to the specified topology information and some bootstrap location information of their neighbors. Messages can be routed inside the proxy network following any given routing algorithm.

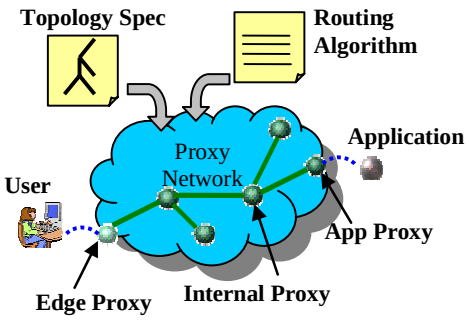


Figure 8.8 Generic Proxy Network Prototype

The proxy network supports all TCP applications transparently. We use the DNS scheme used by content delivery networks [98] to direct user access to proxies.

As shown in Figure 8.8, edge proxies listen to user connection requests, and encode application traffic into messages which are routed via the proxy network to the application. At the exit of the proxy network, application proxies (proxies that directly connect to the application) decode the messages, establish new connections to the application if necessary, and send the data to the application. The TCP connections among proxies are persistent and shared among users.

2) Application Service

We use Apache web server as a representative application front-end. Since we focus on the network impact of DoS attacks, specific details of the application logic at the back-end are not critical. Here we use Apache server to serve files of different sizes as a representative scenario.

3) User Simulator

We use siege – a web test toolkit – to generate user requests. Siege can generate web requests based on a list of URLs and measure the response time for each of the requests. This allows us to simulate user access and collect statistics which characterize user experienced performance.

4) DDoS Attack Toolkit

The attack tool used in experiments is the simTrinoo, which is a simulation module in MaSSF to mimic the behavior of the Trinoo attack tool. Based on two concerns, we do not use the real Trinoo program directly. First, due to the huge traffic created by attackers, the overhead of using Trinoo is quite large, especially in the Agent module of the simulator, which accepts and dispatches requests inside the simulator. It will affect the scalability of the whole system. Second, the logic of the Trinoo is so simple that we can easily reproduce the same traffic pattern inside the simulator using a traffic generator. Comparing to the simTrinoo, it will not bring any benefits to the accuracy of our simulation results.

Just like the Trinoo program, each simTrinoo attacker maintains a list of victims. Periodically, it randomly picks up one victim and sends out UDP attacking packets to it. By controlling the sleep between every two attacks and setting the victim list on every attacker, we can control the attacking traffic enforced on each proxy node.

8.2.3.2. Simulation Setup

The proxy network, apache server, siege programs and simTrinoo attackers are deployed in the MicroGrid simulated network environment. The maBrite topology generator is used to generate Internet-like Power-Law network topologies. We use two virtual networks in our experiments. One includes 1000 routers and 20 ASes, and the other includes 10,000 routers and 40 ASes, which is comparable to the size of a large ISP network. Both networks span a geographic area of 5000 miles by 5000 miles, which is roughly the size of the North American continent. This physical extent determines link latencies. OSPF routing is used inside ASes, and BGP4 is used for inter-AS routing.

Our network simulator is running on an 8-node dual 2.4GHz Xeon Linux cluster with 1G main memory each, connected by a 1Gbps Ethernet switch. The proxy and siege processes are

running on another 24-node dual 450MHz PII Linux cluster with 1G main memory each, connected by a 100Mbps Ethernet switch. These 2 clusters are connected with a 1Gbps link.

8.2.4 Experiments and Results

To answer the questions stated in Section 8.2.2, we conducted three sets of experiments: proxy network performance evaluation, proxy network resilience against DDoS attacks using simple redundancy schemes and proxy network resilience using fail over schemes.

8.2.4.1. Proxy Network Performance

To understand the performance implication of the proxy network approach, we compare the user-observed service performance between the case where users directly access the application and the case where a proxy network is used. We use a sample of 100 users randomly chosen from the simulated network described in Section 8.2.3. Users choose edge proxies based on proximity.

We use a simple heuristic to deploy a proxy network. Edge proxies are uniformly distributed in the simulated network. Application proxies are placed on hosts physically close to where the application service is. All the other proxies are evenly distributed between edge proxies and application proxies. This heuristic tries to align a proxy network to the underlying network to avoid long detours in overlay routes. It is straightforward to implement this heuristic for proxy networks whose topology is a tree, which is the case used in our experiments.

Figure 8.10 shows the results for a tree-topology proxy network with about 200 proxies, 64 of which are edge proxies. The X-axis is the response time for a user to download a given size file (1.5KB or 100KB) either directly from the application service or via the proxy network. The Y-axis is the Cumulative Density Function (CDF) of user-observed response time over the user population.

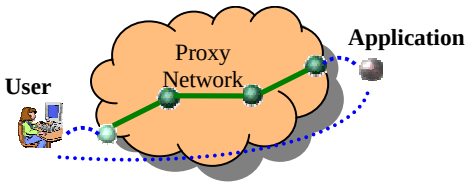
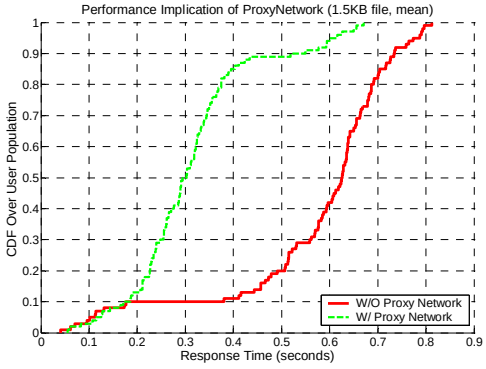


Figure 8.9 Direct Access vs. Proxy Network

Surprisingly the proxy network greatly improves performance. For small requests (e.g. 1.5K), the 50-percentile response time is reduced by half, and for medium size requests (e.g. 100K), the improvement is even more significant. However, the performance gap between the two cases becomes smaller for large files (e.g. >1MB). There are two main reasons for this:

First, proxy network improves connection set up time. As shown in Figure 8.9, there are established TCP connections among proxies. For each virtual connection between a user and the application, instead of establishing a long TCP connection between the user and the application, two shorter TCP connections are established: a connection from the user to the edge proxy it uses and a connection from the corresponding application proxy to the application. Both of these are short connections, because application proxies are close to the application service, and users choose edge proxies based on proximity. Second, the TCP connections among proxies are persistent, and in most cases the TCP congestion windows for those connections have already been fully opened. It no longer needs TCP slow start phase to grow the congestion window over multiple round trips to complete a data transfer. For medium size requests (e.g. 100KB shown in Figure 8.10), this effect is most prominent.



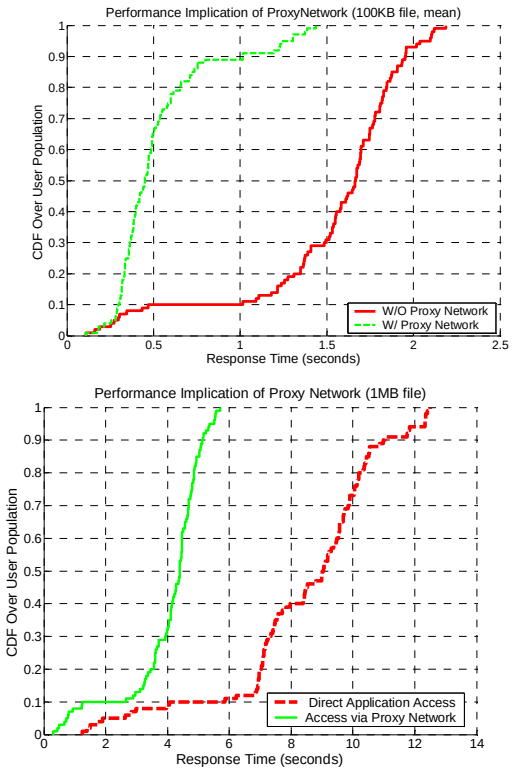


Figure 8.10 Proxy Network Performance Implication

For these reasons, having a proxy network can potentially improve the user-observed application performance, and the following principles should be considered in the deployment of proxy networks. Each overlay hop (i.e. RTT between neighboring proxies) should be kept as short as possible. Edge proxies should be widely distributed to be close to users, and application proxies should be put close to the application.

In this experiment, the online simulation capability of the MicroGrid enable use to study the application performance directly in large networks. The packet level detailed simulation in the MicroGrid is also critical to capture the application performance, which depends the accurate modeling of TCP hand-shaking and slow-start.

8.2.4.2. DoS-Resilience of Proxy Networks

To explore the DoS-resilience capability of proxy networks, we study user-experienced performance under a range of attack scenarios with or without proxy networks. We use the same proxy network, which contains 192 proxies (64 edge proxies), in the simulated network with 20 ASes and 1000 routers. In addition, we constructed a DDoS network, which contains 100 Trinoo daemons randomly distributed in the network.

Our first experiment explores whether a proxy network can really protect an application from DoS attacks. Our second experiment studies the DoS-resilience capability of the proxy network under two large-scale attack scenarios: spreading DoS attacks where attack load is distributed evenly on all the edge proxies and concentrated DoS attacks where attack load is concentrated on a subset of edge proxies to saturate their incoming links. Our final experiment studies the scalability of proxy networks with respect to DoS-resilience, by varying the size and width of proxy networks.

1) Can a proxy network protect applications?

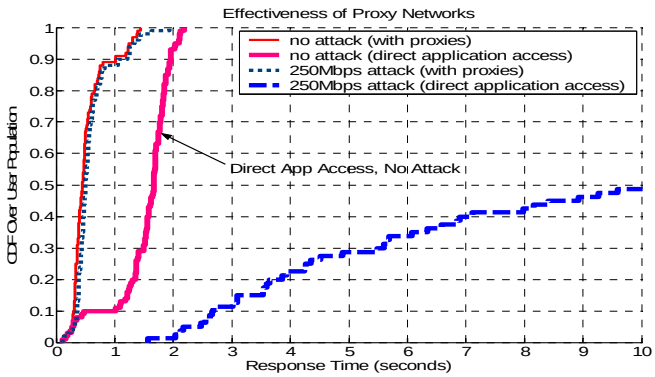


Figure 8.11 DOS-Resilience of Proxy Network

We compare the impact of a DoS attack cast on the application and the proxy network. In our experimental setting, the application service is connected by a 250Mbps link, and each edge proxy is connected by a 100 Mbps link. Figure 8.11 shows the CDF for user-observed service response time of 100KB request size in scenarios with or without a proxy network. The results

show that a 250Mbps attack on the application significantly increases service response time (about 10x) and the application becomes unusable. However, when a proxy network is used, the attack has no observable impact on the user experienced performance. The reason is straightforward. By having a collection of edge proxies to dilute the impact of attack, a proxy network has a greater capacity than the application, thereby not as easily being saturated.

2) How large an attack can a proxy network resist?

To investigate how well a proxy network can tolerate DoS attacks, we launch both spreading and concentrate DoS attacks on the proxy network described in Section 8.2.3, which has 64 edge proxies and 192 proxies in total. Each of the edge proxy has a 100Mbps uplink. In both cases, we vary the aggregated attack magnitude from 3.2Gbps to 6.4Gbps. In this experiment, users do not switch proxies during attacks.

In the case of spreading DoS attacks, Figure 8.12 shows that when attack magnitude is no more than 6.0Gbps (recall that the aggregated uplink capacity for all the edge proxies is 6.4Gbps), more than 95% of the users observe no significant performance degradation --the DoS attack has been successfully tolerated. The reason for this is that the edge proxies successfully dilute attack, and even under heavy attack loads, most of the edge proxies still have sufficient capacity left to serve user requests. Figure 8.12 also shows that when attack load reaches 6.4Gbps, all the edge proxies are saturated, significant performance degradation occurs for all users.

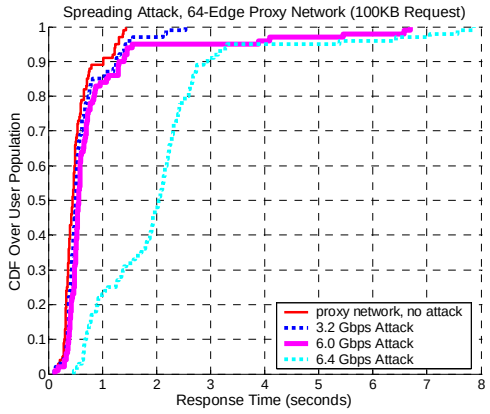


Figure 8.12 Redundancy to Spreading DoS Attack

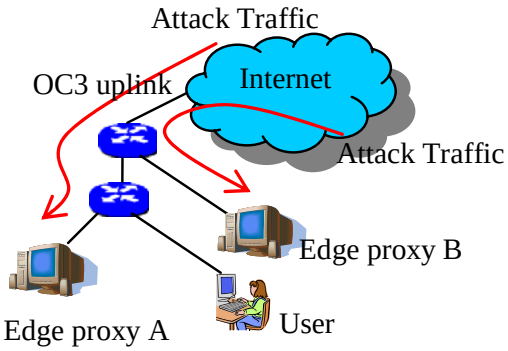


Figure 8.13 Correlation among Proxies and Users

More interesting, we can see large performance degradation for a small fraction of users (<5%) when the attack magnitude is 6.0Gbps. It is due to the correlation among proxies and users (see Figure 8.13). Two edge proxies A and B share an uplink of OC3 (155Mbps). Before attack traffic saturates both proxies' local links (100Mbps), the shared OC3 link gets congested first. Therefore, users who use these two proxies and users who are in the same network as these proxies will be affected. This effect limits the effectiveness of proxy network. Thanks to the accurate simulation of the MicroGrid even under heavy traffic, we can capture this phenomenon in the simulation.

Figure 8.14 shows the case of concentrate attacks, where attack load is concentrated on a subset of proxies. In this case, attack traffic saturates part of the proxy network and a

significant percentage of users are affected due to congestion and packet loss. This effect is more prominent when attack load is higher than the proxies' capacity (e.g. 4.0Gbps attack on 32 proxies).

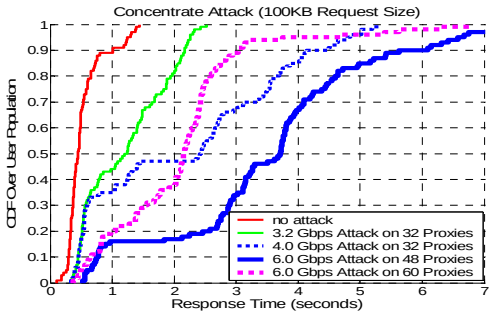


Figure 8.14 Resilience to Concentrate DoS Attack

We observe that parts of the proxy network are not under direct DoS attacks; therefore if users can switch to edge proxies not being attacked, the performance can be potentially improved. We repeat the concentrate DoS attack experiment, and let users switch to the closest proxy not being saturated. Figure 8.15 shows the CDF of user-observed performance. Compared with Figure 8.14, the performance has been significantly improved. For comparison, Figure 8.15 also plots the baseline case where users directly access the application without attack traffic. It shows that even under high attack load (e.g. 6.0Gbps) the proxy network can still maintain slightly better performance than direct application access without attacks for most users. Therefore proxy networks can effectively resist DoS attacks.

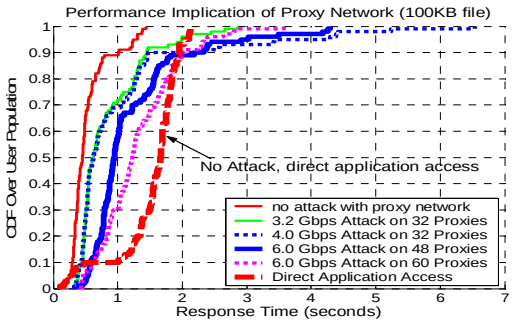


Figure 8.15 Resilience to Concentrate DoS Attacks with Proxy Switching

This experiment demonstrate the capability of the MicroGrid to simulate large network accurately even under heavy traffic. With 6.4Gbps attacking traffic and average 15 hops per stream, we are simulating a 1000 routers network with about 100Gbps traffic flowing in the network.

3) How does proxy network size affect DoS-resilience?

Finally, we explore how varying the size (width) of the proxy network affects DoS resilience. This is an important scaling property of the proxy network, showing how effective we can resist larger scale DoS attacks by building larger proxy networks. The goal of our experiment is to evaluate the amount of attack load proxy networks can withstand for a range of proxy network widths. It is hard to directly measure the maximum attack load a proxy network can tolerate. Instead, we set the attack magnitude to be 95% of the proxy network's capacity, and measure the user-observed performance. We define the capacity of a proxy network to be the sum of the link capacity of its edge proxies. For example, if the proxy network has 16 edge proxies and each edge proxy has a 100 Mbps uplink, then its capacity is 1.6Gbps and the aggregated attack magnitude is 1.52Gbps.

Proxy network scaling results are shown in Figure 8.16. The X-axis is the number of edge proxies in the proxy network (they all have height 3), and the Y-axis is the user-experienced service response time for a certain percentile of users. We can see that for up to 95 percent users, the curves stay horizontal and less than 2 seconds (recall from Section 8.2.4.1 that the 95 percentile performance for direct application access without attacks is 2 seconds). If we define 95% users not being affected by DoS attacks as successful DoS resilience, then the amount of attack traffic can be tolerated grows linearly with the size of the proxy network.

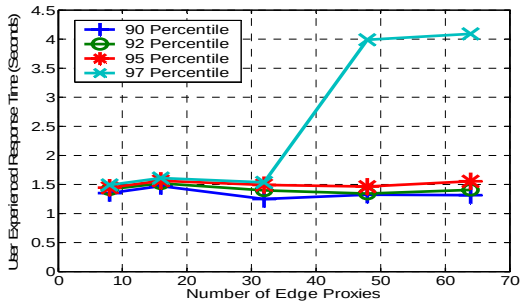


Figure 8.16 Resilience and Proxy Network Size

This experiment is a good demonstration of the flexibility of the MicroGrid resource configuration. It can easily construct proxy networks and deploy them to the virtual network. With the MicroGrid, it is possible to study various network configuration and application scenario under controlled environment.

8.2.5 Conclusion

Our work provides the first detailed and broad study of DoS resilience with proxy network in large-scale realistic networks. The key is that we exploit the unique capability of the MicroGrid to simulate a realistic large-scale network (comparable to several large ISPs). We use a generic proxy network and deploy it in a large simulated network using typical real applications and DoS tools directly. We study detailed system dynamics under various attack scenarios and proxy network configurations. The major conclusion is that, in realistic large network environments, proxy networks can have great performance potential and scalable DoS-resilience capability. It is a promising approach to DoS defense. These experiments and the conclusion are not possible without the scalable, accurate online simulation provided by the MicroGrid.

8.3 Summary

In this chapter, the MicroGrid toolkit is successfully used on two real network related studies, none of them is possible without the MicroGrid. These experiments demonstrate the unique capabilities of the MicroGrid which are critical to the success, including:

1) Scalability. This is required by the simulation of the whole Internet AS-level topology and large attack traffics.

2) Accurate and detailed simulation. The DoS study of proxy network requires very detailed network modeling, including TCP slow start, TCP AIMD congestion control, and router queuing and dropping.

3) Online simulation capability. The proxy network evaluation is not possible without the online simulation capability. Furthermore, our online simulation helps us to detect and fix a batch bugs in the proxy network implementation.

4) Flexible on virtual grid configuration. The DOS study experiments require flexible deployment of a large number of proxy and user hosts.

Chapter 9 Related Work

In this chapter, we discuss the most related work, current research on network emulation for application performance studies. Those are all interesting because they are quite similar to our approach in supporting direct execution of applications. However, there is still a major difference between them and the approach used in the MicroGrid, and we want to point them out clearly. In Section 2.1 we have discussed other related work in application performance modeling.

We will briefly describe their approaches in Section 9.1 and compare them to the MicroGrid in Section 9.2. Then we will summarize the difference at Section 9.3.

9.1 Network Emulation Projects

Several recent research efforts are most similar to the MicroGrid, including ModelNet [35], Netbed [36], Maya[99], and Albatross [100].

9.1.1 ModelNet

The ModelNet [35] project at Duke University (and now at UCSD) is a software emulation environment on a cluster. The ModelNet simplifies network topology as a network of pipes, calculates the shortest-path routing, and then maps the resulting network of queues onto a set of emulation *cores.* Network IP packets from real applications running on end hosts will be routed through one or more *cores*. The *core* will subject each packet to delay, bandwidth, and loss characteristics, according to the target topology. ModelNet moves packet hop-by-hop in the topology and each hop is represented by a *pipe* with a packet queue. Whenever a packet enters a

pipe queue, the emulator will calculate the queuing and link delay and forward the packet to the next hop, after desirable delay, if it is not dropped due to a queue overflow, randomized loss, or a RED policy. Thus ModelNet can track the effects of congestion and competition among competing packets.

Key differences to the MicroGrid include:

1) The MicroGrid models real network entities and their behaviors, while the ModelNet simplifies them to pipes and queues. In the MicroGrid, every router has fully functional Network Interface Cards (NIC), packet buffer queue, and protocol stack of IP, TCP, OSPF or BGP. Thus it is easy for the MicroGrid to incorporate detailed routing configuration and make dynamic routing selection as in the real Internet. The ModelNet, however, has to load a pre-calculated routing path at the emulation startup time, lookup the static routing path for every packet entering the emulators, and then move it through all hops in that path. While this approach reduces the simulation overhead greatly, it is not easy to implement dynamic routing without major modification.
2) The MicroGrid supports scaling of all resources and performance ratio precisely, while the ModelNet must follow the real-time emulation requirement and has no modeling of computation resources. This difference gives the MicroGrid more flexibility in simulating various, and even future, network and resources speed and ratio.
3) The MicroGrid uses advanced load balance and scaled real-time execution for scalability, while the ModelNet mainly counts on approximation and some load balance improvement. The *Distill* phase in ModelNet transfers an original network topology into a network of *pipes*, and it can simplify the network, if the emulator is not fast enough to keep up the real-time execution, trading accuracy for reduced emulation cost. In contrast, the MicroGrid uses full-scale detailed packet-level simulation based

on a distributed discrete-event simulation engine. As for the load balance problem, ModelNet[101] uses the greedy k-cluster algorithm: for k nodes in the core set, randomly selects k nodes in the virtual topology and greedily selects links from the current, connected component in a round-robin fashion. They also use an approach similar to the MicroGrid PLACE mapping, but it is focused on minimizing Network traffic between *cores*. While there are continued improvement on scaling and possibility of emulating a 10,000 nodes network[102], the largest emulation on ModelNet we know has 4000 virtual nodes running on 9 cores [101].

4) The MicroGrid has higher cost on simulating every packet movement, but it can be used on publicly shared general Linux cluster systems, while the ModelNet required dedicated customized FreeBSD clusters. This may seem to be a trivial user interface issue, but it has a big impact in practice; since users of the MicroGrid can do much larger scale simulation on publicly shared large cluster systems (such as TeraGrid[2]).

9.1.2 Netbed/Emulab

The Netbed/Emulab [36] project, developed at Utah University, uses a set of real routers, switches and configurable software routers to emulate wide area network. Netbed can also integrate simulation, wide-area network testbeds, and emulation into a common framework. This framework provides abstractions, services, and namespaces common to all, such as allocation and naming of nodes and links. By mapping the abstractions into domain-specific mechanisms and internal names, Netbed masks much of the heterogeneity of the three approaches. The Netbed users can benefit from choosing appropriate modeling approaches for their special requirements, even in a single simulation experiment.

Key differences to the MicroGrid include:

1) Netbed requires real-time emulation, which has the benefit of quick simulation. At the same time, the real-time execution requirement is also a limit on scalability. The MicroGrid uses scaled real-time execution and can achieve better scalability with the cost of slower simulation.
2) Netbed also provides little to the experiment designer in the way of detailed control of resource speed and modeling. Regardless how many resources are dedicated in the Netbed resource pool, the resource type and number are still limited, when compared to possible virtual network configurations. The user has to select and configure whatever available physical resources to approximate the target virtual network, which will lead to possible inaccuracy. In practice, Netbed's *assign* [103] automatically maps virtual topologies which include endpoint resources, as well as network structures, onto a heterogeneous combination of routers, switches, and computers. In contrast, the MicroGrid provides accurate resource modeling, and has no inaccuracy introduced by this kind of approximation.
3) Netbed provides no load balance solution. While the assign automatically chooses specific endpoint and network resources to optimize their quantity subject to the constraints, load balance is not its direct focus. Instead, the MicroGrid provides advanced load balance mechanism for better scalability.
4) The scalability is also limited by the available physical resources in the Netbed resource pool. The largest automatically-configured Netbed experiment [104] of which we are aware has 520 virtual nodes (routers) mapped to 44 PCs. The MicroGrid can use any publicly available Linux cluster systems and conduct much larger scale simulation.

9.1.3 Maya

The Maya [99] Project at UCLA also provides a network modeling framework for emulating distributed applications. Like ModelNet and Emulab, Maya supports direct execution of applications, and also has the real-time execution requirement.

Key differences to the MicroGrid include:

1) The unique feature of Maya is that it can integrate two disparate modeling approaches into a unique framework; that is, the discrete-event model and the analytic model. The analytic model uses the fluid flow based TCP model [21] for network simulation. As its name suggested, the fluid model treats TCP traffics as fluids, and it derives a set of ordinary differential equations (ODE) to model the rate of traffic changes and queuing process at routers. Unlike the discrete-event model, there is no packet or event in a fluid model; and it only needs to solve the ODE periodically. Thus it can dramatically reduce the overhead of network simulation. The MicroGrid only uses the discrete-event model.
2) With cost of fidelity, Maya has the potential to support a very large network simulation. It is suitable for simulating backbone network with high volume of traffic for traffic engineering and real-time monitor and control, but it cannot capture the detailed packet movement, which is critical to application performance. The MicroGrid, however, does not trade fidelity for scalability. It uses packet-level detailed simulation to capture all the details of network protocols and router behaviors.
3) While it is shown that speed of fluid flow simulation can support real-time execution in long term, the periodical invocations of the computation intensive ODE solver causes the packets to miss their real time deadline repeatedly. This hurts the accuracy of real-time application emulation and limits its scalability. The largest simulation they have reported so far is just 60 nodes [99].

4) Maya has no support for resources modeling either, which leads to little control on application execution. The MicroGrid is an integrated simulation framework that provides simulation for all resource and network components.

9.1.4 Panda in Albatross

The Albatross [100] Project provides programming environments for high-performance Grid computing. To facilitate investigating the application performance in wide-area networks, they developed a Panda WAN emulator as part of their communication library. This Panda WAN emulator works in a way similar to that of the dummynet emulator [33].

Key differences to the MicroGrid include:

1) However, thanks to the tightly couple with the communication library, one unique feature of the Panda emulator is that it can run parallel applications on a single parallel machine with only the wide-area links being emulated. The actual emulation of WAN behavior only models the network delay and bandwidth and cannot catch the network queuing and congestion status. Like all other emulation projects, it is also limited to real-time execution, and has no control on computation resources. The MicroGrid, instead, uses binary interception to redirect all network related functions call to the simulator. We do not distinguish between local area network and wide area network. While it is not clear if the accuracy of whole simulation will be affected by not modeling the local area network, it can definitely reduce the simulation overhead.
2) More accurately, the Panda is not a general network emulator like the MicroGrid, due to the fact that it does not provide multiplex of multiple virtual machines on a single physical resource. This makes it quite limited on the resources configuration that it can emulate. The largest simulation reported is using a 64 nodes cluster to simulate a

distributed application with 64 nodes [100]. This is far beyond the scalability of the MicroGrid system.

9.2 Novelties of the MicroGrid Approach and Capability

While we have mentioned the important differences between these emulation systems and the MicroGrid above, it is clearer to list all novelties of the MicroGrid approach and capability together.

First, all of these systems require real-time execution, and the MicroGrid is unique in providing support for scaled real-time simulation and computation resource modeling. As we have discussed in Section 5.3, this feature is the base of coordination between multiple simulation modules, and it can also improve simulation accuracy and scalability. This capability does not come as an accidence; instead, it requires an implementation of TCP protocol stack in the network simulator, which is quite labor-intensive and slows down the simulation speed. With the support of the computation resource simulation discussed in Section 5.2, the MicroGrid can simulate grid environments with a wide range of heterogeneous resources and various compute and network speeds ratio. For example, the MicroGrid can accurately simulate fast network and resources which are still not currently available. Moreover, it can also accurately simulate various network and resource ratio without the limitation of available physical resources. None of those features are possible with any of the emulation systems listed above.

Second, the network modeling in these emulation systems either use approximation models or have limited scalability. These approximations reduce the cost (compared to the MicroGrid's global synchronized simulation) to achieve faster execution. The MicroGrid is unique in that it uses realistic network topologies, realistic routing protocol, detailed packet level simulation, and background traffic from aggregated large numbers of traffic flows. The MicroGrid does not

make tradeoffs between accuracy and scalability in network simulation, and it tries to provide the most accurate simulation result possible. With scalable hardware like modern clusters, we demonstrate that this approach is feasible, even to simulate a large ISP network.

Third, the MicroGrid has the most advanced support for network routing. It uses OSPF for intra-domain routing and BGP for inter-domain routing. This can help the MicroGrid to provide realistic network routing selection and dynamic routing reaction under network congestion or link failure. This is important when studying the application performance under extreme and unusual conditions. All other projects just use pre-calculated static routing information. For example, the ModelNet uses pre-calculated shortest routing path based on static network topology. Static routing has much less overhead in simulation execution, and the routing table size (not the real emulation yet) can scale to hold a network with about 10,000 nodes[102]. However, it is difficult for those projects to introduce dynamic routing into the simulation.

Fourth, advanced load balance is also a critical feature of the MicroGrid. Load balance is known to be an important and hard problem for the scalability of distributed network simulations or emulations; However, there are only a few efforts in network simulation/emulation community to solve this problem. Many projects, including the Maya and Albatross, use either manual partitioning or simple graph partitioning based on network topology. ModelNet[101] uses the greedy k-cluster algorithm: for k nodes in the core set, randomly selects k nodes in the virtual topology, and greedily selects links from the current connected component in a round-robin fashion. They also use an approach similar to our PLACE mapping, but this is focused on minimizing Network traffic between *cores*. Netbed's *assign* [103] maps virtual topologies which include endpoint resources, as well as network structures, onto a heterogeneous combination of routers, switches, and computers. Critical issues are time to compute mapping, physical resources used, and sufficient link capacity. Thus, *assign* chooses specific endpoint and network resources to optimize their quantity subject to the

constraints. Load balance is not a direct focus. During the time of this dissertation writing, we noticed that the BGP++[105] is also using graph portioning approaches for load balance in its distributed network simulation.

9.3 Summary

Even with similarity in supporting real application execution, the MicroGrid is distinguished from other emulation project for goal, accuracy and scalability.

The key difference between MicroGrid and these emulation approaches is the scaled real-time execution and the more flexible application control. The scaled real-time execution relieves us from the real-time limitation of emulation, and provides much larger scalability and accuracy. Since the MicroGrid is an integrated simulation of network and grid resources, it provides resource modeling and flexible control on application execution. Combined with the scaled real-time execution, the MicroGrid can study various, even future, hardware speeds and ratios.

Beside our novel approach for virtual grid modeling, our automatic load balance mechanisms also provide major scalability advantage over other systems. The realistic packet-level network simulation with $O(10^4)$ routers enables accurate grid dynamic study at unprecedented scale and great opportunities for new insights.

Chapter 10 Summary and Future Work

Having presented and evaluated the scaled real-time online simulation and the load balance algorithms for better scalability, we now summarize our work and list the impact of our work on simulation research. After that, we enumerate some limitations on our system and possible directions of future work.

10.1 Summary

The increasing acceptance of grid computing in both scientific and commercial communities presents significant challenges for understanding the performance of applications and resources together. The associations between applications and resources are no longer static, and dynamic resource sharing and application adaptation further complicate the situation.

To meet the emerging modeling needs and to enable growth in understanding the dynamic properties of grids, we have developed the scaled real-time online simulation mechanism and implemented it in a toolkit called the MicroGrid. The MicroGrid enables accurate and comprehensive study of the dynamic interaction of applications, middleware, resource, and networks. The MicroGrid creates a virtual grid environment – accurately modeling networks, resources, the information services (resource and network metadata) transparently. Thus, the MicroGrid enables users, grid researchers, or grid operators to study arbitrary collections of resources and networks.

Accuracy and scalability are the two major challenges in virtual grid simulation. In computation resource modeling, we use the soft real-time process scheduling, which can provide accurate computation resource simulation efficiently. This technique has few

requirements; it can be used on any OS that supports POSIX.5 thread system. For network modeling, we use packet-level online network simulation based on discrete-event simulation engine, enhanced with OSPF and BGP routing protocols. With the support of transparent live application traffic interception and the coordination through scaled real-time execution, real application can be executed directly on a virtual grid environment; both computation and network behaviors can be modeled accurately. To validate our approach and the MicroGrid implementation, we present experimental results with applications, showing that the MicroGrid not only runs real grid applications and middleware, but it accurately models both the underlying resource and network behavior.

We also study a range of techniques for scaling a critical part of the online network simulator to the simulation of large networks. These techniques employ a sophisticated graph partitioner, and a range of edge and node weighting schemes exploiting a range of static network and dynamic application information. By carefully mapping the virtual network to physical resources using multi-objective graph partitioning algorithms, we achieve good load balance and better scalability in network simulation. Our studies show that the static network topology and application placement information can be exploited to achieve good balance for some application. These load balance approaches are evaluated against large-scale networks, including both single-AS network and multi-AS network. The best of these, called hierarchical profile-based load balance (HPROF), can increase efficiency and scalability by over 100 times, achieving a parallel efficiency of over 40% on a 90-node cluster for a range of experiments. This provides a great chance for scalable network simulation. Combining with our packet-level hop-by-hop network simulator and detailed BGP4 protocol support, we demonstrate that we can provide realistic large-scale network simulation for networks, including about 20,000 routers, which is comparable to a large ISP network.

To demonstrate the capability of the MicroGrid toolkit, it is used in two network related research. The first one is the BGP Simulation reality check study, where we use the MicroGrid to simulate the real Internet AS level topology with detailed BGP routing policy configuration. The result shows that there is still a big gap between the simulated result and real Internet routing choices, which warrants further investigation. The second study is on resilience DOS attacks, using overlay networks. On the virtual grid testbeds provided by the MicroGrid, experiments show that overlay networks can be used to alleviate the resource level attack efficiently.

In summary, the MicroGrid toolkit, then our approach for integrated online simulation, has achieved good scalability and fidelity to study real world large-scale Grid research problems. Its capability is larger than the simulation requirements of most existing grids, and it is large enough to model future grids.

10.2 Impact

The coming MicroGrid toolkit represents a big progress in the practice of simulation on application performance modeling. The large-network simulations at detailed packet-level provide new capability and chances for deeper insight. The MicroGrid toolkit could be useful for network and grid researchers, grid administrators, grid designers, and application designers. For example, beside the BGP reality check and Denial-of-Service attacks in Chapter 8, it can also be used in the study of:

1) Large-scale behavior of peer-to-peer applications (e.g. Kazaa [106], BitTorrent[107], Gnutella[108]) in mixed backbone, access, and local area networks.
2) Adaptive applications and rescheduling in controlled Grid resource environment
3) Resource selection, and the impact of competitive resource sharing in large-scale Grids

4) Grid systems performance bottleneck detection and system abnormal diagnose in a controlled repeatable environments.

This is just short list of direct applications of the MicroGrid. Wide acceptance of the MicroGrid toolkit will fundamentally change the current practice in network and grid related research. People will no longer accept any results or conclusions obtained from experiments on small testbeds or small simulation, with simple dumbbell networks. Instead, they should be exercised and examined in large-scale detailed virtual grid environment, which is a direct simulation, comparable to the final target deploy environments. Since the MicroGrid can provide such virtual grid environment easily, and can be used with direct execution support, this requirement is reasonable and will not raise large overhead for the researchers. The entire community will benefit from this practice that will result in more creditable results and more productive research.

10.3 Limitations

While the MicroGrid represents a big progress in network simulation and grid modeling, it can be further improved if we can address the following limitations.

First, better understanding of the network itself will further improve the realism of network simulation. This includes characteristics of Internet network topologies, link latency and bandwidth distribution, routing configuration, and background traffic. i) Current network topology generation research mainly focuses on the graph connectivity level, and there are few research studies on realistic link bandwidth distribution. As we show in our DoS studies in Section 8.2, realistic link bandwidth is very important to experiments involving large volume of data transfer, which is quite common for grid applications. ii) Realistic routing and its dynamic response to network congestion and failure are also critical to grid application performance. While the MicroGrid provides the dynamic routing capability of OSPF and BGP4, how to get

realistic routing configuration is still a pending challenge. Our automatic BGP configuration in maBrite is just a first step in this direction. iii) There are no realistic background traffic generation and modeling tools available. Currently in MicroGrid we create a large number of traffic flows (WWW, TCP, and UDP traffic) randomly distributed in the network, and expect that the aggregated effect will create reasonable network dynamic similar to real network. While we believe it partially solves the background traffic issue, the result is not validated; it also introduces a large volume of traffic and load on simulation. Usually, this load is not of interest to the user. So a realistic background traffic generation and modeling can greatly improve the realism of the MicroGrid simulation result; it can also improve the capability for simulating larger resources and applications.

Second, better application performance model can further improve the capability of the simulation. The MicroGrid uses direct execution to capture the subtle application details and temporal interaction between application, middleware, resources and network. This is a good choice, given the fact that no good application performance model is available. But this approach also means that we have to run the application directly, consuming the same amount of memory, storage, and computation power. Even the MicroGrid is scalable in nature and it is possible to trade the simulation speed for larger experiment; the overall capability is limited by the available physical resources. The MicroGrid can benefit by better application performance models which abstract and reduce the real memory and computation requirement without hurting the accuracy.

Third, better understanding of methodology for extrapolation can improve the capability on understanding grid dynamics. While we can use the MicroGrid to study a large number of network topologies, different resource configurations, and multiple application setups, the total number of possible experiments is still limited when compared to all possible scenarios. We

need better understanding on how to extrapolate from a small set of Grid simulations to a much broader space of network environment and application behavior.

10.4 Future Work

The three limitations listed above are the long term research directions that can fundamentally improve the overall simulation capability. In the meantime, there are a few efforts are possible to improve the MicroGrid fidelity and scalability directly.

Due to physical resource limitation, we only use a 128-node cluster in our experiments. However, it is clear that there is still more parallelism in the large-scale network simulation. In future work, we will use MicroGrid to study larger networks and application, specifically using a 256-node Itanium-2 Linux cluster to simulate a network with 100,000 network entities, which can be taken as a significant fraction of the real Internet with hundreds of ASes. Under this scale of a network, we expect to experience much larger load balance challenge, and therefore, we have to develop a traffic-based load balance solution for better scalability. While we selected the GridNPB benchmarks for our experiments, our evaluation could be improved by studies with better benchmarks suites or larger real grid applications. In the future, we will also use MicroGrid to study larger scale real Grid applications, including resources scheduling and overlay network behaviors.

The soft real-time process scheduler can be further improved, especially for multiple applications, with computation and communication mixed together. Currently we only guarantee the CPU quota of a virtual machine, and do not emphasize how the quota is allocated to all processes on that virtual machine. Fairness is not guaranteed, and there are may be some processes in starvation that affect the application dramatically. If accuracy is really important, we may have to investigate other more sophisticated scheduling machinist, such as using hard real-time scheduler on real-time operating system, or virtual machine monitors.

Automatic network mapping and the load balance of distributed network simulation still remains one of the hardest problems. Load imbalance happens due to burst/variation of traffic injected from the application. Static partitions are fundamentally limited for large simulation, if traffic varies widely. Even the hierarchical profile-based partitioning algorithm discussed in Section 5.4 will not solve the basic problem, especially when the simulation runs for a long time and the traffic pattern changes dramatically during the simulation. Dynamic remapping of the virtual network, during the simulation, is the only solution. Such dynamic remapping is a major challenge for distributed simulators like MaSSF, since it also has a scaled real-time requirement.

Appendix A Automatic BGP Configuration

Following the heuristic rules listed in Section 2.3, we automatically configure Internet-like network topologies with realistic routing configuration, and expect to get a routing pattern similar to that of the real Internet. The procedure for network topology generation and automatic routing configuration is shown in the following:

1) Generate AS level topology following the Power Law
2) Classify ASes according connection degrees.
   i) Core: ASes with connection degrees of top 2
   ii) Stub: ASes with connection degree of 1 or 2
   iii) Regional ISP: all the other Ases
3) Decide AS relationships
   i) Provider-and-Customer:
      a. Core -- Stub,
      b. Regional ISP – Stub,
      c. Core – Regional ISP
   ii) Peer-and-Peer: between all ASes in the same level
4) Setup Import Routing Policy
   i) Accept all incoming routes
   ii) Set Local Preference according to Next Hop AS, which prefer routes from Customer, over routes from Peer, and over routes from Provider
5) Setup Export Routing Policy

i) To Provider: Export local and Customer routes

ii) To Peer: Export local and Customer routes

iii) To Customer: Export all routes

6) Create topology for every Stub AS

i) Follow the Power Law

ii) Use OSPF routing inside the AS

iii) Use default routing to hosts outside local AS

iv) Pickup default/backup routers for multi-homed Ases

This is just a high level abstract of our implementation in the maBrite topology generator, which is based on BRITE tool. To create a real functional topology, there are more details that need to be addressed. For example, in Step 3, we must guarantee that every non-Core AS has a path including Provider-and-Customer links to a Core AS so that this AS has full connectivity to the whole network. Furthermore, we should also guarantee that the Core ASes form a clique as observed for the Dense Cores, and additional links between Core ASes are added when necessary.

After the AS relationships are defined, the routing policy setup is straightforward. The only problem is how these policies are expressed in the simulator input Domain Model Language (DML) file. For a detailed discussion of this, the interested reader is referred to the MicroGrid user manual.

The last thing we want to emphasize is the default routing embodied in Step 6. It is very important to use default routing in Stub ASes so the huge external BGP routes need not be injected into the OSPF routing tables. This approach can reduce the overhead of Stub AS routers greatly and is widely used in real world practice.

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