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Abstract

This paper presents a new approach that uses neural networks to predict the performance of a number of dynamic decentralized load balancing strategies. A distributed multicomputer system using any distributed load balancing strategy is represented by a unified analytical queuing model. A large simulation data set is used to train a neural network using the back–propagation learning algorithm based on gradient descent. The performance model using the predicted data from the neural network produces the average response time of various load balancing algorithms under various system parameters. The validation and comparison with simulation data show that the neural network is very effective in predicting the performance of dynamic load balancing algorithms. Our work leads to interesting techniques for designing load balancing schemes (for large distributed systems) that are computationally very expensive to simulate. One of the important findings is that performance is affected least by the number of nodes, and most by the number of links at each node in a large distributed system.

1 Introduction

Advances in accurate performance models and appropriate measurement tools are driven by the demands of multicomputer system designs. Conventionally, these models and tools have been developed using analytical and simulation techniques. Though computationally inexpensive, analytical techniques alone do not always accurately represent the behavior of the system under diverse conditions. In addition, the behavior of complex systems is difficult to capture analytically. Simulations, on the other hand, are useful for analyzing complex systems but are both computationally expensive and time consuming. Neural networks have been successfully applied for modelling non–linear phenomena [3], [5], [8], [11], [12], [14], [20]. Application of neural networks for predicting the performance of multicomputer systems is our contribution to the search for new performance evaluation and prediction techniques.

The performance of multicomputer systems can be measured in terms of throughput, utilization, average task response time or interprocessor communication. The performance measure in our context is the average task response time which heavily depends on the underlying scheduling and load balancing mechanisms. In a wide range of environments, scheduling and

load balancing cannot be done statistically and has to be done *on-the-fly*. For example, certain applications having dynamic structures can result in the creation of tasks at run time [6] which cannot be determined in advance. Furthermore, tasks initially assigned to processors can spawn more sub-tasks as computation proceeds [13], [18]. Fox *et al.* [6] show that on hypercube multicomputers, dynamic load balancing is useful for a number of problems such as event–driven simulations, adaptive meshes, many particle dynamics, searching of game trees in parallel chess programs, or simulation of neural networks with time dependent non–uniform activity. The response times of tasks can be considerably improved by migrating load from busy processors to idle processors. Dynamic load balancing is also essential for distributed computing environments such as workstation–based networks, where regular jobs can be migrated from a busy workstation to an idle workstation [10], [19]. In a study conducted for cluster of 70 Sun workstations, it was observed that one third of the workstations were idle, even at the busiest times of the day [21]. In a real–time environment, where periodically generated tasks need to be migrated from one node to another in order to meet critical deadlines, dynamic load balancing can improve the deadline missing probability.

As opposed to static scheduling techniques, dynamic scheduling [1]strategies do not assume availability of a priori knowledge of tasks. Due to timing constraints, a dynamic scheduling algorithm needs to be fast enough to cope with time dependent fluctuations. The second feature that distinguishes dynamic task scheduling from static scheduling problems is that the notion of time is taken into consideration, that is, dynamic task scheduling acts according to the time–dependent state of the system. Dynamic load balancing strategies are centralized [9], decentralized [4], [11], [15], [19], or a combination of both [1]. Decentralized load balancing strategies have been classified into two categories: sender–initiated and receiver–initiated [23]. In a sender–initiated algorithm, the requests to transfer load are originated by heavily loaded nodes whereas an algorithm is said to be server–initiated if the requests are generated by lightly loaded nodes. Load balancing schemes can be classified further depending upon the system architecture: homogeneous or heterogeneous [17].

Given the diversity of load balancing strategies proposed in the literature and their de-

1. Dynamic load balancing has also been referred to as equalizing the workload whereas terms such as load sharing or load distribution, have been used to describe the process of load redistribution. However, in this paper, we use these terms without distinction. We also use dynamic scheduling and dynamic load balancing interchangeably.

pendence on a number of parameters, it is difficult to compare their effectiveness on a unified basis. In a previous study [2], we proposed an approach to predict and compare the performance (average response time) of different load balancing schemes on a unified basis, using simulation, statistics and analytical models. This paper presents an approach to predict the performance of different load balancing schemes using a new technique. The proposed approach, which uses neural networks, takes into account various system parameters such as system load, task migration time, scheduling overhead and system topology, that can affect performance. We show that load balancing strategies, belonging to the sender–initiated class, can be modelled by a central-server queuing network. Through extensive simulation, a large number of values of the average queue length and the probability associated with task migration have been obtained. A neural network has been trained using the simulation data to model the relation between the queuing parameters and the system parameters. We have employed the back–propagation learning algorithm based on gradient–descent, to train our neural network. The network is then used to predict the response time of a system with any set of parameters, for a given load balancing strategy. Using the proposed performance evaluation approach, six load balancing algorithms have been modeled. We have compared the response time predicted by the model with the response time produced by simulation. The validation and comparison with simulation data show that the neural network is very effective in predicting the response time for dynamic load balancing. The neural network is then used to predict the response time for very large systems.

2 Modeling with Neural Networks

Neural networks belong to the class of data–driven approaches, as opposed to model–driven approaches. The analysis depends on available data, with little rationalization about possible interactions. Relationships between variables, models, laws and predictions are constructed post–facto after building a machine whose behavior simulates the data being studied. The process of constructing such a machine based on available data is addressed by certain general–purpose algorithms such as ‘back–propagation’.

Artificial neural networks are computing systems containing many simple non–linear computing units or nodes interconnected by links. In a ‘feed-forward’ network, the units can be partitioned into layers, with links from each unit in the *k*–th layer being directed (only) to each

unit in the *(k*+1*)*–th layer. Inputs from the environment enter the first layer, and outputs from the network are manifested at the last layer. A *d*–*n*–1 network, shown in Figure 1, refers to a network with *d* inputs, *n* units in a single intermediate 'hidden' layer, and one unit in the output layer [24]. As we mention in the subsequent discussion, we train the neural network for learning an output versus a number of input. For example, if the neural network is trying to learn an output Y, as a function of x_1, x_2, x_3, then it would have 3 inputs and one output. The number of hidden nodes to be chosen depends on the application. We have varied them from 3 to 5 and found that best results are obtained for the number of hidden nodes equal to 4. A weight or 'connection strength' is associated with each link, and a network 'learns' or is trained by modifying these weights, thereby modifying the network function which maps inputs to outputs.

We use such *d*–*n*–1 networks to learn and then predict the behavior of dynamic load balancing algorithms. Each hidden and output node realizes a non–linear function of the form:

$$f(x_1, x_2, \ldots, x_m) = \frac{1}{1 + e^{-\sum_{1 \le i \le m} w_i x_i + \Theta}},$$

where w_i's denote real–valued weights of edges leading into the node, θ denotes the adjustable 'threshold' for that node, and *m* denotes the number of inputs to that node from nodes in the previous layer.

We use the error back–propagation algorithm of Rumelhart *et al.* [16], based on gradient–descent, to train the networks, with the goal of minimizing the mean squared deviation between the desired target values and network outputs, averaged over all the training inputs. The training phase can be described as follows. In each step in the training phase, a *d*–tuple of inputs is presented to the network. The network is asked to predict the output value. The error between the value predicted (by the network) and the value actually observed (known data) is then measured and propagated backwards along the connections. The weights of links between units are modified by different amounts, using a technique which apportions 'blame' for the error to various nodes and links. A single 'epoch' (cycle of presentations of all training inputs) comprises applying all input patterns once and modifying the weights after each step. If the mean squared error exceeds some small predetermined value, a new epoch is started after termination of the current epoch.

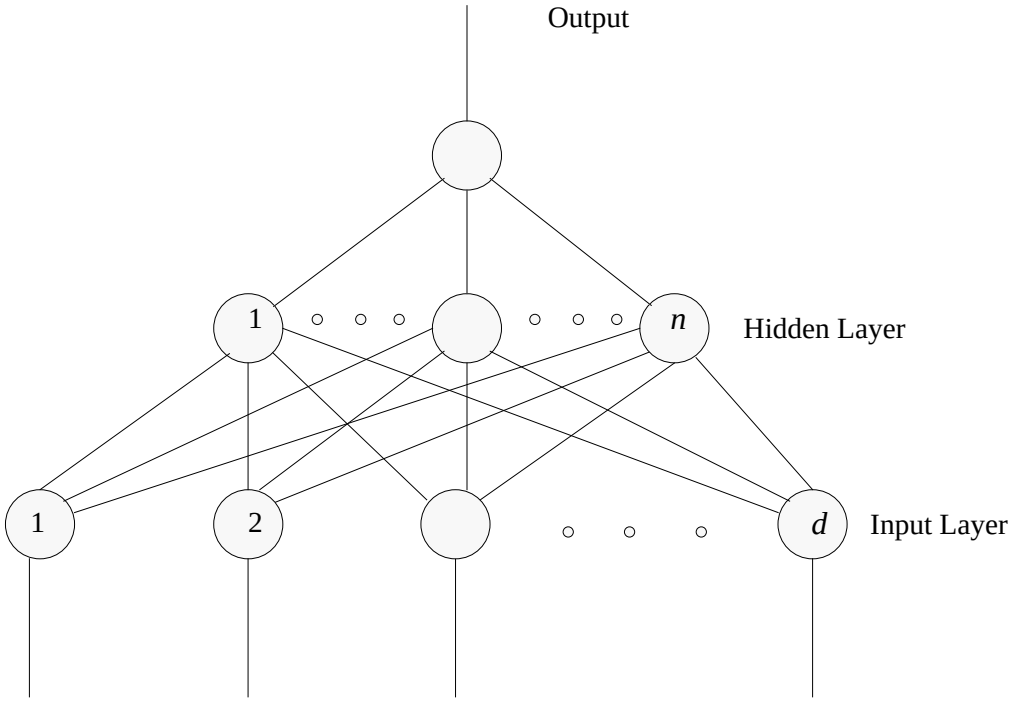

Figure 1: A *d*–*n*–1 feed-forward neural network.

Learning is accomplished by the following rule that indicates how the weight of each connection is modified.

$$\Delta W_{ji}(n+1) = \eta(\delta_{pj} O_{pj}) + \alpha \Delta W_{ji}(n),$$

The parameters of the back–propagation algorithm are the 'learning rate' (η) and 'momentum' (α), which roughly describe the relative importance given to the current and past error values in modifying connection strengths. Here, n is the time index, W_{ji} is the weight from unit i to unit j, p is an index over the cases (input samples), and δ_{pj} is the propagated error signal seen at unit j in case p, and O_{pj} is the output of the corresponding unit. For the sigmoid activation function, where

$$O_{pj} = \frac{1}{1 + exp(-\sum_i W_{ji} O_{\pi} - \theta_j)},$$

the error signal is given by

$$\delta_{pj} = (t_{pj} - O_{pj})\, O_{pj}\, (1 - O_{pj}),$$

for an output unit, and

$$\delta_{pj} = O_{pj}\, (1 - O_{pj}) \sum_{k} \delta_{pk} W_{kj},$$

for a hidden unit where t_{pj} is the j–th element of the target for p–th input pattern.

3 Characterizing Distributed Load Balancing

We consider multicomputer systems that consist of homogeneous processing nodes connected with each other through a symmetric topology, i.e., each node is linked to the same number of nodes. The number of links per node, L, is called the degree of the network. We assume that the task arrival process is Poisson and tasks are submitted to each node with an average arrival rate of λ tasks per time–unit at each node. When a task arrives at a node, it is either scheduled to the local execution queue or migrated to one of the neighbors connected with it via a communication channel. Information gathering and scheduling takes a certain amount of time, which is assumed to be exponentially distributed with an average of $1/\mu_s$ time–units. A communication server at each link of a node transfers a task from one node to another with an average of $1/\mu_c$ time–units. The task communication time is also assumed to be exponentially distributed. At each node, incoming traffic from other nodes joins locally generated traffic, and all traffic is handled with equal priority. Each node maintains an execution queue in which locally scheduled tasks are served by a CPU on the FCFS basis. The load of a node is expressed in terms of the length of the execution queue. Execution time is also assumed to be exponentially distributed with an average of $1/\mu_E$ time–units. Table 1 describes the meanings of a number of symbols used in this paper.

3.1 Load Balancing Strategies

In general, a load balancing strategy consists of three policies [4]: transfer policy, location policy and information collection policy. A transfer policy determines whether a task should be migrated or not. A location policy sets a criterion to select a node if the task is to be

Table 1: Symbols and their meanings.

Symbol	Meaning
λ	External arrival rate at each node
μ_S	Average task scheduling rate
μ_E	Average task execution rate
μ_C	Average task migration rate
ρ	Average load on each node
$E[N_E]$	Average execution queue length
T_u	Load information update period
P_0	Probability of scheduling task locally
P_j	Probability of migration task to j-th neighbor
$E[R]$	Average cumulative task response time
$E[R_{phase1}]$	Average task response time in the first phase
$E[R_{phase2}]$	Average task response time in the second phase

migrated. An information policy decides how information exchange among different nodes is carried out. We have analyzed six sender–initiated distributed load balancing schemes using different transfer, location and information exchange policies. In the first three load balancing strategies, information about the load and the status of other nodes is collected at the time a task is scheduled for execution or migration. In the last three strategies, nodes exchange load information with their neighbors after every (fixed) period of time. The names of strategies are prefixed by *F* and *P*, denoting *Fresh* and *Periodic* information exchanges, respectively; these strategies are explained below.

- ***FRandom:*** In this strategy, the task scheduler calculates the average of the local load and the load of all neighbors. If the local load exceeds the average, the task is sent to a randomly selected neighbor.
- ***FMin:*** In this strategy, the task scheduler first selects the neighbor with the least load. The task is transferred to that neighbor if the difference between the local load and load of

that neighbor exceeds a certain threshold (threshold is 1 in our experiments). The local node is given priority, since migrating a task to a neighbor incurs communication and scheduling delays.

- ***FAverage:*** In this strategy, the task scheduler calculates the average of all neighbors' load and its own load. If the local load exceeds the average, the task is sent to the neighbor with the minimum load. Otherwise, the task is sent to the local execution queue.
- ***PRandom:*** This strategy is similar to *FRandom* except that information is exchanged periodically.
- ***PMin:*** This strategy is similar to *FMin* except that information is exchanged periodically.
- ***PAverage:*** This strategy is similar to *FAverage* except that information exchange is periodic.

3.2 Analytical Modeling

First, we show how the class of distributed load balancing strategies described above can be modeled by an open network central server queuing model. When a task migrates from one node to another, it enters a statistically identical node. Therefore, the steady–state behavior of nearest neighbor load balancing can be approximated by the central-server open queuing model. A distributed multicomputer system consisting of 16–node hypercube topology, with distributed load balancing, is illustrated in Figure 2. Here, each node of the system can be represented by a central-server open queuing network. As described in the next section, simulation results obtained on actual network topologies are very close to the analytical results determined from this model, validating that the proposed model of Figure 2 indeed represents the task scheduling and migration process. The model consists of a waiting queue, L communication queues and an execution queue.

The duration of a task's residence time in the system consists of two phases. In the first phase, the task may repeatedly migrate: it waits in the waiting queue, gets service from the scheduler, waits in the communication queue, and then transfers to another node. At that point, the same cycle may start all over again. In the first phase, each task can be viewed as occupying either the task scheduler or one of the communication links. Once the task is scheduled at the

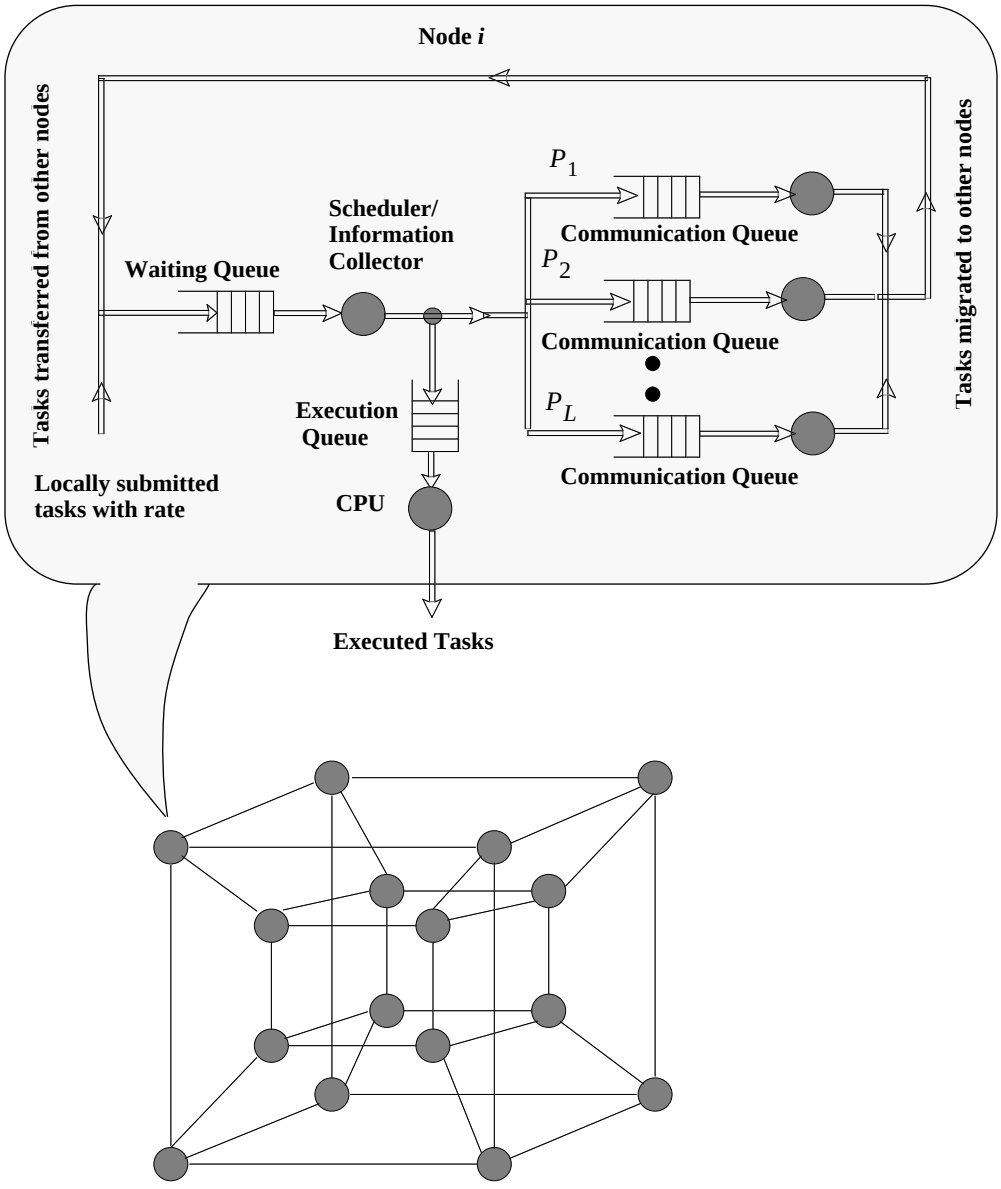

Figure 2: A multicomputer system connected in a 16–node hypercube topology; each node is represented by open network central-server queuing model.

execution queue of a node, the second phase starts, which includes the queuing and service time at the CPU. It follows that the open central server model can be solved by the Jacksonian network [22], which has the product form solution; the joint probability of k_j tasks at queue j (j = 0, 1, . . ., L) is given by the product:

$$p(k_1, k_2, \ldots, k_L) = \prod_{j=0}^{L} p_j(k_j),$$

where $p_j(k_j)$ is the probability that k_j tasks are at the j–th queue, given by:

$$p(k) = (1 - \rho_j)\,\rho_j^{k_j}$$

For the j–th component, the average utilization, ρ_j, is equal to λ_j/μ_j. The equation implies that the lengths of all queues are mutually independent in a steady state. The average queue length and the average response time are given by:

$$E[N_j] = \frac{\rho_j}{1 - \rho_j},$$

and

$$E[R_j] = \frac{\rho_j}{\lambda_j(1 - \rho_j)},$$

respectively.

The average number of tasks at a node is the sum of the average number of tasks at each component of a node and is given by

$$E[N] = \sum_{j=0}^{L} E[N] = \sum_{j=0}^{L} \frac{\rho_j}{1 - \rho_j},$$

from which the average response time before the task is scheduled in the execution queue can be computed as:

$$E[R_{phase1}] = \frac{1}{\lambda} \sum_{j=0}^{L} \frac{\rho_j}{1 - \rho_j} = \frac{(P_0\mu)^{-1}}{1 - \lambda(P_0\mu)^{-1}} + \sum_{j=1}^{L} \frac{P_j(P_0\mu_j)^{-1}}{1 - \lambda P_j(\mu_j P_0)^{-1}},$$

where λ_0 is replaced by λ/P_0 and $\lambda\,(j \geq 1)$ is replaced by $\lambda P_j/P_0$. Once a task is scheduled

at a local execution queue, the response time is given by:

$$E[R_{phase2}] = \frac{E[N_E]}{\lambda} \leq 1.0,$$

where $E[N_E]$ is the average execution queue length. The complete response time, therefore, is:

$$E[R] = E[R_{phase1}] + E[R_{phase2}]$$

The above equation implies that, for a given load, $(\rho = \lambda/\mu_E)$, μ_0 and μ_j's, the response time yielded by a load balancing strategy can be calculated if P_0 and $E[N_E]$ are known. Here, P_0, is the probability with which a load balancing strategy schedules the tasks locally, and $E[N_E]$ is the average execution queue length. For clarity, we replace μ_0 by μ_S, representing the average task scheduling rate. We also assume that μ_j's for each link are the same and the average communication rate is represented by μ_C.

3.3 Simulation Environment

The above mentioned load balancing strategies were simulated. Our simulator, which is of discrete-event type, takes as input the topology of the network along with λ, μ_S, μ_C, μ_E, length of simulation run, and choice of load balancing strategies and their associated parameters. Simulation can be run by using different sets of random number streams. Initial transients in the simulation are removed by ignoring the initial outputs until the system enters into a steady state. Each data point is produced by taking the average of a large number of independent simulation runs and then by taking their means. The confidence interval for each data point has been obtained with 99% confidence interval and the width of the interval is within 5% of the mean values.

A number of simulations were conducted to obtain 500 data values for P_0 and $E[N_E]$, for each strategy. Three different topologies have been selected, including the ring (L = 2), the 16–node hypercube (L = 4) and the 16–node folded hypercube (L = 5) [7]. Points for one particular strategy are obtained for each topology by fixing one parameter and varying the rest. In most cases, λ is varied from 0.3 to 0.9 tasks per time–unit, and μ_C is varied from 8 to 16 task per time–unit. We assume that the average task execution rate, μ_E, is 1 task per time unit. Instead of the actual load $(\rho = \lambda/\mu_E)$, this enables us to consider λ as the parameter represent-

ing load per node. For strategies that require periodic information update, the update time period, T_u, is varied from 0.5 to 1.5 time units. The scheduling overhead includes the exchange of state information and the execution of the scheduling algorithm itself. We have assumed an average scheduling time, $1/\mu_S$, which in turn, can be normalized with respect to the execution time, $1/\mu_E$. In other words, when μ_S is 10 tasks/time–unit and μ_E is 1 task/time–unit, the average task scheduling time is 1/10 of the execution time. For the simulation data, μ_S is varied from 8 to 16 tasks per time unit. Since we simulated the actual interconnection network topologies, mentioned above, and not the central server model shown in Figure 2, P_0 and $E[N_E]$ were observed from the simulation data. The probability, P_0, is estimated by dividing the average number of locally scheduled tasks by the total number of tasks arrived, at each node.

4 Results

In this section, we present the results showing the average response time predicted by the analytical model based on the values of P_0 and $E[N_E]$ predicted by the neural network. For the experiments described in this paper, the learning rate and momentum were varied to train the network to give small mean squared error. For the modeling of probability, we used a network with no hidden layer. For the estimation of queue length a network with one hidden layer was used. The number of hidden nodes was varied; the best results were obtained for 4 hidden nodes. Table 2 gives the root mean square errors in P_0 and $E[N_E]$, between neural network

Table 2: The root mean square error between simulation and neural network in Modeling P_0 and $E[N_E]$.

Strategy	P_0	$E[N_E]$
FRandom	0.4705	3.6200
FMin	0.0654	0.9355
FAverage	0.1486	0.7733
PRandom	0.1358	0.3139
PMin	0.1354	0.5357
PAverage	0.3636	0.4053

results and simulation data. As can be seen the error yielded by the neural network is less than 0.5 for P_0 and less than 0.1, in most cases, for $E[N_E]$.

Using the values of P_0 and $E[N_E]$ predicted by the neural network, the average response time is calculated through the queuing model and is compared with the observed simulation results. We have divided these results in three parts: training, testing and prediction.

Table 3: Average response times obtained by the neural network for the six strategies, at low, medium, and high loading conditions, on a 16–node hypercube topology.

Load	Strategy	Simulation	Neural Net.	Difference%
λ = 0.4 (Low)	FRandom	1.243	1.277	2.73
	FMin	1.403	1.403	0.03
	FAverage	1.186	1.193	0.62
	PRandom	1.239	1.259	–1.61
	PMin	1.412	1.480	4.82
	PAverage	1.214	1.292	6.35
λ = 0.6 (Medium)	FRandom	1.515	1.545	4.40
	FMin	1.585	1.534	–3.25
	FAverage	1.378	1.348	–2.19
	PRandom	1.514	1.496	–1.15
	PMin	1.624	1.598	–1.62
	PAverage	1.475	1.401	–4.97
λ = 0.8 (High)	FRandom	2.056	2.165	5.35
	FMin	1.965	2.083	6.04
	FAverage	1.802	1.929	7.04
	PRandom	2.048	2.085	1.82
	PMin	2.080	2.123	2.09
	PAverage	1.974	1.986	–0.64

4.1 Training

The results presented in this section are those in which the response time predicted by the neural network is compared with the same simulation cases through which empirical data for training was obtained. In other words, when we obtained the training data P_0 and $E[N_E]$ through simulation, we also measured the corresponding simulation response times. These sim-

Table 4: Average responses time obtained by the neural network for the six load balancing strategies, at low, medium, and high loading conditions, on a 16–node ring topology.

Load	Strategy	Simulation	Neural Net.	Difference%
λ = 0.4 (Low)	FRandom	1.318	1.254	–4.85
	FMin	1.437	1.375	4.30
	FAverage	1.263	1.226	–2.96
	PRandom	1.318	1.366	3.66
	PMin	1.452	1.588	9.40
	PAverage	1.290	1.377	6.73
λ = 0.6 (Medium)	FRandom	1.641	1.531	–6.70
	FMin	1.708	1.685	–1.32
	FAverage	1.528	1.478	–3.26
	PRandom	1.638	1.658	1.22
	PMin	1.752	1.769	0.98
	PAverage	1.576	1.529	–2.97
λ = 0.8 (High)	FRandom	2.388	2.577	7.94
	FMin	2.276	2.418	6.23
	FAverage	2.094	2.229	6.41
	PRandom	2.357	2.270	–3.69
	PMin	2.382	2.311	2.99
	PAverage	2.158	2.086	–3.33

ulation response times are then compared with those predicted by the neural network. The objective behind these comparisons is to validate that the average response time can indeed be expressed in terms of P_0 and $E[N_E]$, and to demonstrate that the neural network has been accurately trained.

First, we examine the impact of different loading conditions on the response time, as shown in Table 3. The task scheduling rate, μ_S, and the task communication rate, μ_C, are both chosen to be 16 tasks/time–unit. System topology selected for this case is a 16–node hypercube network and load update period, T_u, is set to 0.5 time–units. For all load balancing strategies, there is very little difference in the response times computed from the neural network and the response time observed from simulation. The differences in the results obtained through the model and simulation are sometimes positive and sometimes negative, implying that the neural network does not have special statistical bias in any direction. Similar observations can be made

Table 5: Average response times obtained by neural network technique for the six load balancing strategies, at low, medium, and high loading conditions, on a 16–node folded hypercube topology.

Load	Strategy	Simulation	Neural Net.	Difference%
λ = 0.4 (Low)	FRandom	1.225	1.297	5.92
	FMin	1.396	1.432	2.55
	FAverage	1.174	1.182	0.71
	PRandom	1.224	1.221	0.29
	PMin	1.408	1.441	2.32
	PAverage	1.202	1.259	4.69
λ = 0.6 (Medium)	FRandom	1.484	1.437	–3.11
	FMin	1.561	1.508	3.41
	FAverage	1.342	1.301	–3.01
	PRandom	1.481	1.431	–3.42
	PMin	1.600	1.529	–4.43
	PAverage	1.464	1.355	–7.46
λ = 0.8 (High)	FRandom	1.994	2.036	2.10
	FMin	1.906	1.961	2.89
	FAverage	1.755	1.803	2.97
	PRandom	1.990	2.002	0.62
	PMin	2.040	2.043	0.12
	PAverage	1.975	1.939	–1.81

about the results in Table 4 and Table 5, with the same set of parameters except that the network topologies have been changed to a 16–node ring and a 16–node folded hypercube, respectively.

4.2 Testing

The validity of the proposed model is more strongly established if we obtain response time from the neural network and compare it with the independent simulation data. This simulation data was not been used in training. We present these results first for a 32–node hypercube network, given in Table 6. A system load of 0.7 is selected while T_u is 1.0. To capture the effects of scheduling and communication overheads, we vary μ_S and μ_C, but keep the rest of the parameters fixed. We consider three different conditions associated with communication and scheduling overheads. First slow communication and fast task scheduling rate(μ_C= 4 tasks/time–units and μ_S = 16 tasks/time–units) are selected. Then we consider fast communication and fast task scheduling rates (μ_C = 16 tasks/time–units and μ_S = 16 tasks/time–units). Finally,

Table 6: Effects of communication and scheduling overheads on the average response times on a 32–node hypercube topology.

Parameters	Strategy	Simulation	Neural Net.	Difference%
Slow communication and fast scheduling rate $\mu_C = 4.0$ $\mu_S = 16.0$	FRandom	1.806	1.783	–1.28
	FMin	1.731	1.697	–2.00
	FAverage	1.615	1.546	–4.29
	PRandom	1.686	1.681	–0.29
	PMin	1.747	1.721	–1.49
	PAverage	1.670	1.602	–4.10
Fast communication and fast scheduling rate $\mu_C = 16.0$ $\mu_S = 16.0$	FRandom	1.625	1.586	2.43
	FMin	1.646	1.633	–0.80
	FAverage	1.448	1.451	–0.96
	PRandom	1.619	1.608	–0.66
	PMin	1.715	1.693	–1.26
	PAverage	1.590	1.530	–3.76
Fast communication and slow scheduling rate $\mu_C = 16.0$ $\mu_S = 4.0$	FRandom	2.218	2.168	–2.26
	FMin	2.034	1.989	–2.19
	FAverage	2.030	1.898	–6.51
	PRandom	2.262	2.268	0.26
	PMin	2.144	2.085	–2.77
	PAverage	2.390	2.191	–8.34

a combination of fast communication and slow task scheduling rate (μ_C = 16 tasks/time–units and μ_S = 4 tasks/time–units) is selected. As can be seen from the table, the response time predicted using the neural network is not affected by the choices of μ_C and μ_S. The neural network is shown to predict the average response time, which closely matches the response time produced by simulation, for any combination of system parameters. One can also notice that task scheduling rate, μ_S, has greater impact on the response time of a task than the task communication rate, μ_C. This can be explained by observing that the scheduler acts as single server that can become a bottleneck in scheduling a task. On the other hand, there are multiple servers at the communication links which reduce the network contention. In order to test the neural network for different network topologies, we present two more test cases. These include an 8–node fully connected network (L = 7) and an 8–node hypercube (L = 3). The results, shown in Table 6 and 7, indicate that the neural network is able to capture the topological differences.

Table 7: Average response times for two additional test cases.

Parameters	Strategy	Simulation	Neural Net.	Difference
λ = 0.7 μ_C = 16.0 μ_S = 16.0 T_u = 0.5 topology = 8–node fully connected	FRandom	1.586	1.542	–2.77
	FMin	1.658	1.561	–5.89
	FAverage	1.451	1.381	–4.33
	PRandom	1.547	1.466	–5.25
	PMin	1.747	1.721	–1.49
	PAverage	1.705	1.630	–4.42
λ = 0.7 μ_C = 16.0 μ_S = 16.0 T_u = 1.0 topology = 8–node hypercube	FRandom	1.725	1.740	0.84
	FMin	1.790	1.788	–0.16
	FAverage	1.598	1.614	1.04
	PRandom	1.656	1.773	8.16
	PMin	1.828	1.849	1.19
	PAverage	1.656	1.672	1.01

4.3 Prediction

Since performance evaluation of distributed load balancing strategies through simulation is practically not feasible for very large systems, we can use the proposed performance model to evaluate the impact of system size on the average response time. An important conclusion reached through our neural network model is that the number of nodes in the system does not have great impact on the performance, given that the average load (ρ) on each node is the same. Instead, the number of communication links incident on each node significantly influences the performance of a nearest neighbor load balancing strategy. In other words, different network topologies with the same degree, *L*, may yield close performance. For instance, a hypercube network with 128–node yields the same performance as a 8–node fully connected network (since *L* for both networks is equal to 7).

The results presented in this section show how the degree of a network, *L*, can affect the response time of a load balancing strategy. Figure 3 shows the average response times obtained with *FRandom, FMin and FAvergae.* Here *L* has been varied from 2 to 40, both μ_S and μ_C are equal to 20 tasks per time–unit while λ is 0.7. We notice that the performance of *FRandom* strategy is highly dependent on the number of links at a node. The response time decreases if the number of links is initially increased from two to 10, and then sharply increases if the number

of links is increased beyond 10. This variation in response time is due to the fact that if the number of links is very small, the scheduler has less number of choices to schedule a task. Consequently, on the other hand, with very large number of links, the scheduler has too many choices which increases the probability of sending a task to an unsuitable node. Sending a task to a wrong node can result in re-migration of the task. Excessive number of migrations of tasks can cause the system to enter into a task-thrashing state where more tasks are migrated than are actually executed. This implies that the minimum response time is obtained when the number of links is neither very large nor very small. For example, Figure 3 indicates that this minimum occurs when L is10 for *FRandom*. It must be noted that this minimum may change if other parameters such as λ, μ_S, and μ_C are changed. Figure 3 also shows that *FMin* and *FAverage* initially exhibit a decrease in the response time if the number of links are increased; response time decreases to a minimum, before increasing again. For example, for *FAverage*, the minima occurs when L is12. For values of L beyond these minima, the response time shows an exponentially increasing behavior. Similarly, the performance of *FMin* initially improves, reaching

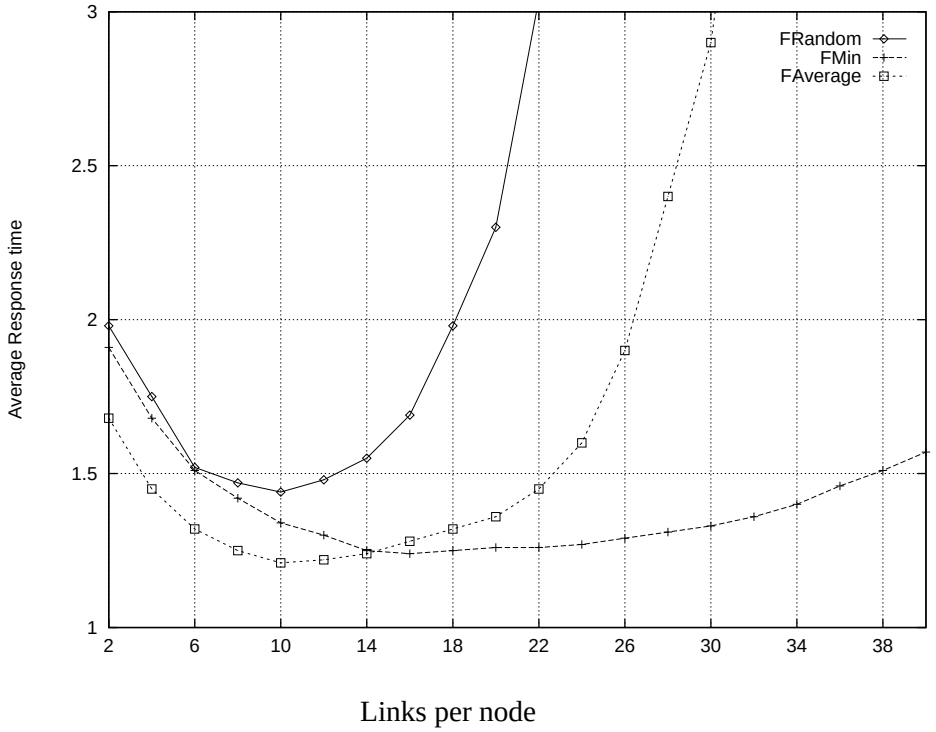

Figure 3: The average task response times versus links per node for fresh information update strategies.

minima when *L* is 18 through 34, before it starts increasing again.

Although these three strategies exhibit similar behavior, the rate at which average response time increases (as we increase the value of *L* beyond minima) is rather slow for *FMin.* This indicates that even though thrashing can happen if we increase *L*, it does not hamper the performance of *FMin* as severely as in the case of the other two strategies. The reason is that *FMin* is a very conservative scheme, where the decision to transfer a task to a neighboring node is made by using precise information in the best possible manner (selecting the least loaded neighbor). On the other hand, the information averaging method used in *FRandom* increases the level of uncertainty and reduces its ability to make the best decision. This is due to the fact that with the increase in number of neighbors, the amount of state information increases. The increase in state information, in turn, can make the information less accurate.

The performance of periodic update strategies, *PRandom*, *PMin* and *PAverage* is shown

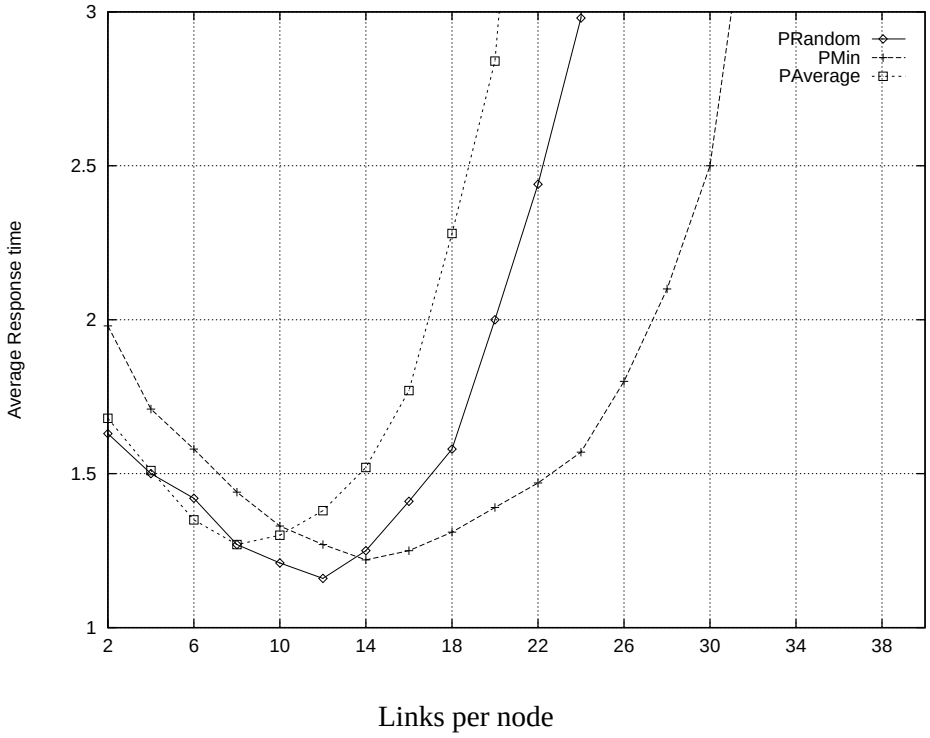

Figure 4: The average task response times versus links per node for periodic information update strategies.

in Figure 4. Here we notice that these strategies exhibit the same behavior as non-periodic update strategies. This is due to the same reasons as described above for fresh information update strategies. The difference is that here an additional parameter, T_u, can also affects the behavior of the response time curves for periodic information update strategies. If T_u is decreased, the curves shown in Figure 4 are expected to shift to the right, indicating some improvement in performance. This is due to the fact that smaller values of T_u result in more recent and reliable information.

The results produced by the neural network and confirmed by the simulation lead to an interesting design aspect of decentralized load balancing schemes for very large distributed systems which are computationally very expensive to simulate. We notice from Figures 3 and 4 that for a given set of values of λ, μ_S, μ_C, and T_u, we can always find the best value of L. In order to find optimal values for the parameters, the minimum value of $E[R]$ in equation (1) needs to be re-evaluated, giving an expression that relates other parameters. For example, in the case of periodic strategies, the average response time will decreases further if μ_S and μ_C are increased, for a given λ and the best value of L. On the other hand, in the case of fresh strategies, the average response time also depends on T_u.

Conclusions

We presented a new approach to model the performance of several distributed dynamic load balancing algorithms in a multicomputer environment. The response time predicted by the neural network closely approximates the response time obtained through simulation. Our performance evaluation methodology accurately determines the variations in performance of all algorithms with a wide range of system parameters. Generalization ability of the neural networks helps in successfully analyzing the performance of very large systems. The neural network model is an effective tool for modeling the performance of dynamic load balancing algorithms. The study has also revealed a number of future research problems. For example, one can consider the nodes in the system to be heterogeneous instead of homogeneous. Furthermore, one can consider an environment where tasks are initially submitted to a node from L different links rather than a single queue. However, these assumption will require new analysis of the central-server queuing model.

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