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ADAPT: A Framework for Coscheduling Multithreaded Programs

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Since multicore systems offer greater performance via parallelism, future computing is progressing towards use of multicore machines with large number of cores. However, the performance of emerging multithreaded programs often does not scale to fully utilize the available cores. Therefore, simultaneously running multiple multithreaded applications becomes inevitable to fully exploit such machines. However, multicore machines pose a challenge for the OS with respect to maximizing performance and throughput in the presence of multiple multithreaded programs. We have observed that the state-of-the-art contention management algorithms fail to effectively coschedule multithreaded programs on multicore machines. To address the above challenge, we present ADAPT, a scheduling framework that continuously monitors the resource usage of multithreaded programs and adaptively coschedules them such that they interfere with each other's performance as little as possible. In addition, it adaptively selects appropriate memory allocation and scheduling policies according to the workload characteristics. We have implemented ADAPT on a 64-core Supermicro server running Solaris 11 and evaluated it using 26 multithreaded programs including the TATP database application, SPECjbb2005, programs from Phoenix, PARSEC, and SPEC OMP. The experimental results show that ADAPT substantially improves total turnaround time and system utilization relative to the default Solaris 11 scheduler.

Categories and Subject Descriptors: D.4.1 [**Process Management**]: Scheduling, Threads; D.4.8 [**Performance**]: Monitors, Measurements

General Terms: Coscheduling, Performance, Measurement, Algorithms

Additional Key Words and Phrases: Multicore, Lock-contention, Cache miss-rate, Fairness

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1. INTRODUCTION

The advent of the multicore architecture provides an attractive opportunity for achieving high performance for a wide variety of multithreaded programs. The performance of a multithreaded program running on a multicore machine often does not scale with the number of cores. Therefore, to fully exploit a machine with a large number of cores, it becomes inevitable that we simultaneously run multiple multithreaded programs. However, coscheduling multithreaded programs effectively on such machines is a challenging problem because of their complex architecture [Boyd-Wickizer et al. 2009; Peter et al. 2010]. For effective coscheduling of multithreaded programs, the OS must

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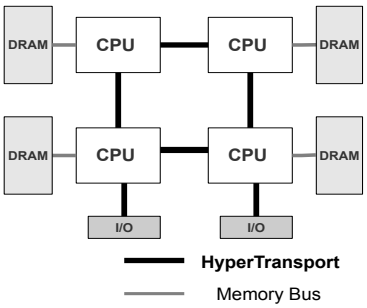
understand their resource usage characteristics and then adaptively allocate cores as well as select appropriate memory allocation and scheduling policies.

To address the above challenge, contention management techniques have been proposed [Blagodurov et al. 2011; Zhuravlev et al. 2010; Bhadauria and McKee 2010; Pusukuri et al. 2011; Knauerhase et al. 2008]. These techniques are primarily guided by the cache usage characteritics of the programs, such as the last-level cache miss-rate, and are aimed at coscheduling of multiple *single threaded* programs [Zhuravlev et al. 2010; Pusukuri et al. 2011; Knauerhase et al. 2008] or for coscheduling threads of a *single multithreaded* program [Blagodurov et al. 2011]. When considering multiple multithreaded programs, cache usage alone is not enough for effective coscheduling. In particular, we demonstrate that it is necessary to also consider *lock contention* and *thread latency* to guide coscheduling decisions. Therefore existing techniques are not effective in coscheduling multithreaded programs. Moreover, existing techniques have some additional limitations. The contention management techniques in [Blagodurov et al. 2011; Zhuravlev et al. 2010; Bhadauria and McKee 2010; Pusukuri et al. 2011; Knauerhase et al. 2008] are applicable to machines with a small number of cores and their evaluations typically use one thread per core configuration. While this configuration gives best performance for systems for machines with four or eight cores, this is not true for machines with a larger number of cores [Pusukuri et al. 2011a]. Furthermore, the performance metrics used in some of the existing techniques [Pusukuri et al. 2011] are not appropriate for coscheduling multithreaded programs [Eyerman and Eeckhout 2008]. Finally, in a realistic scenario, programs randomly enter and leave the system. Therefore, the OS must also adaptively assign process scheduling and memory allocation policies according to the resource usage characteristics of the programs along with allocating cores. However, existing techniques only consider allocation of cores.

To address the above challenges, we develop ADAPT, a framework for effectively coscheduling multithreaded programs on machines with large number of cores. ADAPT uses supervised learning techniques for predicting the effects of interference between programs on their performance and adaptively coschedules programs that interfere with each other's performance as little as possible. Moreover, using simple performance monitoring utilities available on a modern OS, it adaptively allocates cores as well as assigns appropriate memory allocation and scheduling policies according to the resource usage characteristics of the multithreaded programs. We have implemented ADAPT on a 64-core machine running Solaris 11 and evaluated it using 26 programs including the TATP database application [TATP. 2003], SPECjbb2005 [SPECjbb 2005], programs from PARSEC [Bienia et al. 2008], SPEC OMP [SPECOMP 2001], and Phoenix [Yoo et al. 2009]. The experimental results show that ADAPT achieves up to 44% improvement in turnaround time and also improves throughput of TATP and JBB by 23.7% and 18.4% relative to the default Solaris 11 Scheduler. The overhead of ADAPT is negligible and it is an attractive approach as it requires no changes to the application source code or the OS kernel. Furthermore, while existing techniques [Zhuravlev et al. 2010; Blagodurov et al. 2011; Bhadauria and McKee 2010; Knauerhase et al. 2008] are based on fixed heuristics, ADAPT dynamically learns appropriate contention factors and their effect on the performance of target programs on any target architecture. Therefore, we believe ADAPT will be able to evolve with changes in processor architecture and computing environment. The major contributions of this work are as follows:

— We demonstrate that coscheduling decisions must not be exclusively based upon the cache usage behavior, but rather lock contention and thread latency must also be considered.
— We develop statistical models based on supervised learning for identifying the effects of interference between programs on their performance.



(a) Our 64-core machine.

No.	Configuration	#Cores to A	#Cores to B
1	All-cores	64	64
2	Processor-set	32	32
3	Processor-set	24	40
4	Processor-set	40	24
5	Processor-set	16	48
6	Processor-set	48	16

(b) Cores-configurations.

Fig. 1: The machine has four 16-core CPUs and are interconnected with HyperTransport. Table shows the number of cores allocated to two programs A and B in different cores-configurations.

— We develop ADAPT with simple utilities available on Solaris 11. ADAPT improves the turnaround time by 21% on average and by a maximum of 44% relative to the default Solaris 11 scheduler.

The remainder of this paper is organized as follows. Section 2 describes the motivation of this work and Section 3 presents the development of ADAPT framework in detail. Section 4 describes the experimental setup and Section 5 presents the evaluation of ADAPT against a wide variety of multithreaded programs. Related work and conclusions are given in Sections 6 and 7.

2. WHY EXISTING ALGORITHMS DO NOT WORK?

In this section we demonstrate why existing contention management techniques based only on the last-level cache miss-ratio are inadequate for coscheduling multithreaded programs. For this purpose, we conducted experiments involving coscheduling of four multithreaded programs (facesim (FS), bodytrack (BT), equake (EQ), and applu (AP)) taken from the PARSEC and SPEC OMP suites on a 64-core machine running Solaris 11. We run multithreaded programs using OPT number of threads, where OPT for a multithreaded program is the minimum number of threads that give the maximum performance during a solo run on our 64-core machine. Figure 1(a) shows that the machine has four 16-core CPUs (four sockets), that is, it has a total of 64-cores. To capture the distance between different CPUs and memories, a new abstraction called *locality group* (lgroup) has been introduced in Solaris. The lgroups are organized in a hierarchy that represents the latency topology of the machine [McDougall and Mauro 2006].

The existing contention management techniques for single threaded workloads [Zhuravlev et al. 2010; Pusukuri et al. 2011] or threads of a single multithreaded program [Blagodurov et al. 2011] minimize resource contention by separating memory-intensive threads by scheduling them on different sockets or different processor-sets. A processor-set is a pool of cores such that if we assign a multithreaded program to a processor-set, then for the purpose of balancing load, the OS restricts the migration of threads across the cores within the processor-set. A program is treated as being memory-intensive if its last-level cache miss-ratio is high; otherwise it is considered to be CPU-intensive. Other application characteristics such as *lock contention* and *thread latency* are not considered by the existing contention management techniques. Here, lock contention is the percentage of elapsed time a program spends waiting for user

locks, condition-variables, etc. and thread latency is the percentage of elapsed time a program spends waiting for CPU resources, i.e., although the thread is ready to run, it is not scheduled on any core.

For effective coscheduling of multithreaded programs on a machine with large number of cores, we need to run multithreaded programs on processor-sets such that memory-hierarchy interference between them is minimized. Since number of processor-set configurations can be numerous, we identify a subset that includes those that are most suitable for coscheduling. We assume that at least one socket/CPU (16 cores) is needed to obtain good performance for a multithreaded program on our 4 socket/CPU (64 cores) machine. We derived this assumption by running 26 multithreaded programs with varying number of threads. Based upon this assumption, we have chosen five reasonable processor-set configurations shown in Figure 1(b).

In our study, in each of the coscheduled runs, we ran two multithreaded programs concurrently in two configurations: 1) all-cores configuration; and 2) processor-set configuration. In all-cores configuration we ran both programs on all the 64 cores while in processor-set configuration we ran each program on a separate processor-set to minimize interference between the programs. By default, the OS scheduler runs the programs in all-cores configuration. Here we have chosen a processor-set configuration that gives best performance in terms of TTT (smallest total turn-around time) among the five applicable processor-set configurations shown in Figure 1(b). Since, there is a maximum memory access latency gap between some CPU pairs, whenever possible, we avoid placing cores belonging to those CPU pairs in a processor-set.

2.1. Cache Miss-Ratio vs Lock-contention vs Thread Latency

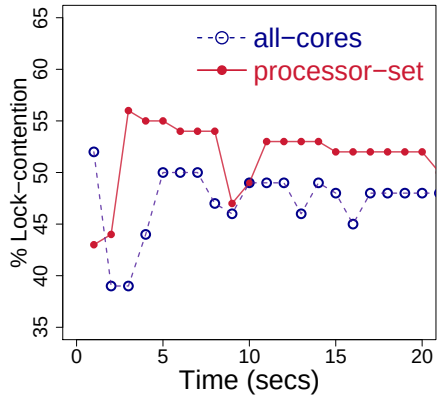
In the first coscheduling run, we run two memory-intensive multithreaded programs: facesim (FS) from PARSEC and equake (EQ) from SPEC OMP on our 64-core machine in the configurations mentioned above. The best processor-set configuration for this pair of programs is (32, 32) – each program runs in a processor-set of 32 cores. In all-cores configuration both FS and EQ share all the 64 cores. We also evaluated the existing contention management technique DINO [Blagodurov et al. 2011], a NUMA version of DI [Zhuravlev et al. 2010], for coscheduling FS and EQ. The key idea of DINO [Blagodurov et al. 2011] is to monitor cache miss-ratio of each thread and then coschedule threads that exhibit least interference with respect to memory hierarchy. It consequently reduces overall last-level cache misses per accesses (MPA)[1] and improves performance. EQ is fairly memory-intensive with solo MPA of 0.79 in comparison to FS which has solo MPA of 0.46. Moreover, different threads belonging to each program experience nearly the same MPA. Therefore, DINO separates high memory-intensive EQ threads by running them along with FS threads -- here we tried all possible combinations of FS and EQ threads on all possible processor-set configurations and chose the one that gives the best performance.

As we can see from Table I, all-cores configuration produces a high MPA, in comparison to both processor-set configuration and DINO, because of high memory-hierarchy interference between EQ and FS. However, all-cores configuration gives low Total Turnaround Time (TTT). Here TTT is the sum of turnaround times of EQ and FS in the coscheduled run. We highlight MPA in this experiment to show that why existing techniques such as DINO are not effective in coscheduling multiple multithreaded programs. This is because FS and EQ are not only memory-intensive, they are also exhibit high lock contention. Therefore, when threads of EQ and FS compete and consequently increase thread preemptions, they slow down the progress of lock-holder threads. As

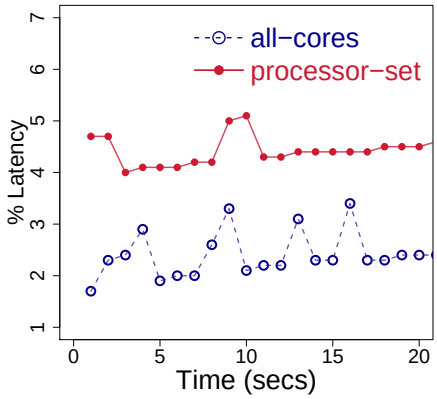
[1]We also considered cache misses per instruction (MPI), but did not observe significant difference in using between MPI and MPA.

Table I: Coscheduling of memory-intensive programs EQ and FS. All-cores provides high performance. T_{EQ} and T_{FS} are the average running times of EQ and FS. TTT = (T_{EQ} + T_{FS}).

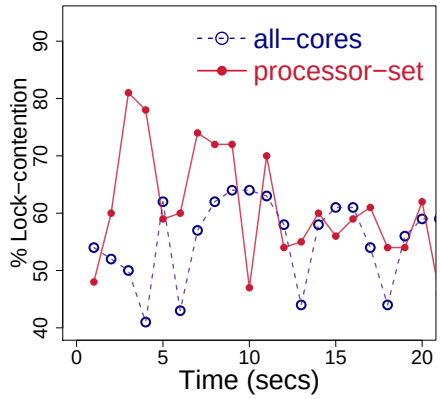
Configuration	MPA	TTT	T_{EQ}	T_{FS}
All-cores	0.78	381	141	240
Processor-set	0.69	409	158	251
DINO	0.72	436	174	262



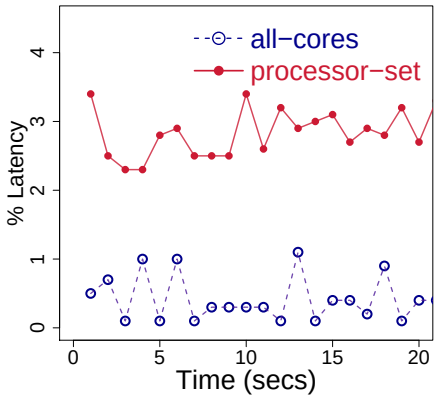
(a) Lock-contention of EQ .



(b) Latency of EQ .



(c) Lock-contention of FS.



(d) Latency of FS.

Fig. 2: Lock-contention and Latency of EQ and FS are higher in processor-set configuration.

per state-of-the-art spin-then-block contention management policy, threads waiting for locks have greater likelihood of having to block [McDougall and Mauro 2006; Johnson et al. 2010]. In all-cores configuration, due to large number of cores, the OS scheduler has a better chance of allocating CPU resources and achieving quick lock hand-offs as the lock-holder threads can complete their critical section quickly and release the lock. This leads to reduction in lock acquisition latencies [McDougall and Mauro 2006]. Figure 2 shows the lock contention and thread latency values of EQ and FS in the coscheduling run. The data is collected by monitoring the percentage of lock contention and the percentage of latency of whole programs at one second intervals. As we can see, both EQ and FS experience higher lock contention and thread latency in processor-set configuration than in all-cores configuration.

When we run two CPU intensive and high lock contention programs BT and AP, processor-set configuration provides higher performance than all-cores configuration as shown in Table II. We ran these programs in both all-cores and processor-set configurations with their respective OPT threads (50 and 24). The best processor-set configuration for BT and AP is (40, 24) -- 40 cores for BT and 24 cores for AP. This coscheduling run is very interesting as there is a trade-off between latency and lock contention, instead of MPA and lock contention that was observed in the previous coscheduling run. Since BT and AP are CPU intensive programs, MPA is not a significant consideration in their coscheduled run. Therefore, techniques presented in [Blagodurov et al. 2011; Bhadauria and McKee 2010; Knauerhase et al. 2008; Pusukuri et al. 2011; Zhuravlev et al. 2010] may not effectively deal with the coscheduling of BT and AP.

As we can see in Table II, the system run-queue length (RQ) is small in all-cores configuration compared to processor-set configuration -- RQ is the total number of runnable threads in the dispatcher queues of the system [McDougall and Mauro 2006]. Therefore, as shown in Figure 3 thread latencies (LAT) of BT and AP in all-cores configuration are low compared to processor-set configuration. However, lock contention (LOCK) for both BT and AP is high in all-cores configuration. Since BT and AP are CPU-intensive and high lock contention programs and because of their high interaction in all-cores configuration, they experience high context-switch (CX) rate [Pusukuri et al. 2011b; Johnson et al. 2010]. Here, we used DTrace scripts for measuring RQ and CX-Rate [Cantrill et al. 2004; McDougall and Mauro 2006].

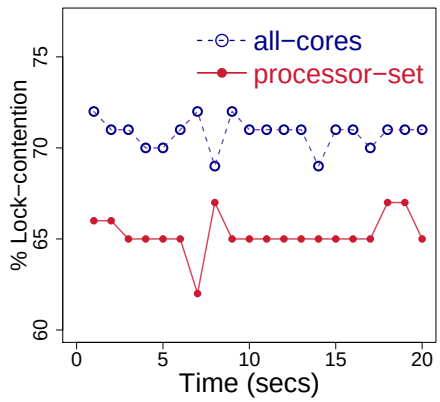
Table II: Coscheduling of CPU-intensive programs BT and AP. Processor-set provides high performance. T_{BT} and T_{AP} are the average running times of BT and AP. TTT = (T_{BT} + T_{AP}).

Configuration	TTT	RQ	CX-Rate
All-cores	116.8	1.6	75552
Processor-set	107.2	4.7	51546

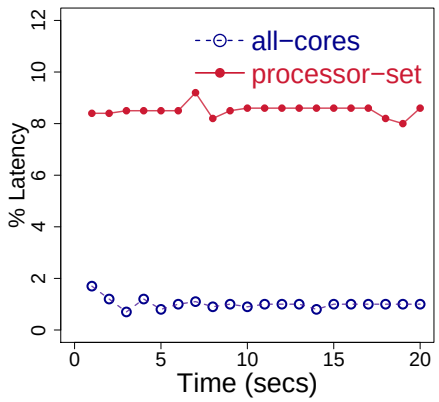
The above experiments demonstrate that MPA alone is not enough for effective coscheduling of multithreaded programs on a multicore system. The OS must consider application characteristics of lock contention and thread latency along with MPA. Based on these observations, in the next section, we present a framework called ADAPT that dynamically monitors resource usage characteristics of multithreaded programs, and based upon these, it effectively coschedules the programs.

3. THE ADAPT FRAMEWORK

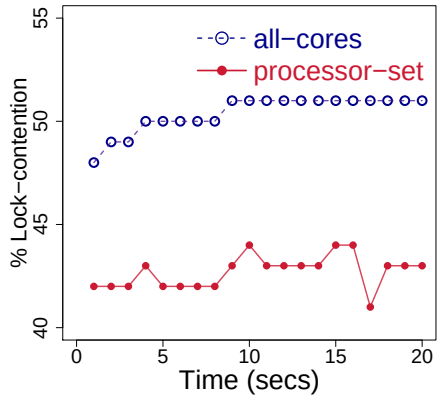
The ADAPT framework has two major components: the Cores Allocator; and the Policy Allocator. The Cores Allocator is responsible for selecting appropriate cores-



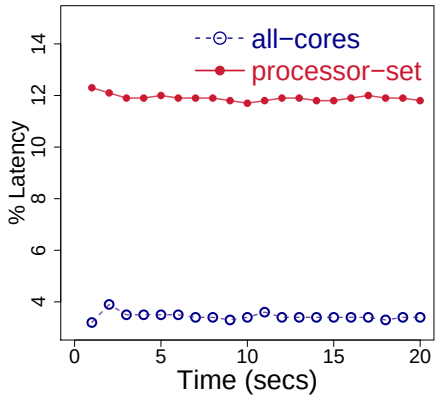
(a) Lock-contention of BT .



(d) Latency of BT.



(a) Lock-contention of AP .



(d) Latency of AP.

Fig. 3: Coscheduling of BT and AP. Thread latencies of BT and AP in all-cores configuration are low compared to processor-set configuration. However, lock contention of BT and AP are high in all-cores configuration

configuration. The Policy Allocator is responsible for adaptively applying appropriate memory allocation and scheduling policies. The following sections provide detailed description of these components.

3.1. The Cores Allocator

To capture application resource usage characteristics for effective coscheduling of multithreaded programs, the Cores Allocator uses statistical models. These models are constructed using supervised learning, where a set of sample input-output values is first observed and then a statistical model is trained to predict similar output values when similar input values are observed [Hastie et al. 2009]. The Cores Allocator uses two statistical models: one for approximating performance loss of a program due to its coscheduling with another program; and another for approximating performance of a

Table III: Initial predictors and the target *usr_ab* of the PAAP model. The goal is to predict *usr_ab* of program *a* when it is running with program *b* and vice-versa.

Predictor	Description
mpa_x	average last-level cache miss ratio of program x.
usr_x	the percentage of elapsed time program x spends in user mode.
sys_x	the percentage of elapsed time program x spends in processing system calls, system traps, etc.
lat_x	latency of program x.
lock_x	lock contention of program x.
ct_x	cores to threads ratio of program x, i.e., (#cores / #threads of x).
usr_ab	the percentage of elapsed time program *a* spends in user mode when it is running with program *b*.

program when we change the configuration from processor-set to all-cores configuration, and vice-versa. Let us call the first model as **PAAP** (**P**erformance **A**pproximation of a program when it is running with **A**nother **P**rogram) and the second model as **PACC** (**P**erformance **A**pproximation of a program when it is running with different **C**ores **C**onfiguration). Using the PAAP model, Cores Allocator predicts average performance of a program in all-cores configuration, and using the PACC model, it predicts average performance of a program in the five different processor-set configurations listed in Figure 1(b). Then it chooses the configuration that gives the best average performance.

To develop the models we proceed as follows. To cover wide range of resource usage characteristics, we categorize the programs as memory intensive, CPU intensive, high lock contention, or low lock contention programs. To develop the models we selected 12 programs from a total of 26 such that a few of programs were chosen from each category. The chosen programs include: bodytrack, facesim, ferret, fluidanimate, streamcluster from PARSEC; applu, art, swim, equake from SPEC OMP; SPEC JBB2005; kmeans and pca from Phoenix. The resource usage characteristics of these programs are used as inputs to the statistical models as explained next.

3.1.1. The PAAP Model.

Data Collection. The goal of the PAAP model is to predict the performance of a program A when it is running with another program B. We chose six types of predictors for developing the PAAP model. Since we have two programs, we have 12 predictors in all representing the resource usage characteristics of both programs A and B. The seventh parameter shown in Table III is the response variable. *r_x* represents a resource usage characteristic value 'r' of program 'x' in its solo run with OPT Threads. Figure 4 explains the relationship between the elapsed time and the predictors. We use prstat(1) utility [McDougall et al. 2006] to monitor the predictors. prstat(1) provides microstat information for the individuals threads and for the whole application, which is simply the average across threads, according to the options we provide. Since ADAPT considers application level scheduling instead of thread level, we monitor microstat information of whole application in this work. The elapsed time for the full program in terms of other microstat information is given in Fig 4.

From the combinations of the aforementioned 12 programs, we collect 144 data points, where each data point is a 13-tuple containing 12 predictors and the observed *usr_ab* as the target parameter shown in Table III. Here each of the 12 programs contributes 12 data points including a combination with itself. We collect 100 samples using Solaris 11 utilities prstat(1) and cpustat(1) with 100 ms time interval and the averages of these samples are used as the final values of the predictors. The cpustat(1) utility is

```
100% of elapsed time of a program =  the percentage of time program spends in user space
                                   + the percentage of time program spends lock contention
                                   + the percentage of time program spends latency
                                   + the percentage of time program spends in kernel space.
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Fig. 4: Relationship between elapsed time (or turnaround time) and the predictors.

Table IV: VIF values of PAAP predictors.

mpa_a	lock_a	lat_b	ct_b	sys_a
1.6	2.1	2.1	1.6	1.3

$$usr\_ab = (65.2)+(-0.6 * lock\_a)+(-0.8 * lat\_b)+(-9.6 * mpa\_a)+(-10.2 * sys\_a)+(7.8 * ct\_b) \quad (1)$$

used to collect *mpa* and the prstat(1) utility is for the remaining predictors. Here, we assume that the percentage of elapsed time a program spends in user mode represents its progress or performance in the coscheduling run. Solaris provides utilities that effectively monitors application resource usage characteristics even in the presence of thread migrations.

Finding Important Predictors. To balance the prediction accuracy and cost of the approximation, we use forward and backward input selection techniques with Akaike Information Criterion (AIC) for finding important predictors among the 12 initial predictors. The AIC is a measure of the relative goodness of fit of a statistical model [Hastie et al. 2009]. Using R stepAIC() [R] method, we identified the five most important predictors: *lock_a, lat_b, ct_b, mpa_a,* and *sys_a*. We also tested the predictors against multicollinearity problem for developing robust models. Multicollinearity is a statistical phenomenon in which two or more predictor variables in a multiple regression model are highly correlated. In this situation the coefficient estimates may change erratically in response to small changes in the model or the data. We use R Variance Inflation Factor (VIF) method to observe the correlation strength among the predictors. If VIF $>$ 5, then the variables are highly correlated [vif]. As shown in Table IV, the variables are not highly correlated and therefore there is no multicollinearity problem.

Model Selection. Using the above five important predictors we develop three popular models based on supervised learning techniques. The models are: a) Linear Regression (LR); b) Decision Tree (DT); and c) K-Nearest Neighbour (KNN) [Hastie et al. 2009]. We use R statistical methods lm() [R], rpart() [R], and kknn() [R] for developing these models. Here the decision tree model is pruned using R prune() [R] method to avoid the over-fitting problem. As we can see in the LR model (Equation 1), lock contention, latency, cache miss-ratio, system overhead of program A negatively affects A's performance when it is running with program B. Thus, if there is an increase in any of these four predictors, then *usr_ab* decreases. If cores-to-threads ratio of program B is increased (i.e., number of threads of B is decreased), then the performance of program A will improve and vice-versa.

We evaluate the three models: LR, DT, and KNN using a 12-fold cross-validation (CV) test [Hastie et al. 2009]. Table V shows the adjusted R^2 values of these models on full training data and prediction accuracies in the 12-fold CV test. In a 12-fold CV test, we split the data (144 points) into 12 equal-sized partitions. The function approximator is trained using all the data except for one partition and a prediction is made for that partition. For testing the models thoroughly, we trained the models using the data from 11 different programs (132 data points) and tested it against the data of 12th program. The testing data used is different from the training data.

Table V: Models

Model	Adjusted R^2	Prediction Accuracy
LR	0.90	88.5
DT	0.94	90.4
KNN	0.88	87.1

$$sMAPE = \frac{1}{N}\sum_{i=1}^{N}\frac{|A_i - F_i|}{(A_i + F_i)/2} \times 100 \quad (2)$$

where A_i is the actual value and F_i is the forecast value.

Table VI: Models

Model	Adjusted R^2	Prediction Accuracy
LR	0.88	89.2
DT	0.86	87.6
KNN	0.86	85.2

We use the metric Symmetric Mean Absolute Percentage Error (sMAPE) for measuring prediction accuracy. The metric *prediction accuracy* is defined as: (100 - sMAPE), where sMAPE is symmetric mean absolute percentage error defined in Equation 2 [smape]. We use sMAPE instead of Mean Absolute Error Percentage (MAPE) due to the following drawbacks of using MAPE [mape]:

— If there are zero values, which sometimes happens for demand series, there will be a division by zero.
— When having a perfect fit, MAPE is zero. But in regard to its upper level the MAPE has no restriction.

Moreover, when calculating the average MAPE for a number of time series, the following problem may arise. Few of the series that have a very high MAPE might distort a comparison between the average MAPE of time series fitted with one method, when compared to the average MAPE using another method.

DT model is found to have the highest prediction accuracy among the three models and therefore we chose the DT model as the PAAP model.

3.1.2. The PAAC Model.

Data Collection. We chose six predictors for developing the PACC model. The goal is to predict the performance of a program A when it is running under different cores-configuration. The six predictors are: *usr_A, sys_A, lat_A, lock_A, ct_A*, and *rct_A*. As in case of the PAAP model, the first five predictors represent the resource usage characteristics values of program A in its solo run and, the remaining predictor rct_A, is a cores-configuration with reduced cores to threads ratio of program A. The goal is to predict the performance, i.e., *usr_acc* (the percentage of user-mode time), of program A when it is running with different cores-configuration. We ran each of the above 12 programs using OPT threads on 64, 56, 48, 40, 32, 24, and 16 cores to collect 6 points from each run. Therefore from the solo runs of the above 12 programs, we collected 72 data points, where each data point is a 7-tuple containing six predictors and the observed *usr_acc*.

Table VII: VIF values of the PACC model predictors.

Predictor	lock_a	rct_a
VIF	1.2	1.2

$$usr\_acc = (18.6) + (-0.3 * lock\_a) + (32.5 * rct\_a) \quad (3)$$

Finding Important Predictors and Model Selection. We identified the two most important predictors for the PACC model from among the six predictors and the two predictors are: *lock_a* and *rct_a*. The LR model developed with these two predictors is shown in Equation 3. As we can see in the LR model (Equation 3), lock contention negatively affects performance when it is running in different processor-set configurations, i.e., if there is an increase in lock contention then usr_acc decreases. If rct_a increases (i.e., number of cores) increases then the performance of the program also increases. As we can see in Table VII, the VIF values of these predictors are also less than 5. Therefore, there is no multicollinearity problem.

As in deriving the PAAP model, we develop LR, DT, and KNN models using the two important predictors: *lock_a* and *rct_a*. As shown in Table VI, LR model (Equation 3) has the best prediction accuracy in a 12-fold CV test. Therefore, we chose the LR model as the PACC model.

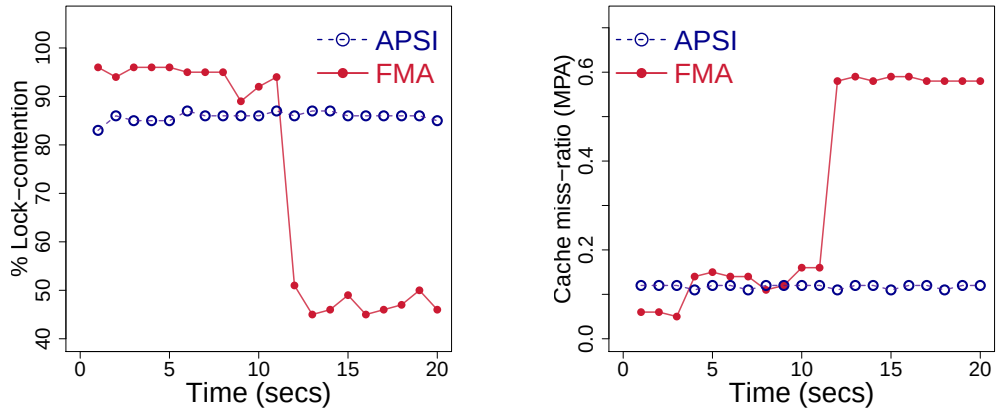
Using the PAAP and PACC models, Cores Allocator selects appropriate cores-configurations based upon the resource usage characteristics of programs. The overhead of these models is modest as they use very few predictors that capture all of the important information. In the next section, we describe the design of Cores Allocator.

3.1.3. Design of Cores Allocator. Cores Allocator considers a realistic scenario where programs can enter and leave the system at any time. Let us consider the case of coscheduling two programs. While program P_1 is running with its corresponding OPT threads, another program P_2 enters the system. If P_2 is CPU-intensive and low lock contention program, then irrespective of the current cores-configuration and the programs already running on system, Cores Allocator allocates all-cores configuration to P_2. Otherwise, it predicts performances of P_1 and P_2 using the PAAP and PACC models, and allocates the cores-configuration that gives better average TTT. Likewise, it coschedules N programs by allocating appropriate cores-configuration using the PAAP and PACC models. Let us consider another scenario, where programs P_1, P_2, ..., P_N are already running and then the program P_i completes its execution and leaves the system. If P_i is CPU-intensive and contention-free program, the current configuration for the remaining programs is maintained. Otherwise, the cores released by P_i are distributed equally among the remaining programs.

Let us consider an example that shows how Cores Allocator selects an appropriate cores-configuration for programs fluidanimate (FA) and swim (SM). Both FA and SM are memory-intensive and low lock contention programs, and their corresponding OPT threads are 49 and 32. Using the PAAP and PACC models, first Cores Allocator predicts the performance of FA and SM in all-cores and in the best processor-set configuration (40 cores to FA, 24 cores to SM). Table VIII shows that both FA and SM programs have high %USR (the percentage of elapsed time a program spends in user-mode) in the all-cores configuration. Therefore, Cores Allocator selects the all-cores configuration for coscheduling FA and SM. The all-cores configuration improves TTT of FA and SM by 14% compared to the processor-set configuration.

Table VIII: The actual and predicted *usr_FA* and *usr_SM* values with the PAAP and PACC models are shown here.

Program	All-cores		Processor-set	
	Actual	Predicted	Actual	Predicted
FA	52.3	56.4	41.2	44.5
SM	49.4	45.2	46.8	41.6



(a) Lock-contention (b) Cache Miss-Ratio

Fig. 5: While APSI has steady behavior, FMA shows a significant phase change.

Dealing with Phase Changes. Since FA and SM do not show *significant* phase changes on our machine, there is no switching back and forth between different cores configurations. The initial predicted processor-set configuration gives the best performance. Thus the Cores Allocator maintains all-cores configuration for the entire duration of the FA and SM coscheduled run. However, some programs show significant phase changes. Therefore, we continuously monitor the program for adaptively allocating appropriate cores-configuration according to the phase changes of the programs.

Let us consider a coscheduled run of two high lock contention programs apsi (APSI) and fma3d (FMA) with their OPT threads 16 and 56 respectively. As we can see from Figure 5, FMA has one significant phase change, while APSI shows steady behavior. FMA experiences very high lock contention in its first 11 seconds of its life-time, while APSI experiences very high lock contention steadily throughout its life-time. Therefore, by continuous monitoring, using the PAAP and PACC models, the Cores Allocator applies (16, 48) processor-set configuration during the first 11 seconds and then all-cores configuration for the remaining time. This results in performance improvement of 8% relative to the default OS scheduler (i.e., all-cores configuration).

Overhead of Cores Allocator. Since we monitor resource usage information of the whole *application* instead of individual *threads*, the overhead of Cores Allocator is negligible and it scales well. For n programs, (n)C(n-2) combinations are evaluated by PAAP. For example, for 4 applications (A, B, C, D), we evaluate 6 combinations (AB, AC, AD, BC, BD, CD). Cores Allocator takes a maximum of 2 milliseconds on our machine for selecting the best cores-configuration for coscheduling four applications.

We have shown that, using the PAAP and PACC models, Cores Allocator adaptively allocates appropriate cores-configuration according to the resource usage characteristics of the programs and effectively deals with the phase changes of programs. In the next section, we describe how the Policy Allocator adaptively selects appropriate memory allocation and processor scheduling policies based on the resource usage characteristics.

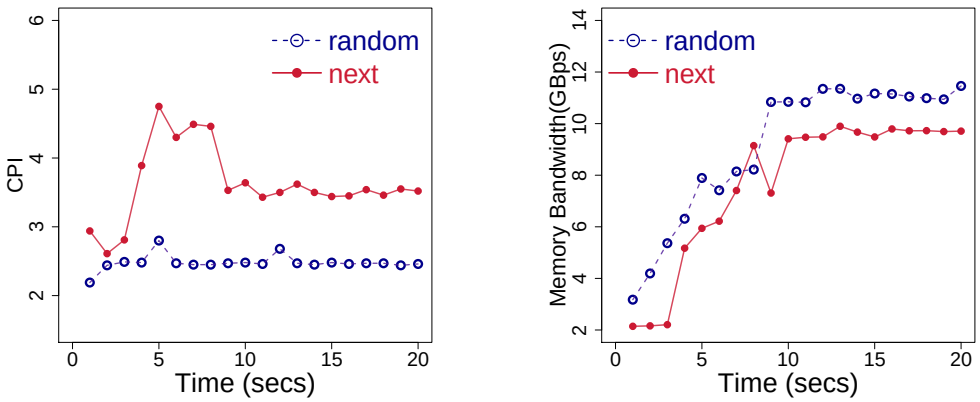
3.2. The Policy Allocator

Contemporary operating systems such as Solaris and Linux do not distinguish between threads from multiple single threaded programs and multiple threads corresponding to a single multithreaded program. Though, the default OS scheduling and memory allocation policies work well for multiple single threaded programs, this is not the case for multithreaded programs. This is because many multithreaded programs involve communication between threads, leading to contention for shared objects and resources. Since the OS does not consider application level characteristics in scheduling and memory allocation decisions, the default OS scheduling and memory allocation policies may not be appropriate for achieving scalable performance. Most of the existing contention management techniques are primarily designed for single threaded programs and they only deal with allocation of cores among the threads. To address these limitations, ADAPT uses another component, the Policy Allocator, which is responsible for dynamically selecting appropriate memory-allocation and process scheduling policies based on programs resource usage characteristics.

3.2.1. Memory Allocation vs OS Load-balancing. As shown in Figure 1, the HyperTransport (HT) is used as the CPU interconnect and the path to the I/O controllers. Using HT, CPUs can access each other's memory, and any data transferred from the I/O cards travels via the HT. Effective utilization of HT on a NUMA machine is important for achieving scalable performance for multithreaded programs, particularly when for memory-intensive multithreaded programs the OS scheduler distributes the threads across the CPUs for load balancing.

In Solaris 11, *next policy* (which allocates memory next to the thread) is the default memory allocation policy for private memory (heap, stack) and *random policy* is the default memory allocation policy for shared memory when the size of shared memory exceeds the threshold value of 8 MB. This threshold is set based on the communication characteristics of Message Passing Interface (MPI) programs [McDougall and Mauro 2006]. Therefore, it is not guaranteed that the *random policy* will be always applied to the shared memory for multithreaded programs that are based on pthreads. If the shared memory is less than 8 MB, then the *next* is also used as the memory allocation policy for shared memory. Moreover, with the default *next* policy, a memory-intensive thread can experience high memory latency overhead, and consequently high cache miss-ratio, when it is started on one core and then migrated to another core not in its home lgroup. More importantly, this makes HT a performance limiting hot spot. Therefore, the interaction between inappropriate memory allocation policy and OS load balancing degrades memory bandwidth and prevents scalable performance for memory-intensive multithreaded programs.

Unlike the *next policy*, the *random policy* picks a random leaf lgroup to allocate memory for each page and it eventually allocates memory across all the leaf lgroups. Thus the threads of memory intensive programs get a chance to reuse the data in both private and shared memory. This reduces memory latency penalty and cache miss-ratio. Moreover, it spreads the allocated memory across the memory banks; thus, distributing the load across many memory controllers and bus interfaces, thereby preventing any single component from becoming a performance limiting hot spot [McDougall and



(a) CPI (b) Memory-bandwidth

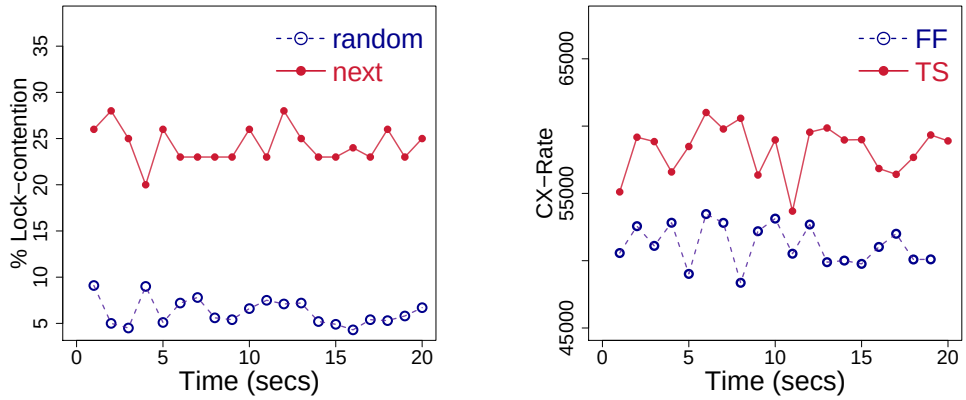
Fig. 6: CPI is high with next policy. Random policy improves memory-bandwidth.

Mauro 2006]. Next this is demonstrated by running a very memory-intensive program streamcluster (SC) with both *next* and *random* policies in all-cores configuration.

In this experiment, we run SC with its OPT Threads of 17 in all-cores configuration. Cycles per instruction (CPI) indicates whether HT and Memory buses are performance limiting spots or not. As shown in Figure 6, CPI of SC with *next-touch* is higher than with *random policy* and total memory bandwidth (GB/sec) is improved by 17% with *random policy*. Therefore, random policy relieves pressure on HT, improves overall performance of memory-intensive programs, and also improves system utilization. Thus, multithreaded programs with huge private memory benefit greatly from the *random policy*. Moreover, random policy not only improves performance, it also reduces performance variation in multithreaded programs [Pusukuri et al. 2012].

Memory-allocation vs Access-latency of Locks. The performance of SC is dramatically improved by 56% with *random policy* in comparison to *next policy*. This improvement is not only because of the improved memory-bandwidth, there is also a reduction in lock contention because of the random allocation of private memory (heap and stack) across lgroups. Allocating private memory across lgroups using *random policy* allows threads to quickly access lock data structures in the shared cache; thus minimizing memory traffic and the delay loop time for acquiring locks. As shown in Figure 7(a), applying *random policy* for private memory reduces lock contention of SC by 19% and improves performance.

3.2.2. Scheduling Policy vs Lock-contention. The default Time Share (TS) scheduling policy is not appropriate for high lock contention multithreaded programs under high loads. Prior work has shown that the interaction between TS policy and the state-of-the-art spin-then-lock contention management policy dramatically increases the thread context-switch rate and leads to drastic degradation in the performance [Johnson et al. 2010; Pusukuri et al. 2011b]. We considered both the Load Controller [Johnson et al. 2010] and FF policy [Pusukuri et al. 2011b] solutions as replacement of TS policy for dealing with lock contention of the programs in coscheduled runs. However, since Load Controller requires changes to application code, and its overhead increases linearly with the number of threads, we decided to make use of the FF policy. Our Policy Allocator selectively uses the FF policy. By assigning same priority to all the threads of a given



(a) Random policy reduces lock contention. (b) FF policy reduces context-switch rate.

Fig. 7: Random policy reduces lock contention of SC by 19%. FF policy reduces context-switch rate of APSI.

multithreaded program, FF policy breaks the vicious cycle between thread priority changes and context-switches. This dramatically reduces the context-switch rate (CX-Rate) and improves the performance especially under high loads. FF policy allocates time-quantum based on the resource usage of a multithreaded program for achieving fair allocation of CPU cycles among the threads. For example, when we run a high lock contention program apsi with its OPT threads (16), FF policy reduces its CX-Rate (shown in Figure 7(b)) and improves its performance by 9%.

3.2.3. Design of Policy Allocator. Policy Allocator continuously monitors cores-configuration selected by the Cores Allocator and the resource usage characteristics, MPA and Lock-contention, of the multithreaded programs for selecting appropriate memory-allocation and scheduling policies. If the program is CPU-intensive and low lock contention, and it is in all-cores configuration, then the Policy Allocator applies *next* policy and TS policy. Otherwise, it applies *random* policy (or *random_pset* policy for processor-set configuration) and FF policy with appropriate time-quantum. Since, there is interference between programs in all-cores configuration, Policy Allocator always applies one of the policies (TS or FF) in *all-cores* configuration. This is because, we observe that running the programs with different scheduling policies (TS and FF) in all-cores configuration dramatically degrades overall performance for some programs. However, we apply both policies (TS and FF) at a time in processor-set configuration selectively according to the resource usage characteristics of applications. This is not clear from [Pusukuri et al. 2011b; 2012] as those works did not explore coscheduling of multithreaded programs. However, in this work, we selectively apply FF policy for effectively coscheduling multithreaded programs.

3.3. Implementation of ADAPT

Our implementation of ADAPT uses a daemon thread for continuously monitoring running programs, maintaining their resource usage characteristics, assigning cores-configuration using the Cores Allocator, and selecting memory allocation and scheduling policies using the Policy Allocator. A Resource Usage Vector (RSV) is maintained for each program. More specifically, RSV of a program contains the following: resource

usage characteristics including *usr, lock, lat, sys, ct, mpa*; *CPU utilization* per processor-set if program is coscheduled in a processor-set configuration; and *cores-configuration* selected by the Cores Allocator. Based on the cores-configuration, cores-to-threads (*ct_a*) ratio is interpreted as either *ct_a* for the PAAP model or *rct_a* for the PACC model.

For monitoring programs and collecting resource usage data, assigning different cores-configurations as well as memory allocation and scheduling policies, ADAPT uses the following Solaris 11 utilities: *prstat, mpstat, priocntl, pmadvise, mdb*, and *cputrack*. *prstat* is used to collect *usr, lock, lat*, and *sys* characteristics, while *cputrack* is used to collect *mpa*. *mpstat* collects system-wide resource usage characteristics such as overall system utilization and CPU utilization per processor-set. We use *mdb* and *pmadvise* to apply memory allocation policies and *priocntl* for applying scheduling policies. While *mdb* is used to apply memory allocation policies system-wide for all programs, *pmadvise* is used for applying memory-allocation policy per program.

With the minimum time interval of one second provided by the default implementation of *prstat* and *mpstat* utilities, it is difficult to respond to rapid phase changes in programs. Therefore, we enhanced these utilities[2] to allow time intervals with millisecond resolution and capture phase changes of programs. Furthermore, the default *cpustat* utility does not support the use of performance monitoring events to collect system-wide resource usage characteristics (e.g., last-level cache miss-ratio) when there is more than one active processor-set. Therefore, we have also enhanced the *cpustat* utility to collect system-wide characteristics with arbitrary number of processor-sets.

Selecting Appropriate Monitoring Time-interval:. Using the above enhanced utilities, ADAPT is able to collect resource usage characteristics of the target programs with millisecond resolution. The time interval for collecting resource usage data directly impacts the overhead of ADAPT. Although small time interval allows fine-grain details of the resource usage data to be collected, it increases the monitoring overhead. Therefore selecting appropriate time interval is very important. To select an appropriate time interval, as shown in Figure 8, we evaluated ADAPT with different time intervals for monitoring four multithreaded programs simultaneously running on our machine. As Figure 8 shows, when we use ADAPT with 50 ms and 100 ms time intervals, the system overhead is considerably high. This is because the high rate of interprocessor interrupts and cross-calls leads to high system time [McDougall and Mauro 2006]. With time interval of 200 ms or greater, the overhead of ADAPT is negligible ($< 1.5\%$ of system time). Therefore, ADAPT uses 200 ms time interval for collecting RSVs of the multithreaded programs. ADAPT collects 10 samples of the resource usage data of the target programs with 200 ms time interval and updates RSVs of programs with the average of these 10 samples every two seconds. Therefore, every two seconds, based on the phase changes, it applies appropriate cores-configuration, memory allocation, and scheduling policies.

We have observed that rapid changes in *cores-configuration* diminishes the benefits of ADAPT. Therefore ADAPT keeps the last three RSVs of each program and then changes cores-configuration if one of the following conditions is satisfied:

(1) If programs are running in a processor-set configuration, and the average CPU utilization of any processor-set is less than that of any other processor-set by a threshold of at least α.
(2) For any program P_i, if its usr_Pi decreases at a rate greater than a threshold of β in the last two intervals.

[2]Source code is at http://www.cs.ucr.edu/∼kishore/hipeac13.html

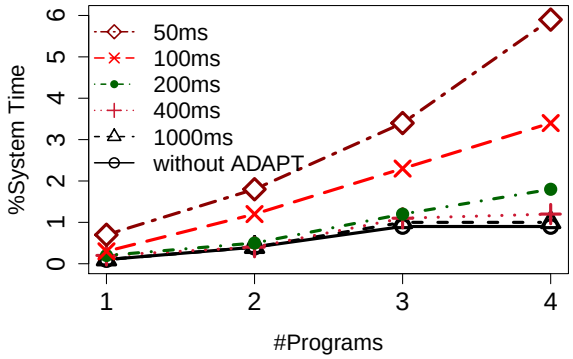


Fig. 8: Time interval duration vs. system overhead.

(3) $\frac{\sum_{i=1}^{N}(usr\_P_i^P)}{N} > (\frac{\sum_{i=1}^{N}(usr\_P_i^C)}{N} + \gamma)$ in the last two-intervals, where γ is the threshold value.

where usr$_P_i^C$ is the actual %USR time of P_i in current cores-configuration, while usr$_P_i^P$ is the predicted %USR time of program P_i using either the PAAP or the PACC model based on the current cores-configuration. From extensive experimentation with the programs used, we derived the threshold values α, β, and γ as 6%, 4%, and 8%. By employing these thresholds, we are able to reduce the impact of unnecessary rapid changes between cores configurations on the performance of the programs. In the current implementation of ADAPT, we assume that solo run RSVs of the target programs are available. Alternatively, we can run the application for a few millisecond as it enters the system and collect its RSV. Using signals (SIGSTOP/SIGSTART) we can pause other applications while the RSV of the new application is being collected.

4. EXPERIMENTAL SETUP

4.1. Target Machine and OS

Our experimental setup consists of a 64-core machine running Solaris 11. Table IX shows its configuration.

Table IX: Target Machine and Operating System.

Supermicro 64-core server: 4 × 16-Core 64-bit AMD Opteron^{TM} 6272 Processors (2.1 GHz); L1 : 48 KB; Private to a core; L2 : 1024 KB; Private to a core; L3 : 16384 KB; Shared among 16 cores; Memory: 64 GB RAM;
Operating System: Oracle Solaris 11^{TM}

Why Solaris. The Memory Placement Optimization feature and Chip Multithreading optimization allow Solaris OS to effectively support hardware with asymmetric memory hierarchies such as NUMA [McDougall and Mauro 2006]. Specifically Solaris kernel is aware of the latency topology of the hardware via lgroups which allows it to optimize decisions on scheduling and resource allocation. Moreover, Solaris provides a rich user interface to modify process scheduling and memory allocation policies. It also provides

several effective low-overhead observability tools including DTrace, a dynamic kernel tracing framework [Cantrill et al. 2004].

4.2. Benchmarks and Performance Metrics

We evaluate ADAPT using 26 programs -- TATP [TATP. 2003] database transaction application; SPECjbb2005 [SPECOMP 2001]; eight programs from PARSEC [Bienia et al. 2008] including streamcluster (SC), facesim (FS), canneal (CA), x264 (X264), fluidanimate (FA), swaptions (SW), ferret (FR), and bodytrack (BT); 11 programs from SPEC OMP [SPECOMP 2001] including swim (SM), equake (EQ), wupwise (WW), gafort (GA), art (ART), apsi (AS), ammp (AM), applu (AP), fma3d (FMA), galgel, (GL), and mgrid (MG); and five programs from Phoenix [Yoo et al. 2009] including kmeans (KM), pca (PCA), matrix-multiply (MM), word-count (WC), and string-match (STRM).

The implementations of PARSEC programs are based upon pthreads and we ran them using native inputs (i.e., the largest inputs available). SPEC OMP programs were run on medium input data sets. SPECjbb2005 (JBB) with single JVM is used in all our experiments. TATP (a.k.a NDBB and TM-1) uses a 10000 subscriber dataset of size 20MB with a solidDB [solidDB] engine. TATP is not IO-intensive and disk performance does not affect it significantly [Johnson et al. 2010]. Phoenix programs are based upon MapReduce. We are unable to use some other programs of the above benchmark suites because they have very short running-times. In this work, we ran each experiment 10 times and present average results from the ten runs.

Performance Metrics. We use two metrics inspired from [Eyerman and Eeckhout 2008] to evaluate ADAPT: a user-oriented metric: average total turnaround time (TTT); and a system-oriented performance metric: average system utilization, where system utilization = 100 − (%CPU idle time).

5. EVALUATING ADAPT

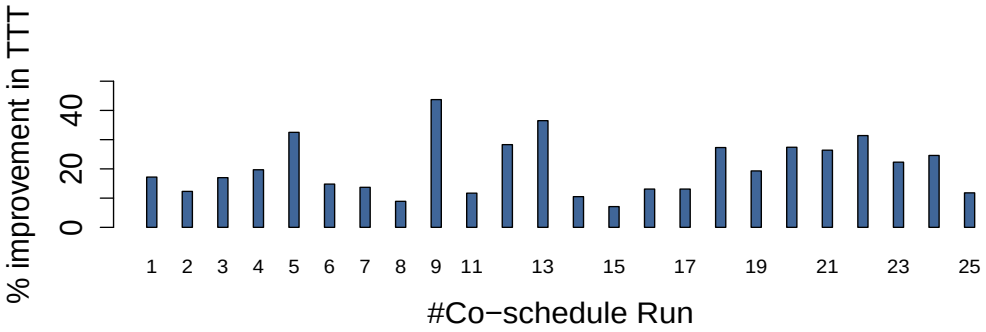
In this section, we analyze the effectiveness of ADAPT framework using several coscheduling experiments with the 26 multithreaded programs as shown in Figure 9(a). As we can see, we evaluate ADAPT by coscheduling either two, three, or four programs. As we can see from Figure 9(b), TTT improvement with ADAPT is on average 21% (average lies between 16.1% and 25.2% with 99% confidence interval) and up to 44% relative to the default Solaris 11 scheduler.

As shown in Figure 9(b), while ADAPT achieves high TTT improvements for the coscheduled runs of memory-intensive and high lock contention programs (e.g. FS), it achieves moderate TTT improvements for the coscheduled runs of CPU-intensive and low lock contention programs (e.g. SW). ADAPT achieves high throughput improvements for the coscheduled runs of TATP database transaction application and JBB. ADAPT improves throughput of TATP and JBB by 23.7% and 18.4% compared to the default Solaris scheduler. For CPU-intensive and low lock contention programs, Policy Allocator contributes more to the improvements in TTT than the Cores Allocator because Cores Allocator allocates all-cores configuration like the default OS scheduler for these programs. Figure 9(c) shows that ADAPT achieves high system utilization, compared to the default Solaris scheduler. Thus ADAPT simultaneously improves performance of programs and system utilization.

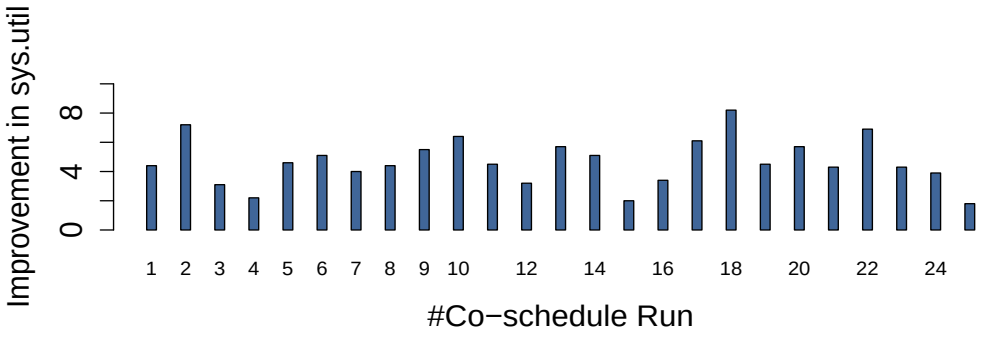
ADAPT vs Existing Techniques:. As discussed in Section 3, the existing coscheduling algorithms [Zhuravlev et al. 2010; Blagodurov et al. 2011; Pusukuri et al. 2011] are primarily designed for a mix of *single threaded* workloads or threads of a *single multithreaded* workload. Therefore they use thread level scheduling while ADAPT uses application level scheduling to enable handling of multiple multithreaded programs. Since DINO [Blagodurov et al. 2011] uses one thread per core configuration, to compare

#	Programs	OPT Threads	#	Programs	OPT Threads
1	FS;EQ	(32,32)	9	AM;SC	(56,17)
2	BT;AP	(50,24)	10	TATP;JBB	(54,69)
3	AS;FMA	(16,56)	11	SM;EQ	(32,32)
4	SW;MG	(73,16)	12	PCA;STM	(48,16)
5	FA;SC	(49,17)	13	MG;PCA	(16,48)
6	GL;BT	(16,50)	14	KM;ART	(24,40)
7	FA;SM	(49,32)	15	MM;SW	(64,73)
8	ART;x264	(40,68)	16	WC;MG	(48,16)
17	KM;CA;X264	(16,33,68)	20	FS;AP;STM	(32,24,16)
18	AS;BT;FR	(16,50,83)	21	AM;WW;PCA	(56,24,48)
19	GA;SM;FA	(64,32,24)			
22	FS;SC;EQ;WW	(32,17,32,24)	24	PCA;AM;AS;ART	(48,48,34,40)
23	AS;AP;BT;FMA	(16,24,50,56)	25	GA;FMA;x264;FA	(64,56,68,49)

(a) Coschedule run numbers and corresponding programs.



(b) % Improvement in TTT.



(c) Improvement in System Utilization.

Fig. 9: ADAPT improves TTT and system utilization compared to the default Solaris scheduler. Here, improvement in system utilization = (utilization with ADAPT - utilization with Solaris).

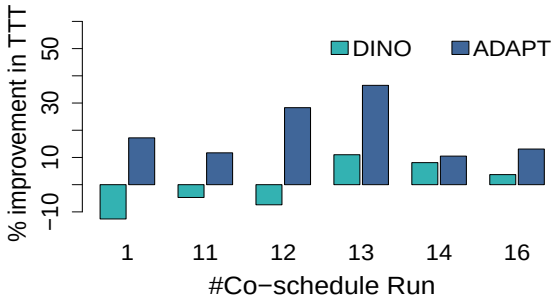


Fig. 10: TTT improvements are relative to the default Solaris scheduler. ADAPT significantly outperforms DINO.

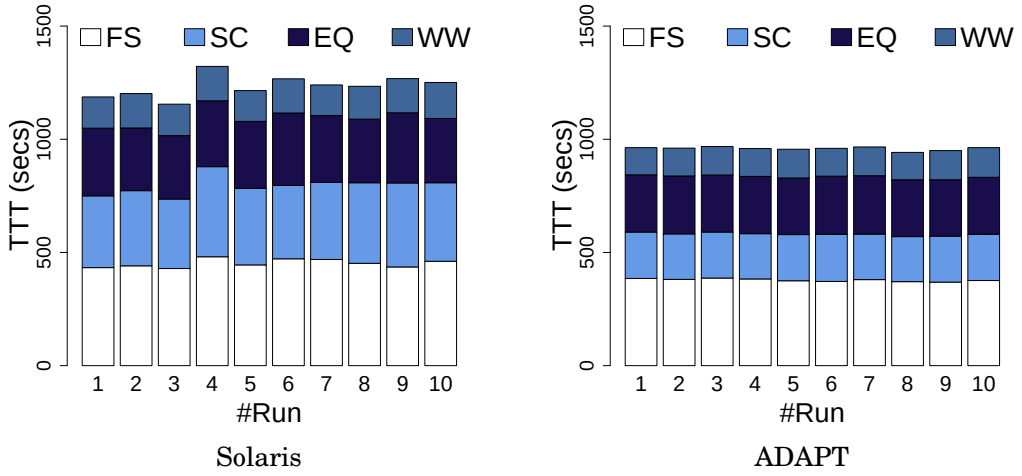


Fig. 11: ADAPT improves performance of all the four memory-intensive programs: FS, SC, EQ, and WW.

ADAPT with DINO, we have chosen coscheduling runs where ADAPT also uses number of threads that equal the number of cores. There are only 6 coscheduled runs with this configuration (see Figure 9(a)). Figure 10 shows the % TTT improvements of both ADAPT and DINO relative to the default Solaris scheduler. As we can see in Figure 10, ADAPT significantly outperforms DINO. Though DINO is also effective in coscheduling some multithreaded programs, its performance is the worse for coscheduling of high lock contention programs.

Since the above existing techniques are based on cache usage, they are very effective for a mix of workloads where half of the threads are memory-intensive and other half are CPU-intensive. However, they may not work well on a mix of workloads where all the threads are either CPU-intensive or Memory-intensive. Therefore, we evaluated ADAPT against a mix of four Memory-intensive multithreaded programs (FS:SC:EQ:WW) and as well as against a mix of four CPU-intensive multithreaded

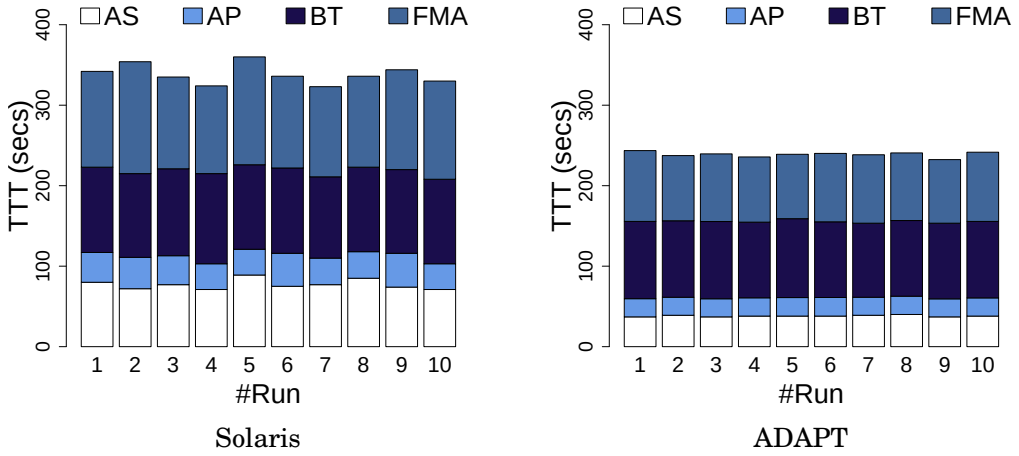


Fig. 12: ADAPT improves performance of all the four CPU-intensive programs: AS, AP, BT, and FMA.

Table X: Normalized running-times of the memory-intensive programs in a coschedule run.

Program	**Normalized Running-time**	
	Solaris	ADAPT
FS	2.1	1.6
SC	1.6	1.2
EQ	1.5	1.3
WW	1.7	1.4

programs (AS:AP:BT:FMA). Figures 11 and 12 show the total running-times (or TTT) of the four programs in each run. As we discussed in Section 3, for memory-intensive and high lock contention programs, ADAPT simultaneously improves memory bandwidth and reduces lock contention. It relieves pressure on HT module, and consequently reduces paging activity and improves performance. In the second coscheduled run of four programs, we evaluated ADAPT for a mix of four CPU-intensive and high lock contention programs. By assigning appropriate cores-configuration and the FF scheduling policy with appropriate time-quanta, ADAPT dramatically reduces context-switch rate and improves overall TTT of the programs.

Furthermore, as we can see in Figures 11 and 12, ADAPT not only improves performance of programs, it simultaneously reduces variation in their performance. We also computed normalized running-times of the programs to see how fairly the resources are distributed across the four programs in the above mentioned coscheduled runs. Here normalized running-time is computed as the ratio of running-time of the program in the coschedule run to the running-time of the program in solo run. As we can see in Tables X and XI, not only ADAPT improves TTT, it also distributes the resources fairly across the coscheduled programs. Thus, ADAPT improves fairness and does better than default Solaris scheduler.

In summary the above experiments demonstrate that ADAPT is effective in coscheduling multithreaded programs on multicore systems. By using simple and efficient modern

Table XI: Normalized running-times of the CPU-intensive programs in a coschedule run.

Program	Normalized Running-time	
	Solaris	ADAPT
AS	2.3	1.2
AP	1.9	1.2
BT	1.5	1.3
FM	1.9	1.3

OS performance monitoring utilities, ADAPT continuously monitors the resource usage characteristics of programs, adaptively allocates resources such as cores, and assigns appropriate memory allocation and scheduling policies. Moreover, it is an attractive approach as it does not require any changes to either the application source code or the OS kernel. Furthermore, the overhead of ADAPT is negligible for the appropriately chosen monitoring interval. Thus ADAPT scales well with the number of multithreaded programs on machines with large number of cores.

6. RELATED WORK

While coscheduling of programs on a multicore system is a well studied area, there are only a few works [Bhadauria and McKee 2010] that deal with contention management during coscheduling of *multithreaded* programs. Bhauaria et al. [Bhadauria and McKee 2010] proposed a symbiotic scheduler based on memory-hierarchy contention considerations (i.e., last-level cache miss-rate) for coscheduling multithreaded programs on a machine with a small number of cores (eight cores). However, they [Bhadauria and McKee 2010] pursue a different goal of balancing power and performance. Moreover, they used one thread per core configuration for evaluating their scheduler using the metric of overall throughput per watt.

[Moore and Childers 2012] uses statistical models to predict appropriate number of threads for a multithreaded program when it is running with another multithreaded program on a multicore system for achieving high throughput. [Moore and Childers 2012] shows that varying number of threads for an application according to the workload improves throughput. This is a good observation but exploiting this observation requires that the applications written to accept number of threads as input be modified. In contrast to this work, ADAPT does not require modification of applications. ADAPT always runs multithreaded programs with OPT threads. Here, OPT threads is the minimum number of threads of a multithreaded programs in its solo run on our multicore machine. Moreover, unlike the above work, ADAPT aims to achieve both low total turnaround times and high system utilization. More importantly, [Moore and Childers 2012] does not exploit application characteristics such as lock contention, scheduling, and memory allocation policies that ADAPT exploits. Allocating appropriate number of cores is also a critical factor in coscheduling multithreaded programs that ADAPT considers. One can view ADAPT and [Moore and Childers 2012] technique as complimentary techniques that can be potentially combined to further improve performance.

Other existing contention management techniques [Zhuravlev et al. 2010; Blagodurov et al. 2011; Pusukuri et al. 2011; Knauerhase et al. 2008; Merkel et al. 2010] are also based upon consideration of memory-hierarchy contention factors such as cache-usage. However, as we demonstrated in this work, cache-usage alone is not enough for coscheduling multithreaded programs on machines with large number cores. We showed better results by considering characteristics of lock contention and thread latency. Complementary to these works, some researchers [Tam et al. 2007] developed

techniques for coscheduling threads of a single multithreaded program that share data on the same chip, but they did not address coscheduling of multithreaded programs.

Several researchers [Brecht 1993; LaRowe et al. 1992; Corbalan et al. 2003; VMware 2005; Gamsa et al. 1999; Li et al. 2007] have developed NUMA-related optimization techniques for efficient colocation of computation and related memory on the same node. However, they have not addressed resource contention management in multicore machines. Likewise, [Severance and Enbody 1997] developed adaptive scheduling techniques for parallel applications based on MPI on large discrete computers. However, this scheduling technique does not address the contention of shared resources when coscheduling multiple programs concurrently. Corbalan et al. [Corbalán et al. 2000] use techniques to allocate processors adaptively based on program efficiency. However, like the above works, they also do not consider resource contention among the programs. McGregor et al. [McGregor et al. 2005] developed coscheduling techniques using architectural factors such as cache resource usage for coscheduling NAS parallel benchmarks on a quad core machine. However, each of the workload used in this work is either a single threaded or a multithreaded with only two threads. Like the above existing contention management techniques, this technique also will not work for coscheduling multithreaded programs on large multicore machines. Gupta et al. [Gupta et al. 1991] explored the impact of the scheduling strategies on the caching behavior of the applications. Likewise, Chandra et al. [Chandra et al. 1994] evaluated different scheduling and page migration policies on a CC-NUMA multiprocessor system.

Unlike the above approaches, by considering appropriate contention factors and using supervised learning techniques for identifying the interference between multithreaded programs, our work provides efficient coscheduling techniques for multithreaded programs on a multicore machine. Several other researchers also explored machine learning and control theory for developing adaptive resource optimization techniques for utility computing [Padala et al. 2007; Padala et al. 2009], network management [Barham et al. 2008], mobile computing [Narayanan and Satyanarayanan 2003], computer architecture [Ipek et al. 2008], and compiler optimizations [Pekhimenko and Brown 2008].

7. CONCLUSIONS

Coscheduling multithreaded programs on a multicore machine is a challenging problem. We presented ADAPT, a framework for effective coscheduling multithreaded programs on multicore systems. ADAPT is based on supervised learning techniques for identifying the effects of the interference between multithreaded programs on their performance. It uses simple modern OS performance monitoring utilities for continuously monitoring the resource usage characteristics of the target programs, adaptively allocating resources such as cores, and selecting appropriate memory allocation and scheduling policies. Moreover, it is an attractive approach as it does not require any changes to either the application source code or the OS kernel. Furthermore, the overhead of ADAPT is negligible with appropriate choice of monitoring interval. Thus, ADAPT scales well with the number of multithreaded programs on machines with a large number of cores.

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