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A Novel Thread Scheduler Design for Polymorphic Embedded Systems

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by

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DEDICATION

I would like to dedicate my thesis to my mother Prema Krishnamurthy, father Mr. N. Krishnamurthy, sister Vaasanthy Krishnamurthy and my dear friend Karthik Ganesan.

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ABSTRACT

The ever-increasing complexity of current day embedded systems necessitates that these systems be adaptable and scalable to user demands. With the growing use of consumer electronic devices, embedded computing is steadily approaching the desktop computing trend. End users expect their consumer electronic devices to operate faster than before and offer support for a wide range of applications. In order to accommodate a broad range of user applications, the challenge is to come up with an efficient design for the embedded system scheduler. Hence the primary goal of this thesis is to design a thread scheduler for a polymorphic thread computing embedded system. This is the first ever novel attempt at designing a polymorphic thread scheduler. None of the existing or conventional schedulers have been targeted for a polymorphic embedded environment. To summarize the thesis work, a dynamic thread scheduler for a Multiple Application, Multithreaded polymorphic system has been implemented with User satisfaction as its objective function. The sigmoid function helps to accurately model end user perception in an embedded system as opposed to the conventional systems where the objective is to maximize/minimize the performance metric such as performance, power, energy etc. The Polymorphic thread scheduler framework which operates in a dynamic environment with N multithreaded applications has been explained and evaluated. Randomly generated Application graphs are used to test the Polymorphic scheduler framework. The benefits obtained by using User Satisfaction as the objective function and the performance enhancements obtained using the novel thread scheduler are demonstrated clearly using the result graphs. The advantages of the proposed greedy thread scheduling algorithm are demonstrated by comparison against conventional thread scheduling approaches like First Come First Serve (FCFS) and priority scheduling schemes.

CHAPTER 1. Introduction and Motivation

The ever-increasing complexity of current day embedded systems necessitates that these systems be adaptable and scalable to user demands. With the growing use of consumer electronic devices, software applications supported by embedded processors is steadily approaching the complexity of desktop computing applications. If this functionality trend continues, a stage might be reached where embedded computing would outpace desktop computing. In the last decade, rapid advancements have taken place in the processing and display capabilities of consumer electronic devices. As a result, drastic reductions have been achieved in the size and cost of embedded systems. Traditional embedded systems supported voice-only services along with basic features in user interface. End users expect their consumer electronic devices to operate faster than before and offer support for a wide range of applications. In any innovative embedded system design, the design methodology plays a pivotal role. Future generation embedded systems need to incorporate more user-friendliness into their devices and cater to a heterogeneous class of applications. The design challenge is to offer multimedia and entertainment support, in addition to traditional voice-only services to the end user. Among the several design challenges, the resource allocation problem has gained a lot of interest in the embedded systems community. In order to accommodate a broad range of user applications, the challenge is to come up with an efficient design for the embedded system scheduler. Given the precise timing constraints and unpredictable resource requirements in a highly dynamic real time embedded system, the need for a clever thread scheduler design becomes inevitable. The computational load in the system is data-dependent and varies with respect to time. It also depends on the total number of tasks in the system. Hence to cope with this complexity, the thesis proposes an embedded systems scheduler, which effectively operates in a dynamic environment and ensures execution of threads with stringent timing constraints. The thread scheduler makes resource allocation decisions with the intent of maximizing user satisfaction. The complexity of current-day embedded systems is explained using Figure 1.1.

To give a brief introduction, 'Scheduling' is the method by which threads or processes are given access to system resources (processor time, memory, I/O channels). The processor software component which is in charge of scheduling is called 'Scheduler'. In general, the aim of the process/thread scheduler is to increase system throughput, maximize CPU utilization or to ensure fairness among applications. In some cases, it could be minimizing metrics such as Turn- around time, power, energy etc. Since modern day embedded systems work in a highly dynamic environment, it is difficult to predict in advance the applications that will be run and their resource requirements. The computational load in the system is data-dependent and varies with respect to time and number of tasks in the system. We proceed further and describe the concepts that help us define a polymorphic embedded system.

1.1 Polymorphic Computing System

In this section, we define and specify a polymorphic embedded system, a futuristic approach for embedded system design. Before defining what a polymorphic thread system, we need an efficient way for representing operating system tasks. Scheduling can be accomplished at different granularities, course level(application level) or at fine grained level(threads/process) level. Threads are optimized representation of tasks, due to their low context switching overhead. Since modern day processors offer extensive support for multithreading, task scheduling is accomplished at thread level granularity. Also, thread level resource information is considerably high compared to other task representations. Due to these compelling reasons, applications are examined at thread level granularity in the proposed scheduler framework.

The origin of the word 'Polymorphism' comes from words 'Poly' and 'Morph'. Morphism is the quality of taking up a particular form or shape. The word 'Poly' means Multiple and

TRADITIONAL CELL PHONE
CURRENT-DAY CELL PHONE
VOICE-ONLY SERVICES
VOICE SERVICES
MULTIMEDIA SUPPORT
BASIC USER INTERFACE
ADVANCED USER INTERFACE

Figure 1.1 Growth of Embedded Systems

hence the term 'Polymorphism' stands for multiple forms. The notion of morphism is similar to Design Space Exploration. Design space exploration is the process of examining several implementation choices, which are functionally similar, in order to identify an optimal solution. The threads within an application can be implemented in a multitude of ways, where each thread's implementation is referred to as morphism. A polymorphic embedded system is one which supports execution of multiple multithreaded applications. The scheduler for such a system has to efficiently choose morphisms for the threads lined up for execution in the ready queue. The morphism choices for the threads, depends on the instantaneous resource availability. Chapter 2 elucidates the concept of morphism in finer detail.

1.2 Novelty of Proposed Work

This is the pioneer attempt at designing a thread scheduler for a polymorphic embedded system. None of the existing literature on thread scheduler design has accounted for thread polymorphism. We describe the novelty and performance advantages of the proposed system versus conventional high performance embedded systems. In the case of conventional high performance embedded systems, makeup of applications is known at design time. We further describe how the existing scheduling strategies tackled the resource allocation problem.

Priority scheduling has been predominantly employed for task scheduling in conventional systems VxWorks [1997], QNX [1999]. The traditional models for resource allocation, in real-time embedded systems are based on periodic or sporadic execution model. C.L.Liu et Al. [1973], Mok [1983], Spuri et Al. [1994], Buttazo et Al. [1995] discuss about the aperiodic and sporadic resource allocation models. In the case of **Rate Monotonic Scheduling**(RMS) scheme, tasks which have high recurrence rates receive precedence over tasks with low frequency rates. The RMS scheduling approach is detailed in C.L.Liu et Al. [1973] Lehoczky [1989]. In the **Earliest Deadline First**(EDF) scheduling strategy, the scheduler must ensure that all tasks complete execution before their specified deadlines. Spuri et Al. [1994] Leung et

Al. [1982], elaborate about the Earliest Deadline Scheduling(EDS) technique. But the priority scheduling scheme used in the EDF and RMS schemes, suffers from a number of shortcomings. In the case of static priority scheduling, tasks are assigned priorities which remain the same throughout the task's execution. Priority scheduling performs badly for tasks whose run-time behavior deviates significantly from its expected or design time behavior. Moreover the behavior of these tasks may vary with respect to time and the number of tasks in the system. Another drawback in priority scheduling is that there is no foolproof mechanism for mapping task requirements into priority values. In many cases, the system designer accomplishes this mapping based on a pre-determined set of facts. The user-satisfaction based resource allocation scheme employed by the proposed polymorphic thread scheduler addresses the above issues, offering significant performance benefits over classical scheduling schemes.

Hybrid Reconfigurable Systems(HRS), an emerging trend in current embedded system design has CPU cores and reconfigurable fabric on a single die. Programming models for hybrid CPU/FPGA systems were studied in D.Andrews et Al. [2004] Peck et Al. [2006]. In these systems, the scheduler categorizes a thread as either software or hardware. But the design choices for the scheduler are limited in these systems. The polymorphic embedded system explores a much bigger design space, by considering several functionally equivalent software implementation alternatives for a given thread. In conventional embedded systems, the makeup of applications is known at design time and the user has no way of dictating priority for the applications. But in the proposed polymorphic embedded system, application characteristics are known only at run time. Unlike conventional systems, where the objective is to increase performance, reduce energy or power, the proposed polymorphic scheduler places an emphasis on increasing user satisfaction. In any typical embedded system, human perception matters the most. This is because of the fact that, user perception is a clear indicator of application performance. Since there are limits to human perception, there are upper and lower limits to the user satisfaction function. Considering an illustration, let the end-user be watching a video at DVD clarity. The user satisfaction in this case, would have reached the upper saturation limit and any further increase in video quality, doesn't significantly alter user satisfaction. The lower limit is the point, below which there is zero user satisfaction. There is a middle region, where there is non-linear increase in user satisfaction with increase in performance metric. The upper limit is the region beyond which, no pronounced increase in user satisfaction is achieved with increase in resources.

In order to capture user perception, we require a function which holds similar properties. The Sigmoid function is an S-shaped knee curve with near-linear central response and saturating limits. The novelty in our approach compared to prior work is that, sigmoid function is used for modeling user satisfaction. The function helps us to establish the Lower/Upper limit or Desired Operating Points (DOP). Desired Operating Point is the region in the sigmoid curve, above which marginal user satisfaction gain is imperceptible to the end user. Resources to enhance output parameter (User satisfaction) is not proportional to actual/perceived enhancement. This is the principal reason behind choosing sigmoid function to model user satisfaction. This is the advantage of the proposed system over conventional systems, which have no clear way of establishing the **Desired Operating Points**. To summarize, the thesis work, a dynamic thread scheduler which effectively functions in a multiple application, multithreaded polymorphic environment has been implemented and evaluated. The rest of the thesis is organized in the following manner.

The related work for the thesis is summarized in Chapter 2. Chapter 3 discusses the preliminary concepts, which form the basis for our scheduler framework. Chapter 4 describes the data structures for the scheduler and explains how resource contention is modeled using marginal utility approach. Chapter 5 elaborates on the proposed greedy scheduling algorithm and discusses the scheduling heuristics implemented. Chapter 6 presents a methodology for performance evaluation and testing of the polymorphic scheduler framework. This chapter details the algorithm for generating random graphs, which serve as benchmarks for testing the proposed scheduler framework. Chapter 7 discusses the experimental setup and the simulation results, which demonstrate the performance benefits of the proposed greedy scheduler algorithm over classical scheduling schemes.

CHAPTER 2. Related Work

The related work for the thesis can be categorized into three main classes. The first class of literature is about the usage of sigmoid function for modeling user satisfaction in mobile systems. The polymorphic thread scheduler proposed in thesis, employs the sigmoid function to capture user satisfaction changes. The second class of literature explores the design techniques for Hybrid Reconfigurable Systems (HRS), an emerging trend in high performance embedded computing systems. The third class of papers discuss about admission control, which is implemented as part of the resource allocation strategy in an embedded system.

2.1 Hybrid Reconfigurable Systems

Embedded domain applications require high computing power. Jason et Al. [2006], proposed the methodology to migrate application portions to custom hardware or ASIC (Application Specific Integrated Circuit). Hybrid Reconfigurable System (HRS) is the ideal computing platform which supports execution of a diverse class of applications. These systems have reconfigurable fabric interspersed with high performance CPU cores. Hence, programming models and operating system support for Hybrid Reconfigurable Systems (HRS) has gained a lot of interest in the embedded systems community. Traditional programming models and operating systems for hybrid systems have treated CPU cores as masters and the reconfigurable fabric as slaves. Recently proposed programming models such as H-threads model in D.Andrews et Al. [2004] Peck et Al. [2006], have introduced the concept of abstraction at the process level for Hybrid Reconfigurable systems. The H-threads programming model abstracts the FPGA/CPU components to form a custom unified multiprocessor architecture platform. Hence the designer is freed from specifying and embedding platform specific instructions for communicating across the Hardware/Software Interface.

David et Al. [2005] talks about the design of a multithreaded RTOS kernel Hthreads - for Hybrid CPU/FPGA systems. Jason et Al. [2006] discusses the methodology used by the scheduler to execute software threads and threads implemented in programming logic. The essential feature with this model is that Operating System thread services such as Thread Management, Thread Synchronization Primitives, and Thread Scheduling components are moved to hardware to support scheduling of threads across the Hardware/Software Boundary. The other relevant works on Operating System design for Hybrid Reconfigurable Systems (CPU/FPGA Hybrid systems) is discussed in Nollet et Al. [2003], Mignolet et Al. [2003], Nollet et Al. [2008]. The papers on Hybrid Reconfigurable Systems, do not account for thread polymorphism. In these systems, the design space for the scheduler is limited, as the scheduler can categorize a thread only as software or a hardware thread. This voids out the advantages that might be offered by investigating other design spaces. In general, the embedded system designer can realize a thread's functionality using different algorithms. In other words, a thread can have multiple software morphisms. The polymorphic thread scheduler helps the embedded system designer explore such design spaces. The concept of thread morphism and its associated benefits are examined in greater detail in Chapter 3.

2.2 Literature on Sigmoid Function

In our polymorphic thread scheduler design, the objective function to be maximized is user satisfaction. We accomplish the task of maximizing user satisfaction by modeling it using the sigmoid function. Chapter 3 talks in detail about how user satisfaction is modeled using sigmoid function.

The work by Nicholas et Al. [2003] Sourav et Al. [2005] have used sigmoid function for modeling user satisfaction. The effectiveness of sigmoid function lies in modeling variations between user satisfaction and service quality as mentioned in Xiao et Al. [2001], Stamoulis et Al. [1999].

Depending on the Quality of Service (QOS) offered to an application, the corresponding user satisfaction changes. Ahmad et Al. [2005] addresses the issue of increasing user satisfaction by preempting resources from other applications. When higher priority applications need to be executed, lesser privileged applications are preempted. Sourav et Al. [2005] Pal et Al. [2005] model user satisfaction/dissatisfaction using user irritation, i.e., the amount of performance degradation or delay the user is willing to tolerate. Alpha is the parameter denoting service quality in the sigmoid function. It is also a measure of user sensitivity to performance degradation. Hence for premium users, parameter alpha's value is higher as users are willing to pay a high price for a service and these users are more sensitive to performance degradation. Nicholas et Al. [2003] proposes a Radio resource allocation strategy and discusses how sigmoid function is used for modeling the user satisfaction for the different class of users. Current day mobile phones, in addition to traditional voice services, offer a broad range of multimedia application support to mobile users. In order to accommodate both these class of services, an efficient resource management and allocation scheme as presented in Sampath et Al. [1995] Zhao et Al. [2002] is needed. The users are categorized into different classes depending on the revenue paid. Sourav et Al. [2005] Pal et Al. [2005] classify the traffic for user applications into conversational, interactive and background. Each user class supports all services with different commitment depending on the delay, the user is willing to tolerate for each traffic class. Other relevant approaches such as Zhao et Al. [2002], Liang et Al. [2002], propose resource management schemes for future generation wireless networks.

2.3 Literature on Admission control

In real time systems, admission control determines the feasibility for task scheduling. Admission control is a process which determines how to allocate network resources, e.g. bandwidth to different applications. An application that wishes to use the network's resources must first request a QOS connection, which involves informing the network about its characteristics and QOS requirements. If there are sufficient resources in the network to guarantee the QOS level, then the application is admitted into the system. Admission control is implemented in the first phase and the second phase reserves bandwidth and does resource allocation to admitted requests. Pal et Al. [2005], Zhao et Al. [2002] present radio resource management schemes which implements admission control Pellizoni et Al. [2007]. Admission control is also implemented in the polymorphic scheduler, where threads are admitted into the system based on their contribution to the user satisfaction function. We elaborate about how admission control is implemented in our scheduler in chapter 5. In the next chapter, i.e. Chapter 3, we introduce the underlying concepts and formulate objective function for the polymorphic embedded system.

CHAPTER 3. INTRODUCTION

3.1 Concept of Morphism

Let us introduce the concept behind morphism in this section. Morphism is the property to take up a specified form. In other words, morphisms are alternate ways of implementing a thread's functionality. A thread's morphism decides the resource consumption for a thread and its contribution to the application's performance metric. The morphisms differs in their resource requirements to realize a thread's functionality. For illustration, let us assume a thread has three morphisms. The first thread morphism can be tuned for faster execution, second optimized for memory storage, while the third might be designed to operate in a power-saver mode. Moreover, a thread's behavior could be implemented in software/hardware. Multiple software implementations possible for a thread by changing the algorithm used to realize a thread's functionality.

Morphism selection can be done at different levels such as (Algorithm or Design level), Source code Level, Compile level etc. For instance if a thread needs to perform sorting, heap sort, merge sort and quick sort are the different design choices. Let us assume that we picked one among these design choices at the source code level. At the source code level, parallel and sequential code implementations of a procedure form the different morphisms. At the compile level, compiler optimized versions of the same program are the various morphisms. Hence, there is a close analogy between thread morphisms and software optimization. Software optimization involves modification of a software system aspect for efficient execution or for consuming fewer resources. Similar to morphisms, software optimization can be carried out at various levels such as at Algorithm, source code level etc.

Let us demonstrate the concept behind thread morphisms using an illustration. For instance, given below is a *for* loop to add two arrays of size 1000 and store it in a third array.

```
**for** $i = 1$ to 1000 **do**
    $c[i] = a[i] + b[i]$
**end for**
```

The *for* loop where the index variable runs from 1-1000 can be executed serially on the functional units of the processor. This constitutes one morphism, or way of executing the procedure onto the processor. Another morphism could be that the loop can be parallelized and executed on a vector adder unit. Depending on compiler optimizations available and also based on resource availability, one among these two morphisms will be chosen at run time. Consider the following C code snippet, whose purpose is to obtain the sum of all integers from 1 - N.

```
**for** $i = 1$ to $N$ **do**
    $sum+ = i;$
**end for**
```

Assuming no arithmetic overflow, the above code can be rewritten efficiently using a mathematical formula sum $= (N * (N + 1)) >> 1$. We see that $>> 1$, is right shift by 1, which is equivalent to divide by 2 when N is non-negative. Our choice of the algorithm version, depends on the problem size N. For lower values of N the first morphism version is preferred over the second. This is because, the looping operation takes lesser time to execute compared to the multiplication and bit-shifting hardware time complexity. As the value of N increases, the second version might be opted.

Morphism of a thread plays a role in determining how much a thread's implementation enhances the performance metric. Each thread morphism differs in its resource requirements in order to realize a thread's behavior. The scheduler decides on the appropriate morphism choice for a thread depending on current resource availability and the thread's relative priority. For instance, some morphism might achieve considerable reduction in execution time, but at the price of making it consume more memory. In systems where memory is at a premium, a morphism which consumes less memory is preferred over the other morphisms. Modern day processors have Graphic Processor Units (GPU), Field Programmable Gate Arrays (FPGA), CPU and other heterogeneous computing units. The motivation of the morphism problem in such cases, is to come up with the ideal system design, which includes the proper mix of processor units, FPGA and GPU units in order to achieve enhanced user satisfaction. The next section elaborates on user satisfaction and how it is modeled using the sigmoid function.

3.2 Performance Assessment in Embedded System

In an embedded system, user input is provided usig an input device such as mouse or pen and output can be realized using LCD Display and speakers. In any typical embedded system, it is human perception that matters the most. Unlike many conventional embedded systems, where the objective of the system is to increase performance, reduce power or energy consumption, our system plays an emphasis on increasing user satisfaction. In conventional embedded systems, the makeup of applications is known at design time and the user has no way of dictating priority for the applications. This is exactly where our scheduling algorithm differs in its objective. The scheduler dynamically schedules threads from multiple applications with the intent of maximizing user satisfaction. The marginal increase in user satisfaction per unit resource decides application priority. This is because of the fact that user perception is a clear indicator of application performance. Since there are limits to human perception, there are upper and lower limits to the user satisfaction function. There is a lower limit on the perception of human eye, or lower knee below which there is zero or no user satisfaction. There is a middle region, where there is non-linear increase in user satisfaction with increase in performance metric. Voice perception coupled with perceptible frequency range exhibits these characteristics. In order to accurately capture user experience, user satisfaction is modeled using sigmoid function, which is illustrated in the subsequent section.

3.3 Modeling User Satisfaction

Lower Knee In any embedded system, user-perceived satisfaction, which is a function of the application throughput, is what matters the most. The aim of an embedded system designer, is to maximize this user-perceived satisfaction. Since there is a limit to the perception of the human senses, there is a lower bound on the performance metric, below which, there is zero or no user satisfaction. In other words, this marks the lower threshold of the performance metric, below which human perceived satisfaction is zero as shown in Figure 3.1.

Upper Knee In a similar manner, human eye cannot distinguish marginal user satisfaction increase obtained due to additional performance gains beyond a particular point. This establishes the upper bound or the upper knee in the S-shaped sigmoid curve, corresponding to a sigmoid function as shown in Figure 3.1. Above this region, the user is unable to perceive any notable increase in performance.

Middle Region Also there is a middle region between these lower and upper threshold values, where the marginal increase in user satisfaction exhibits non-linear behavior with increasing values of performance metric. Voice perception, audio and video applications exhibit this behavior. Sigmoid function captures the user experience for all these applications. The User Satisfaction function, represented by $u(t)$, modeled using the sigmoid function has a characteristic S-shaped curve whose equation is as follows.

$$u(t) = \frac{1}{1 + c_0\ e^{-c_1 t}}$$

s

In the above equation $c_0, c1$ are constants. The term t in the expression for sigmoid function, represents the normalized throughput. $Throughput_{max}$ is the maximum throughput among all the thread morphisms. $Throughput_{min}$ is the thread morphism with minimum throughput. $Throughput_{mid}$ is the thread morphism with median throughput. Normalized throughput t, where $-1 \leq t \leq 1$ is given by the following expression. Since normalized throughput is the parameter in the sigmoid function, user satisfaction is a function of normalized throughput. The normalized throughput value helps in achieving a bounded value for sigmoid function, due to convergence of Taylor series. Throughput information is provided by the embedded system designer in form of a morphism table, which is discussed in Chapter 4.

$$t = \frac{Throughput_{cur} - Throughput_{mid}}{Throughput_{max} - Throughput_{min}}$$

The value of sigmoid function is bounded between 0 and 1. For illustration let a user be watching or playing a movie with DVD clarity. In this case, user satisfaction would have already reached its peak and any further increase in clarity is unlikely to be perceived by the end user. This point is chosen as the upper threshold. Beyond this point, there is no significant increase in user satisfaction, with increase in application's performance metric. The sigmoid function clearly captures that behavior and another reason for choosing this function is because it is defined at all points for parameter t. The sigmoid function therefore helps in clearly establishing the lower and upper bounds for performance metric. This is an advantage over conventional systems, where there is no clear way to establish these performance metric bounds.

The parameters of the sigmoid function can be either discrete or continuous. In the case of video applications, the frame rate is a discrete parameter, since digital video sampling is done at discrete intervals. On the other hand, webpage loading delay is an example of a continuous parameter. Frame rate is one of the parameters which helps capture user experience in the case of visual multimedia applications such as video chatting, teleconferencing etc. A video player plays movie files/DVD can have a frame rate of 15 frames/sec (fps) to 30 fps in steps of 2 fps. 3D Gaming applications need 30 fps to 60 fps in steps of 5 fps and video chatting has frame rate of 3 fps to 15 fps. The diagram illustrated in Figure 3.1 shows the plot of the user satisfaction function versus the application's performance metric namely throughput.

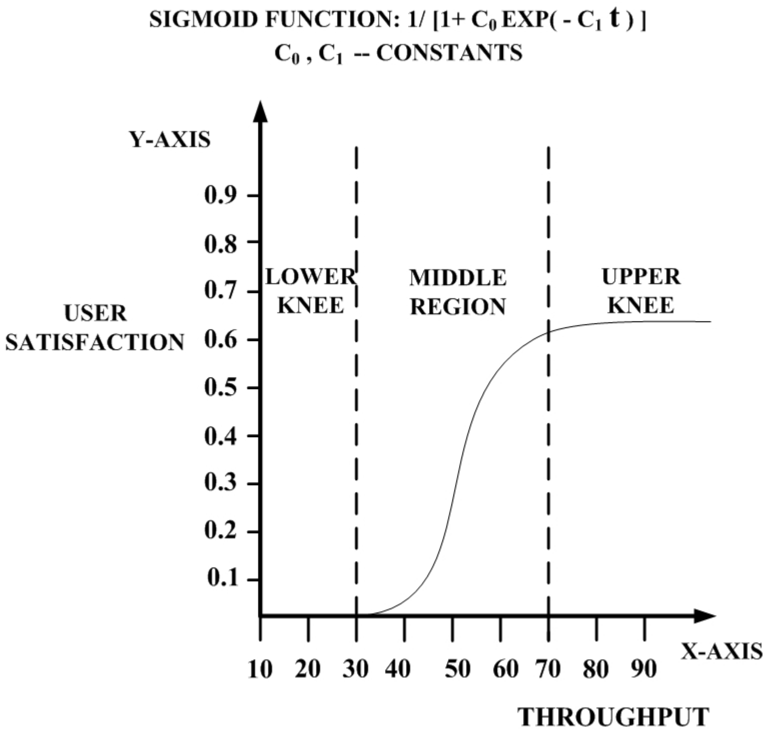


Figure 3.1 User Satisfaction Plotted Against Throughput

3.3.1 Approximation of sigmoid function

In the sigmoid equation, let us assume values for constants, $c_0 = 1$, and $c_1 = 1$. The value of the sigmoid function can be approximated using the following Taylor series expansion.

$$\frac{1}{1+e^{-t}} = \frac{1}{2} + \frac{t}{4} - \frac{t^3}{48} + \frac{t^5}{480} + \ldots$$

Since we know that $-1 \leq t \leq 1$, and the scheduler must make decisions quickly, we can approximate the value of the user satisfaction by considering the first N terms. The value of N is decided, based on the precision desired for the system and the time taken to compute the approximation. Fixing the optimal number of terms, would speed up scheduling decisions and give us the right precision. In general, since the scheduling algorithm itself should not be an overhead, the first three or four terms in the Taylor series expansion are considered to evaluate the user satisfaction function. In the next section, we describe the Application model used in the Polymorphic thread scheduler. The Application model depicts a typical state scenario in any embedded system.

3.4 Overview of Application Model

The system framework consists of N multithreaded applications $A_0, A_1 \ldots A_{n-1}$, with each application A_i having p_i threads. The morphism space for thread $T_{i,j}$ $0 \leq j < p_i$ is denoted by $T_{i,j,r}$ where $0 \leq r < m_{i,j}$. Here $m_{i,j}$ denotes the morphism space for the thread $T_{i,j}$.

3.4.1 Application State Transition Graph

In this section, we introduce the notion of an **Application State Transition Graph (ASTG)**, to capture the asynchronous nature of external events in an embedded system. Here, a state is labeled with an n-bit vector, where the i^{th} bit represents if application A_i $0 \leq i < n$ is active or not. In general, only a fraction of the entire space of 2^n states are feasible, due to the design constraints enforced by the embedded systems designer. The embedded system design is greatly simplified, as the resource allocation problem has to be solved at each state in the Application State Transition Graph(ASTG).

Let us consider an Application State Transition Graph as shown in Figure 3.2. For illustration, we study the case with two applications in the embedded system, namely video and phone. We have four states in the system namely $\mathbf{S_0}, \mathbf{S_1}, \mathbf{S_2}, \mathbf{S_3}$. Initially the system is in the idle or start state S_0, which reflects no user activity. When the user wants to watch a video or a movie, a state transition occurs from state S_0 to state S_1 where, only the video application is active. When the system is in state S_0, and if the user receives a phone call, a state transition occurs to state S_2. This is an indication, that the user is attending a phone call and is not engaged in any other activity. When the user is watching a video, and if there is a phone call, the system allows both these applications to co-exist and transitions to state S_3. The next section describes scheduling in Real time systems and discusses in detail about polymorphic thread scheduling.

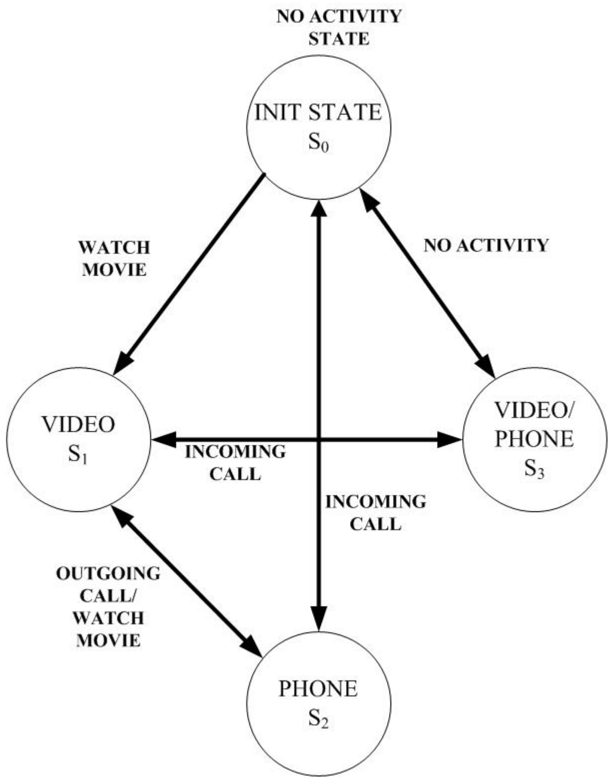


Figure 3.2 Illustration of Application State Transition Graph

3.5 Scheduling in Real-time Systems

In Real time systems, admission control decides the feasibility for task scheduling. If a certain level of QOS or minimum level of QOS cannot be guaranteed for a thread, it is not admitted into the system. The application wishing to be scheduled onto the processor, informs the processor about the characteristics of its computational load and its desired level of QOS. The thread scheduler corresponds with the resource allocation layer and decides whether to admit or reject the application's request to enter the ready queue. If resources are not available to guarantee a certain level of QOS, the task is not admitted. The task is admitted at some later point of time when the system has sufficient resources. The objective here is to ensure execution of tasks which have stringent deadlines. In general, the feasibility for scheduling a set of tasks together is decided by their execution times and deadlines. Examples of some of the scheduling strategies are Earliest Deadline First, Rate Monotonic Scheduling(RMS), Shortest Job First(SJF) etc. The objective function in these strategies is to maximize the number of tasks admitted into the system.

3.6 Polymorphic Thread Scheduling

Thread scheduling poses a lot of challenges in a polymorphic embedded system environment. The scheduler has to deal with two cases which might arise during scheduling. Let us discuss the motivation behind polymorphic thread scheduler design by considering a simple scenario of running a single multithreaded application in the system. We then generalize the approach for N multithreaded applications running in the system. In both these cases, the scheduler has to choose a common optimization metric across applications.

3.6.1 Single Application Scenario

The scheduler decides to optimize the performance metric for that application e.g. Maximize System throughput. When there is resource contention among threads, the thread with higher marginal increase in performance metric is given precedence over others.

3.6.2 Multiple Application Scenario

The scheduler design for a multiple application multi-threaded scenario becomes a lot complex. When multiple applications are active, with each application consisting of multiple threads, the question is which thread from which application is to be scheduled. The problem's complexity increases when there is more than one morphism implementation is possible for a thread. The aim of the scheduler is to come up with the correct morphism choices for the different threads to be scheduled. Hence the scheduler's job is to decide the admissible set(threads which can be admitted into the system) as well as come up with morphism choices for ready-to-run threads.

3.6.3 Need for Objective Function

We need a common metric to help us determine the marginal utility of scheduling a thread per unit resource. We formulate an objective function for the multithreaded multiple application framework, with user satisfaction as the optimization metric. The objective function aids in making resource allocation decisions and establishes the underlying application model. We introduce the concepts of thread control flow graph and scaling factor in following section, which forms the basis for the thread scheduler's objective function.

3.7 Thread Control Flow Graph

We build the objective function S for a single multithreaded application. The scheduler chooses to optimize the performance metric for an application, e.g. System or network throughput. Throughput is expressed in terms of frames/sec or network throughput B/sec. The scheduler's goal is to maximize this throughput at the sink node. This is because of the fact that an application's actual user satisfaction can be perceived only at the sink node In our system, a subset of N multithreaded applications can be active at any time instant. A single multithreaded application's functionality can be represented using a data structure called as thread control flow graph. The graph clearly captures the computational and communication flow between threads constituting an application. Nodes in the graph represent the threads and the edges between nodes at different levels denote the scaling factor corresponding to each thread. Each Application A_i, $0 \leq i < n$ consists of p_i threads $T_{i,j}$, $0 \leq j < p_i$. Each of these threads are designed by application designers for multiple morphisms. The morphism space for a thread $T_{i,j}$ is represented by $m_{i,j}$, $0 \leq r < m_{i,j}$.

3.8 Scaling Factor

Let us introduce the notion behind scaling factor associated with a particular thread. The scaling factor determines the number of computational units of a particular thread required to generate one computational unit of output information at the sink node. For instance if 1 frame at the output of a thread $T_{i,j}$, results in 1 frame at the output of the sink thread scaling factor $s_{i,j} = 1$. If $f(A_i)$ represents the performance metric for application A_i, the aim of the local optimization function is to maximize $s_{i,j} * f(A_i)$. An application's actual user satisfaction is perceivable only at the sink node in the thread control flow graph and the scheduler's goal is to maximize the same. Therefore the maximization of performance metric problem, is mapped into a local optimization problem. Since the scaling factor is a normalized metric, for any thread j, $0 \leq j < p_i$, we have $0 \leq s_{0,j,k} \leq 1$. Here k denotes the edge associated with a particular thread j. If the total number of outgoing edges from thread j is e then $0 \leq k < e$.

Recall the fact that, morphism corresponds to the different ways of implementing a particular algorithm choice. The scaling factor for a thread is dependent only on the algorithm choice and not on morphism selection. Moreover, it decides a thread's relative contribution to the overall throughput. It is dependent on the design algorithm choice and remains unaffected by morphism changes. Morphism of a thread decides the per unit time notion of the performance metric. Morphism has zero effect on the scaling factor and morphism changes affect the individual thread's throughput and also system throughput. Let us better understand this fact with an illustration.

3.8.1 Illustration - Scaling Factor

Let us illustrate how scaling factor and morphism are independent of each other. Consider four equal sized jobs assigned to 4 strong individuals. Four equal sized jobs are assigned to 4 strong individuals. The jobs cannot be shared among people and each person is responsible for completing the task assigned to him. Assuming that one among these strong persons falls sick, we replace him by a weaker individual. Observe that the amount of work assigned to the person remains the same, irrespective of the nature of individual. In other words, the workload assigned to a person remains constant, regardless of the physical stature of the person. When a person is exchanged in place of another, the time taken to complete the task changes thereby affecting system performance.

3.8.2 Analogy with morphisms

Drawing similarity between the previous illustration and morphisms, tasks are analogous to threads. The work expected from each person is comparable to the thread throughputs. The switch in person's nature is similar to switch in a thread's morphism. When a person's nature changes from strong to weak, it affects the task's throughput. Similarly when a thread undergoes a morphism change, there is a corresponding throughput change affecting system throughput. The figure 3.3 illustrates the above analogy with the strong-weak example. The concepts relating to thread control flow graph and scaling factor have been explained. The following section makes use of these concepts to formulate the objective function for the polymorphic thread scheduler.

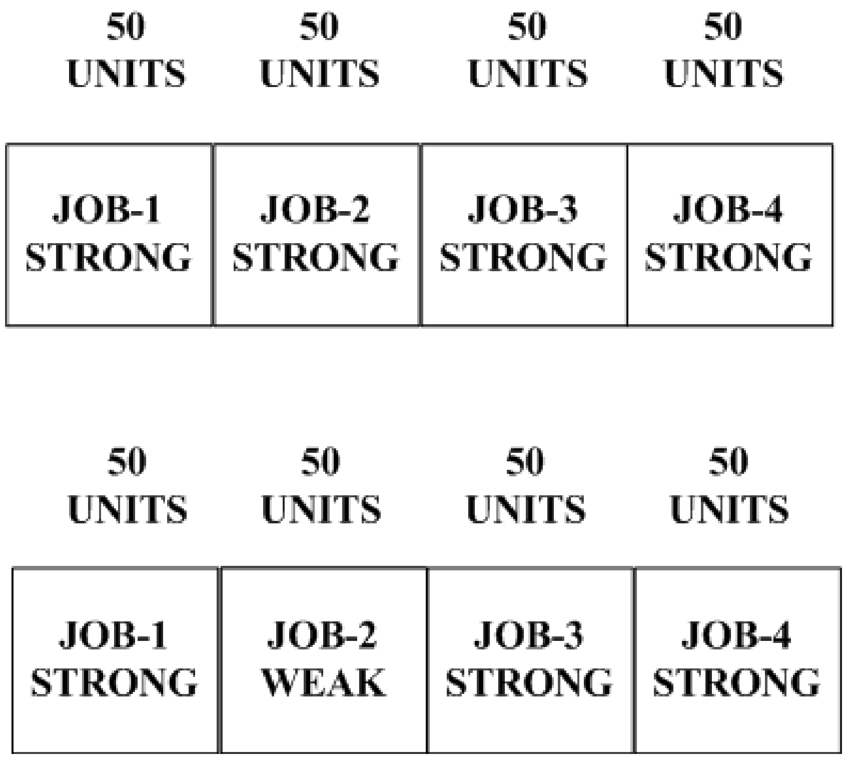


Figure 3.3 Independence of Scaling Factor and Morphisms

3.9 Objective Function

We adopt the following approach to model the system behavior. As the first step, we model the behavior of a single multi-threaded application and then generalize the approach to model the system behavior of N applications. An application A_0's functionality, represented by a thread control flow graph is illustrated in Figure 3.4. The nodes in the graph represent the threads and the edges denote the scaling factors associated with the threads. Since the scaling factor is a normalized metric, for any thread j, $0 \leq j < p_i$, we have $0 \leq s_{0,j,k} \leq 1$. Here k denotes the edge associated with a particular thread j. If the total number of edges in the graph is e then $0 \leq k < e$. One interesting fact to note is that, a thread's contribution to the overall application throughput is dependent on the threads and edges which are active at any time instant(active cut). From Figure 3.4, it is evident that a thread could be part of several cuts at different time instants. For instance, both the threads $T_{0,1}$ and $T_{0,2}$ are part of cuts C_1 and C_2.

Let us consider a single multithreaded application A_0 having p_i threads, $T_{0,j}$ for $0 \leq j < p_i$. Let the performance metric be throughput, for these threads, denoted by $Throughput(T_{0,j})$. A thread's throughput can be decided only when a corresponding morphism has been selected for it. The morphism space or the maximum number of morphisms possible for a thread $T_{i,j}$ is denoted by $m_{i,j}$. Let us find out a thread's contribution to the overall performance metric. As we mentioned earlier, this depends on the threads in the application, which are lined up for execution in the ready queue. The sink node in the thread control flow graph is where the user satisfaction for an application can be perceived. Since we cannot exactly determine an application's user satisfaction, a greedy approach is adopted, where the sensitivity of the currently executing threads is maximized. Hence, the maximization problem of performance metric translates into a local optimization problem, where we approximate the effect of currently executing threads on the application's actual user satisfaction.

Let the threads present in the cut C_2 for application A_0 be active. Hence, threads $T_{0,1}, T_{0,2}, T_{0,5}$

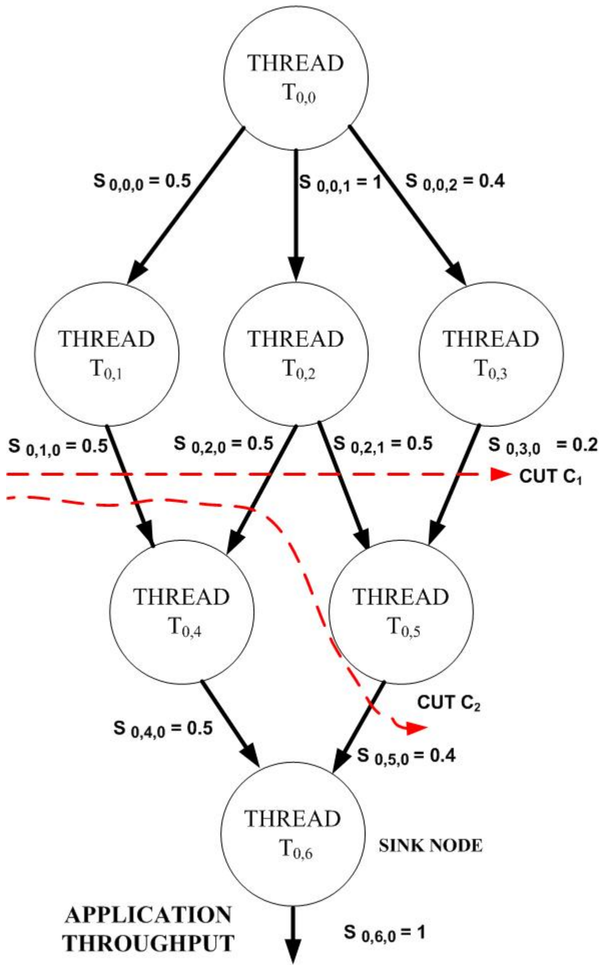


Figure 3.4 Illustration - Thread Control Flow Graph

are waiting in the ready queue and their scaling factors, $s_{0,1,0}, s_{0,2,0}, s_{0,5,0}$ are 1, 0.5 and 0.4 respectively. The combined throughput of these three threads is obtained using the following equation.

$$\sum_{j,k \in C_2} s_{0,j,k} * throughput(T_{0,j})$$

Hence, the thread morphism which maximizes the objective function,i.e. throughput needs to be ascertained. We can approximate or estimate application's throughput, based on the throughputs of the active set of threads. The application designer knows the resource requirements of each thread morphism and hence its corresponding throughput $throughput(T_{0,j})$ can be determined using a table lookup. Let us determine thread $T_{0,2}$'s relative contribution to the overall throughput considering that cut C_2 is active.

$$\frac{s_{0,2,0}}{\sum_{j,k \in C_2} s_{0,j,k}} * \mathit{throughput}(T_{0,2}) = \frac{0.5}{1.9} * \mathit{throughput}(T_{0,2})$$

The value computed above, is the contribution of thread $T_{0,2}$ to the overall throughput and varies for each morphism r where $0 \leq r < m_{i,j}$, denoted by $\mathit{throughput}(T_{0,2,r})$. If the thread $T_{0,2}$ is part of another active cut, namely C_1, where the scaling factors for the threads are $0.5, 1, 0.2$ for threads $T_{0,1}, T_{0,2}, T_{0,3}$ respectively, thread $T_{0,2}$'s contribution to the overall throughput is as follows.

$$\frac{s_{0,2,0} + s_{0,2,1}}{\sum_{j \in C_1} s_{0,j}} * \mathit{throughput}(T_{0,2}) = \frac{1}{1.7} * \mathit{throughput}(T_{0,2})$$

Let us restate the maximization problem in terms of the throughput of a thread morphism, namely $\mathit{throughput}(T_{0,j,r})$. Our aim is to maximize the objective function given below.

$$S = \sum_{j=0}^{p_i} \sum_{r=0}^{m_{0,j}-1} s_{0,j,k} * \mathit{throughput}(T_{0,j,r}) * \mathit{Ready}(T_{0,j}) * M_{0,j,r}.$$

$$\mathit{Ready}(T_{i,j}) = \begin{cases} 1 & \text{if thread } j \text{ is in ready to run} \\ 0 & \text{otherwise} \end{cases}$$

$M_{0,j,r}$ is a Boolean variable, which represents if morphism r of a thread j is active or not in the current scheduling cycle. Value of $M_{0,j,r} = 1$ if thread $T_{0,j}$ assumes morphism r, $0 \leq r < m_{0,j}$, in the current scheduling cycle. Otherwise $M_{0,j,r} = 0$, if the thread does not assume this morphism. Maximum number of morphisms possible for a thread is given by $m_{0,j}$. In general, the performance metric for a thread is denoted by $f(T_{0,j})$. The performance metric makes more sense, when it is specific to a thread morphism and is denoted by $f_{0,j,r}$. The objective function can be modified as follows.

$$S = \sum_{j=0}^{p_i} \sum_{r=0}^{m_{0,j}-1} s_{0,j,k} * f_{0,j,r} * \mathit{Ready}(T_{0,j}) * M_{0,j,r}$$

3.9.1 Constraints

The scheduling algorithm is bound by certain constraints at run time. Constraint one is that, the scheduler also has to ensure that at most only one morphism for a thread can be active during a scheduling cycle, by enforcing a constraint on the value of $M_{0,j,r}$, i.e., $\sum_{r=0}^{m_{0,j}-1} M_{0,j,r} \leq 1$, where $\forall j, 0 \leq j < p_i$.

Also another constraint that must be obeyed is, the sum of the total number of resources of each type allocated to all the active threads in the application can never exceed the total number of resources present in the system. If we have q different resource types present in the system ranging from $R_0, R_1 \ldots R_{q-1}$ where each resource type can represent memory, processing units or I/O devices. If $res_{i,j,r,a}$, represents the number of resource units of type R_a allocated to thread j $0 \leq j < p_i$ in application A_0, where resource type $a \in \{0, 1, 2 \ldots q-1\}$, the second constraint is as follows.

$$\sum_{j,r} M_{0,j,r} \times res_{0,j,r,a} \leq R_a \forall a \in \{0, 1, 2 \ldots q-1\}$$

3.10 User Satisfaction as Objective Function

From the Application State Transition Graph(ASTG), we can generalize the relative throughput contribution of a thread. If we have a single application A_0, then each thread l's relative contribution is given by the following equation, $0 \leq l < p_i$. Here k' represents the set of outgoing edges from thread l, part of the active cut C_1.

$\frac{\sum_{k \in k'} s_{0,l,k}}{\sum_{j,k \in C_1} s_{0,j,k}} * throughput(T_{0,l})$.

We can restate objective function in terms of user satisfaction function, which we want to maximize using the following expression.

$$USat = \sum_{j=0}^{p_i} \sum_{k \in cut} \sum_{r=0}^{m_{0,j}-1} s_{0,j,k} * UserSat(NormalizedThrput(T_{0,j,r}) * Ready(T_{0,j}) * M_{0,j,r}$$

$UserSat(NormalizedThrput(T_{0,j,r}))$ denotes the normalized user satisfaction increase obtained due to a thread morphism and is given by the following expression.

$$USat = \sum_{j=0}^{p_i} \sum_{k \in cut} \sum_{r=0}^{m_{0,j}-1} s_{0,j,k} * UserSat(NormalizedThrput(T_{0,j,r})) * Ready(T_{0,j}) * M_{0,j,r}$$

Hence substituting the Sigmoid function for the User Satisfaction function, we have the following expression.

$$USat = \sum_{j=0}^{p_i} \sum_{k \in cut} \sum_{r=0}^{m_{0,j}-1} s_{0,j,k} * \frac{1}{1 + e^{\frac{Thrput(T_{0,j,mid}) - Thrput(T_{0,j,r})}{Thrput(T_{0,j,max}) - Thrput(T_{0,j,min})}}} * Ready(T_{0,j}) * M_{0,j,r}$$

Generalizing the above expression for N applications in the system, we have the following equation.

$$USat = \sum_{i=0}^{N-1} \sum_{j=0}^{p_i} \sum_{k \in cut} \sum_{r=0}^{m_{i,j}-1} s_{i,j,k} * \frac{1}{1 + e^{\frac{Thrput(T_{i,j,mid}) - Thrput(T_{i,j,r})}{Thrput(T_{i,j,max}) - Thrput(T_{i,j,min})}}} * Ready(T_{i,j}) * M_{i,j,r}$$

CHAPTER 4. MARGINAL UTILITY APPROACH

4.1 Scheduler Data Structures

The sections in this chapter are organized in the following manner. The first section details the data structures maintained by the scheduler and the constraints for operation of the polymorphic thread scheduler. The subsequent sections introduce the idea behind Marginal Utility Scheduling and elucidate it in finer detail. The scheduling algorithm has tables as data structures, in order to maintain information about the different thread morphisms. Any application thread requires resources for execution, in order to produce a certain throughput. Since these tables store morphism information for the different application threads, the data structure is called morphism table. Morphism tables are maintained for each thread j, $0 \leq j < p_i$, for every application A_i, $0 \leq i < n$ in the system. The entries in the morphism table are sorted in decreasing order of their performance metric (throughput). Hence, the first row in the morphism table corresponds to the thread morphism which yields maximum throughput. The columns in the morphism table are as follows. There is a column to index the different morphisms for a thread and the subsequent columns store details about the amount of resources required for its execution and throughput of the thread morphism. The resources in the system could be the amount of Random Access Memory (M) required, Disk Memory (D) and Processing Units (P), which form the various columns M, P, D in the morphism table. The application designer can statically estimate the needs of the thread morphisms and sort the entries in the table in decreasing order of the throughputs. The constraints for the scheduling algorithm are as follows.

The scheduler algorithm is bound by 2 constraints. Constraint 1 is as follows. A thread can be assigned a maximum of one morphism r, $0 \leq r < m_{i,j}$. The morphism space for thread $T_{i,j}$ is denoted by $m_{i,j}$. Hence, a morphism table for a thread has a total of $m_{i,j}$ rows or morphism entries. $M_{i,j,r}$ is a Boolean variable, which represents if morphism r of a thread j is active or not for Application A_i in the current scheduling cycle. Value of $M_{i,j,r} = 1$ if thread $T_{i,j}$ assumes morphism r, $0 \leq r < m_{i,j}$, in the current scheduling cycle. Otherwise $M_{i,j,r} = 0$, if the thread does not assume this morphism. Constraint 1 is given by the equation $\sum_{r=0}^{m_{i,j}-1} M_{i,j,r} \leq 1$, $\forall i, j$. Constraint 2 states that the sum of resource requirements for thread morphisms must never exceed the total resource limit. The above statement must hold good for every resource type present in the system. The total number of resource types in the system are denoted by q, with each resource type denoted by R_a,a$\in \{0, 1, 2 \ldots q - 1\}$. If (M, P, D), denotes resources present in the system, memory requirements of currently running thread morphisms should never exceed the total available memory in system. The same constraint should be enforced, for the other resource types in the system namely Processing Elements and Disk Memory. If $R_{i,j,r,a}$, represents the number of resource units of type R_a allocated to thread j, $0 \leq j < p_i$ in an application A_i, $0 \leq i < n$, the second constraint is as follows.

$$\sum_{i,j,r} M_{0,j,r} \times R_{i,j,r,a} \leq R_a \forall a \in \{0, 1, 2 \ldots q - 1\}$$

4.2 User Sensitivity

In this section, we introduce the concept behind user sensitivity, before describing how resource contention is modeled in a multiple application multithreaded scenario. In any embedded system, human perception is the actual measure of user satisfaction. The sink node in the thread control flow graph is where, the actual user satisfaction for an application can be perceived. But in any scheduling cycle, the executing threads might be located elsewhere in the thread flow graph. So, we need to approximate the user satisfaction effect of the currently executing threads on the application's actual user satisfaction, referred to as user sensitivity. A greedy approach is adopted, to predict the sensitivity on the sink node. The sum of user sensitivities of individual threads part of the active cut is a good approximation of the application's actual user satisfaction. Hence for every thread part of the active cut, once morphism assignment is done and resource constraints met, user sensitivity value is computed for all thread morphisms. The value of user sensitivity is the approximation of first N terms in the sigmoid function. The following equations show how user sensitivity fits into the sigmoid function, used to model user satisfaction. The objective function (user satisfaction), which we want to maximize is given by the following expression.

$$USat = \sum_{i=0}^{n-1} \sum_{j=0}^{p_i} \sum_{k \in cut} \sum_{r=0}^{m_{i,j}-1} s_{i,j,k} * \frac{1}{1 + e^{\frac{Thrput(T_{i,j,mid}) - Thrput(T_{i,j,r})}{Thrput(T_{i,j,max}) - Thrput(T_{i,j,min})}}} * Ready(T_{i,j}) * M_{i,j,r}$$

The Sigmoid function's approximation using taylor series is as follows.

$$\frac{1}{1+e^{-t}} = \frac{1}{2} + \frac{t}{4} - \frac{t^3}{48} + \frac{t^5}{480} + \ldots$$

The first step in the algorithm is to assign morphisms for threads part of the active cut. The starting point or initial morphism assignment level for all threads could be at any entry in the morphism table. The scheduler adopts various scheduling heuristics and accordingly the starting point in the morphism tables can be decided. The entry position could be at the bottommost morphism entry with minimum throughput, topmost one which yields maximum throughput or at the median entry, adopting a binary search approach. The polymorphic thread scheduler has to come up with an efficient morphism assignment strategy for threads lined up for execution in the ready queue. The morphism choices for the threads depend on the instantaneous resource availability. In a multiple application, multithreaded scenario, the scheduling complexity increases. When multiple applications are active, each application consisting of multiple threads, the question is which application thread would be scheduled. The problem's complexity increases when more than one morphism implementation is possible for a thread. Hence, we need an effective scheme for modeling resource contention which will help us make resource allocation decisions. The following section elaborates about this topic in greater depth.

4.3 Modeling Resource Contention

This section explains how resolve contention is resolved in a multiple application scheduling scenario. The objective of our scheduling algorithm is to maximize user satisfaction in the system. In addition, it must also handle issues relating to resource contention. In a multiple application scenario, there must be a way to deal with the resource contention problem. There are different approaches to tackle the resource contention issue in an multiple applications scenario, $A_0, A_1 \ldots A_{n-1}$. For ease of explanation, the problem is illustrated by considering two applications A_0, A_1 with S_0, S_1, being the performance metrics corresponding to these two applications. Let $u_0(S_0), u_1(S_1)$ denote the user satisfaction functions of these two applications, expressed as a function of their performance metrics. $S_0(A_0, morph_1, morph_2)$, $S_1(A_1, morph_1, morph_2)$ represents the performance metrics for the applications expressed as a function of morphisms, where $morph_1$, $morph_2$ are any two morphism table entries. The following section elaborates on the weighted average method for modeling resource contention. The subsequent sections describe the marginal utility approach and highlight its advantages over the weighted average approach.

4.3.1 Weighted Average Method

A simple, yet straightforward way of combining resource contention is to calculate weighted average of the user satisfaction functions as given by the equation below.

$$F(S_0, S_1) = w_0 * u_0(S_0) + w_1 * u_1(S_1)$$

The above equation, which takes the weighted average of the user satisfaction functions, has several disadvantages. One main drawback is that, the weights in the above equation are constants. In practice, the weights do not remain the same during the course of program execution. Depending on the active cut (threads from application lined up for execution in ready queue), and also on morphism assignments, an application's throughput varies. If the thread throughputs vary, it affects the weighting factors and an application's user satisfaction. Also, the weighted mean equation does not capture changes (increase or decrease) in user satisfaction, with changes in morphism or configuration. Hence, it loses the essential properties of a sigmoid function. Although user satisfaction function's value is present in the equation, the cost at which it is achieved i.e., in terms of resources is not part of the equation. The sigmoid function is used to model user satisfaction, in terms of the parameter throughput t. Sigmoid function captures modifications to the user satisfaction with increase in the performance metric (throughput). When a thread switches morphism, the amount of resources assigned to it also undergoes changes. We know that when morphism or configuration changes, performance metric changes. With changes in performance metric, variations in user satisfaction function can be analyzed and plotted. In a nutshell, merely taking a weighted average of the user satisfaction function does not capture the dynamic nature of the objective function.

4.3.2 Marginal Utility Function

As discussed in the previous section, taking the weighted mean of user satisfaction functions would not work. What we need is a normalized function, which must account for an application's user satisfaction changes, considering the amount of resources assigned to it. In order to resolve resource contention among the currently executing application set, our scheduling algorithm adopts the following strategy. The application which yields higher marginal utility in user satisfaction per unit resource would be allocated with its requested resources. Hence the idea behind marginal utility approach is that, when a thread undergoes a morphism change there is a change in the performance metric. The corresponding change in the performance metric reflects a change in the application's user satisfaction function, which is captured by the sigmoid function. Changes in user satisfaction and performance metric are expressed through partial differential equations. Two applications A_0, A_1 are taken into consideration. Morphism change for application A_0 is denoted by ∂M_0. Performance metric changes are denoted by ∂S_0. As the performance metric changes, there are variations in the user satisfaction function represented by ∂u_0. Change in user satisfaction with respect to performance metric for the applications is given by $\frac{\partial u_0}{\partial S_0}$ and $\frac{\partial u_1}{\partial S_1}$. Performance metric changes with respect to morphism changes are represented by $\frac{\partial S_0}{\partial M_0}$ and $\frac{\partial S_1}{\partial M_1}$. The marginal utility for the 2 applications are given by the following equations.

$$U_0 = \frac{\partial u_0}{\partial S_0} * \frac{\partial S_0}{\partial M_0}$$

$$U_1 = \frac{\partial u_1}{\partial S_1} * \frac{\partial S_1}{\partial M_1}$$

The component $\frac{\partial S_0}{\partial M_0}$, can be approximated by the following method. For each polymorphic thread in the ready queue, corresponding to the application A_0, the throughput differences between morphisms is averaged out. In other words, the second term's approximation is given by the following equation, where $morph_1, morph_2$ are any two morphism table entries corresponding to thread $T_{i,j}$.

$$\frac{\partial S_0}{\partial M_0} = \sum_{T_{i,j} \in ReadyQueue} f(T_{i,j,morph1}) - f(T_{i,j,morph_2})$$

The marginal increase in user satisfaction for each application is computed taking all resource types into consideration. Whichever application yields higher marginal utility in user satisfaction receives more precedence during resource allocation. Hence in a nutshell, the idea behind marginal utility approach is whenever a thread undergoes morphism change, there is a change in the performance metric. The corresponding change in the performance metric triggers changes in the application's user satisfaction function, which is captured by the sigmoid function. But a common currency of marginal utility per unit resource is needed, for resolving resource contention across multiple applications. Hence morphism tables need to be normalized in order to determine the marginal increase per unit resource. The next section describes the procedure for normalization of morphism tables to compute marginal utility per unit resource.

4.4 Normalization

This section outlines the steps for normalization of morphism tables, which is followed by an illustration. Consider an application thread whose morphism table entries given in table 4.1.

Entry	Throughput	Mem	Proc Unit	Disk Mem
1	50	500	5	150
2	40	400	4	120
3	30	300	3	90
4	20	200	2	60
5	10	100	1	30

Table 4.1 Morphism Table

Index	Usersat	NorThrput	Mem	Proc Unit	Disk Mem
1	0.6224	0.5	1	1	1
2	0.5622	0.25	0.8	0.8	0.8
3	0.0000	0	0.6	0.6	0.6
4	0.4378	-0.25	0.4	0.4	0.4
5	0.3776	-0.5	0.2	0.2	0.2

Table 4.2 Normalized Morphism Table

We assume that the application thread switches morphism from entry 2 to entry 1 in the table. Considering the first three terms in the sigmoid function, the equation is as follows.

$$u(t) = \frac{1}{1+e^{-t}} = \frac{1}{2} + \frac{t}{4} - \frac{t^3}{48}$$

1. First step is to normalize each resource type with respect to the maximum number of resources required by the thread morphism.

2. Find the difference between the normalized values of morphism table entries 1 and 2. The difference is found for each resource type present in the system.

3. Calculate the average of the differences, and denote is as **Avg**.

4. Calculate the difference between the user sensitivity values and call it user sensitivity difference. Sensitivity is the effect of this particular thread on the application's overall user satisfaction. Call it **Sensdiff**.

5. Determine **Sensdiff/Avg**. This is Marginal increase in user satisfaction per unit resource and is used as the scheduling metric.

The user sensitivity per unit resource values are summed for all active threads belonging to an application. This value is used as a scheduling metric to resolve resource contention among applications. The application, which has the maximum value, will receive higher precedence over other contending applications. The illustration of the normalization approach is as follows.

4.4.1 Illustration

The bottommost morphism entry has throughput of 10 units, memory requirements being 100 MB, processor(1 unit) and disk memory consumption being 30 MB respectively.

Step 1: Normalize the resources with respect to the maximum resource requirements for each resource type. Normalizing resources on a scale of 0 to 1 we get the following.

Memory: 100 MB = 0.2, 200 MB = 0.4, 300 MB = 0.6, 400 MB = 0.8, 500 MB = 1.

Processor: 5 units = 1, 4 units = 4/5 = 0.8, 3 units = 3/5 = 0.6, 2 units = 2/5 = 0.4 , 1 unit = 1/5 = 0.2.

Disk Memory: 150 MB = 1 , 120 MB = 120/150 = 0.8 , 90 MB = 90/150 = 0.6 , 60 MB = 60/150 = 0.4 , 30 MB = 30/150 = 0.2. These normalized entries are shown in table 4.2.

Step 2: Find the difference between normalized values of entries 1 and 2. This is found for every resource type present in the system.
Change in disk memory space = $|0.2 - 0.4| = 0.2$
Change in memory = $|0.2 - 0.4| = 0.2$
Change in disk memory = $|0.2 - 0.4| = 0.2$

Step 3: Find Mean Change in resource, **Avg** = $\frac{(0.2+0.2+0.2)}{3} = 0.2$.

Step 4: Increase in user satisfaction, **Sensdiff** = $|0.3776 - 0.4378| = 0.0602$.

Step 5: Calculate **Sensdiff/Avg**. This value is increase in user sensitivity per unit resource. $0.0602/0.2 = 0.301$. This is increase in user satisfaction per unit resource or otherwise marginal increase in user satisfaction per unit resource.

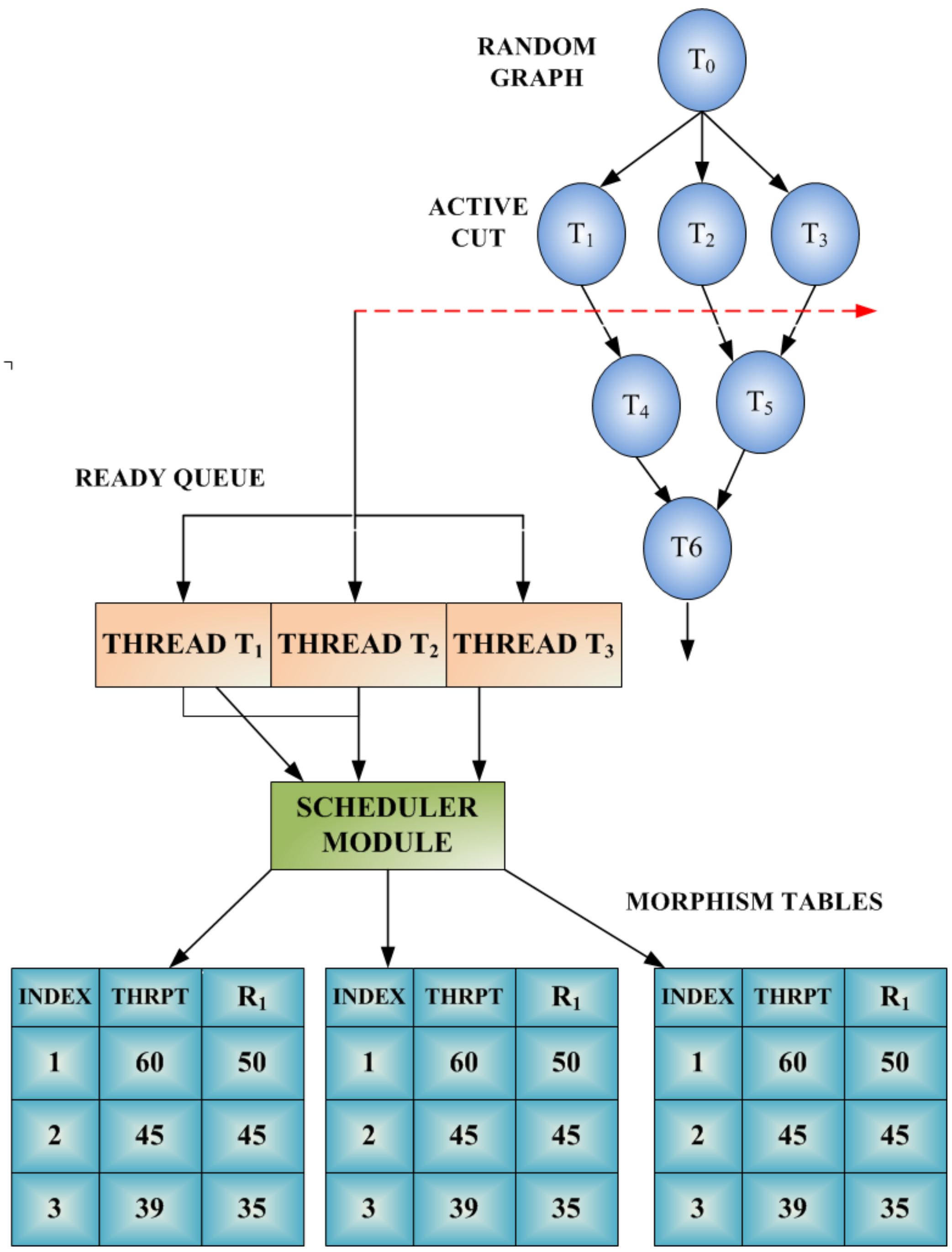
4.5 Scheduler Dataflow

The input data structures to the polymorphic thread scheduler are as follows.

1. Random graphs for N multi-threaded application.

2. Thread Morphism Tables

Scheduler maintains a ready queue to keep track of the thread identifiers currently active in the different multithreaded applications. The scheduler carries out the task of morphism assignment for threads currently in the ready queue, taking thread morphism tables as its input. The scheduler's output is individual and total user satisfaction for all threads in the active cut. Figure 4.1 illustrates the polymorphic thread scheduler's working.



INDEX	THRPT	R_1
1	60	50
2	45	45
3	39	35

INDEX	THRPT	R_1
1	60	50
2	45	45
3	39	35

INDEX	THRPT	R_1
1	60	50
2	45	45
3	39	35

Figure 4.1 Scheduler Dataflow

CHAPTER 5. Scheduling Algorithm

This chapter discusses the greedy scheduler algorithm employed by the polymorphic thread scheduler. The polymorphic thread scheduler operates in a multiple application, multithreaded environment. Benchmarks are established standards for evaluating performance of computer architectures. Since the proposed polymorphic thread scheduler is a futuristic approach for embedded system design, no industry standard benchmarks are available to test the framework. In order to test the scheduling algorithm, random graphs are generated for the N applications, which are represented using adjacency matrices. These random graphs reflect the properties of real benchmarks and are used for testing the proposed polymorphic thread scheduler framework. Chapter 6 outlines the procedure to accomplish random graph generation. In this chapter, we detail the steps for the greedy scheduler algorithm. The ready queue maintains the threads from the multiple applications, which are lined up for execution. Depending on the scheduling heuristic, the starting point for the morphism table entries can be at any row in the thread morphism table. The scheduler heuristics are discussed in the section following the greedy scheduler algorithm. The sequence in which the different scheduler modules will be invoked is described below.

5.1 Greedy Scheduling Algorithm

1. The first step is to fix the starting point in the morphism table, or pick an appropriate scheduling heuristic. The aim of the scheduler algorithm is to move higher up in the morphism table. This is because throughput increases as move up the table, which is directly proportional to user satisfaction.

2. The second step is to check whether resource requirements are satisfied for threads part

of the active cut. To accomplish the above step, resource requirements for each thread in the ready queue are summed for every resource type. The resource check module is invoked to check if resource constraints are satisfied. This module takes the integer resource array as its input and returns true, if resource constraints are satisfied and false, if violations occur.

3. User satisfaction is calculated for every thread in the ready queue. Intuitively, at any time instant, only a single morphism can be assigned to a thread.

4. In the equation for sigmoid function, let us assume $c_0 = 1$, and $c_1 = 1$. To recall, the objective function or user satisfaction which we want to maximize is given by the following expression.

$$\sum_{i=0}^{n-1}\sum_{j=0}^{p_i}\sum_{k\in cut}\sum_{r=0}^{m_{i,j}-1} s_{i,j,k} * \frac{1}{1+e^{\frac{Thrput(T_{i,j,r})-Thrput(T_{i,j,mid})}{Thrput(T_{i,j,max})-Thrput(T_{i,j,min})}}} * Ready(T_{i,j}) * M_{i,j,r}$$

$Thrput(T_{i,j,max})$ - Morphism for thread j in Application A_i with maximum throughput.
$Thrput(T_{i,j,min})$ - Morphism for thread j in Application A_i with minimum throughput.
$Thrput(T_{i,j,mid})$ - Morphism for thread j in Application A_i with median throughput.

5. User satisfaction for threads in the ready queue is determined. The absolute value for total user satisfaction is obtained for threads in the active cut.

6. The scheduler needs to determine if any thread can undergo morphism transition. In order to know this information, feasible set is computed. Feasible set contains threads from multiple applications when they satisfy two conditions. Condition 1 is there should be a possibility for a morphism switch. In other words, there should be some morphism entry for the application thread, above their currently assigned morphism in the morphism table, to which transition may occur. Once this is ensured, the second condition is that after morphism transition, resource constraints should be satisfied. Threads in the ready queue which do not satisfy the above 2 conditions are not part of the feasible set.

7. Determine the marginal increase in user satisfaction per unit resource for threads in the feasible set. The thread identifier with the maximum increase in user satisfaction per unit resource undergoes morphism transition. Such a thread identifier is stored in a variable **targetid**.

8. Increment the row index for thread **targetid** indicating that it has undergone morphism transition. The updated user satisfaction value for thread **targetid** is calculated. The algorithm proceeds in an iterative fashion, until the feasible set is empty.

5.2 Scheduling Heuristics

It is the scheduler's job to assign morphisms for threads resident in the ready queue. Depending on the starting point in the morphism tables for the threads, the scheduler can adopt different scheduling heuristics. The following section elaborates on the different heuristics in finer detail.

5.2.1 Bottommost traversal

In this scheduling heuristic, the starting point is the bottommost morphism entry for all the threads in the active cut. The throughput for thread morphisms increases as we move from bottom to top in a thread morphism table. The resource requirements for the threads in the active cut are summed up. If resource constraints are obeyed, we compute the feasible set, which are the threads which can undergo morphism transition considering the current state of resource allocation. Precedence among threads in the feasible set is decided by the metric **user satisfaction per unit resource**. The thread which gives maximum value of this metric gets scheduled. The procedure proceeds in an iterative fashion until the feasible set is empty. The current row indices for the threads reflect their final morphism states.

5.2.2 Topmost traversal

The starting point in the morphism table is the topmost or first morphism entry for all the threads in the active cut in their corresponding morphism tables. Resource requirements for threads in the active cut are determined. If resource violations occur, all the thread pointers are moved one level down in their morphism tables. This process continues until resource constraints are obeyed. Once this stage is reached, check if any thread can undergo morphism transition by computing the feasible set. The thread in the feasible set, with maximum increase in user satisfaction per unit resource undergoes morphism transition. The algorithm iterates until the feasible set is empty.

5.2.3 Topvariation Traversal

This scheduling heuristic is a variation of the top-down traversal approach. The starting point in the morphism table is the topmost or first morphism entry for threads in the ready queue. If resource requirements are obeyed, user satisfaction value is computed for all threads and algorithm terminates. If resource violations occur, feasible set is computed. The thread in the feasible set, with minimum decrease in user satisfaction per unit resource undergoes morphism changes. This is due to the fact that throughput for thread morphisms decreases, when a top-down traversal approach is adopted. If feasible set is empty, all the thread pointers are moved one level down from their current positions. The algorithm terminates if the feasible set is non-empty or when resource constraints are satisfied.

5.2.4 Binary search Traversal

The starting point for this heuristic is at the middle of the morphism tables for threads in the ready queue. The resource requirements for threads are summed and if resource constraints are not satisfied, thread pointers are moved down to row index **current + (rows -1)/2**. Here **current** denotes the current row index and **rows** is the total number of rows present in the each thread's morphism table. This process is repeated until resource constraints hold. The user satisfaction is computed for all threads in the ready queue. Feasible set is computed, to check if any thread benefits from morphism changes. The thread in the feasible set, with maximum increase in user satisfaction per unit resource undergoes morphism transition. The algorithm proceeds in an iterative fashion till the feasible set is empty. The following section illustrates the classical thread scheduling approaches such as First-Come-First-Serve (FCFS) and priority scheduling, against which the marginal utility approach will be compared.

5.3 Comparison Approaches

5.3.1 First Come First Serve(FCFS) Scheduling

FCFS is a traditional thread scheduling algorithm, which relies on the thread ordering in the ready queue to accomplish scheduling and doesn't take into account an application's past performance. The middle morphism table entry is chosen as the starting point for all threads in ready queue. User satisfaction is calculated for threads currently in the ready queue. Threads are scheduled for execution until system resources are exhausted. If resource constraints prevent all threads in ready queue from being scheduled, we track the last thread identifier until which resource constraints are satisfied. The remaining threads in the ready queue are scheduled in the next time cycle. The algorithm proceeds in an iterative fashion, until the ready queue is empty. FCFS can never guarantee a good response time for interactive tasks, since higher priority(interactive applications) may be made to wait for lower priority applications to complete execution.

5.3.2 Priority Scheduling

Since priority scheduling is a conventional thread scheduling approach, there must be a metric to categorize applications into low or high priority classes. The priority metric in our case, is the number of application threads. The priority values for applications are derived after analyzing the past behavior of applications run in embedded systems. More often than not, end users run a set of applications in an embedded system regularly. In general, past application behavior provides a reasonable estimate in predicting its future characteristics. Thread identifiers are loaded into a new queue called priority queue, based on their decreasing application priority. The middle morphism entry is chosen as the starting point for threads in the ready queue. FCFS scheduling strategy is implemented on the set of threads in the priority queue. Threads in the priority queue are assigned morphisms until resource constraints hold. Threads in the ready queue which cannot be scheduled due to lack of resources, are scheduled in the next time cycle. The algorithm proceeds in an iterative fashion scheduling threads, until the ready queue is empty.

5.3.3 Advantage of Greedy Scheduling Algorithm

The proposed greedy scheduling algorithm performs better than the classical thread scheduling approaches. This is because, when resource violations occur, the greedy scheduling approach accepts threads into the ready queue in the decreasing order of user satisfaction. In such a situation, threads are admitted into the system depending on their user satisfaction increase. Hence, the greedy scheduling approach is more effective in enhancing user satisfaction compared to the conventional scheduling strategies. In FCFS scheduling, threads are scheduled for execution based on their order of occurrence in ready queue. In priority scheduling, threads are scheduled for execution depending on statically assigned application priorities.

CHAPTER 6. Random Graph Generation

This chapter details the algorithm for generating random graphs, which serve as benchmarks for testing the proposed scheduler framework. In the proposed system, a multithreaded application's functionality is characterized using a data structure called as thread control flow graph. This graph clearly captures the computational and communication flow between threads constituting an application. Nodes in the graph represent the threads and the edges between nodes at different levels denote the scaling factor corresponding to each thread. The polymorphic scheduler framework consists of Applications A $= A_i$, $0 \leq i < n$. Each application has p_i threads $T_{i,j}$ for $0 \leq j < p_i$. Each of these application threads can be implemented in a multitude of ways, where each thread's implementation is referred to as morphism. The maximum number of morphisms possible or morphism space for a thread $T_{i,j}$ is represented by $m_{i,j}$, $0 \leq r < m_{i,j}$. Benchmarks are established standards to evaluate the performance of computer architectures. Since the polymorphic scheduler is a futuristic approach for embedded system design, no industry standard benchmarks are available to test the proposed framework. Consequently, it is of paramount importance, for these random graphs to be representative of real benchmarks. In order to accurately evaluate the performance of the proposed polymorphic scheduler framework, it must be tested against a broad range of applications. Hence a test suite of N random graphs, represented using adjacency matrices are generated to test the polymorphic thread scheduler. The characteristics of typical multimedia applications such as video, audio etc. are analyzed. This analysis helps to determine the lower and upper bounds on the total number of nodes, levels and the nodes at a particular level. Random graphs are generated based on these bounds, so that they reflect the properties of industry standard benchmarks. Hence in a multithreaded application, the total number of nodes, levels and node count at every level is random. Also the edges which exist between adjacent and non-adjacent levels follow a random pattern. The Random graph generation process takes place in two steps. The first step is to create edges between nodes at adjacent levels and the second step is to create edges between nodes at non-adjacent levels. The constraint for random graph generation algorithm is that no dangling nodes must be generated, which are nodes without any outgoing edges.

6.1 Random graph generation

We have the following variables to keep track of the random graph generation process. The total number of nodes that can be generated in a graph is stored in a variable **total**. The variable **assigned** keeps track of the number of nodes generated till the current level. To store the number of nodes to be generated at a particular level, variable **num** is used. Since the number of nodes at a level is a random number, generate $num = (rand()\%t) + a$, where t, a are variables, $a \geq 1$ and $t \geq 2$. The effective number of nodes we can generate is $total - 1$, since provision has to be included for the sink node. Maintain two different queues q_1, q_2, which aid the random graph generation process. The first queue q_1 keeps track of the edges or connectivity information between the nodes in the graph. q_2 queue keeps track of the unique nodes present in the thread control flow graph. A procedure similar to breadth first traversal is followed, to generate nodes and its corresponding children. The number of nodes at a particular level num is random and so is the edge pattern connecting a node to its children. Objects pushed into the edge queue q_1 have the following attributes.

1. A node/ thread's identifier
2. Scaling factor for the incoming edge into the node
3. Parent for the node
4. Level at which a particular node lies.

For instance, the attributes of the root node in the graph is as follows. The thread identifier for root is 0, scaling factor = 0.0 as the root node has no incoming edge, level for root node is 0 and the parent is initialized to -1, as root has no parent. Objects in queue q_2 have the following attributes.

1. Thread/node's identifier
2. Level at which a node is present

6.2 Edges between Adjacent Levels- Pseudocode

```
1. Add the root element for the graph into $q_2$ queue with attributes threadid and level.
2. While $q_2$ queue is not empty loop the following.
   {
3. Remove the first element from the queue, and denote it as **currentelem** at level **currentlevel**.
4. Generate randomly, the number of children for thread **currentelem** $num = (rand()\%t) + a$
5. Check if there is provision to accommodate $num$ children nodes at level $currentlevel + 1$.
   If $(num \geq (total - assigned))$
   {
   $num = total - assigned$
   }
6. Find the last thread identifier at level $currentlevel$ and denote it as **prevtid**.
7. Run a loop to generate random edge connections between currentelem and its children.
   For $(k = prevtid + 1; k < (prevtid + 1 + num); k++)$
   {
   Check if node count has exceeded total, excluding sink and nodes assigned.
   If $(num <= (total - assigned) k <= (total - 2))$
   {
```

```
Declare a variable **Randval** which decides whether to include an edge between $currentelem$
and child node with thread identifier $k$.
$randval = (rand()\%p), p \geq 2.$
Check if $(randval > p/2)$
{
Create a child node for thread $currentelem$ with following attributes.
Thread identifier = k;
Scaling factor = Random value generated, using rand() function;
Parent = $currentelem$;
Level = $currentlevel + 1$;
Check if thread identifier $k$ is present in unique node queue $q_2$
{
Create a unique node with following attributes.
Thread identifier = $k$;
Set the level to one greater than its parent, i.e. Level = $currentlevel + 1$.
Push the unique thread object into the q2 queue.
Increment the number of nodes assigned, i.e. $assigned = assigned + 1$.
}
Push edge information into $q_1$ queue.
}
Check if thread identifier $k$ has reached $total - 1$
{
Break For loop;
}
}
}
```

8. Connect all nodes at penultimate level to sink node.

(a) The level of the last element in queue is the penultimate level, or $lastlevel$.

(b) Determine the number of elements at penultimate level, **Numelements**.

(c) Penultimate level elements are stored in array **arr** with size **Numelements**.

(d) Connect all elements in array arr to the sink node.

6.2.1 Forming Adjacency Matrix

We represent the random graph by an adjacency matrix. Declare an adjacency matrix $Adjacencymat$ with size equal to total number of application threads. Read from the queue q_1 and form the adjacency matrix created for the application.

While q_1 is not empty, loop the following

{

Remove the thread object at head of queue with following attributes.

Thread identifier tid, Scale factor $scalefac$, Node's parent $parent$.

Store Scaling factor at the location matrix location, Adjacencymat [parent][tid] = Scalefac;

}

6.3 Adding edges between Non-Adjacent levels

Step 1: Figure out the last level in the application thread control flow graph.

Step 2: Run a loop from $lev = 0tolev = lastlevel - 2$. Within the body of the loop, collect all elements at level lev in array arr_1. Collect all thread elements at level $lev + 2$ in array arr_2.

Step 3: Let $numelements$ denote the number of elements in arr_1. Let $numelements1$ be the number of elements in $arr2$. Now traverse each thread **tid** in arr_1 and generate a random number $randval = (rand()\%t), t \geq 4$, which yields a value between 0 and $t - 1$. $Randval$ decides if there will be a connection from thread **tid** to any thread at level $lev + 2$.

Step 4: Generate index of the element to be connected in $arr2$. Check if $randval >= t/2$. If condition holds, randomly generate index = $rand()\%numelements1$.

Step 5: **tid1** = arr2 [index] would return the thread identifier at position *index* in $arr2$. Connect the threads **tid** and **tid1** by an edge.

6.3.1 Necessary Condition on Outgoing Edges

Since we generate the nodes and edges connecting a node with its children randomly, there is a possibility to create dangling nodes which have no outgoing edges. Here is a procedure to ensure at least one outgoing edge exists for all nodes except for the sink.s

1. After finishing the two step process of random graph generation, the final step is to track nodes which have no outgoing edges. This is accomplished by maintaining a Boolean array **visited** with number of entries equal to the total number of threads in the application, i.e. **total**. All entries in the visited array are initialized to 0. Threads with no outgoing edges, except the sink node have their corresponding entries in the visited array set to 1.

2. Figure out the level at which a dangling node exists and denote the level as *curlevel*. Designate the thread identifier as *tid*. We need to connect *tid* to some arbitrary node at the next level, i.e. $curlevel + 1$.

3. Let numelements be the number of elements at level $curlevel + 1$. Store these thread elements in array $arr1$. Randomly generate a value for $index = rand()\%numelements$. $tid_1 = arr1[index]$ returns thread identifier present at index in array arr1. Connect the edge between threads tid and tid1. In this way, we ensure that every thread identifier at a level level has at least one outgoing edge.

CHAPTER 7. Simulation Framework and Experimental Results

This chapter outlines the components of the scheduler framework, and describes the experimental setup and evaluation infrastructure. This chapter also presents the methodology to generate morphism tables which serves as an essential input for the polymorphic thread scheduler. The subsequent sections in the chapter elaborate on the experiments conducted and summarize key results. The benefits obtained by using User Satisfaction as the objective function and the performance enhancements using the novel thread scheduler are demonstrated clearly using the result graphs. The advantages of the proposed greedy thread scheduling algorithm are demonstrated by comparison against conventional thread scheduling approaches like First Come First Serve (FCFS) and priority scheduling schemes. The chapter ends with conclusions and scope for future work.

7.1 Simulation Framework

Extensive simulations have been conducted to evaluate the performance of the proposed user-satisfaction based allocation scheme for heterogeneous class of applications. In our scheduler framework, the common performance metric across all the multithreaded applications is throughput. For many embedded system applications such as movie players, streaming video, video chatting, frame rate is a parameter which clearly captures user experience. Hence, throughput generally expressed in terms of frames/sec is used as the discrete parameter in the sigmoid function, which models user satisfaction. The following section describes the components of the polymorphic thread scheduler framework. Figure 7.1 presents the simulation framework for the polymorphic embedded systems scheduler in finer detail. An embedded system simulator has been developed and implemented. A ready queue data structure is maintained, which keeps track of threads from multiple applications which are ready to run at any time instant. The threads from different applications have a random arrival pattern when they enter the ready queue. The other input data structures to the embedded systems scheduler are morphism tables and the random thread flow graphs corresponding to the N multithreaded applications, which are active in the system. Depending on the application threads lined up for execution in the ready queue, the corresponding morphism tables are loaded at run time into memory. As mentioned in Chapter 6, random graphs serve as benchmarks to evaluate the proposed scheduler framework, due to the absence of industry-standard benchmarks. The scheduler has to efficiently carry out the task of morphism assignment for the threads in the ready queue. As mentioned in Chapter 5, the scheduler adopts different greedy scheduling heuristics, depending on the starting position in the thread morphism tables. The morphism choices for the threads, depends on the instantaneous resource availability. A resource allocation module is invoked by the scheduler to check if resource constraints hold. This module accepts the current resource allocation for the different thread morphisms as its input. After communication with the resource availability layer, it returns true, if resource constraints are satisfied and false if resource violations occur. The scheduler framework's output is the final morphism assignment for threads in the active cut along with their individual and total user satisfaction. The following section describes the morphism data structure and elaborates on the algorithm classes considered for morphism table generation.

7.2 Morphism Table Generation

This section motivates the problem of constructing morphism table patterns, based on properties of commonly used algorithm classes in embedded systems. Since polymorphic scheduler is a futuristic approach for embedded system design, no industry standard benchmarks are available to test the proposed framework. In order to evaluate the accuracy and usefulness of the scheduler framework, random graphs are generated which are representative of scientific embedded domain benchmarks. Consequently, it is of paramount importance, for these random graphs to be representative of real benchmarks. Morphism tables also form one of the

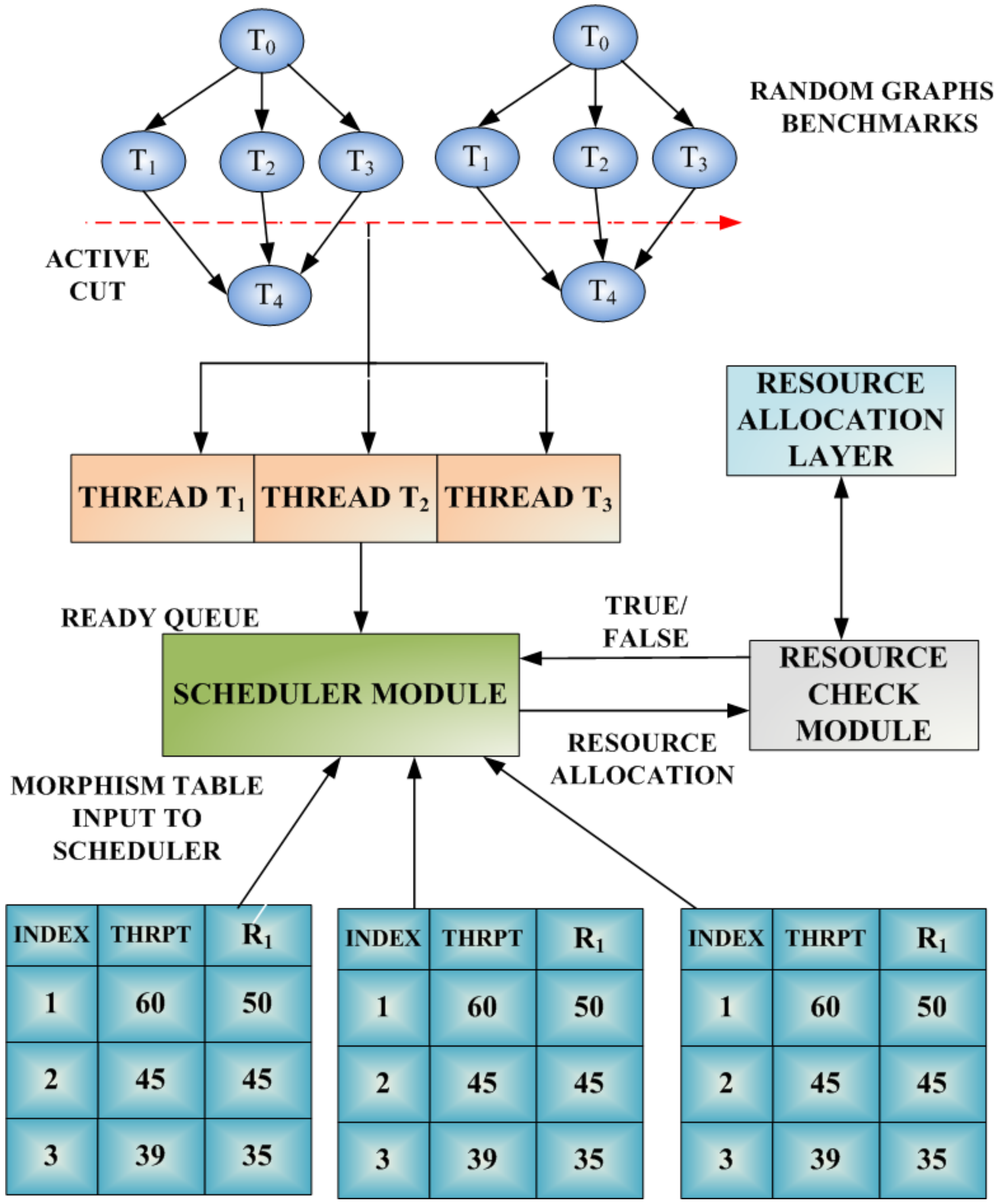


Figure 7.1 Components of Scheduler framework

essential inputs to the scheduler algorithm. As mentioned in Chapter 4, morphism table is a scheduler data structure which stores information about thread morphisms. The entries in the morphism table are sorted in decreasing order of their performance metric (throughput). The columns in the morphism table are as follows. There is one column to index the different morphism entries. The second column stores information about the throughput of a thread morphism and the subsequent columns store details about the amount of resources required for its execution. If the number of resource types is R, the total number of columns in a morphism table is $R+2$. The resources in the system could be the amount of Random Access Memory (M) required, Disk Memory (D) and Processing Units (P), which form the various columns M, P, D in the morphism table. In the polymorphic scheduler framework, since the makeup of applications is known only at run time, the morphism tables for the application threads are also generated dynamically at run time. The thread morphism tables should reflect characteristics of commonly run algorithms on embedded system. The entries in the thread morphism tables should have variation patterns resembling the properties of an algorithm class. The number of rows in a morphism table or thread morphisms is also decided randomly. There are five classes of algorithms, based on which morphism table patterns are generated. When morphism table entries adhere to an algorithm class pattern, it helps us conclusively decide which greedy scheduling heuristic performs best, for an algorithm class. Extensive simulations using these morphism classes and application benchmarks reveal that, the proposed polymorphic scheduler framework offers significant performance improvements in terms of user satisfaction over other classical scheduling approaches. The different algorithm classes which serve as basis for morphism table generation are as follows.

1. Matrix Manipulation class

2. Sorting Algorithm class

3. Polynomial class

4. Multiplication algorithms class

5. GCD algorithms class

Each algorithm class maintains the time complexities for the different thread morphisms. For instance, the sorting class has ratios of time complexities for morphisms which realize the sorting functionality. These ratios are stored in an array specific to each algorithm class. At run time, a random number is generated which selects one among the five algorithm classes. Morphism table entries are generated based on these class properties. To recall, rows in morphism table are organized in the decreasing order of their throughputs. Hence the row entries for thread morphism tables are generated from the bottom-upward. The number of row entries in a thread morphism table is decided randomly. The first thread morphism or bottommost row entry has random values generated for its throughput and resource requirements. The subsequent thread morphisms are generated based on ratios within the selected algorithm class, and values for previous row entries. The throughput for the thread morphism immediately above the currently generated one and its corresponding resource requirements are scaled by a ratio, randomly chosen within the algorithm class. A similar procedure is followed for generating rows all the way up to the topmost row entry in the morphism table. The following section describes the central idea behind context size, which serves as an important metric for performance evaluation.

7.3 Context Size

Traditional mobile phones offered support for voice-only services along with basic features in user interface. Current day mobile phones offer extensive support for multimedia applications along with supporting voice services. Moreover, end users expect their consumer electronic devices to operate faster, in addition to offering support for a wide range of applications. Hence it is a challenge to measure or evaluate the performance of such evolving embedded systems. Since resource limitations are more severe in embedded systems, resource allocation plays a crucial role in the design of an embedded system scheduler. The efficacy of the polymorphic scheduler framework, in supporting a heterogeneous application class has to be evaluated. Hence extreme load conditions are generated, by running several applications concurrently on the embedded system. This includes testing the system under heavy loads and high concurrency, thereby constraining or limiting the computational resources. The goal of stress testing the embedded system is to observe how the scheduling algorithm responds to situations, where applications contend for limited system resources such as memory, processor cycles, network bandwidth etc. This will present a perfect scenario for testing and evaluating the performance of the greedy scheduler algorithm. The effectiveness of the proposed scheduler framework in making resource allocation decisions becomes apparent only in such extreme conditions. A good resource allocation strategy will effectively handle issues relating to resource contention and lead to minimal performance degradations in the embedded system. When congestion occurs in an embedded system, the quality of service deteriorates for applications in the system. The typical effects of congestion include delayed response time for applications, packet loss, and inability to accept additional applications into the system. Consequentially, any incremental increase in computational load in the system results in drastic reductions in system throughput.

Congestion in an embedded system is analogous to the total number of applications running concurrently along with an application. The target application is the application of interest whose performance characteristics needs to be analyzed or observed. The target application is randomly chosen from the currently running active set of applications. In this case, context size refers to the total number of applications running in the system along with the target application. In the proposed polymorphic thread scheduler, the value of the objective function (user satisfaction) is plotted against the context size. Embedded system applications are driven by use case scenarios created by the user. Use case scenarios define the way, a system responds to a request that originates from outside of that system. A typical use case scenario is considered, where an embedded system user intends to run an MP3 application along with other applications such as video, phone call etc. The end user's interest lies in analyzing the variations in user satisfaction exhibited by this application, during varying system loads (context size). The context size in the system varies as applications leave or enter the system, assuming the original MP3 application still keeps running. The performance of the MP3 application can be analyzed by plotting its user satisfaction behavior for the different greedy scheduling heuristics. Extensive simulations have been conducted to capture the user satisfaction variations for a target application with increase in context size or computational load in the system. The result graphs demonstrate that with increase in computational load, the greedy scheduling heuristics outperform the classical thread scheduling schemes FCFS and priority scheduling.

7.4 Experimental Results and Analysis

As mentioned in the previous section, the dynamic nature of workloads that run concurrently along with the target application affects its performance. The extensive experiments conducted demonstrate that the greedy scheduling heuristics adopted by the proposed scheduler, would improve task scheduling in a multiple application, multithreaded environment. In the following section, we discuss experimental results, where result graphs are plotted with user satisfaction for the target application against the context size. The X-axis denotes the context size, or number applications running concurrently along with the target application in the system. The greedy scheduler heuristics adopted by the polymorphic scheduler traverse the morphism table in different order. These heuristics are as follows.

1. Bottommost traversal
2. Topmost traversal
3. Top-variation traversal
4. Binary Search traversal
5. FCFS scheduling - Conventional approach
6. Priority scheduling - Conventional approach.

The experimental graphs plot user satisfaction for the target application against the total number of applications running in the system. The target application is the application, whose user satisfaction behavior is to be analyzed. The scheduling heuristics adopted by the polymorphic thread scheduler scheme achieve greater performance benefits and resource utilization. Therefore the proposed greedy scheduling heuristic approaches are more desirable compared to classical scheduling schemes.

7.5 Matrix Manipulation Class

The first class of algorithms considered for generating morphism table patterns is the matrix manipulation class. The time complexities for the matrix class of algorithms are $O(n^2)$, $O(n^{2.807})$ and $O(n^{2.376})$ etc. The common matrix algorithms examined are matrix inversion, determinant and matrix multiplication etc. From the results, show in Figure 7.2, we conclude that for the matrix class of algorithms, the binary search traversal option has higher increase in user satisfaction compared to other scheduling heuristics. The next best scheduling heuristic for this algorithm class, is the topmost scheduling heuristic which comes close to the binary search traversal in terms of achieving significant user satisfaction gain. This is closely followed by the bottommost traversal approach. Overall, the bottommost scheduling heuristic suffers the least, whereas top-variation scheduling heuristic suffers the most. From the results, we conclude that for the matrix class of algorithms, the binary search traversal option has higher increase in user satisfaction compared to other scheduling heuristics. Let us examine why binary scheduling heuristic performs better compared to the bottommost and other scheduling heuristics.

For the bottommost heuristic, a case might arise, where the throughput of the thread, may not monotonically increase with a corresponding increase in resources. Assuming one resource type, a graph is plotted with resource type on the x-axis and throughput on the y-axis. If there is more than one resource type, accordingly so many dimensions are present. In this graph, there could be some regions, where a bursty increase in the throughput is experienced for increase in resources and there may be some regions, where there is no significant throughput increase, for increase in resources. A very good example of this kind of a behavior can be found in application threads that have smaller data structures within bigger data structures. E.g. inner structure nested within an outer structure. These application threads respond to an increase in the cache size in the aforementioned manner. After the inner data structure fits in the cache, the application may not show any improvement until the bigger data structure can fully fit into the cache. Let us denote these kinds of application threads as class A. Application threads without the bursty increase in throughput are categorized under class B. Class B threads, may exhibit a monotonic or linear relationship between throughput and resources. When there is a mix of both these class of application threads A and B in an active cut, the bottommost traversal approach will allocate more resources to application threads in class B. This would result in process starvation for applications in class A. Until the Class A application threads reach a point, where bursty throughput appears, the bottommost scheduling heuristic keeps allocating resources to Class B application threads. This results in an unbalanced or skewed resource allocation among application threads, resulting in a sub-optimal solution in terms of user satisfaction. But, this may necessarily not be the case with binary search scheduling heuristic, since the starting position in the morphism table is at the middle morphism entries for all threads. Since the greedy scheduling algorithm is applied from this point, it results in a near uniform allocation state for the binary scheduling heuristic.

For illustration, consider an application which is composed of 5 threads. For the bottommost scheduling heuristic, let the first 3 threads in the active cut be the ones that always exhibit linear increase in throughput during morphism transitions, i.e: threads which come under Class B category. Meanwhile, let the morphism entries for the remaining 2 threads experience bursty throughput increase in certain regions and let other regions, exhibit a non-monotonic increase in their throughput per unit resource, similar to Class A threads. Let these two application threads reach a point where there is temporarily no increase in the throughput at this instant. In such a case, the bottommost scheduling heuristic always allocates more resources for the first 3 threads compared to the other 2 threads, where the throughput increase per unit resource value is considerably low. Due to tight bounds on the amount of resources, this could result in a very skewed/unbalanced allocation of resources, resulting in local maxima. In such cases, the binary search heuristic performs better than the bottommost approach. The heuristic initially allocates resources uniformly for all 5 threads which constitute an application. This is because the starting position is at the middle entry in the morphism table, which can yield an optimal solution without getting stuck at the local maxima. Since the bottommost approach decides on its scheduling options too early in such cases, it prevents it from finding the best overall solution.

Coming to the comparison approaches for the matrix manipulation class, FCFS scheduling outperforms priority scheduling as shown in Figure 7.2. It is to be noted that, priority scheduling performs badly for tasks whose run-time behavior deviates significantly from its expected or design time behavior. Moreover the behavior of these tasks may vary with respect to time and the number of tasks in the system. Another drawback in priority scheduling is that there is no foolproof mechanism for mapping task requirements into priority values. In many cases, the system designer accomplishes this mapping based on a pre-determined set of facts. Priority scheduling performs badly in cases where, applications with low priority have higher marginal user satisfaction increase, compared to applications with higher priority. Moreover, there may be cases where applications with higher priority could potentially block all lower priority tasks indefinitely from executing. If the target application chosen is one among these lower priority tasks, it is very likely that its user satisfaction value would undergo a significant reduction because of process starving.

7.6 Sorting class of Algorithms

The second class of algorithms considered for generating morphism table patterns is the sorting class of algorithms. The complexities of the thread morphisms in the sorting class are $O(n^2)$ and $O(nlogn)$. Figure 7.3 plots the user satisfaction behavior for an application in the sorting class against the context size, or the number of applications running concurrently in the

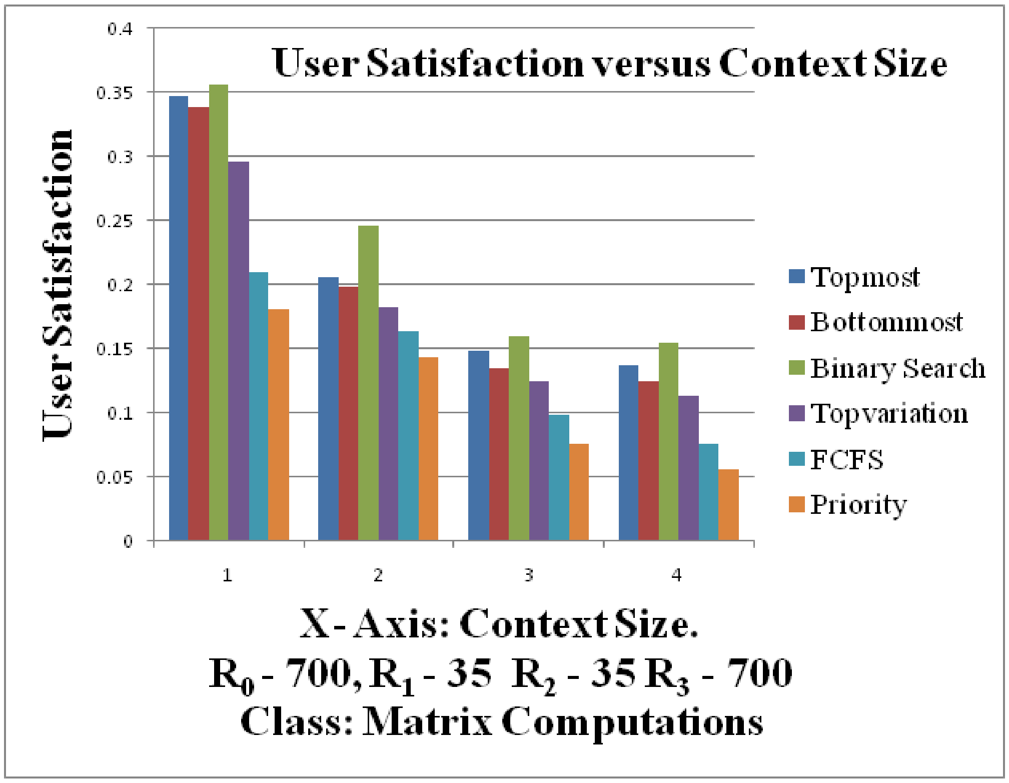


Figure 7.2 Matrix class: User Satisfaction vs Context Size

system. The performance of the greedy scheduling heuristics implemented by the polymorphic thread scheduler is compared against conventional thread scheduling techniques. When the congestion increases in an embedded system, QOS (Quality of Service) levels for application are reduced drastically. In order to effectively handle such scenarios, a clever resource allocation strategy is needed. The scheduling performance for a greedy scheduling heuristic is measured by the user satisfaction reduction obtained as context size increases. For the sorting class of algorithms, the observation is that the bottommost traversal heuristic outperforms the other scheduling heuristics. The next best scheduling heuristic, which comes close to the bottommost traversal in achieving significant user satisfaction gain, is the topmost scheduling heuristic. For the scheduling heuristics under consideration, the value for the target application's user satisfaction is averaged over 50 iterations. The result graph in Figure 7.3 clearly demonstrate that with increase in computational load, the greedy scheduling heuristics outperform classical thread scheduling schemes, namely FCFS and priority scheduling. During times of congestion in the system, applications contend for system resources such as memory, processor cycles etc. For the binary search scheduling heuristic, there is drastic reduction in user satisfaction when the context size increases initially. With further increase in context size, there is minimal variation in the target application's user satisfaction for this heuristic. The results also demonstrate that the topmost scheduling heuristic comes close to the bottommost heuristic approach in achieving significant user satisfaction increases. This is closely followed by the binary search and top-variation scheduling heuristics. Let us explain why bottommost scheduling heuristic outperforms rest of the scheduling heuristics.

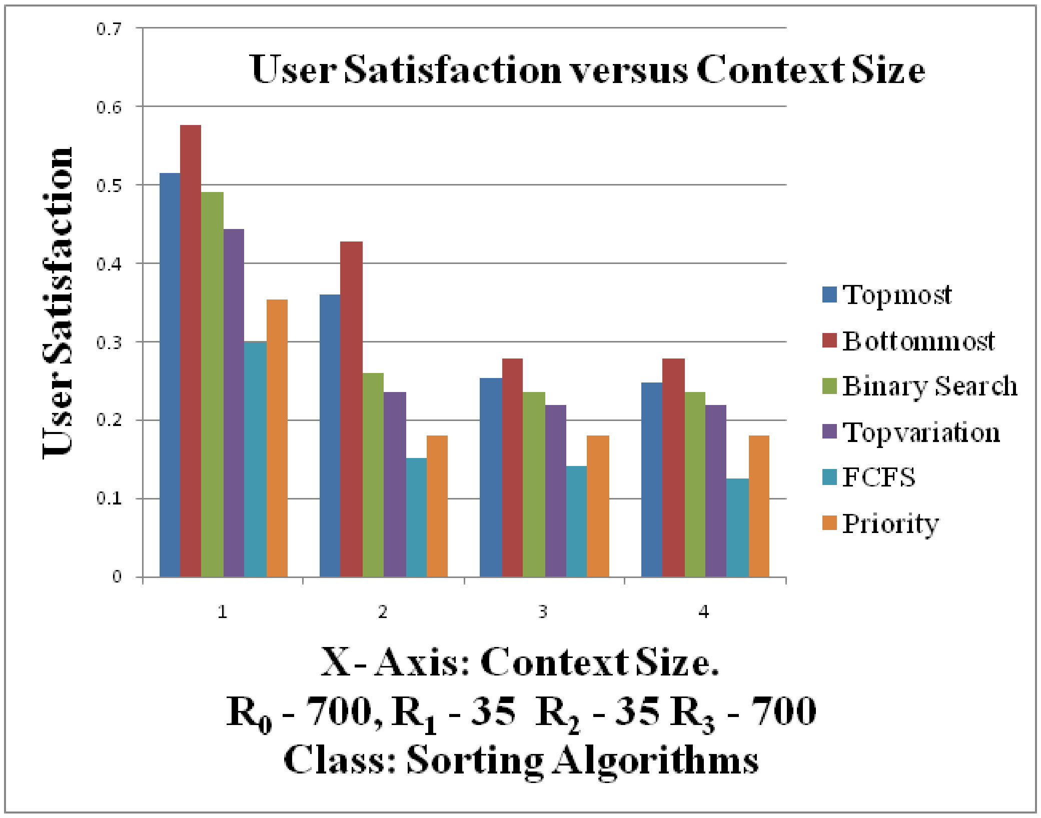


Figure 7.3 Sorting class: User Satisfaction vs Context Size

Let us recall the notion behind feasible set. The feasible set is computed at every intermediate step, which contains threads from multiple applications when they satisfy two conditions. Condition 1 is there should be a possibility for a morphism switch. In other words, there should be some morphism entry for the application thread, above their currently assigned morphism in the morphism table, to which transition may occur. Once this is ensured, the second condition is that after morphism transition, resource constraints should be satisfied. Precedence among threads in the feasible set is decided by the metric user satisfaction gain per unit resource. When there is a mix of class A and class B's application threads in an active cut, the bottom most traversal approach will allocate more resources to application threads in class B. This results in an unbalanced or skewed resource allocation among application threads, resulting in a sub-optimal solution in terms of user satisfaction. But the sorting algorithm class consists of threads from class B. Hence the bottommost scheduling heuristic outperforms the other scheduling heuristics. FCFS and priority scheduling are implemented as comparison scheduling schemes. For the sorting class, priority scheduling outperforms FCFS scheduling. As shown in Figure 7.3, regardless of the context size, priority scheduling outperforms FCFS scheduling heuristics for this algorithm class. While it may be true in some cases that threads may enter the ready queue according to their application priorities, it might not be necessarily true in all cases. In other words, there is no guarantee that the threads which enter the ready queue earlier, have higher priority than the others appearing later in the queue.

In many cases, the embedded system designer accomplishes the mapping between problem constraints into priority values, based on pre-determined set of facts. The priority values for applications are derived after analyzing the past behavior of applications run in embedded systems. More often than not, end users run a set of applications in an embedded system regularly. In general, past application behavior provides a reasonable estimate in predicting its future characteristics. Since the priority values for applications are based on established set of facts, intuitively priority scheduling performs better than FCFS scheduling. On the other hand, FCFS scheduling does not take an application's past performance into account and relies on the thread ordering in the ready queue to accomplish scheduling. If the target application is one which requires more user interaction, then FCFS scheduling might not serve the purpose. This is because FCFS can never guarantee a good response time for interactive tasks and hence is not useful for scheduling interactive processes. Also, in FCFS application threads are dispatched for execution depending on their arrival time into the ready queue. This can result in cases, where higher priority or interactive applications may be made to wait for lower priority applications to complete execution. This is the primary reason for priority scheduling to outperform the FCFS scheduling strategy in the sorting algorithm class.

7.7 Polynomial Manipulation Class

The algorithm class considered for pattern generation in morphism tables is finding the GCD for two polynomials of degree n, with fixed-size polynomial coefficients. The time complexities of the thread morphisms in this class $O(n^2)$ and $O(n(logn)^2 log\ logn)$. Figure 7.4 plots the user satisfaction behavior for a target application in the polynomial manipulation class against the context size. The general observation from these graphs is that even though binary search traversal approach performs better when the context size is less, it is affected by performance degradations as context size increases. The bottommost traversal approach also undergoes reductions in user satisfaction and stabilizes with increase in context size. Overall from these results, we can conclude that for this algorithm class, the bottommost traversal heuristic has higher increase in user satisfaction compared to the other approaches. Intuitively, one can infer that for all the experiments conducted, as the context size increases, there are user satisfaction reductions for all the scheduling heuristics. Similar to the sorting class, the bottommost scheduling heuristic performs better than the binary search scheduling heuristic. When there is a mix of class A and class B's application threads in an active cut, the bottom most traversal approach will allocate more resources to application threads in class B. This results in an unbalanced or skewed resource allocation among application threads, resulting in a sub-optimal solution in terms of user satisfaction. But the polynomial algorithm class consists of threads only from class B. Hence the bottommost scheduling heuristic outperforms the other scheduling heuristics. The next best scheduling heuristic which comes close to the bottommost traversal in achieving significant user satisfaction gain is the binary search scheduling heuristic, closely followed by topmost and top-variation scheduling schemes. Coming to the comparison approaches for the polynomial manipulation class, FCFS scheduling scheme performs better than the priority scheduling scheme because of the following reason. It is to be noted that, priority scheduling performs badly for tasks whose run-time behavior deviates significantly from its expected or design time behavior. Moreover the behavior of these tasks may vary with respect to time and the number of tasks in the system. Another drawback in priority scheduling is that there is no foolproof mechanism for mapping task requirements into priority values. In many cases, the system designer accomplishes this mapping based on a pre-determined set of facts. Priority scheduling performs badly in cases where, applications with lower priority have higher marginal user satisfaction increase, compared to applications with relatively higher priority. Moreover, there may be cases where applications with higher priority could potentially block all lower priority tasks indefinitely from executing. If the target application chosen is one among these lower priority tasks, it is very likely that its user satisfaction value would undergo a significant reduction because of process starving. Hence FCFS scheduling offers better user satisfaction gain compared to priority scheduling as shown in Figure 7.4.

7.8 Multiplication Class of Algorithms

The time complexities for the multiplication class morphisms are generally $O(n^2)$, $O(n^{1.585})$ and $O(n^{1.465})$ etc. The result graphs for the multiplication class of algorithm plot the user satisfaction behavior for the target application against the context size (total number of applications concurrently running along with target application), as shown in Figure 7.5. Similar to the sorting and polynomial classes, even here the bottommost scheduling heuristic performs better than the other scheduling heuristics. Overall the results conclusively demonstrate that the bottommost scheduling heuristic performs better than the other scheduling heuristics, similar to sorting and polynomial classes. As mentioned earlier in the polynomial class, when there is a mix of class A and class B's application threads in an active cut, the bottom

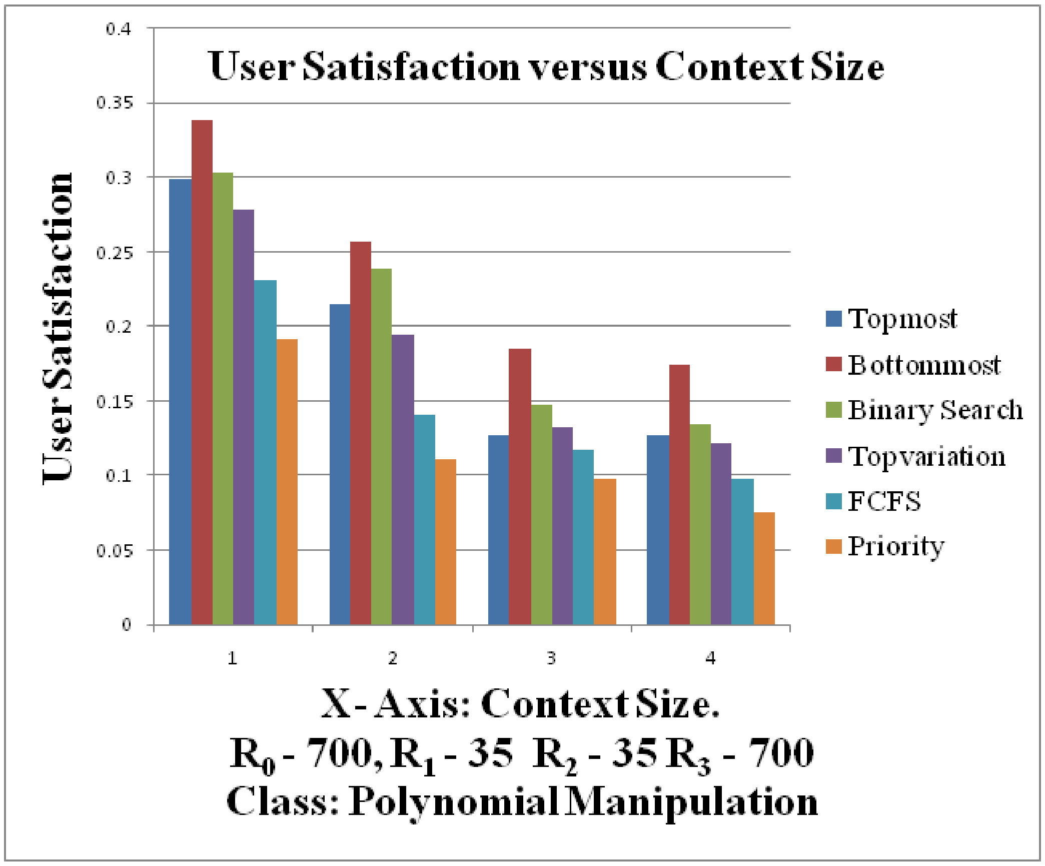


Figure 7.4 Polynomial class: User Satisfaction vs Context Size

most traversal approach will allocate more resources to application threads in class B. This results in an unbalanced or skewed resource allocation among application threads, resulting in a sub-optimal solution in terms of user satisfaction. But the multiplication algorithm class consists of threads from class B. Hence the bottommost scheduling heuristic outperforms the other scheduling heuristics. Another observation for the multiplication class of algorithms is that as context size increases, applications contend for resources. When resource contention increases, the classical scheduling approaches like FCFS and priority scheduling undergo drastic performance degradations, but the greedy scheduler heuristics like are least affected by the resource contention. This is because all these scheduler heuristics effectively implement admission control in two phases. First phase admits resource requests into the system and the second phase does resource allocation, for the admitted requests. The proposed greedy scheduling algorithm performs better than the classical thread scheduling approaches. This is because, when resource violations occur, the greedy scheduling heuristic approaches accept threads into the ready queue in the decreasing order of their user satisfaction. In other words, threads which yield higher user satisfaction increase are serviced before threads which give rise to lesser user satisfaction increase. In FCFS scheduling, threads are scheduled based on their order of occurrence in ready queue. In priority scheduling, threads are scheduled depending on statically assigned application priorities. Hence, the greedy scheduling approach is more effective in enhancing user satisfaction compared to the conventional scheduling strategies. In FCFS, if due to resource constraints all threads in ready queue cannot be scheduled, threads are admitted into the system, depending on their order of occurrence in the ready queue. In the case of priority scheduling, admission control is implemented depending on statically assigned application priorities. Coming to the comparison approaches, the FCFS scheduling strategy outperforms the priority scheduling scheme. Due to similar reasons mentioned under the polynomial algorithm class, FCFS scheduling performs better than priority scheduling.

7.9 GCD Class of Algorithms

This class is about finding the Greatest Common Divisor (GCD) for two n digit numbers. The time complexities for the GCD class morphisms are $O(n^2)$ and $O(\frac{n^2}{logn})$. As before, the result graphs shown in Figure 7.6, plot the variations in user satisfaction for the target application with increase in congestion(total number of applications concurrently running along with target application). Similar to the sorting and polynomial classes, even in this class the bottommost scheduling heuristic performs better than the other scheduling heuristics. Another observation for the GCD class of algorithms is that, as context size increases, applications contend for resources. When resource contention increases, the classical scheduling approaches like FCFS and priority scheduling undergo drastic performance degradations, but the greedy scheduler heuristics suffer the least due to the resource contention. Overall from the graphs we observe that similar to the polynomial, multiplication and sorting classes, the bottommost scheduling

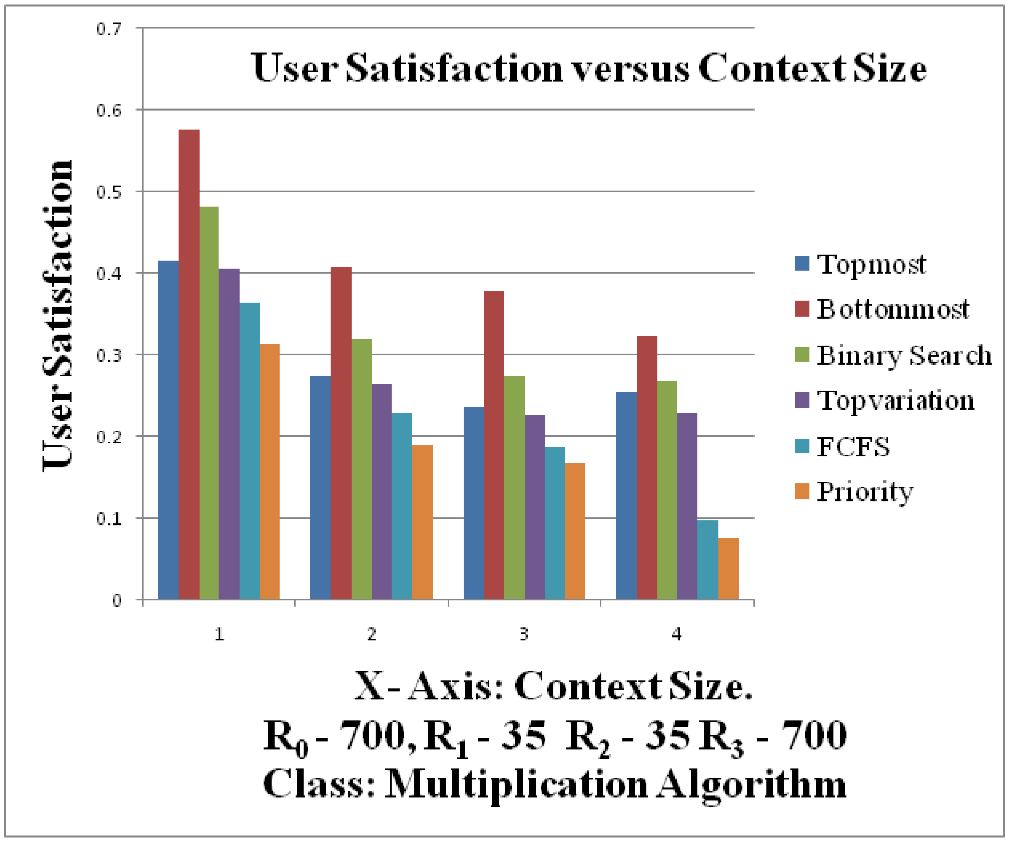


Figure 7.5 Multiplication class: User Satisfaction vs Context Size

heuristic performs better than the other scheduling heuristics. As mentioned earlier in the polynomial and multiplication classes, when there is a mix of class A and class B's application threads in an active cut, the bottommost traversal approach will allocate more resources to application threads in class B. This results in an unbalanced or skewed resource allocation among application threads, resulting in a sub-optimal solution in terms of user satisfaction. But the GCD algorithm class consists of threads from class B. Hence the bottommost scheduling heuristic outperforms the other scheduling heuristics. Coming to the comparison approaches, priority scheduling performs better than FCFS scheduling. In general, the embedded system designer accomplishes the mapping between problem constraints into priority values, based on well established set of facts. Since priority values for applications are derived after analyzing their past behavior in embedded systems, it provides a reasonable estimate in predicting its future characteristics. Moreover, priority values for applications are based on established set of facts, intuitively priority scheduling performs better than FCFS scheduling. On the other hand, FCFS scheduling does not take an application's past performance into account and relies on the thread ordering in the ready queue to accomplish scheduling.

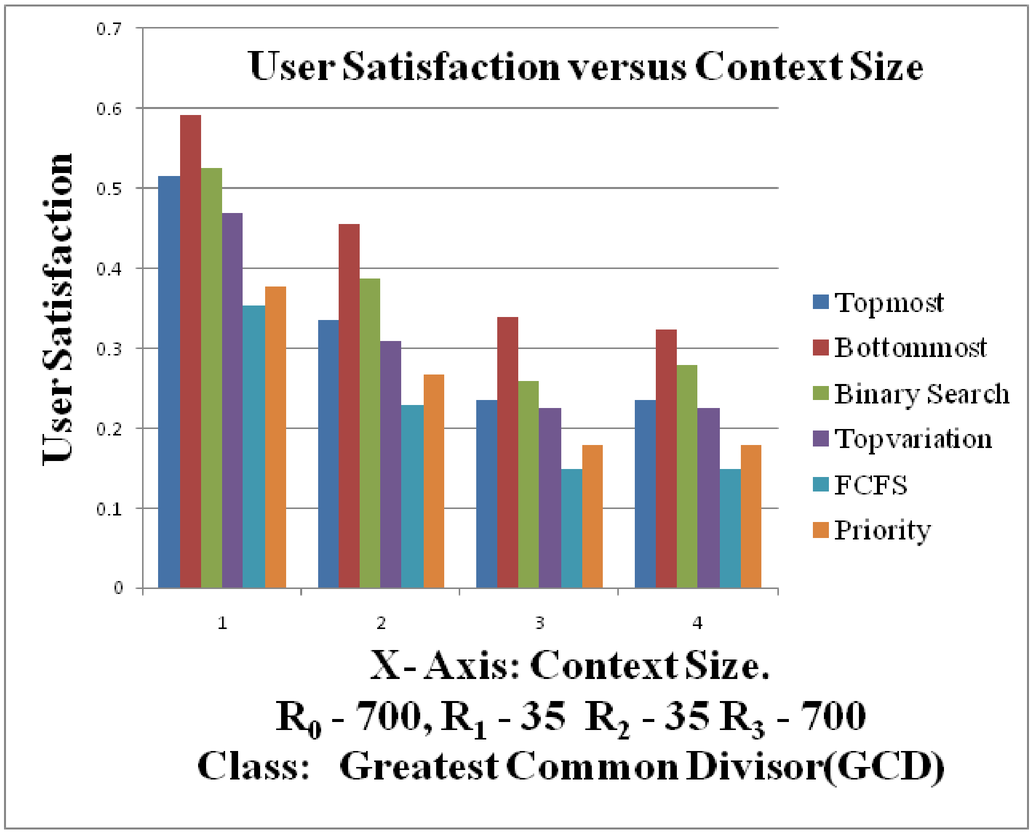


Figure 7.6 GCD class: User Satisfaction vs Context Size

7.10 Analysis- Performance Overhead

The performance overhead of the proposed greedy scheduling heuristics compared to the classical scheduling approaches needs to be quantified. Hence result graphs are plotted with execution time of the greedy scheduler heuristics on the Y-axis and context size along X-axis, for every algorithm class. These applications are run on a processor with 3.791 GHz Processor clock frequency. The execution time of these scheduler heuristics is measured in terms of

Micro-seconds (μs). It is observed that bottommost scheduling approach has higher performance overhead compared to the other heuristics. Intuitively, this heuristic takes more time to execute because it traverses the morphism table in a bottom-up manner incrementally allocating resources to threads. This is closely followed by the top-variation and topmost scheduling heuristics. The binary scheduling heuristic has relatively less execution time as the starting position is at the middle morphism entries for all the threads, resulting in a balanced resource allocation. Coming to the classical scheduling schemes, priority scheduling has relatively higher execution over FCFS as the latter is a simple scheduling approach compared to the former. The graphs demonstrating performance overhead for the various algorithm classes are shown in figures 7.7, 7.8, 7.9, 7.10 and 7.11. From the graphs it can be inferred that for the proposed scheduler heuristics, a typical scheduling decision takes order of $25 - 30$ Micro-seconds (μs) for a context size of 4 applications. This implies that the proposed greedy scheduling schemes are applicable for scheduling intervals in the order of 100 Micro-seconds (μs).

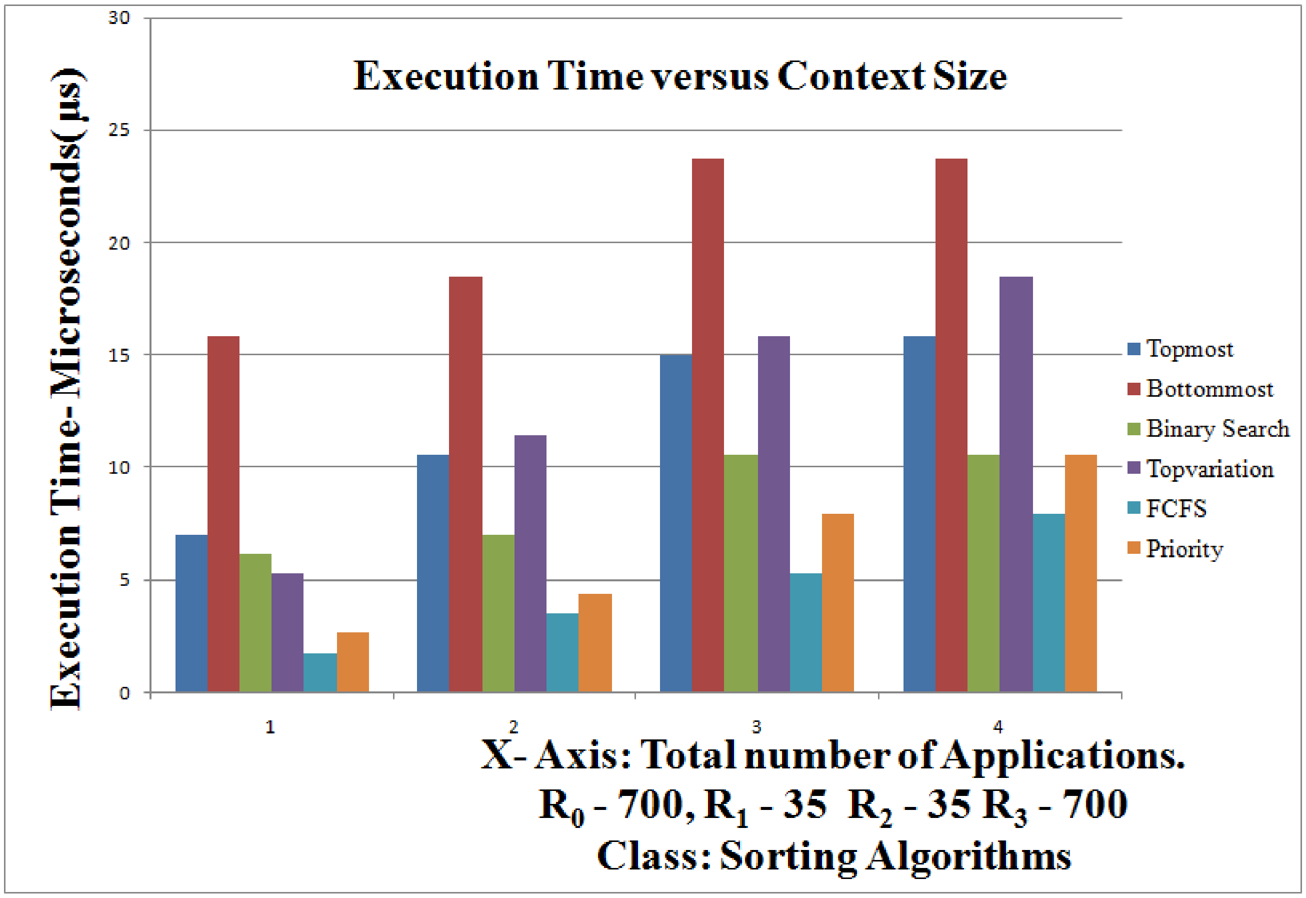


Figure 7.7 Sorting class: Execution Time vs Context Size

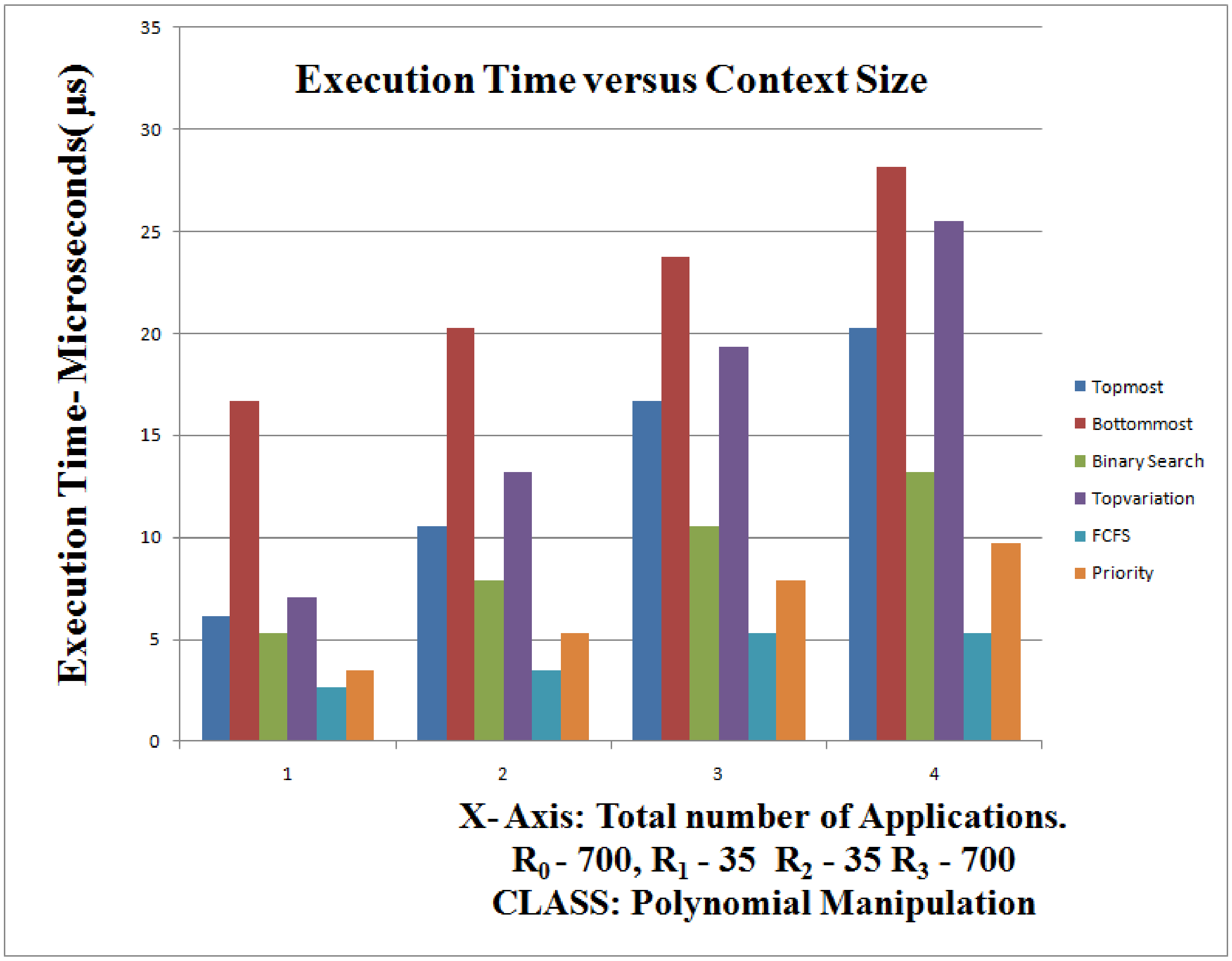


Figure 7.8 Polynomial class: Execution Time vs Context Size

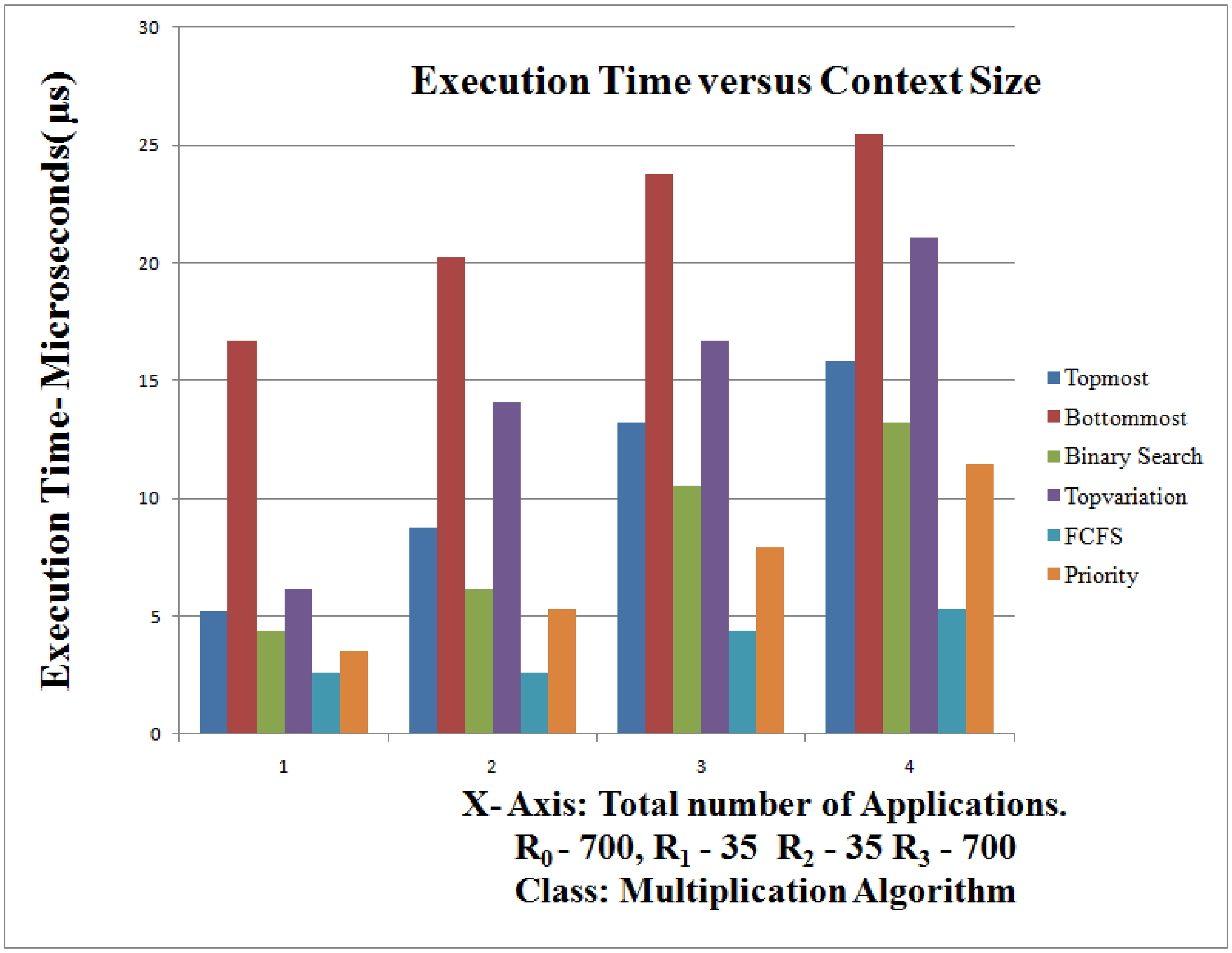


Figure 7.9 Multiplication class: Execution Time vs Context Size

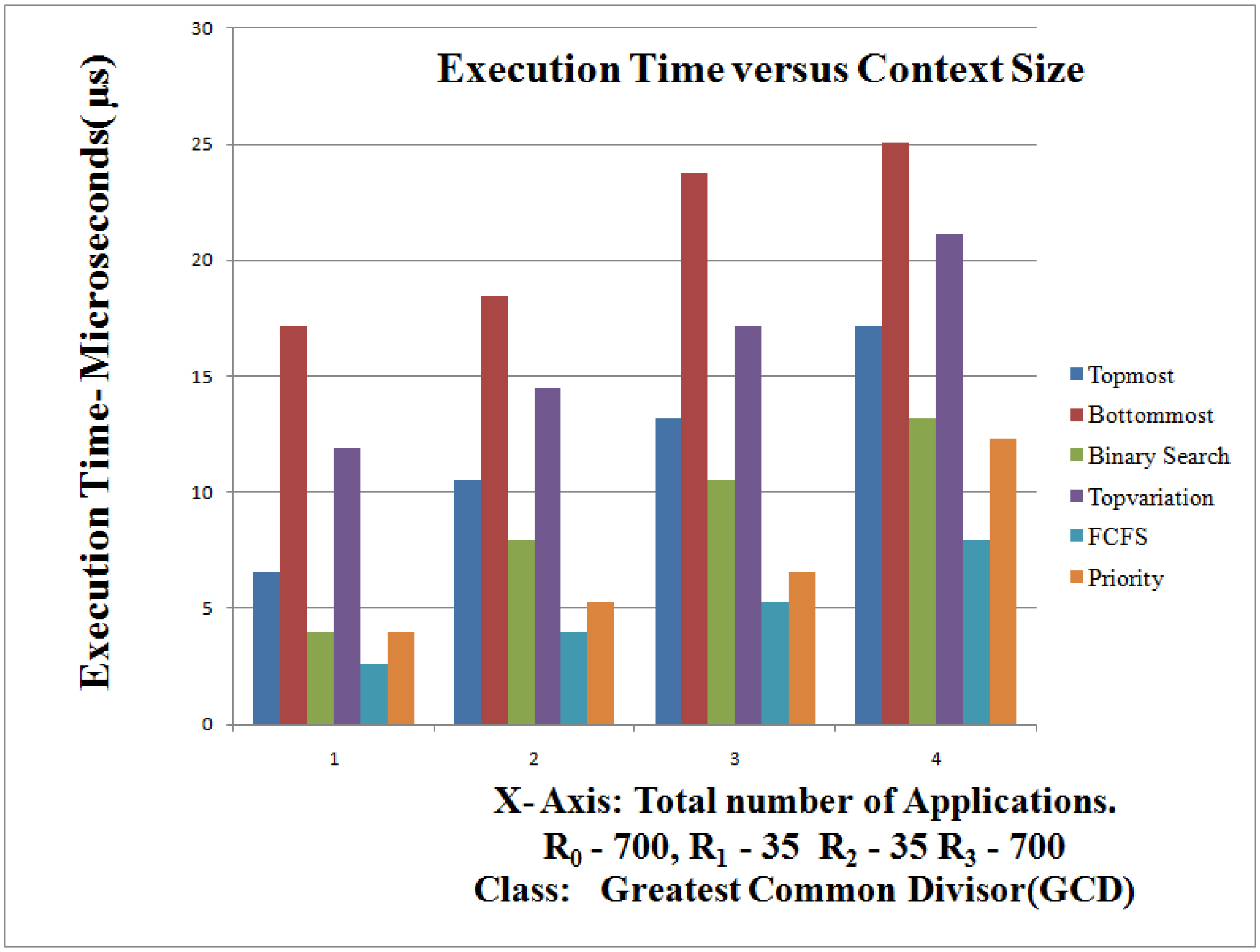


Figure 7.10 GCD class: Execution Time vs Context Size

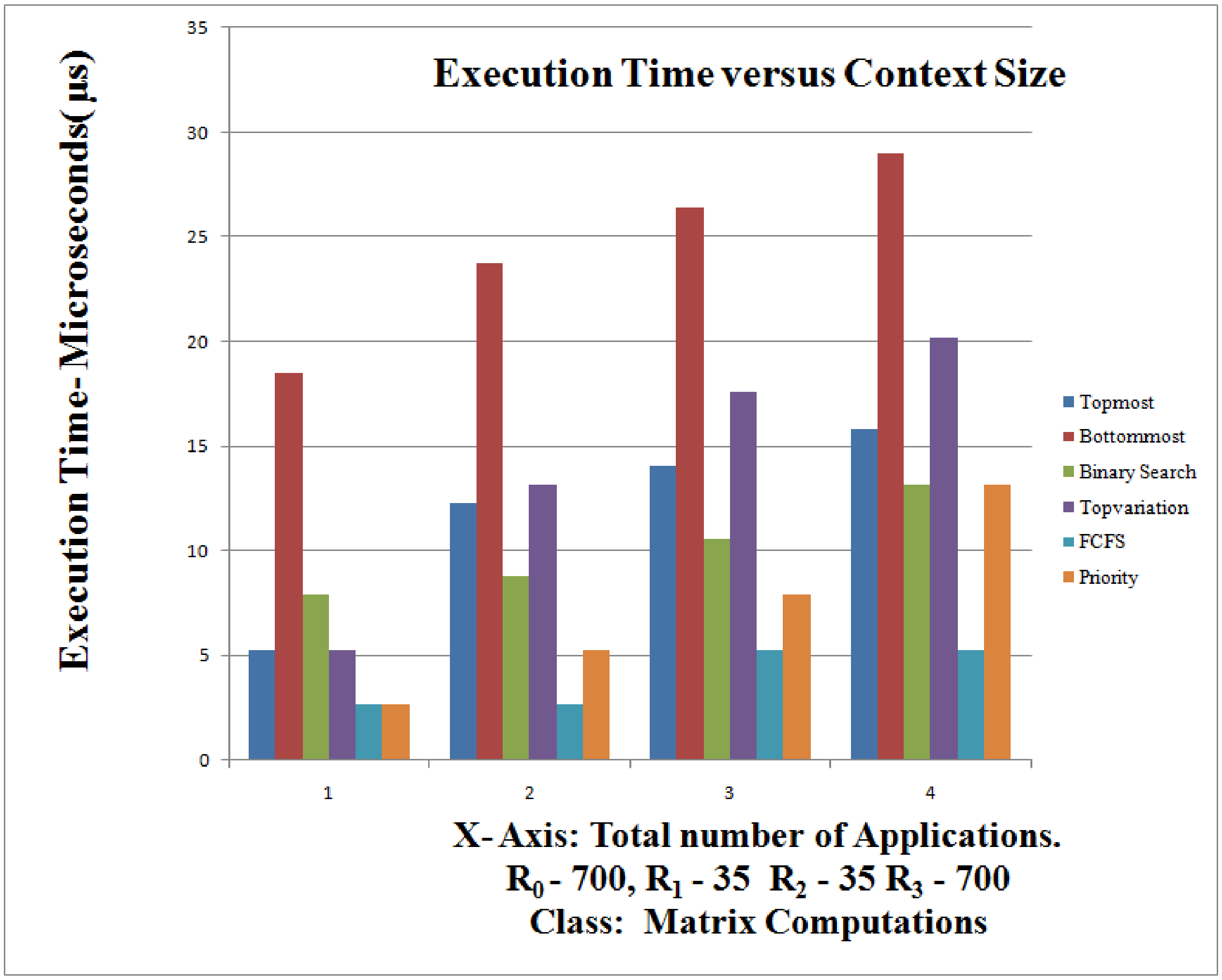


Figure 7.11 Matrix class: Execution Time vs Context Size

CHAPTER 8. Conclusion

This thesis proposes a futuristic approach for embedded system scheduler design, which offers extensive support to embedded system architects and designers. This is a pioneering attempt at designing a novel thread scheduler for a polymorphic embedded system. In summary, a dynamic thread scheduler which effectively operates in a multiple application, multithreaded framework has been implemented and evaluated. Polymorphic embedded systems help in exploring bigger design spaces compared to conventional systems like Hybrid Reconfigurable Systems (HRS), where the design space is limited. In the proposed scheduler framework, user satisfaction is used as the objective as opposed to conventional systems, where the performance measure is power, energy etc. In any typical embedded system, user perception plays a key role as it is a clear indicator of an application's performance. Sigmoid function, an S-shaped knee curve with near-linear central response and saturating limits, is employed to capture user perception. The polymorphic scheduler uses the marginal utility approach to resolve resource contention, with the intent of maximizing the objective function, which is user satisfaction. In order to evaluate the performance of the proposed polymorphic thread scheduler framework random graphs are used. These random graphs evaluate the efficacy of the proposed framework. Using a set of benchmarks, which are representative of general purpose embedded applications, we demonstrate the performance benefits of the proposed scheduler over classical scheduling schemes like FCFS and priority scheduling. The conclusions derived from the experimental results are stated as follows.

1. The greedy scheduling heuristics adopted by the proposed polymorphic thread scheduler guarantees significant user satisfaction enhancements over classical thread scheduling schemes namely FCFS and priority scheduling.

2. As the context size (congestion) increases, the user-satisfaction based resource allocation strategy employed by the scheduler framework, effectively makes resource allocations, leading to minimal performance degradations even under such extreme conditions, compared to conventional thread scheduling schemes.

3. For application threads, where the increase in throughput with resources exhibits a uniform or monotonic relationship, bottommost scheduling heuristic gives the near-optimal solution.

4. For application threads, where the increase in throughput with resources exhibits a non-uniform or non-monotonic relationship, the binary search scheduling heuristic gives the near-optimal solution.

5. Among the greedy scheduling heuristics presented, the bottommost scheduling heuristic outperforms the other scheduling heuristics for the sorting, polynomial, GCD computation and multiplication classes. The binary scheduling heuristic performs better than the other scheduling heuristics for the matrix algorithms class.

The proposed scheduling framework offers scope for future extensions. Currently the polymorphic embedded system considers several functionally equivalent software implementation alternatives for a thread. Future research activities could extend the proposed scheduler framework to accommodate a much broader morphism space, offering support for hardware morphisms as well. Also, any future work extending the proposed framework might want to explore a broader algorithm class to generate morphism table patterns.

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