Task concurrency management methodology to schedule
the MPEG4 IM1 player on a highly parallel processor
platform

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ABSTRACT
This paper addresses the concurrent task management of complex
multi-media systems, like the MPEG4 IM1 player, with empha-
sis on how to derive energy-cost vs time-budget curves through
task scheduling on a multi-processor platform. Starting from
the original “standard” specification, we extract the concurrency
originally hidden by implementation decisions in a “grey-box” model.
Then we have applied two high-level transformations on this model
to improve the task-level concurrency. Finally, by scheduling the
transformed task-graph, we have derived energy-cost vs time-budget
curves. These curves will be used to get globally optimized design
decisions when combining subsystems into one complete system or
to be used by a dynamic scheduler. The results on the MPEG4 IM1
player confirm the validity of our assumptions and the usefulness
of our approach.

Keywords
concurrency, scheduling, MPEG-4, embedded system, cost-efficiency

1. INTRODUCTION
Today, a new heterogeneous architectural design paradigm is emerg-
ing, usually called a platform. It includes several programmable
components, augmented with some specialized data paths or co-
processors (accelerators). The programmable components run soft-
ware, being slow to medium speed algorithms, while time-critical
parts are executed on dedicated hardware accelerators. By this evo-
lution, embedded processors become ubiquitous and a new role for
embedded software in contemporary and future ASIC (application
specific IC) systems is reserved. When looking at existing design
practices for mapping software (and hardware) on such a platform,
one can only conclude that these systems nowadays are designed in
a very ad hoc manner. The design trajectory starts by identifying
the global specification entities that functionally belong together,
called tasks or processes. Most of the time, these tasks and pro-
cesses are at least partly dynamically created and deleted. This
step is followed by a manual hardware-software partitioning. Be-
cause of separate implementation of the different tasks and of the
software and hardware, afterwards a system integration step is in-
evitable. This manual step performs the system/software embed-
ding, and synthesizes the interface hardware, which closes the gap
between the software and the hardware component.

The main goal of system/software embedding is to encapsulate the
concurrent tasks in a control shell which takes care of the task
scheduling (software scheduling in the restricted sense) and the
inter-task communication. Task scheduling is an error-prone pro-
tocol that requires computer assistance to consider the many interac-
tions between constraints. Unfortunately, current design practices
for reactive real-time systems are ad hoc and not very retargetable.
From this, one can conclude that a need exists for a systematic
methodology at the system level for the co-design of hardware and
software including especially the management of dynamic concur-
rent tasks. In this paper we will present in Section 3 the framework
of a methodology that we are currently developing to solve the task
concurrency problem. An important step in this methodology is
the design-time mapping of different tasks in a cost-efficient way
on a multiple processor platform. In Section 4.2 we will explain a
heuristic that helps us to select the most important task to run first
on the platform. We will illustrate this scheduling heuristic with
an example extracted from a very complex realistic driver, namely
the MPEG4 IM1 player. The results will be represented in Pareto
curves which do not give a single working point but which allow
us to globally trade-off cost (e.g. energy) vs constraints (e.g. time-
budget).

2. TARGET APPLICATION
The target applications of our task-level system synthesis approach
are advanced real-time multi-media and information processing(RMP)
systems, such as consumer multi-media electronics and personal
communication systems. These applications involve a combination
of complex data- and control-flow where complex data types are
manipulated and transferred in a dynamic way including creation
and deletion of both data and tasks. Most of these applications
are implemented with compact and portable devices, putting strin-
gent constraints on the degree of integration (i.e. chip area) and on
their power consumption. Secondly, these systems are extremely
heterogeneous in nature and combine high performance data pro-
cessing (e.g. data processing on transmission data input) as well as
slow rate control processing (e.g. system control functions), syn-

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chronous as well as asynchronous parts, analog and digital, and so on. Thirdly, time-to-market has become a critical factor in the design phase. Finally, these systems are subjected to stringent real-time constraints (both hard and soft deadlines are present), complicating their implementation considerably.

The main driver for our research is the IM1 player (see Fig. 1). This player is based on the MPEG4 standard, which specifies a system for the communication of interactive audio-visual scenes composed of objects. As this player consists of many different modules (audio, video, 3D animation, etc., coded in over 80,000 lines of high-level C++ specification), we believe it is representative for other multi-media applications.

![Figure 1: System level modules of the MPEG4 IM1 player](image)

Each frame in a MPEG4 compatible input stream consists of several parts, video object planes (VOPs), that can be decoded independently. In this paper, we will assume that up to 5 different VOPs are simultaneously active, which is realistic. For each VOP two interacting controllers need to be scheduled (see Fig. 3). Several other decoders may be needed to interpret additional information required by the VOPs (such as texture-data, audio, video). In this paper, we focus on the mapping of the controllers on the programmable components of the platform. The other more static signal processing tasks are assigned to dedicated accelerators.

3. FRAMEWORK OF THE TASK CONCURRENCY MANAGEMENT METHODOLOGY AT THE GREY-BOX ABSTRACTION LEVEL

The design of concurrent real-time embedded systems, especially embedded software, is a difficult problem to be performed manually due to the complex consumer-producer relationships, the presence of various timing constraints, the non-determinism in the specification and the sometimes tight interaction with the underlying hardware. Here we present a new cost-oriented approach to the problem of task scheduling on multiple processors. It fits in a global task concurrency management approach outlined in [2]. The approach uses as much as possible pre-ordering of the concurrent behavior under real-time constraints and minimizes the run-time overhead. At the same time, the scheduler tries to minimize cost such as the energy consumption.

The framework of our methodology is depicted in Fig. 2. An embedded system can be specified at a grey-box abstraction level in a combined MTG-CDFG model [1, 33, 36]. This specification is functional in representing the concepts of concurrency, timing constraints and interaction at either an abstract or a more detailed level, depending on what is required to perform good exploration decisions afterwards. As in [2], the task concurrency management can be implemented in four major steps. Firstly, the concurrency extraction is performed. Transformations [3] on the specified MTG-CDFG are then applied to increase the opportunities for concurrency exploration and cost minimization. After the extraction, we obtain a set of tasks, each of which consists of many thread nodes. Tasks can be viewed as a more or less independent part of the whole application. Then static scheduling will be applied inside each task at design time, including processor assignment in the context of multiple processing elements (PEs). Finally, a dynamic scheduler will schedule these tasks at run time on the given platform [5].

The purpose of task concurrency management is to determine a cost-optimal constraint-driven scheduling, allocation, and assignment of various thread nodes to a set of processors. Each thread node will be executed at a different speed on a different processor with a different cost, i.e., energy consumption. Given a task, static scheduling is done at design time to explore all the possibilities of valid assignment and scheduling. Each possibility means a different choice in time budget and energy consumption trade-off (i.e., another working point) and together they compose the global Pareto curve. Since the static scheduling is done at design time, computation efforts can be paid as much as necessary, provided that it can give a better scheduling result and reduce the computation efforts of dynamic scheduling.

4. SCHEDULING HEURISTIC FOR A LARGE NUMBER OF THREAD NODES

4.1 Related work and motivation

Abundant work has been done on scheduling. In literature, the granularity levels which different scheduling algorithms work at are quite different. However, the entity which scheduling algorithms deal with is always called task, job or node. To avoid confusion,
it is better to know that the meaning of these terminologies in our work can be different from other existing work.

When a set of concurrent tasks, i.e., tasks that can overlap in time, has to be executed on one or more processors, scheduling algorithm, must be applied to decide the order in which those tasks are executed. For a multiprocessor system, another procedure, assignment is also needed to determine on which processor one task will be executed.

In the real-time community, researchers use a black-box view of the task behavior. Comprehensive overviews of scheduling algorithms for real-time systems are given in [1, 6, 7, 8]. In contrast, in the embedded system community, many papers focus on white-box task descriptions [9, 10], which are typically not available at the early design stage. A grey-box model is used in our approach. As an example, we show in Fig. 3 the grey-box model we are going to use in the following scheduling experiment. Formal definition of this model is given in [1]. The most important semantics of this model is explained in the appendix.

A large body of scheduling algorithms stem from Liu and Layland’s classical paper[11], in which they gave five basic assumptions and studied the optimizability and schedulability of Rate Monotonic (RM) and Earliest Deadline First (EDF) algorithms in a fixed and dynamic priority environment respectively. Most of the later work can be classified as one of the two above, namely fixed priority or dynamic priority, and aims at relaxing the assumptions given in Liu’s paper and dealing with shared resources, aperiodic tasks, and tasks with different importance levels. Leung and Whitehead [12] suggested Deadline Monotonic to relax the deadline assumption. Later Chetto et al [13] introduced a transformation to the original task set to include the precedence constraints in EDF. To provide services for aperiodic or sporadic tasks, several bandwidth preserving algorithms have been proposed [14, 15, 16, 17, 18]. The problem of resource sharing is tackled with Priority Inheritance Protocol in [6, 19]. They provide a solid basis of performance oriented scheduling theory.

Since more and more embedded systems are targeted at multiple processor architectures, multiple processor scheduling plays a more and more important role. El-Rewini et al [20] give a clear introduction to the task scheduling in multiprocession systems. Hou et al [21] alleviate the saturation effect caused by excessive inter-processor communication in distributed embedded systems. Hoang et al [22] try to maximize the throughput by balancing the computation load of the distributed processors. All the partition and scheduling decisions are made at design time. This approach is limited to pure data flow applications. Teich et al [23] try to handle non-determinism in the heterogeneous embedded system. They have avoided the explicit enumeration of execution paths. However, since their work is based on the white-box viewpoint, it can not scale to large systems. On the contrary, our grey-box approach aims at handling such large systems. Yen et al [24, 25] try to combine the processor allocation and process scheduling into a gradient-search cosynthesis algorithm. It’s a heuristic method and can only handle periodic tasks statically.

However, in most of the above work, performance is the only concern. In other words, they only consider how to meet real-time constraints. For embedded systems, cost factors, like energy, must be taken into account.

Only a few papers involve the cost, like power, apart from performance issues. Gruian et al [26] used constraint programming to minimize the energy consumption at system level but their method is purely static and no dynamic tactic is applied to exploit more energy reduction. Since the energy consumption of CMOS digital circuits is approximately proportional to the square of the supply voltage, decreasing the supply voltage is lucrative to low power design, though it will also slow down the clock speed. Traditionally, the CPU works at a fixed supply voltage, even though at a light workload. In fact, under such situations, the fast speed of the CPU is unnecessary and can be traded for a lower energy/power consumption by reducing the supply voltage. Chandrakasan[27] compared several energy saving tactics concerned Dynamic Voltage Scheduling. Based on this investigation, several real-time scheduling algorithms are provided, e.g. by Hong[28] and Okuma[29]. However, the platforms for such algorithms are restricted to a single processor with dynamically variable supply voltage. Jha et al [30, 31, 32] go pretty far in the power-consicious design. Their early work [30, 31] focus more on how to meet hard real-time constraints of aperiodic tasks and how to reduce hardware cost. Based on techniques in this early work, power in multiple processor context is treated by

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**Figure 3: Grey-box model of the compression layer of the IM1 player**

Existing scheduling algorithms can be roughly divided into dynamic and static scheduling. In a multiprocessor context, when the application has a large amount of non-deterministic behavior, dynamic scheduling has the flexibility to balance the computation load of processors at run-time. However, the run-time overhead for code size and energy consumption may be excessive. In addition, most multimedia applications have limited non-deterministic behavior. Moreover, it is usually impossible to make globally optimal scheduling decisions at run-time. Consequently, scheduling decisions should be made as much as possible at design-time. We selected a combination of the static and dynamic scheduling to take advantage of both of them.
evenly distributing the workload [32]. However, their work doesn’t tackle power consumption directly. No manifest power and performance relation is used to steer the design-space exploration. In addition, they assume a continuously scaled voltage, which simplifies the processor assignment problem.

4.2 A new scheduling heuristic for large number of tasks

Our approach can be applied to the multiprocessor platform without the need of changing the processor voltage dynamically. For a given platform, i.e., the number of high-speed processors and low-speed processors, the heuristic will derive an energy-cost vs time-budget curve. Compared with other scheduling algorithms, like MILP (mixed integer linear programming), the heuristic does not treat real-time constraints directly. Hence, the computation complexity is reduced. The heuristic derives a set of working points on the energy-cost vs time-budget plane instead of only one point. These working points range from the most optimal performance point within that given platform to the point barely meeting timing constraints. Existence of these different working points is mostly due to the different thread node to processor assignments (some of it is due to idle time in the schedule). As a result we also have to deal with a crucial assignment problem. We will show in Section 5 how a trade-off between energy-cost and time-budget can be made by a proper assignment decision. These points are crucial when combining subsystems into a complete system or during the dynamic scheduling stage. The reason is that in both cases we need to select working points of subsystems and combine them into a globally optimal working point.

To schedule the thread nodes on the above multiple processor platform, we have developed a static scheduling heuristic. The heuristic uses two criteria to decide which thread node to run first. The first criterion is the self-weight of a thread node. It is defined as the execution time of the thread node on the low-speed processor. The larger the self-weight of a thread node, the higher its priority to be mapped on a high-speed processor.

The second criterion is the load of a thread node. If some thread nodes are depending on a thread node, the sum of the self-weights of all the dependent thread nodes is defined as the load of the thread node. It is worth noting that “dependent” means control dependence. The more load a thread node has, the earlier it should start to execute.

From the above criteria, when a processor is available, the following strategy takes care of selecting a candidate thread node.

1. When a thread node is dominant both in the self-weight and load over the other candidate thread nodes, it will be scheduled first.

2. When one thread node has a dominant self-weight and another thread node has a dominant load, either of them can be scheduled first. By alternating their order different points on the energy-cost vs time-budget plane can be generated.

It is better to realize that the heuristic implicitly includes energy considerations. Because for a given processor, the energy consumption is directly related to the execution time. The self-weight and load in the heuristic are merely two interpretations of execution time from different perspectives. Applying this heuristic to the IM1 player will be discussed in the following section. Even though it seems relatively simple, it turns out to be very effective for scheduling the tasks in the MPEG-4 IM1 player.

5. TASK SCHEDULING EXPERIMENT

To get smooth scenes, a frame rate of 30ms is required. Currently, the IM1 player is implemented on a Pentium or Pentium-compatible platform. Such an implementation is far from meeting the 30ms timing constraint. This real-time constraint is only reachable when an extremely parallel and powerful instruction-set processor is used. In our experiment, the IM1 player is mapped to a multiple processor platform including custom accelerators next to the instruction-set processors. We have extracted the task graph from the IM1 implementation code. By analyzing the profiling information, we know how many VOPs one frame contains, how many BIFS nodes one VOP has and how many decoder setup are done in one VOP.

We pick up an example frame of 5 VOPs. The number of BIFS nodes and the number of decoder setup are listed in Table 1. For every BIFS node decoding and decoder setup, we get the execution time from the profiling data. The grey-box model of a typical BIFS decoding and decoder setup is shown in Fig. 4. The left part of Fig. 4 is the context of the BIFS decoding or decoder setup. The right part is the unfolding of an example BIFS decoding. In reality, instances of the BIFS decoding and decoder setup take place inside a VOP with variations in the underlying graphs and execution times.

<table>
<thead>
<tr>
<th>VOP</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of BIFS nodes</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Number of decoder setup</td>
<td>12</td>
<td>3</td>
<td>5</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: A typical frame structure

To meet the 30ms timing constraint for the protocol subsystem, we use a number of StrongARM processors [34] and custom accelerators. The accelerator can be for example, the Ozone custom processor design of wavelet functionality [35]. The processors run at either 100MHz or 233MHz. For a thread node, the execution time and energy cost are different on the two processors. We use $t_L$ and $t_H$ to denote the execution time on the low-speed and high-speed
processor respectively. $\Delta t$ is the difference between these two execution times. Similarly, we use $E_L$ and $E_H$ to denote its energy cost on these two processors. $\Delta E$ is the energy difference. Our calculations are based on the following formulae:

$$\Delta t = t_L - t_H = \left(1 - \frac{1}{2.33}\right)t_L$$  \hspace{1cm} (1)

$$\Delta E = E_H - E_L = (2.33^3 - 1)E_L$$  \hspace{1cm} (2)

We have tried different processor combinations. A given processor combination means a number of fixed high-speed and low-speed processors. For each processor combination, we make different processor assignment and put thread nodes into different orders by the static scheduling heuristic described in Section 4.2. Hence, an energy cost vs time-budget curve is derived. Altogether, there are four processor combinations which satisfy the timing constraints (Table 2).

<table>
<thead>
<tr>
<th>Processor combination</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of high-speed processors</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Number of low-speed processors</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Total Number of processors</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

**Table 2: Different processor combinations**

For Combination 1 and 4, only one solution exists which meets the timing constraints. Consequently, there is no trade-off between energy cost and time-budget. For Combination 2 and 3, we have derived a Pareto-optimal energy vs time-budget curve for each of them.

Applying this scheduling heuristic to the sample problem, we have derived two curves for processor combination 2 and 3, which are shown in Fig. 5. From the two Pareto curves, we know that points on the curve of Combination 3 provide globally optimal working points until point 6 is reached. A lower time-budget, i.e., a more tight timing constraint cannot be satisfied by the platform of Combination 3. This is because the existing concurrency in the task graph has been fully utilized by the processors in Combination 3. To further decrease the time-budget, we have to use extra high-speed processors to reduce the critical path. That is, either to replace low-speed (low-power) processors with high-speed (high-power) processors or to introduce additional high-speed processors. In other words, two ways exist to decrease the time-budget. One is to utilize the concurrency, the other is to reduce the critical path. Therefore, to get a lower time-budget, we have to resort to the platform of Combination 2 and pay a large energy penalty. This explains the big jump of the global Pareto curve from point 6 of Combination 3 to point 6 of Combination 2.

As no related work exists that fully matches our problem statement, we have made a comparison with an exact MILP formulation. We have applied a well-known public domain MILP solver [4] to this scheduling problem. Since the amount of MILP description for scheduling the task graph on a multiple processor platform will explode, we have to apply the MILP solver to a two processor platform. Shown in Fig. 6 are three curves. One is got from the heuristic, the rest two are the outputs from the MILP solver for the first time and after it runs for five days, respectively. It is clearly seen that the MILP solver has made large improvement after five days. However, to get all the optimal points over the time-budget axis, which should be lower than the points given by the heuristic, it will take even longer time. The fact motivates the need for a heuristic. It also substantiates our claim that our heuristic provides a good quality and run-time complexity. We have only one major demonstrator at present, but we believe that the complexity and heterogeniety of the IM1 player is representative of a whole class of dynamic and concurrent applications. Therefore the result in this section should be conclusive enough.

![Figure 5: Pareto curves for processor combination 2 and 3](image)

![Figure 6: Comparison of energy vs time-budget curves derived by the heuristic and MILP](image)

### 6. CONCLUSIONS

We have demonstrated in this paper that a grey-box task graph model should be used to design advanced real-time dynamic multimedia applications. This task-level model allows us to systematically explore the design at a high abstraction level in order to obtain more and better task schedules. Transformations on the task graph level have been applied to improve this further. On a multiprocessor targeted platform including custom accelerators for the video coders, the different schedules obtained with a heuristic scheduling approach are represented in Pareto curves trading-off time-budget vs energy-cost. This information is crucial to decide on run-time
trade-offs involving other subsystems present in the entire application.

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8. REFERENCES