
**POWER OPTIMIZATION
AND SYNTHESIS AT
BEHAVIORAL AND SYSTEM LEVELS
USING FORMAL METHODS**

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USING FORMAL METHODS**

by

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Printed on acid-free paper.

**This book is dedicated to the
development of greater
understanding and the
reduction of conflicts among
people.**

Contents

List of Figures	xi
List of Tables	xv
Preface	xxi
1. INTRODUCTION	1
1.1 Low Power Design	1
1.2 Review of Behavioral Synthesis Techniques	3
Scheduling	5
Resource allocation and binding	8
Functional pipelining	9
Power optimization techniques	10
1.3 Hardware/Software Co-design	12
Fine-grain HW/SW co-design	13
Coarse-grain HW/SW co-design	14
1.4 Organization of the Book	16
2. REGISTER ALLOCATION AND BINDING	17
2.1 Introduction	17
2.2 Switching Activity Calculation	19
Calculation of pdf's in a data flow graph	19
Power consumption model	21
2.3 Register Binding with Minimum Power Dissipation	26
Max-cost flow formulation	26
A detailed example	33
2.4 Experimental Results	37
2.5 Chapter Summary	39
3. POWER-OPTIMAL MODULE ALLOCATION AND BINDING	47
3.1 Introduction	47
3.2 Terminology and Overview	48
3.3 Switching Activity Calculation	51
3.4 Module Binding with Minimum Power Dissipation	54
Power dissipation of a functional unit	54

A functionally pipelined data path	55
Optimization problem	57
3.5 Multi-Commodity Flow Formulation	60
A detailed example	65
3.6 Experimental Results and Discussions	67
Impact on circuit speed	69
Impact on interconnects	69
Impact on multiplexor cost	70
Impact on register assignment	72
Handling conditional branches	74
3.7 Chapter Summary	74
4. MULTIPLE SUPPLY VOLTAGE SCHEDULING	79
4.1 Introduction	79
4.2 Related Problems	81
4.3 Energy-delay Curves	83
Timing model	83
Energy dissipation model	84
Trade-off curves	91
4.4 The Scheduling Algorithm	91
Post-order traversal	93
Pre-order traversal	94
Extension to general DFG's	94
Complexity analysis	98
Module sharing after scheduling	99
4.5 Functionally Pipelined Data-path	101
Background	101
Handling multi-frame operations	102
Module sharing after scheduling	106
Controllable parameters	107
4.6 Experimental Results	107
4.7 Chapter Summary	113
5. CO-DESIGN OF COMMUNICATING SYSTEMS	119
5.1 Introduction	119
5.2 Related Work	123
5.3 Process Decomposition in a Task Graph	124
5.4 MILP Formulation for the Scheduling	125
5.5 Scheduling Using Dynamic Programming	128
Area vs. delay curves	128
Simple task graphs	129
Complex task graphs	130
Complexity Analysis	141
5.6 Allocation and Binding	143
TDM scheduling	144
Extension to allow subprocesses with different processor utilization	145
Handling other cost functions, e.g. energy	145

Discussion	146
5.7 Experimental Results	147
5.8 Chapter Summary	149
6. CONCLUSION	153
6.1 Book Summary	153
6.2 Directions for Future Research	155
References	157
Index	165

List of Figures

2.1	Register sharing model.	22
2.2	A static D flip-flop.	23
2.3	Lumped model of a D flip-flop.	23
2.4	From data flow graph to network N'_G .	30
2.5	An example scheduled CDFG.	34
2.6	Oriented compatibility graph for the register allocation problem.	35
2.7	Network after applying the vertex splitting technique.	38
2.8	Simple CDFG used in experimental results.	39
2.9	A simple DFG with only one D - J block.	42
2.10	A DFG with nested D - J blocks and four branches.	43
2.11	DFG G_1 with branch A .	43
2.12	DFG G_2 with branches B and C .	44
2.13	DFG G_3 with branches B and D .	44
3.1	An example data flow graph with conditional branches and its relabeling.	49
3.2	Basic allocation table after scheduling of data flow graph in Fig. 3.1 and its relabeling. Note that the superscript on each operation denotes the pipeline initiation index (or data sample index) of that operation.	49
3.3	Definitions of AI and TC . Note that the superscript on each operation denotes the pipeline initiation index (or data sample index).	56
3.4	(a) is the result of optimal solution obtained across two frames, (b) is the optimal solution obtained within one frame.	58

3.5	Valid binding resulting from the permutation of column entries in the <i>AT</i> .	58
3.6	Three whole chains of nine time steps composed of three optimal sub-chains. When we consider FU sharing within one time frame only, then the sharing solution within that frame (say frame # 1) will be replicated across all frames.	59
3.7	Boundary switching between two frames.	59
3.8	Extended allocation table (<i>EAT</i>).	59
3.9	Rotating the basic <i>AT</i> and obtaining the new <i>EAT</i> .	61
3.10	Network N_H constructed from the new <i>EAT</i> shown in Fig. 3.9. Dark edges represent edges from level i to $i + 1$ while light edges represent edges from level i to $j > i + 1$.	62
3.11	Node splitting process on node i .	64
3.12	A very simple DFG whose basic <i>AT</i> is shown in Fig. 3.9.	66
3.13	(a)Min and (b)Max power binding for the allocation table of Fig. 3.9.	66
3.14	RTL structure for the example.	67
3.15	Allocation tables when using different number of adders.	72
3.16	Minimum power register allocation obtained by the network flow method.	74
3.17	Example used for Appendix A.	77
4.1	Energy vs. input switching activities for add16 (shown for $\Delta\alpha=0.1$, at 5V).	86
4.2	Energy vs. input switching activities for mult16 (shown for $\Delta\alpha=0.1$, at 5V).	86
4.3	A level shifter circuit.	89
4.4	Characterization of our module library using the second method in Section 4.3 for a 16 bit adder and the energy vs. delay curves under different α 's.	92
4.5	Lower bound merge of delay curves.	95
4.6	Add operation on two delay curves.	95
4.7	Post-order energy-delay curve propagation in a DAG (<i>PO</i> denotes a primary output node).	96
4.8	Cost calculation in a DFG with a conditional branch.	98

4.9	Module sharing during post-order traversal in dynamic programming.	100
4.10	Example to show the revolving schedule on 3 module $MA's$, for the module delay = $7t_c$ and pipeline latency, $L = 3(t_c)$. Note that A_i denotes the execution of operation A in pipeline initiation i , and c -step 1 = time steps $\{1,4,7,\dots\}$, c -step 2 = time steps $\{2,5,8,\dots\}$.	103
4.11	Four pipeline initiations and the corresponding revolving schedule on multiple modules instances of corresponding operations.	105
4.12	A small example used in the experimental results.	108
4.13	Another small example to compare the dynamic programming algorithm with that of [RS95].	110
4.14	Histogram results.	117
4.15	Histogram results continued.	118
5.1	Decomposition of communicating processes with different type of midway communication.	126
5.2	Example to illustrate decomposition of single and multi-threaded processes.	127
5.3	Example to show the definition of re-convergence.	132
5.4	Example to show why binning is required during dynamic programming.	133
5.5	Pseudo code for creating binning strings.	134
5.6	Drawing to be used in Theorem 5.5.1.	135
5.7	Drawing to be used in Theorem 5.5.2.	135
5.8	Two examples to show how the binning strings (shown in parantheses) are calculated.	137
5.9	Example to illustrate the need to merge $PO's$ into a single root.	141
5.10	A very simple task graph with only end/begin communication used in experimental results.	149
5.11	Task graph with only end/begin communication but with re-convergent fanout used in experimental results.	150
5.12	Task graph of Voice Activity Detection (VAD) used in the GSM system.	151

List of Tables

2.1	Normalized switching activities sw_n .	35
2.2	Edge weights for the network.	36
2.3	Experimental results for various benchmarks. Note, †: Corresponds to the case of using minimum number of registers for the DFG.	39
2.4	Experimental results using Max-cost flow solution for various benchmarks. Note †: Corresponds to the case of using minimum number of registers for the DFG.	40
3.1	Data-path circuits and their simulation results.	55
3.2	Different α 's obtained from simulation.	65
3.3	Cost matrix for arcs in the network of the second example.	65
3.4	P_{total} (power dissipations in FU 's with unit (μW)).	68
3.5	P'_{total} (power dissipations in FU 's + <i>muxes</i>).	69
3.6	Comparison of power consumed in designs using adders and <i>muxes</i> with designs using only adders.	72
3.7	Comparison continued.	73
4.1	Data-path circuits and their gate-level simulation results under random sequence with $\alpha_1 = \alpha_2 = 0.5$ ($V=5$ volts).	88
4.2	Data-path circuits and their gate-level simulation results under random sequence with $\alpha_1 = 0.5, \alpha_2 = 0.1$ ($V=5$ volts).	88
4.3	Data-path circuits and their gate-level simulation results under random sequence with $\alpha_1 = \alpha_2 = 0.1$ ($V=5$ volts).	88

4.4	Average energy consumption (in units of pJ) for 16-bit level shifter per logic transition (all 16-bits are switching) produced by SPICE simulation. Note that, entry (\mathbf{x}, \mathbf{y}) in this table is the energy used for converting the output of a module which uses supply voltage x to the input of a module which uses supply voltage y .	89
4.5	Module library used for example DFG ($\alpha_1^{\mathbf{FU}} = \alpha_2^{\mathbf{FU}} = 0.5$).	108
4.6	Module energy dissipation (in pJ) under a pseudo-random white noise data model at $\alpha_1^{\mathbf{FU}} = \alpha_2^{\mathbf{FU}} = 0.5$.	109
4.7	Module energy (in pJ) for $\alpha_1^{\mathbf{FU}} = \alpha_2^{\mathbf{FU}} = 0.5$.	112
4.8	Experimental results for various benchmarks. Note, that E^1 is energy dissipation corresponding to the supply voltage of 5 volts. E^2 , E^3 and E^4 are the average energy obtained when the libraries contain modules of $\{5V, 3.3V\}$, $\{5V, 3.3V, 2.4V\}$ and $\{5V, 3.3V, 2.4V, 1.5V\}$, respectively. †: Corresponds to the critical path delay of the DFG. In this table, $t_c = 30$ ns and $L = 3$.	113
4.9	Experimental results continued.	114
4.10	Energy consumption vs. t_c under $T_{comp} = 2T_{crit}$ for various benchmarks. E^1 is energy dissipation corresponding to the supply voltage of 3.3 volts. E^4 column is not shown since results are similar to that of E^3 .	115
4.11	Energy consumption vs. t_c continued.	116
5.1	Experimental results for various benchmarks.	149

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Dr. Pedram was the co-founder and General Chair of the 1995 International Symposium on Low Power Design and the technical co-chair and general co-chair of the 1996 and 1997 International Symposium on Low Power Electronics and Design, respectively. He has given several tutorials on low power design at major CAD conferences and forums including DAC and ICCAD. He has

published more than 100 journal and conference papers, and co-edited two books on low power design methodologies and techniques. His current research focuses on developing methodologies, techniques, and software tools for lowering the power dissipation in electronic circuits and systems, and on design flows and algorithms for logical/physical codesign of deep submicron circuits. Dr. Pedram is a senior member of IEEE - Circuits and Systems Society and ACM - SIGDA, and an associate editor of the IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems and of the ACM Transactions on Design Automation of Electronic Systems.

Foreword

System-level design is a challenging task because engineers are confronted with a variety of problems, including the need of trading off different objectives, such as performance and power consumption, in the search for design implementations with increasing features, constraints and complexity.

When looking at electronic systems, whether computational or embedded, as information processing machines, an immediate question comes up on the efficiency by which they perform their tasks, as in the case of thermo-dynamical machines. Designing electronic systems with high energy efficiency, or equivalently designing systems that perform under bounds on electric energy consumption, is one of the essential problems to be solved. Despite efforts in this direction in the last decade, new solutions - such as those presented in this book - are crucial for the improvement of system design technologies. Systems with increasingly higher energy efficiency are required by the ongoing needs of batter-power portable systems to support complex software application programs, and by the desire of reducing the environmental impact of all electronic systems.

Design technologies for system-level design have evolved through the years while facing the formidable challenge of addressing computationally complex problems. The widespread use of heuristics in solving design problems has enabled the creation of several computer-aided design tools in a short time. Nevertheless, the quality of the results achieved by design tools based on heuristics is hard to quantify. Algorithms with guaranteed optimality properties are highly-desired because they can enable a thorough search of the design space.

This book makes an important contribution to the field of system design technologies by presenting a set of algorithms with guaranteed optimality properties, that can be readily applied to system-level design. This contribution is timely, because it fills the need of new methods for a new design tool generation, which supports the design of electronic systems with even more demanding requirements.

Giovanni De Micheli, Professor
Stanford University

Preface

With the Moore's law still in effect, integrated circuit densities and operating speeds continue to rise at an exponential rate. Chips however cannot get larger and faster without a sharp increase in power consumption beyond the current levels. Minimization of power consumption in VLSI chips has thus become an important design objective. In fact, with the explosive growth in demand for portable electronics and the usual push toward more complex functionality and higher performance, power consumption has in many cases become the limiting factor in satisfying the market demand.

The low power design challenge has been met by an active research and development community both in industry and academia. Rapid advances are taking place in low-power process technologies, architecture and circuit optimization techniques, power-aware simple and complex cell design, use of variable and/or multiple supply voltages and dynamic power management schemes, and low power computer aided design (CAD) tools from system and software levels to layout and transistor levels. In particular, a new generation of power-conscious CAD tools are coming into the market to help designers estimate, optimize and verify power consumption levels at most stages of the IC design process. These tools are especially prevalent at the register-transfer level and below. There is great need for similar tools and capabilities at the behavioral and system levels of the design process.

The increased degree of automation of industrial design frameworks has produced a substantial change in the way digital ICs are developed. The design of modern systems usually starts from specifications given at a very high level of abstraction. This is because existing EDA tools are able to automatically pro-

duce low-level design implementations directly from descriptions of this type. Circuit and system designers need tools that allow them to explicitly control the power budget during the early phases of the design process. This is because the power savings obtainable through automatic optimization early in the design process is usually more significant than that achievable by means of lower level optimization.

This need has not gone unnoticed. Many researchers and CAD tool developers are working on high-level power modeling and estimation, as well as power-constrained high-level synthesis and optimization. Techniques and tools alone are however insufficient to optimize the VLSI circuit power dissipation – a consistent and convergent design methodology is required as well. Components of such a low power design methodology include: upfront specification, early analysis and optimization, forward timing and power constraint propagation and backward capacitance annotation, as well as multi-level power simulation and verification. Tools that support such a flow would include power macro-models for such library primitives as gates, adders, multipliers and register files as well as more complex functions such as memories, controllers, encoder/decoders and in general, intellectual property (IP) blocks.

The present book is written to address some of the key problems in power analysis and optimization early in the design process. In particular, this book focuses on power macro-modeling based on regression analysis and power minimization through behavioral transformations, scheduling, resource assignment and hardware/software partitioning and mapping. What differentiates this book from the other published work on the subject is that the mathematical basis and formalism behind our algorithms and the optimality of the these algorithms subject to the stated assumptions.

This book is organized into six chapters. Chapter 1 lays the groundwork by presenting an overview of the behavioral-level and system-level synthesis techniques and design representations. In Chapters 2 and 3, we present optimal algorithms for activity-driven register and module allocation and binding. The power consumed by a resource mainly depends on the input switching activities induced by the data being stored or processed. Since the patterns flowing through a circuit may have specific probability distribution, the way registers and modules are allocated in a control/data flow graph may heavily impact the switching activities at the interface of the resources. These chapters present

graph-theory-based algorithms for power-efficient allocation and binding of registers and modules based on accurate computation of the probability density functions at the inputs of various resources, given probability distributions for the system primary input. In Chapter 4, we describe an algorithm based on dynamic programming for solving the multiple-voltage scheduling problem. The technique, which is based on dynamic programming requires the availability of accurate timing and power models for the modules in the RTL library for all possible supply voltage levels. Using this information, and by a post-order traversal of the data flow graph, it is then possible to calculate the energy-delay trade-off curves at each node of the graph. Supply voltage level assignment and scheduling of all operations take place during a pre-order traversal of the data flow graph. In Chapter 5, we provide an optimal algorithm for finding the minimum cost (area and/or energy dissipation) hardware/software partitioning, and mapping of a generalized task graph subject to performance constraints. Processes in a generalized task graph may communicate with each other at times other than the beginning or end of their lifetimes by various blocking/non-blocking communication mechanisms. The coarse-grain HW/SW partitioning/mapping technique used a modified (symbolic) dynamic programming algorithm with binning strings to produce a globally optimal solution subject to model assumptions. When needed, we also present power estimation models and techniques to support the optimization algorithms. Chapter 6 presents the book summary and outline of possible research venues.

We wish to express our appreciation to the students in the low power CAD group at USC for providing a stimulating and challenging environment, to Professor Giovanni De Micheli for writing the foreword for the book, to Carl Harris and staff at Kluwer Academic Publishers for their help in editing and publishing the book, and finally to our families for their indulgence of our interest in this project.

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