

Diastolic Arrays: Throughput-Driven Reconfigurable Computing

by

Myong Hyon Cho

Submitted to the Department of Electrical Engineering and Computer
Science

in partial fulfillment of the requirements for the degree of

Master of Science in Electrical Engineering and Computer Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2008

© Massachusetts Institute of Technology 2008. All rights reserved.

Author
Department of Electrical Engineering and Computer Science
May 20, 2008

Certified by
Srinivas Devadas
Professor of Electrical Engineering and Computer Science
Thesis Supervisor

Accepted by
Arthur C. Smith
Chairman, Department Committee on Graduate Students

Diastolic Arrays: Throughput-Driven Reconfigurable Computing

by

Myong Hyon Cho

Submitted to the Department of Electrical Engineering and Computer Science
on May 20, 2008, in partial fulfillment of the
requirements for the degree of
Master of Science in Electrical Engineering and Computer Science

Abstract

In this thesis, we propose a new reconfigurable computer substrate: diastolic arrays. Diastolic arrays are arrays of processing elements that communicate exclusively through First-In First-Out (FIFO) queues, and provide hardware support to guarantee bandwidth and buffer space for all data transfers. FIFO control implies that a module idles if its input FIFOs are empty, and stalls if its output FIFOs are full. The timing of data transfers between processing elements in diastolic arrays is therefore significantly more relaxed than in systolic arrays or pipelines. All specified data transfers are statically routed, and the routing problem to maximize average throughput can be optimally or near-optimally solved in polynomial time by formulating it as a maximum concurrent multicommodity flow problem and using linear programming. We show that the architecture of diastolic arrays enables efficient synthesis from high-level specifications of communicating finite state machines, providing a high-performance, off-the-shelf computer substrate that can be easily programmed.

Thesis Supervisor: Srinivas Devadas

Title: Professor of Electrical Engineering and Computer Science

Acknowledgments

First, I would like to express my sincere gratitude to Professor Srinivas Devadas for his extraordinary guidance and support throughout this research. His great insight has always inspired me and with his supervision I have never felt like I was lost. I also thank Professor Edward Suh who have so kindly helped me in this research as well as in every aspects of my graduate life. I thank Joel Emer, Vijay Ganesh, Mieszko Lis, Michael Pellauer, Bill Thies and David Wentzlaff for helpful comments on this research.

I also would like to thank all of Computation Structures Group people. I greatly thank Chih-chi Cheng for his help in application experiments and Michel Kinsy for the simulator development, and above all, for their being good friends. I send my heartfelt gratitude to Charles O'Donnell who helped me find everything I need, Alfred Ng and Murali Vijayaraghavan who gave me wonderful feedback, and Jaewook Lee who has been my mentor in graduate school. I warmly thank Mieszko Lis again, this time for greeting me everytime in Korean language.

I cannot thank enough to my parents and family who always helped me in every possible way. I truly thank them for their encouragement and their love, and I also thank all of my friend. Last but not least, I would like to extend my special gratitude to Samsung Scholarship who financially supported me during my master study.

Contents

1	Introduction	13
2	Background and Related Work	17
2.1	Computing Substrates	17
2.2	Interconnection Network and Multi-commodity Flow Problem	20
3	Motivating Applications	23
3.1	Computational Model	23
3.2	Example: H.264 Decoder	24
3.3	Example: Performance Modeling	27
3.4	Other Applications	28
4	Diastolic Architecture	29
4.1	Microarchitecture Overview	30
4.2	PE and PE-to-PFIFO Interface	31
4.3	Physical FIFOs (PFIFOs)	32
4.3.1	Buffer Allocation for Virtual FIFOs	32
4.3.2	Scheduling for Composite-path Routes	33
4.3.3	Arbitration of VFIFOs with the Same Destination	34
4.3.4	Data Reception Protocol	34
4.4	Performance Optimization: Timestamp	35
4.5	Diastolic Architecture Simulator	37

5	Synthesis Flow	39
5.1	Synthesis Overview	39
5.2	Application Specification	41
5.3	Profiling	41
5.3.1	High-level Profiling	42
5.3.2	Bandwidth Profiling	42
5.3.3	Buffer Profiling	43
5.4	Module Grouping and Partitioning	43
5.5	PE Compilation	45
5.6	PE Placement	46
5.7	Routing and Buffer Allocation of Virtual FIFOs	47
5.7.1	Multi-commodity Flow Linear Program	47
5.7.2	Buffer Allocation Linear Program	49
5.7.3	Alternative Routing Algorithms	51
5.8	Configuration	52
5.9	Minimizing Latency of Virtual FIFOs	53
6	Experimental Results	55
6.1	H.264 Decoder	55
6.2	Processor Performance Modeling	59
7	Conclusion and Future Directions	63

List of Figures

3-1	High-level Module Description of H.264 Decoder	24
3-2	FIFO size vs. Data Throughput of H.264 Decoder Modules: Entropy Decoder and Inter-prediction	26
4-1	A PE Architecture and a Single-path and a Composite-path Route of a VFIFO	30
4-2	The PFIFO to PFIFO Interface	35
4-3	Optimization through Explicit Synchronization by Timestamp	37
5-1	Synthesis Flow for Diastolic Arrays	40
5-2	H.264 Specification after Module Group and Partition	44
5-3	Configuring Marking and Acknowledgement Algorithms for Composite- path Routes	53
6-1	Throughput Demand of each VFIFO in H.264 Decoder	56
6-2	Routing results of H.264 decoder for different link bandwidths	57
6-3	Routing Results of H.264 Decoder for a Different Placement and with the Link Bandwidth of Figure 6-2(d).	58
6-4	Buffer allocation of H.264 decoder for the route of Figure 6-2 (c).	59
6-5	Throughput Demand of each VFIFO in Processor Performance Modeling	60
6-6	Synthesis Result of Processor Performance Modeling	61
6-7	Average PE Substrate Cycles per System Cycle and the Maximum and the Average Latencies for each VFIFO	61

List of Tables

3.1	Profiling Results of H.264 Decoder Modules for a Standard Input . . .	25
4.1	Basic Instructions for VFIFO Communication	31
5.1	Profiling for the Synthesis for Diastolic Arrays	42
6.1	Buffer Requirements for VFIFOs in H.264 Decoder	58

Chapter 1

Introduction

Many computer substrates have been proposed which share the characteristic of having two-dimensional arrays of processing elements interconnected by a routing fabric. Although having the same characteristic, different architectures show very different area-power-performance tradeoffs because their processing elements and routing fabrics are very different to each other. At one end of the spectrum, for example, Field Programmable Gate Arrays (FPGAs) have many tens of thousands of computing elements that are single-output programmable logic functions interconnected through configurable wires. And at the other end, recent multicore processors have multiple-issue 64-bit processors communicating via high-speed bus interconnect. Other architectures also use homogeneous and heterogeneous processing elements of varying complexity connected by multifarious on-chip networks.

This thesis proposes a diastolic array system ¹ which is a reconfigurable substrate that is meant to serve as a coprocessing platform to speed up applications or parts of applications that are throughput-sensitive and latency-tolerant. We will argue, in this thesis, that various applications such as movie decoders and processor performance modeling can be implemented on diastolic array systems more easily and efficiently than on other computing substrates such as FPGAs and multicore processors.

FPGAs are popular for prototyping applications as well as low-volume production.

¹The adjective diastolic is used to refer to the relaxation of the heart between muscle contractions. Data transfers in diastolic arrays have more relaxed latency requirements than in systolic arrays, hence the name.

They avoid the long turnaround time of an Application-Specific Integrated Circuit (ASIC), but have 10-30X area overhead in relation to ASICs and 3-4X performance overhead [24]. Synthesis to FPGAs is a matter of mapping combinational logic and registers to Configurable Logic Blocks (CLBs), and then performing global routing and detailed routing of potentially millions of wires. Routing a wire from one location to another requires configuration of switchboxes, potentially making wires long and slow. The sheer number of wires and the limited bandwidth of the routing channels exacerbate the routing problem. Synthesis to FPGAs can often fail due to routing congestion even though there are many Configuration Logic Blocks (CLBs) that are unused.

Multicore processors such as Quadcore x86 processors and multicore digital signal processors with hundreds of cores have entered the commercial marketplace. Processors in multicores are typically connected via high-speed bus interconnect. These multicores can take advantage of thread-level parallelism in web applications or data parallelism in video applications. Processes can be compiled to run mostly independently on the different cores and to communicate with each other through the high-speed interconnect. However, significant programming effort is required to exploit fine-grained parallelism in these architectures.

On the other hand, diastolic arrays are coarser-grained than FPGAs and data communication is defined through high-level design of applications resulting in a synthesis flow that is simpler than in FPGAs. On the other hand, diastolic arrays are finer-grained than multicores and can exploit parallelism more easily. Data transfers in a diastolic array are all statically routed and are allowed a varying number of clocks depending on the length of, and congestion in, the transfer path comprising a sequence of physical FIFOs. FIFO control implies that a module idles if its input FIFOs are empty, and stalls if its output FIFOs are full. FIFOs (that have room for more than one value) average out data-dependent variances in each module's execution and communication, and the performance of the design will be determined by the module with the maximum average latency, not the worst-case input that causes the longest latency in a module.

To be more specific, a diastolic array has programmable processing elements with a simple ISA, running on a fast substrate clock. Diastolic array processors communicate exclusively through First-In First-Out (FIFO) queues attached to a network ², and “physical” FIFOs, the routing logic embedded in each processing element, provide hardware support to guarantee bandwidth and buffer space for all data transfers. The architecture of diastolic arrays enables efficient synthesis from high-level specifications of communicating finite state machines so *average* throughput is maximized.

To program diastolic arrays, the designer writes high-level specifications of applications that describes FSM modules that manipulate data and which communicate exclusively via FIFOs. During synthesis to diastolic arrays, some FSM modules are grouped or partitioned, and modules are assigned to processing elements (placement) while the FIFOs used for communication between modules, named “virtual” FIFOs, are realized as a sequence of physical FIFOs (routing). Then, modules are compiled into instructions for processing elements (compilation), and the physical FIFOs are statically configured to implement the correct virtual FIFO routing, while guaranteeing bandwidth and buffer space (configuration). For a class of designs, including acyclic stream computations, given a placement, finding routes for all the virtual FIFOs that produce maximum throughput for the design is a maximum concurrent multi-commodity flow problem. An optimal flow under given hardware bandwidth constraints can be found in polynomial time using linear programming. For general designs with tight feedback, heuristic routing methods can be used to maximize throughput.

This thesis is structured as follows. First, Chapter 2 briefly summarizes related work in reconfigurable logic and interconnect networks. Case studies in Chapter 3 show that averaging data-dependent variances is critical to achieve high throughput for applications such as H.264 decoding and processor performance modeling, motivating a diastolic array architecture. Rather than having pipeline registers separating modules as in conventional designs, the use of FIFOs and associated FIFO control

²The interconnect architecture can vary; we will focus on mesh networks here. However, our algorithms apply to general network topologies.

can result in significantly better average-case performance, provided the FIFOs can store a small number of intermediate values. A candidate architecture for a diastolic array is presented in Chapter 4. The synthesis flow is presented in Chapter 5. Chapter 6 provides preliminary experimental results on H.264 and processor performance modeling benchmarks. Finally, Chapter 7 draws conclusions.

Chapter 2

Background and Related Work

2.1 Computing Substrates

There has been extensive research into computing substrates such as systolic arrays, network-overlaid FPGAs and other FPGA variants, coarse-grained processing platforms, and multicore architectures. Their characteristics and differences to diastolic arrays will be briefly summarized in this section.

Systolic arrays [22, 23] have been used to efficiently run many regular applications such as matrix multiplication. These SIMD processors contain synchronously-operating elements which receive and send data in a highly regular manner through a processor array so that the application works at the slowest rate of processors. To the contrary, the timing of data transfers in MIMD diastolic arrays is much more relaxed than in systolic arrays due to FIFO control and the maximum average performance is attained provided the FIFOs have enough buffer space.

Time-multiplexed and packet-switched networks have been overlaid on FPGAs and tradeoffs in implementing these networks and the performance of these overlaid networks has been studied [20]. Modern FPGAs such as those in the Virtex family from Xilinx have optimized carry chains, XOR Lookup Tables, and other features. Commercial synthesis tools can take advantage of these features to produce better implementations. A diastolic array uses time-multiplexing in the processing elements and interconnect and FIFOs for communication and is therefore significantly different

from FPGAs, while remaining homogeneous, which results in a very different synthesis flow.

In addition, systems like the Xilinx CORE Generator System [38] provide parameterizable Intellectual Property (IP) cores for Xilinx FPGAs that are optimized for higher density. These cores include DSP functions, memories, storage elements and math functions. The CoWare Signal Processing Worksystem (SPW) [9] tool interfaces with the Xilinx CORE Generator System and this integration enables custom DSP data path development on FPGAs using SPW. Jones [19] presents a time-multiplexed FPGA architecture for logic emulation designed to achieve maximum utilization of silicon area for configuration information and fast mapping, with emulation rate, i.e., performance, being only a minor concern. High density is achieved by providing only one physical logic element, and time-multiplexing configuration information for this logic element to provide several virtual logic blocks. Trimberger [36] also presents time-multiplexed FPGAs, where multiple FPGA configurations are stored in on-chip memory. This inactive on-chip memory is distributed around the chip, and accessible in such a way that the entire configuration of the FPGA can be changed in a single cycle of the memory.

Regarding the granularity of processing elements, many coarse-grained reconfigurable logics have been proposed. MathStar's Field Programmable Object Arrays (FPOA's) [27] are heterogeneous, medium grain, silicon object arrays with 1GHz internal clock speed and flexible I/O interconnect. FPOAs target high performance DSP and multi-gigabit line-rate data processing and bus bridging applications. There are six or more different types of silicon objects. Each silicon object has a loadable configuration map that contains both operation and communication instructions. Other medium or coarse grain processing platforms with a few hundred cores include the eXtreme Processing Platform (XPP) [2] and multicore DSPs from Picochip [13] which facilitates bus-based interconnect. MATRIX [28] is a reconfigurable chip with an array of 8-bit processing elements working like a dynamically programmable FPGA. The MATRIX network is a hierarchical collection of 8-bit busses as well. Diastolic arrays use a mesh-based routing network with FIFOs rather than using bus-based

interconnect.

While diastolic arrays have some similarity to multicore architectures, they are simpler than commercial multicores or architectures such as Raw [37] and Tiler [12], and also target a smaller class of throughput-sensitive, latency-insensitive applications. Raw uses software to control inter-processor communication and has relatively small FIFOs between processor tiles. Unlike Raw, diastolic arrays allow sharing of physical FIFOs by virtual FIFOs in a non-blocking way for data transfers. Tiler has five different networks that interconnect tiles including a static network, whereas diastolic arrays implement a single logically static network that supports sharing of flows, split flows and buffer allocation.

There are many other multicore systems that have been studied. TRIPS [34] uses significantly larger cores that are 16-issue, and Asynchronous Array of simple Processors (AsAP) [40, 39] is a multicore processor for DSP applications, which primarily targets small DSP applications with short-distance communications. AsAP consists of a 2-D array of simple processors connected through dual-clock FIFOs in a Globally Asynchronous Locally Synchronous (GALS) fashion. The FIFO sizes in AsAP are appreciably smaller than those in diastolic arrays, these FIFOs are mainly used to interface two clock domains and hide communication latencies rather than optimizing average case performance as in diastolic arrays. The main purpose of FIFOs in diastolic arrays is not GALS, but a diastolic array implementation under GALS is also possible.

Additionally, Synchroscale [30] groups columns of processors into SIMD arrays, and makes heavy use of statically configurable interconnect that can be used as a bus or similarly to a mesh. Ambric [4] uses a circuit-switched network as opposed to a packet-switched network, to avoid the cost of switches and buffers. Channels are set up by configuring the network much like in a FPGA, and synthesis to the Ambric chip is similar to FPGA synthesis, though significantly faster due to structure provided by the designer [3]. There is a small amount of buffering in the channel, and processors stall if they cannot write into the channel or if there is no data available.

2.2 Interconnection Network and Multi-commodity Flow Problem

Many types of on-chip interconnect networks have been studied. Dally’s virtual channels were introduced to avoid deadlock in multiprocessor interconnection networks [10] and the use of virtual channels for flow control allocates buffer space for virtual channels in a decoupled way from bandwidth allocation [11]. On the other hand, diastolic arrays guarantee bandwidth as well as buffer space in a coupled way, and implement multiple-hop, flow-controlled logical channels. Similarly, iWarp [16] could set up fine-grained, buffered direct paths, but only in a regular systolic topology.

The multicommodity problem is a network flow problem with multiple commodities flowing through the network, with different source and sink nodes, and is solvable in polynomial time using linear programming (LP) [8]. Multicommodity flow has been used for global routing of wires with buffering, e.g., [33], [1]. Multicommodity flow has also been used for physical planning on on-chip interconnect architectures (e.g., [6]), to optimize latencies and power consumption network-on-chip architectures (e.g., [17]), and to explore FPGA routing architectures (e.g., [18]). Multicommodity flow has also been used in internet routing of packets (e.g., [29]) and wireless routing (e.g., [5]).

We are using multicommodity flow to determine single-path or composite-path routes for data transfers in an on-chip interconnection network for maximum throughput. Virtual FIFOs in diastolic arrays connect arbitrary pairs of processing elements through physical links shared by multiple virtual FIFOs, making the routing problem with throughput constraints a typical multicommodity flow problem. The buffer space allocation for a given route is also solvable by using LP.

Numerous approximation schemes that are faster than using LP have been developed, e.g., [26]. Also, multicommodity problems with auxiliary conditions such as unsplittable flow or integer throughput have been studied, e.g., [21]. Our problem usually has significantly fewer commodities and we can directly use LP rather than approximation methods. Other algorithm variants such as unsplittable multicom-

modity problem can be used in the synthesis step (cf. Section 5.7.3). We can also produce integral weights for the round-robin schedulers by appropriately multiplying any non-integral solutions to stay optimal or very close to optimal.

Chapter 3

Motivating Applications

In this chapter, two motivating applications are described in a high-level computational model where all communication is via FIFOs. We examine these applications to show that diastolic arrays can enable flexible implementation of applications and achieve high performance.

3.1 Computational Model

A design is represented as multiple processing modules (finite state machines) connected through point-to-point virtual FIFOs. Each virtual FIFO connects a fixed source-destination pair for one input-output pair; if two modules need multiple connections, each connection gets its own virtual FIFO. The virtual FIFOs provide means for efficient communication and synchronization among processing modules with focus on average case performance. For example, FIFO-based communication naturally supports simple synchronization through waiting on inputs and backpressure; a processing module stalls if either an input FIFO is empty or an output FIFO is full.

Many interesting applications can be specified under this computational model; H.264 decoder and processor performance modeling are described below in detail. We note that this model can be generalized to “multicast” virtual FIFOs, where a single source sends packets to multiple destinations. However, we will not describe this generalization in this thesis.

3.2 Example: H.264 Decoder

H.264 is widely being used for video compression and there is surging demand for efficient H.264 decoder hardware. Figure 3-1 shows a specification of H.264 decoder; each module has data-dependent latencies. The entropy decoder module and the inter-prediction module will be examined, which will show that an architecture which targets average case latency has a performance benefit over a conventional pipelined design that assumes the worst case.

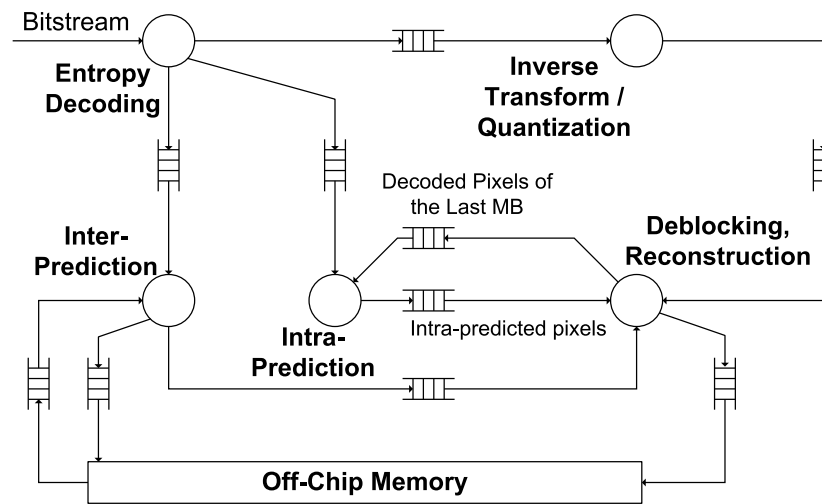


Figure 3-1: High-level Module Description of H.264 Decoder

The entropy decoder module in H.264 decoder performs context-adaptive variable length decoding (CAVLD) that uses 20 different code tables. Each image block from the input stream requires access to different code tables and the number of table lookups varies significantly across inputs. Because the table lookup and following computations take up the majority of time in entropy decoding, one can assume that the latency of the entropy decoder module is proportional to the number of table lookups for each input (image block). In the inter-prediction module, the latency is dominated by the number of pixels it reads from reference frames, which depends on the input block's offset from the reference block (motion vector). Therefore, the latency of inter-prediction module is again highly dependent on the input block and can be different for each input.

Table 3.1 shows the profiling results of both modules for a standard input stream ‘toys and calendar’, illustrating the large difference between the worst-case latency and the average-case latency.

Entropy Decoder		Inter-prediction	
#lookups	Occurrence %	Data read (bytes)	Occurrence %
0~5	43.5%	0~239	0.01%
6~11	38.6%	240~399	9.3%
12~17	14.4%	400~559	19.6%
18~23	3.0%	560~719	67.5%
24~	0.4%	720~	0.4%
Average	7.56 lookups	Average	589.3 bytes
Maximum	32 lookups	Maximum	954 bytes

Table 3.1: Profiling Results of H.264 Decoder Modules for a Standard Input

If each module is completely decoupled through infinite size FIFOs, the average-case design on a diastolic array will have 40% to 80% lower latency (or higher throughput) compared to the pipelined design that always performs the maximum number of operations, i.e., performs 32 lookups in the entropy decoder and reads the entire reference frame in the inter-prediction module.

In practice, however, the throughput could be lower than the average case if the FIFO is not large enough because individual module latencies vary from input to input. The simulation results of the throughput of each H.264 module as a function of a FIFO buffer size are shown in Figure 3-2. The simulation assumed that all of other modules have a fixed throughput that is the same as the target module’s average. The figure also shows the estimated throughput for a conventional pipelined design where the maximum number of operations are performed regardless of the input.

From the results, the performance of the single-entry FIFO design is seen to be worse than the pipeline design for inter-prediction, and better for entropy decoder. In the inter-prediction module, this is because a producer in the single-entry FIFO design in this simulation stalls until a consumer finishes using it, thus serializing the producer and the consumer. On the other hand, in the pipeline design of the inter-

prediction module, a producer is assumed to be able to write into pipeline registers at the same cycle when a consumer is reading the register value produced in the previous cycle. As a result, the total latency of the single-entry FIFO design could be worse than the pipeline design if the sum of average latencies of the producer and the consumer is larger than the worst-case latency of the producer and the consumer. From Table 3.1, the average amount of data read in inter-prediction is greater than half of the maximum amount. Therefore, the sum of average latencies of the producer and the consumer becomes larger than the worst-case latency, and hence the performance of the single-entry FIFO design is worse than the pipeline design. However, in the entropy decoder module, the average number of lookups in entropy decoder is only about 24% of the worst case, and therefore the performance of the single-entry FIFO design is better than the pipeline design.

Note that if FIFOs have more than one entry for data, there are no such serialization effects and the results clearly illustrate the benefit of the average-case design over the pipelined design. The figure also shows that the throughput increases as buffer size grows before saturating, which demonstrates that it is important to have a large enough FIFO in order to achieve the best possible throughput.

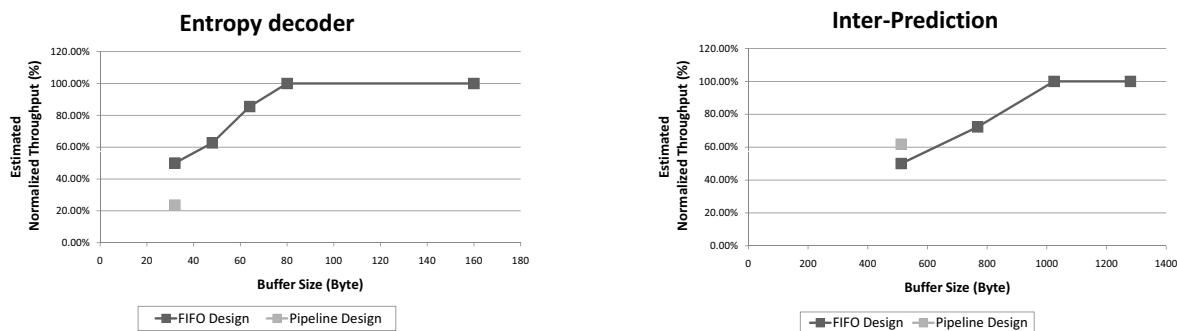


Figure 3-2: FIFO size vs. Data Throughput of H.264 Decoder Modules: Entropy Decoder and Inter-prediction

From these experiments, it is clear that the average-case design can have substantial performance benefit over a worst-case design. Unfortunately, implementing FIFOs on conventional reconfigurable substrates such as FPGAs is very expensive due to the routing overhead connecting FIFO buffers and logic, which results in sig-

nificant performance loss in each module. As a diastolic array has dedicated hardware to support FIFO-based communication between computing elements, designers can efficiently exploit the benefit of average-case design.

3.3 Example: Performance Modeling

Performance modeling estimates the performance of a hardware design so that architects can evaluate various alternatives at an early stage of the design. Fast performance modeling is important because it enables a designer to explore more design choices for more complex designs. Traditionally, performance modeling has been done purely in software. However, to further speed up performance modeling, recent work such as HAsim [32, 31] and FAST [7] use FPGAs to implement performance modeling in hardware.

The goal of performance modeling is simply to obtain timing information of a target system, not to faithfully emulate the target system cycle by cycle. Therefore, a performance model may take multiple substrate clocks (FPGA or array processor clocks) to perform a single-cycle operation on the target machine. For example, an associative cache look-up can be implemented with a single-ported SRAM in multiple cycles by checking one cache line in each cycle as long as the model counts one model cycle for all these look-ups. The latency of such a cache module varies dramatically depending on the input: one cycle if there is a hit in the first line that is checked or many cycles to check every line in the set in the case where an access eventually incurs a cache miss. Therefore, the performance modeling application has significant differences between the average-case latency and the worst-case latency.

In the same way that a diastolic array improves H.264 performance, it can also improve the performance of the performance modeling application by only performing necessary operations with an average-case design. The architecture will be able to achieve much greater performance than FPGAs thanks to the FIFO support for the average-case design and its word-level granularity.

3.4 Other Applications

Another interesting application for diastolic arrays is processor emulation. Unlike performance modeling, processor emulation faithfully simulates all cycle-by-cycle hardware operations of target systems. Even though processor emulation needs to perform all operations in the design, each module in a processor will have a different number of operations to perform depending on the input. As a result, average-case design can still be greatly beneficial.

H.264 encoder is also a very interesting application for diastolic arrays as it has more modules and more complex data flow than H.264 decoder. Many DSP applications such as IEEE 802.11a/11g wireless LAN transmitter (cf. Section 5) are also well-suited to the architecture for similar reasons. In general, if an application can be modularized to a number of modules and the latency of each module significantly varies depending on input and the average latency is much less than the worst-case latency then a diastolic array can provide performance benefits over traditional systolic arrays or pipelines.

Chapter 4

Diastolic Architecture

This chapter describes a candidate diastolic array architecture. The architecture provides guarantees of bandwidth and buffer space for all data transfers through:

- Non-blocking, weighted round-robin transfers of packets corresponding to different virtual FIFOs (VFIFOs) from one physical FIFO (PFIFO) to a neighbor,
- Ratioed transfer of packets corresponding to the same VFIFO from a PFIFO to its neighbors and in-order reception of said packets at PFIFOs to enable composite-path data transfers where sub-paths split and reconverge (cf. Figure 4-1(b)), and
- Allocation of PFIFO space to particular VFIFO packets to avoid deadlock and to maximize throughput.

Section 4.1 depicts the overall architecture of diastolic arrays. The processing element and the interface between processing elements and PFIFO are described in Section 4.2, and Section 4.3 shows how PFIFOs work and communicate with other PFIFOs.

Additionally, Section 4.4 describes optional hardware support for data synchronization through FIFO connections, using a notion of *system time*. It should be noted that system time is only for performance optimization and not essential for throughput guarantee and deadlock avoidance. Section 4.5 briefly introduces the diastolic architecture simulator.

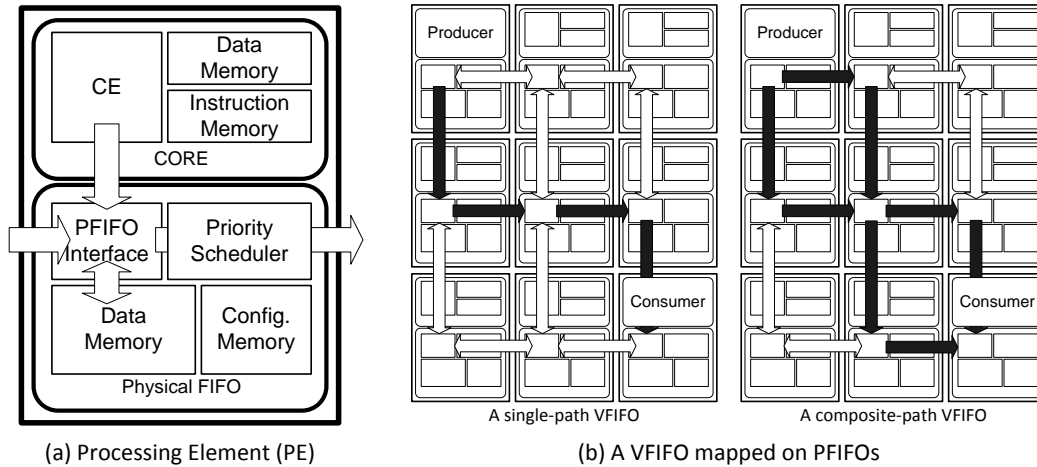


Figure 4-1: A PE Architecture and a Single-path and a Composite-path Route of a VFIFO

4.1 Microarchitecture Overview

A diastolic array realizes the high-level computation model with a grid of processing elements (PEs) each with an attached PFIFO as shown in Figure 4-1 (a). In this architecture, all PEs operate synchronously using a single global substrate clock. PFIFOs are connected to neighboring PFIFOs and support many VFIFOs with synchronization mechanisms; from the PE’s perspective, PFIFOs appear as many VFIFOs. In our candidate architecture, PEs are simple MIPS-like processors and the PFIFO network consists of 4 nearest-neighbor connections. In this architecture, each PFIFO can take up to 5 inputs (4 neighbors and the PE) and produce up to 5 outputs in each clock cycle. PFIFOs in the periphery of the PE grid interface with I/O pads in one direction. I/O logic will attach VFIFO ID’s to packets if they are not given by the external source so they can be routed to the appropriate destination.

Figure 4-1 (b) illustrates how a VFIFO is implemented with multiple PFIFOs – a single-path and a composite-path VFIFO marked by black arrows. In both examples, the VFIFO connects the top-left PE (producer) and the bottom-right PE (consumer). PFIFOs need to route VFIFO packets along single- as well as composite-path routes (cf. Section 4.3). The synthesis tool statically determines the routing and maps each

VFIFO to corresponding PFIFOs along possibly multiple paths where each individual path has a pre-determined rate or flow (cf. Section 5.7).

4.2 PE and PE-to-PFIFO Interface

Our initial PE design is based on a MIPS-like 32-bit 5-stage in-order processing core. The ISA for computation is almost identical to the MIPS ISA with a branch delay slot allowing the use of a standard MIPS compiler backend to generate efficient PE code. We use the gcc backend for MIPS in our synthesis framework. The main difference between the PE and a traditional MIPS core is in its support for VFIFO mechanisms; our PE supports additional instructions for VFIFO communication. Table 4.1 summarizes the additional PE instructions.

Instruction	Operands	Descriptions
<code>deq</code>	<code>Rt, Rs</code>	Dequeue data from VFIFO <code>\$Rs</code> and write to <code>Rt</code> (blocking)
<code>deqi</code>	<code>Rt, imm</code>	Dequeue data from VFIFO <code>imm</code> and write to <code>Rt</code> (blocking)
<code>enq</code>	<code>Rt, Rs</code>	Enqueue <code>\$Rt</code> to VFIFO <code>\$Rs</code> (blocking)
<code>enqi</code>	<code>Rt, imm</code>	Enqueue <code>\$Rt</code> to VFIFO <code>imm</code> (blocking)
<code>drdy</code>	<code>Rt, Rs</code>	$\$Rt \leftarrow 1$ if data is ready from VFIFO <code>\$Rs</code> , 0 otherwise
<code>drdyi</code>	<code>Rt, imm</code>	$\$Rt \leftarrow 1$ if data is ready from VFIFO <code>imm</code> , 0 otherwise
<code>erdy</code>	<code>Rt, Rs</code>	$\$Rt \leftarrow 1$ if VFIFO <code>\$Rs</code> can accept data, 0 otherwise
<code>erdyi</code>	<code>Rt, imm</code>	$\$Rt \leftarrow 1$ if VFIFO <code>imm</code> can accept data, 0 otherwise

Table 4.1: Basic Instructions for VFIFO Communication

In each cycle, a PE can dequeue a 32-bit value from a VFIFO, by using a blocking instruction `deq` and `deqi` specifying a VFIFO number and a destination register. If data of the VFIFO is ready in the attached PFIFO, this instruction dequeues data from the VFIFO and updates the destination register. Otherwise, the instruction will stall the processor until data becomes ready.

Before issuing blocking dequeue instructions, the PE may first check the status of the VFIFO by `drdy` or `drdyi` instructions and use branch instructions to use dequeue instructions only if data is ready. This explicit check allows the PE to continue its computation instead of just waiting when no data is ready for a VFIFO.

In any given cycle, the PE can write a value to a particular VFIFO with a blocking

enqueue instruction `enq` and `enqi` specifying a data value and a VFIFO number. This instruction enqueues the value (in a register) into the VFIFO if the attached PFIFO has an available entry for that VFIFO. Otherwise, the instruction stalls the PE until the VFIFO becomes available.

The PE can also use `erdy` or `erdyi` instructions to check the availability of target VFIFO before using blocking enqueue instructions. When the PFIFO attached to the PE says that it can accept data for the specified VFIFO, it reserves buffer space for the VFIFO because data of other VFIFOs may fill empty buffer space before the PE actually sends data to be enqueued.

4.3 Physical FIFOs (PFIFOs)

PFIFOs implement the VFIFOs and synchronization mechanisms through backpressure and idling. In addition to the PE-to-PFIFO interface described in Section 4.2, a PFIFO has to fulfill two main goals:

- Allocate buffer space for VFIFO packets that cannot be used by other VFIFOs to guarantee deadlock avoidance and maximum transfer rate.
- Route packets corresponding to each VFIFO with appropriate rates. The routes may be single- or composite-path routes, with the latter requiring increased PFIFO complexity. When transferring data for a VFIFO, a PFIFO must ensure that the receiving PFIFO has space available for the corresponding VFIFO.

PFIFOs perform the following four steps in order to achieve these goals.

4.3.1 Buffer Allocation for Virtual FIFOs

Each PFIFO has one data memory that is shared among all VFIFOs mapped to the PFIFO. The synthesis tool statically partitions a large part of this data memory amongst VFIFOs by setting the pointers in the configuration table. Each VFIFO assigned to a PFIFO has a partition size of at least one packet and these partitions are exclusively used for each VFIFO while the remaining data memory can be shared

by all of the VFIFOs. In this way, the synthesis tool can guarantee that each virtual FIFO has the necessary number of FIFO entries to avoid deadlock no matter what the traffic pattern is. Further, when hardware resources allow, the synthesis tool allocates buffer space to achieve the maximum transfer rate for each VFIFO across the corresponding PFIFOs. The synthesis tool determines the buffer allocation for deadlock avoidance and maximum transfer rate with information given by application specification and profiling results (cf. Section 5.8).

4.3.2 Scheduling for Composite-path Routes

In each substrate cycle, all PFIFOs try to send out packets to their next hops. Obviously, PFIFOs need to know to which PFIFO packets for each VFIFO should be sent. The configuration table in each PFIFO stores information about each VFIFO that maps to this PFIFO as given by the synthesis tool, and each entry of the table contains the VFIFO ID, and a list of possible previous and next PFIFOs. When a VFIFO has a single-path route or a PFIFO is not a split point of the VFIFO, there is only one possible next PFIFO specified in the configuration table.

However, if a PFIFO corresponds to a split point for a composite-path VFIFO route, then the PFIFO need to choose one from a number of possible next PFIFOs in each substrate cycle. The routing step during the synthesis computes the predefined ratios of the flow rates for the different directions, and the PFIFO sends out packets for the VFIFO in each direction in a deterministic order to control the flow rates. For example, if there are two possible next PFIFOs A and B at a split point and the routing specifies that A requires two times more bandwidth than B, then the PFIFO sends the first two packets for the VFIFO to A, and sends the next packet to B, repeatedly.

As packets are routed in deterministic order, they can be received in order at the reconvergent PFIFO. At a PFIFO that is a reconvergent point for a VFIFO, an acknowledgement algorithm allows an incoming packet from multiple neighbors to come in at appropriate ratios so as to guarantee in-order communication through

this PFIFO, and to ensure that deadlock due to out-of-order packets will not occur.¹ The ratios in the acknowledgement algorithms depend on the throughput ratios of the split and reconvergent flows and are determined after the routing step as described in Section 5.8. PFIFOs are then configured with appropriate weights for the round-robin send algorithm and ratios for the acknowledgement algorithms.

4.3.3 Arbitration of VFIFOs with the Same Destination

After the process described in Section 4.3.2, next hops for all packets in each PFIFO are known. As multiple VFIFOs may share the same channel to another PFIFO, a PFIFO may have many packets corresponding to different VFIFOs which are to be sent to the same destination for a given cycle. In this case, the PFIFO selects one VFIFO for each subsequent hop in a weighted round-robin fashion and forwards its data. This is done in a *non-blocking* fashion; if there is no data available for a VFIFO, the next VFIFO is selected. The algorithm does not wait for data to become available. The weights are determined after the routing step (cf. Section 5.7) to meet the desired flow rates and applied in the configuration step (cf. Section 5.8).

4.3.4 Data Reception Protocol

To ensure that the receiving PFIFO does have an entry available for the particular VFIFO, the PFIFO uses a two-phase protocol. In the first cycle, the PFIFO sends data with an associated VFIFO ID to the next hop. However, the PFIFO does not immediately remove the entry from its data memory. In the second cycle, the receiving PFIFO replies through a dedicated wire whether the data was accepted or not; the receiver rejects the data if there is no space remaining for this VFIFO's packet. The sending PFIFO removes data only after it receives a positive acknowledgement in the second cycle. This two-phase protocol is pipelined to allow a new data transfer every cycle, and is illustrated in Figure 4-2.

¹A later packet should not use up space in a reconvergent PFIFO on a composite path and block an earlier packet.

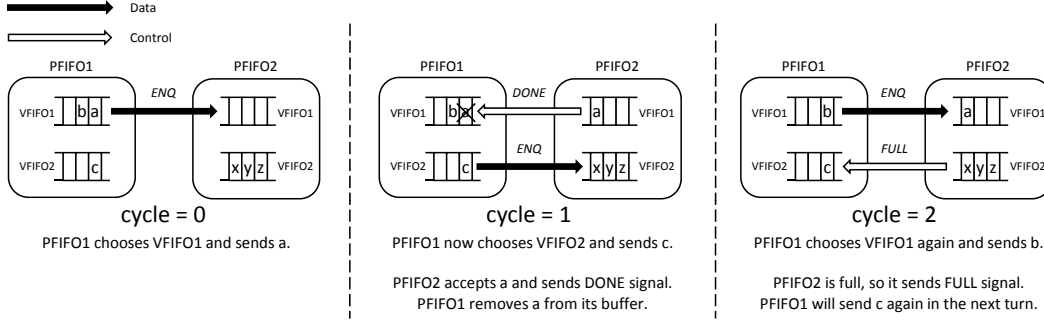


Figure 4-2: The PFIFO to PFIFO Interface

4.4 Performance Optimization: Timestamp

In addition to the basic diastolic architecture illustrated in the previous sections, the candidate architecture examined in this thesis has optional hardware support to optimize performance for some types of applications using *timestamping*.

Conceptually, the *system time* in diastolic arrays is similar to clock cycles in synchronous circuits. In synchronous circuits, combinational logic takes updated inputs and produces new outputs in each clock cycle. In a diastolic array, in each system time slice, a processing module reads a set of input FIFOs and produces results for a set of output FIFOs. Note that one unit of system time may correspond to multiple clock cycles of a diastolic array chip (*substrate cycles*); a processing module can take multiple substrate cycles to produce outputs from inputs, and this number can vary depending on the input data.

In H.264 decoder application, for an instance, each module processes one macroblock² per one system “clock”. As each module may take different number of substrate cycles for a system clock, modules need to be synchronized according to system time.

If the number of data produced and consumed at each system time is constant for all PEs, synchronization is automatically achieved through FIFO connections because after consuming a fixed number of data packets a consumer will always proceed

²A macroblock in H.264 is a small rectangular block of pixels which is the minimum unit of decoding process.

to the next system cycle. However, if any producer sends out different numbers of data packets depending on input, or any consumer takes different numbers of data packets, then there needs to be an explicit mechanism for system time synchronization. For example, the size of macroblock in H.264 decoder varies for each system time, depending on input video streams. Therefore, any consumer taking pixels of macroblocks does not know how many data packets it should take from its producer for a given system time unless there is auxiliary information or control telling it when to stop taking data.

One simple way to achieve synchronization without architectural support is to use “end” packets for each VFIFO, which indicate that there will be no other data for a given system time. This is done by software very simply, but one additional packet needs to be transferred to its consumer for every VFIFO, for every system time. Most other software schemes for the synchronization cost the diastolic array network bandwidth as well as PE computation time.

Timestamping provides hardware support for system time synchronization. It lets PFIFOs handle the synchronization instead of PEs so that the computation time of PEs and especially the PE-to-PFIFO communication time at the consumer side can be significantly saved. In this scheme, each PE individually tracks the current system time and attaches a time-stamp to each FIFO packet, which indicates when the receiving PE should use the packet. At the consumer side, a PE specifies its system time and the attached PFIFO determines whether arrived data can be consumed, or whether it needs to wait for incoming data, or whether there will be no data for the given system time. For this purpose, each VFIFO has its own counter for the system time (VFIFO time in the figure). If the VFIFO time is greater than its current time, it indicates to a consumer that the producer does not have more data for the current time and to a producer that the consumer does not need more data. This scheme increases communication bandwidth for timestamps. However, the information for synchronization is integrated in data packets so that PEs can be properly synchronized while only transferring necessary data through FIFOs.

This architecture also supports explicit synchronization operations by both pro-

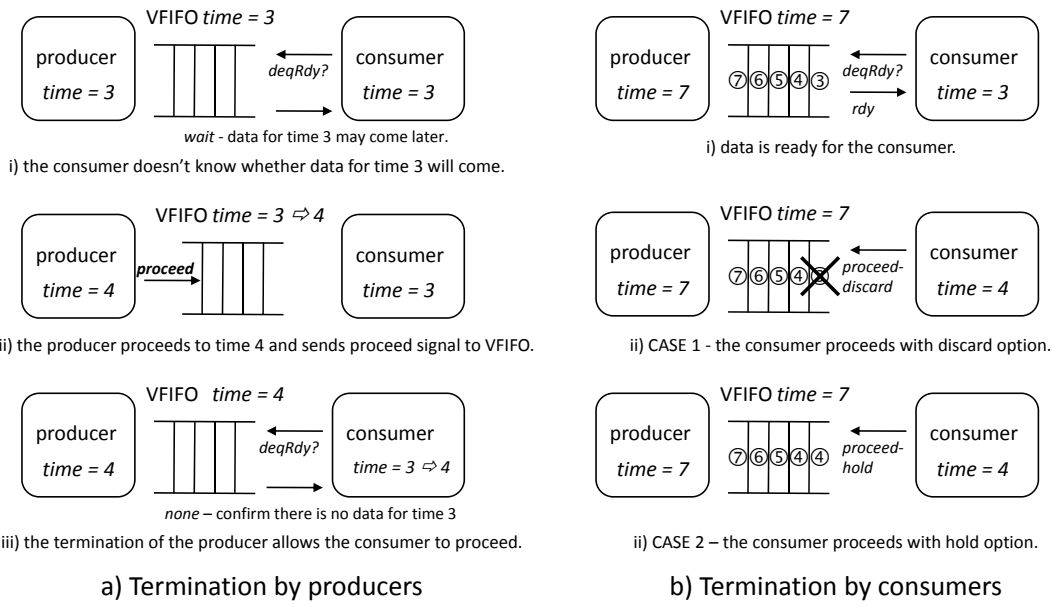


Figure 4-3: Optimization through Explicit Synchronization by Timestamp

ducers and consumers without transferring data (see Figure 4-3). Both producers and consumers can explicitly notify a VFIFO to increment the VFIFO time. Additionally, a consumer can choose whether a FIFO should keep data for the past time slices. If the consumer indicates that it would not need old data then the FIFO will discard all data with an old time-stamp. The performance benefit due to explicit synchronization can be significant especially when the consumer decides not to take any data for a certain period of system time because a number of packets can be discarded in the PFIFO, without spending any substrate cycles of the PE. An example of this case is the ALU module in the processor emulator application: if the module resolves a branch and knows it should discard the following instructions, it just explicitly moves to the next valid system time and the PFIFO discards every invalid instruction.

4.5 Diastolic Architecture Simulator

The candidate diastolic architecture was simulated by a cycle-accurate software simulator written in the C++ language. The simulation framework provides diastolic array components such as PFIFOs, PEs and I/Os, and a simulation file uses these

components to define an array network and fetch the configuration bits for a target application to each component. The PE components are connected to another simulator, which is a 5-stage pipelined MIPS simulator for this candidate architecture.

This simulator allows fast microarchitectural exploration of diastolic arrays by turning on or off some of the features described in this chapter, such as composite-path routing or timestamping. This simulator can also perform the profiling steps in the synthesis flow by using ideal FIFO connections rather than PFIFO connections, as described in Section 5.3.

Chapter 5

Synthesis Flow

While we described a candidate diastolic architecture in Chapter 4, various PE microarchitectures and PFIFO network topologies can be supported with the synthesis flow described in this chapter.

The challenge when targeting an architecture with nearest-neighbor communication is efficiently mapping applications that exhibit significant long-distance communication. This problem is made tractable in diastolic arrays by statically allocating both bandwidth and buffer space for communication that can be shared by many logical channels, allowing us to focus on maximum average throughput, while largely ignoring communication latencies.

5.1 Synthesis Overview

The synthesis flow for diastolic arrays is illustrated in Figure 5-1. The input for synthesis is an application specification that is a high level description of the hardware design (cf. Section 5.2). Functional modules in the specification are grouped or partitioned by synthesis tools so each module corresponds to a PE of diastolic arrays (cf. Section 5.4). This generates PE descriptions and VFIFO specifications and PE descriptions are compiled to configuration bits for each PE (cf. Section 5.5). From VFIFO specifications, the PE placement step explores candidate placements which are used in VFIFO routing (cf. Section 5.6). After a feasible or the best route is

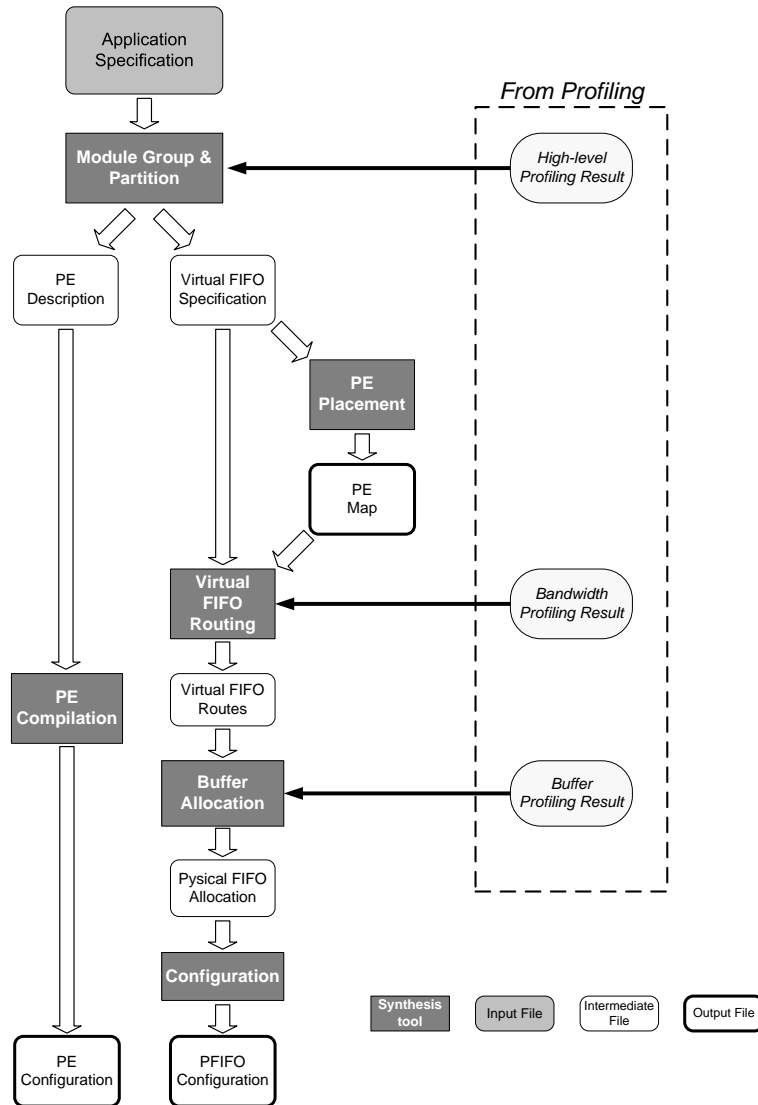


Figure 5-1: Synthesis Flow for Diastolic Arrays

found, PFIFO buffers are allocated to VFIFOs (cf. Section 5.7), and finally PFIFO configuration bits are generated according to the synthesis results (cf. Section 5.8).

Note that module grouping and partitioning, VFIFO routing, and buffer allocation step take additional input from different types of profiling results. The profiling is done by software simulation and provides information about the target application so the synthesis tool can optimize the performance. Section 5.3 will describe each profiling step.

5.2 Application Specification

Synthesis begins from a specification of the hardware design as finite state machine (FSM) modules described in C that communicate via virtual FIFOs (VFIFOs). The specification will also provide minimum VFIFO sizes that ensure that the design does not deadlock. We will assume that for VFIFO i , z_i packets are required, with p_i bits in each packet. In most cases, z_i is determined by the maximum number of packets that the VFIFO needs to hold in order to synchronize PEs. For example, if a producer sends out up to 3 packets per system time (cf. Section 4.4) and its consumer takes data from 5 system times ago, the VFIFO between them may need to hold 15 packets in order to synchronize them.

The application specification is simpler than synchronous data flow [25], and similar to an *intermediate output* of a parallelizing compiler such as StreamIt [35] after parallelism extraction, but could also be directly written by a designer. Minimum requirements for FIFO sizes can be determined by compilers such as StreamIt [15]. Modules in the specification may be grouped or partitioned during the synthesis flow. Therefore, modules in the specification does not have a one-to-one matching with PE hardware.

A high-level view of the specification of an H.264 decoder application was previously shown in Figure 3-1. The goal of synthesis is to maximize average throughput, which requires that bandwidth *and* buffer space be properly allocated to all VFIFOs. The H.264 decoder example will be used to illustrate each synthesis step throughout this chapter.

5.3 Profiling

Profiling can provide important information about the performance of target applications which cannot be attained from their specifications. There are three different profiling steps performed through the synthesis flow for diastolic arrays. Table 5.1 summarizes those profiling steps.

Profiling Step	Computational Node	VFIFO Connection	Purpose
High-level Profiling	High-level module, isolated	Ideal	To group or partition modules
Bandwidth Profiling	PE, correlated	Ideal	To determine demanded throughput
Buffer Profiling	PE, correlated	shared link PFIFOs (individual buffer)	To determine buffer requirement

Table 5.1: Profiling for the Synthesis for Diastolic Arrays

5.3.1 High-level Profiling

High-level profiling takes the application specification described as communicating high-level modules and determines how much computation each module performs. This information is used for module grouping and partitioning so that after grouping and partitioning each PE has a similar amount of computation time. In high-level profiling, each high-level module is simulated separately on an array PE and a histogram of module latency over different module inputs is produced, which gives a range of latency as well as an average. Module latencies are computed as processor cycles per packet produced – each module produces data packets that correspond to a VFIFO. This is converted into cycles per bit produced. The case study of entropy decoder and inter-prediction modules in Section 3.2 is an example of high-level profiling.

5.3.2 Bandwidth Profiling

Bandwidth profiling takes place after module grouping and partitioning. At this time all PEs and the entire network are simulated; consumers should wait until producers send out data so the throughput of each VFIFO in bandwidth profiling reflects possible correlations between VFIFOs. However, the VFIFO connections are assumed to be ideal: each VFIFO has a very large buffer ¹ and VFIFOs do not share physical links and have minimum latency. If there is a target system throughput, then the output of the system is pulled at this rate. ² In this step, profiling computes a rate

¹The buffer size is not infinite because a FIFO with infinite buffer size will decouple the rate before its producer and after its consumer when the producer is faster.

²For H.264 decoder, the target system throughput was set to decode HDTV video stream (1920x1088) in real time.

distribution and average transfer rate d_i in bits per second for each VFIFO i , which is a key measure used in the routing step. These rates are correlated and depend on the target system throughput if specified. Because the VFIFO connections are ideal and the performance is unaffected by routing (either by latencies or by congestion), these rates become the optimal goal for the routing step.

5.3.3 Buffer Profiling

The last profiling step is buffer profiling which provides a distribution of buffer size and average buffer size m_i in bits for each VFIFO i that is required for sustaining the average transfer rate d_i . This is derived from the variation in occupied buffer sizes during simulation.

The simulation for buffer profiling takes account of the PFIFO network; VFIFOs have various latencies and physical links between PFIFOs are shared by multiple VFIFOs. Unlike the actual diastolic architecture, however, VFIFOs do not share the memory of PFIFOs. Each VFIFO is assumed to have a large dedicated buffer. Therefore, the average buffer size measured during buffer profiling is not affected by other VFIFOs.

If a producer is always faster than its consumer in a given producer-consumer pair, then the buffer of the corresponding VFIFO always becomes full and m_i has no actual bound. In this case, the minimum buffer size of the VFIFO that does not affect other rates is chosen.

5.4 Module Grouping and Partitioning

Based on the high-level profiling results, modules are grouped or partitioned. Grouping involves assigning two or more modules to the same PE, while partitioning involves splitting a module across multiple PEs in order to exploit parallelism and reduce the effective average latency.

Module grouping is done if there are more modules than the number of available PEs, or if there is tight feedback between modules whose latency can affect through-

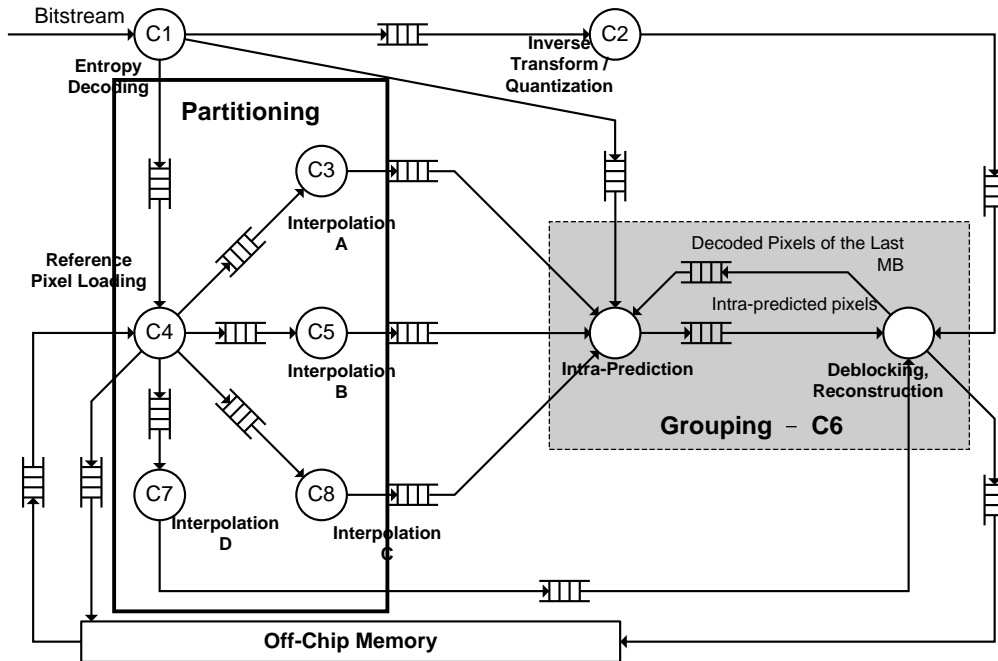


Figure 5-2: H.264 Specification after Module Group and Partition

put.³ When two modules are run on the same PE, their latencies will increase to their sum. If the inverse of this combined latency is equal to or more than the VFIFO rates corresponding to each of these modules, the modules can be grouped together. Grouped modules are executed in interleaved fashion on a PE. If a module does not have inputs available it cedes to the next module. After a module execution, if there is no space available in the PE's FIFO for the result, the module will stall until space is available.⁴

If it is impossible to obtain the target system throughput, the modules whose latencies are too high are targets for partitioning. Partitioning mostly depends on the parallelism that can be extracted from actions described in the specification. For example, if a module performs actions *A*, *B*, *C* and *D*, where *B* depends on *A*, and *D* depends on both *C* and *A*, we can execute actions *A* and *B* on a PE, and *C* and *D* on a different PE, possibly improving average latency, since *C* and *A*

³If a tight feedback connection cannot be removed by module grouping, the synthesis tool tries to minimize its latency (cf. Section 5.6 and Section 5.9).

⁴The actual latency becomes larger than the sum because of increased congestion in the VFIFOs sharing the same PFIFOs and context switching costs.

can be simultaneously executed. Note that partitioned modules introduce additional VFIFOs that communicate between PEs, and a partition has to be carefully selected to optimize the resulting average latency which depends on the additional FIFO latency. Modules are not partitioned if a large number of additional FIFOs are required. Automatic partitioning is a difficult problem that corresponds to parallelism extraction, and is not a focus of this thesis.

An example of a module grouping and partitioning result for the H.264 decoder is shown in Figure 5-2. The intra-prediction module and deblocking module were grouped together, and the inter-prediction module was partitioned across PEs. The high-level profiling results showed that the inter-prediction module needs a lot of computation time; the partitioning was done by extracting parallelism in the module, and the grouping was done to eliminate tight feedback. After grouping and partitioning, the profiling step is run again to determine the new module and VFIFO latencies.

5.5 PE Compilation

After the module grouping and partitioning step, the system has a set of PEs with corresponding modules. Modules are compiled to each PE in a decoupled way and the results of the compilation provide each PE with scheduling information and executables. The PEs in the diastolic architecture have an ISA that is a subset of the MIPS ISA and modules are described in the C language. The gcc backend for the MIPS-II processor was used in the experiments of Chapter 6.

All communications to other PEs are through PFIFOs with FIFO control, which the compilation step is aware of only at the level of writing and reading data values to and from the VFIFO. A PE will wait on a given read (dequeue) instruction when there is no data available, or on a write (enqueue) instruction when the output FIFO is full. Therefore, the compilation step need not know about the routes and the timing of data communication of VFIFOs.

5.6 PE Placement

The primary goal of the placement step is to find a placement of the modules such that a feasible route can be determined for each of the VFIFOs. A *feasible route* is a set of routes comprising a route for each of the VFIFOs that has enough bandwidth for each FIFO's average transfer rate d_i obtained through bandwidth profiling, and therefore allows the system to achieve maximum average throughput. The heuristic used in placement to maximize the likelihood of achieving a feasible route is to minimize the total number of hops across all the VFIFOs, weighted by the criticality of the FIFOs (cf. Section 5.9), and inversely weighted by the required amount of buffering for the FIFO (cf. Section 5.7.2). A simple greedy algorithm with various weights is used to generate many candidate placements.

For acyclic specifications, such as stream computations without feedback [35, 15], there are no hard requirements on the communication latency of VFIFO packets. It is important to note that there may be false cycles in the specification, because a module is a collection of computations. For example, a module that reads off-chip memory, i.e., sends an address to off-chip memory and is returned a data value that is computed on, can be viewed as two different modules that communicate with memory through FIFOs; the first executes a read, and the second receives the value. A read operation thus does not represent a true cycle.

In the H.264 application, modules both write and read off-chip memory. A macroblock (16x16 pixels) is a data element in a VFIFO and will require *processed* macroblocks from a previous frame, which is stored in off-chip memory. If the frame is a HDTV (1920x1088) frame, then one frame previously means 8160 macroblocks previously. Thus, even though there is a write to memory that is followed by a read, these two operations are so far apart that this feedback can be ignored during throughput-driven synthesis.

If feedback across modules occurs within a few substrate clocks, then the latency of communication paths can affect system throughput. An example of such feedback is a bypass path in a pipelined processor. The latency of communication can be included

in the module latency, but we wish for other communication and decisions made during synthesis to not adversely affect this latency. We will need communication paths with minimum latency in the implementation (cf. Section 5.9), in addition to guaranteeing bandwidth and buffer space for all communications. To minimize the latency of such critical communication paths, their producers and consumers must be placed as close to each other as possible.

In the next two sections, we assume that we have acyclic specifications, and then generalize our methodology.

5.7 Routing and Buffer Allocation of Virtual FIFOs

The route for each VFIFO is determined after module placement. The routing step chooses paths for each virtual FIFO that require multiple hops using the transfer rates for each VFIFO. A VFIFO route can correspond to *multiple* paths through the mesh network, each with the same source and same destination. A route with multiple paths is referred to as a split flow. The source processor sends data at pre-determined ratios through multiple paths, and the data elements are received and processed in order at the destination processor. In addition, intermediate PFIFOs may need to collect packets for a given VFIFO and send them out at pre-determined ratios – the reconvergent points of Section 4.3.

5.7.1 Multi-commodity Flow Linear Program

We can formulate the search for a feasible route as a maximum concurrent multi-commodity flow problem, where the commodities correspond to the data packets in each VFIFO. This problem is solvable in polynomial time using linear programming (LP) (cf. Section 2.2).

Definition 1 Maximum concurrent multi-commodity flow: *Given a flow network $G(V, E)$, where edge $(u, v) \in E$ has capacity $c(u, v)$. There are k commodities*

K_1, K_2, \dots, K_k , defined by $K_i = (s_i, t_i, d_i)$, where s_i and t_i are the source and sink, respectively for commodity i , and d_i is the demand. The flow of commodity i along edge (u, v) is $f_i(u, v)$. Find an assignment of flow, i.e., $\forall (u, v) \in E \quad f_i(u, v) \geq 0$, which satisfies the constraints:

$$\text{Capacity constraints :} \quad \sum_{i=1}^k f_i(u, v) \leq c(u, v)$$

Flow conservation :

$$\forall i, \forall u \neq s_i, t_i \quad \sum_{(w,u) \in E} f_i(w, u) = \sum_{(u,w) \in E} f_i(u, w)$$

$$\forall i \quad \sum_{(s_i,w) \in E} f_i(s_i, w) = \sum_{(w,t_i) \in E} f_i(w, t_i) \leq d_i$$

and maximizes the minimal fraction of the flow of each commodity to its demand:

$$T = \min_{1 \leq i \leq k} \frac{\sum_{(s_i,w) \in E} f_i(s_i, w)}{d_i} \quad (5.1)$$

In the routing problem for diastolic arrays the commodities are the data elements in the VFIFOs, so k is the number of VFIFOs. The capacities for the edges in the network are equal to the bandwidth of the link between adjacent PFIFOs in the diastolic array architecture. The link bandwidths $c(u, v)$ are all equal to L by default, but may be set to lower values when we have critical FIFOs whose latency affects system throughput because they are in tight feedback loops (cf. Section 5.9). The source for commodity i is the source processor in the given placement for VFIFO i , and similarly the destination. The demand d_i for VFIFO i is the average transfer rate for that FIFO obtained through profiling. Of course, we would like for T to be 1.

The only known polynomial-time solution to multi-commodity flow problems is to use linear programming (LP). In practice, approximation algorithms that are more efficient than LP are used, which can provide near-optimal or optimal results. We do

not explore these algorithms in this thesis.

5.7.2 Buffer Allocation Linear Program

We still need to incorporate the requirements on buffer sizes for deadlock avoidance and to achieve the d_i rates. After we run LP and obtain the $f_i(u, v)$'s, we have a flow for each VFIFO i , i.e., a set of paths with particular rates on each link in the diastolic array. We can run another linear program to perform buffer allocation along each chosen VFIFO route.

We first determine the PFIFOs in the PE's that correspond to each VFIFO's commodity flow.

$$\forall u, \forall i \text{ iff } \exists v \text{ s.t. } (f_i(u, v) > 0 \text{ or } f_i(v, u) > 0) \ g_i(u) = 1$$

Note that for a given flow the g_i 's are constants that are either 1 or 0, corresponding to whether or not packets from the VFIFO will reside in the PFIFO corresponding to PE u .

The buffer size in PE u that we wish to allocate to VFIFO i in terms of the number of packets is denoted $l_i(u)$, and these are the variables in the LP. The available buffering in a PE u is $b(u)$ bits. In our candidate architecture, these are all equal to M bits, however, critical FIFOs (cf. Section 5.9) may be assigned some of the buffer space prior to running the LP. Recall that m_i is the average buffer size required for VFIFO i to sustain its transfer rate d_i , as obtained by the buffer profiling step (cf. Section 5.3.3), z_i is the number of packets in VFIFO i that ensures that deadlock will not occur and p_i is the packet size for the virtual FIFO packet in bits (cf. Section 5.2).

Definition 2 Optimal Buffer Allocation: *For each VFIFO i , we are given a buffer size requirement m_i and a set of PFIFOs $g_i(u) = 1$ that are on the VFIFO's route. We are given available buffer sizes $b(u)$ for each PE u . Find an assignment of*

buffers $l_i(u)$ for each VFIFO i that satisfies:

$$\text{PFIFO Buffer Limit : } \forall u \sum_{i=1}^k p_i \cdot l_i(u) \leq b(u)$$

$$\text{Deadlock Avoidance : } \forall i, \forall u \ l_i(u) \geq g_i(u)$$

$$\forall i \sum_{w:g_i(w)=1} l_i(w) \geq z_i$$

$$\text{Allocation : } \forall i \ p_i \cdot \sum_{w:g_i(w)=1} l_i(w) \leq m_i$$

and maximizes the minimal fraction of the allocated buffers of each commodity to its demand for buffering:

$$U = \min_{1 \leq i \leq k} \frac{p_i \cdot \sum_{w:g_i(w)=1} l_i(w)}{m_i} \quad (5.2)$$

The deadlock avoidance requirement comes from the *specification*; there should be at least p_i bits worth of dedicated space available in *each* PFIFO that is used by a VFIFO to route its packets, and further the set of PFIFOs implementing the VFIFOs should provide z_i packets worth of space. Since the PFIFOs in the diastolic array will accept packets from VFIFOs whose limit has not been exceeded, while possibly rejecting packets from other VFIFOs, deadlock will not occur in the array implementation. There is a limit on the number of VFIFOs that can be mapped to a PFIFO due to the deadlock requirement, and because the configuration tables (cf. Section 4.3) are finite in size. We assume large tables and therefore the first requirement is more stringent.

On top of the deadlock avoidance requirement, we would also like to allocate enough buffer space for each VFIFO so the transfer rates can be met, while ensuring fair allocation across VFIFOs (cf. Eqn. 5.2).

Note that the $l_i(u)$'s corresponding to $g_i(u) = 0$ can be set to zero. Of course, we need the $l_i(u)$'s to be integers, so the values will be truncated or rounded up the solution to the LP is obtained.

Given a user-specified amount of CPU time, we choose many solutions with corresponding maximum T for the first LP, to maximize U . We also repeat this process for many placements, and pick the maximum T , followed by the maximum U .

5.7.3 Alternative Routing Algorithms

Searching for a feasible route as a maximum concurrent multi-commodity flow problem satisfies all demands or determines the best throughput solution in polynomial time. However, it does not guarantee the best solution with regard to latencies because it does not attempt to find shortest paths for each commodity. Further, paths may be split which introduces additional latency in shorter paths due to in-order communication constraints.

When a target application has tight feedback loops which cannot be eliminated by module grouping, communication latencies affect the throughput and the maximum throughput guarantee of the routing algorithm does not hold. To minimize latency, heuristics for unsplittable multi-commodity flow can be used [21]. In one such heuristic, the shortest path for each commodity is found by Dijkstra's shortest path algorithm where each link is weighted by the reciprocal of its current residual bandwidth capacity. After the shortest path is found for a commodity, the rate of the commodity is subtracted from the bandwidth capacity of the links on the path. Our research group is exploring these heuristics in ongoing work.

The latency of each commodity depends on the order in which commodities are routed. The commodities whose latencies significantly affect system throughput have higher priorities. Unlike in the LP-based formulation, the shortest-path algorithm needs to perform binary search to get the best fraction of demanded throughput that the network can support when there is no feasible route. Also, because there are no composite-paths generated by the algorithm, any commodity with a throughput larger than the bandwidth capacity of physical links should be divided into multiple commodities.

5.8 Configuration

Once we have found a feasible route, or settled on a throughput less than the maximum, the final step is to generate configurations for each processor and PFIFO. The PEs are configured with the compiled code of the modules that will execute on the PE.

The flow rates determined by the LP are made integral with appropriate multiplications to keep the ratios as close as possible in the case where an integral flow is not provided by LP. Each link in each PFIFO is first configured with the set of VFIFOs that share this link. Each link is configured to send out packets in a weighted round-robin fashion over all the VFIFOs that share this link. If a PFIFO is a split point for a VFIFO, the marking algorithm for incoming packets is configured with appropriate ratios for the different links that this VFIFO's packets will depart the PFIFO on. At reconvergent PFIFOs including the destination, packets corresponding to each VFIFO are received in order, by choosing the packets from different links using an acknowledgement algorithm, as elaborated in the following paragraph.

A PFIFO may split a flow of packets two to four ways. Consider the example of Figure 5-3. For a three-way split in ratio $a^R : b^B : c^T$, the marking algorithm at PFIFO S will mark the first a packets to the right, the next b packets to the bottom, and the next c packets to the top, repeatedly. Note that these a packets will contend for bandwidth in the link to the right with other VFIFO packets, and a weighted round-robin send algorithm will periodically send these packets out. The right sub-flow is represented as $\bar{a}\bar{b}\bar{c}$ indicating that the first a packets from the source were picked, the next b packets were sent somewhere else, etc; this pattern repeats indefinitely. The right sub-flow is split again in PFIFO V in the ratio $a_1^T : a_2^B$; the patterns generated will be $a_1\bar{a}_2\bar{b}\bar{c}$, and $\bar{a}_1a_2\bar{b}\bar{c}$. At PFIFO Q , the sub-flows $a_1\bar{a}_2\bar{b}\bar{c}$ and $\bar{a}_1a_2\bar{b}\bar{c}$ converge. The acknowledgement algorithm at Q will pick a_1 packets from the bottom and c packets from the left, repeatedly. This produces a sub-flow represented as $a_1\bar{a}_2\bar{b}\bar{c}$. The acknowledgement algorithm at destination PFIFO D will pick a_1 packets from the left, $a_2 + b$ packets from the bottom, and c packets from the left,

repeatedly.

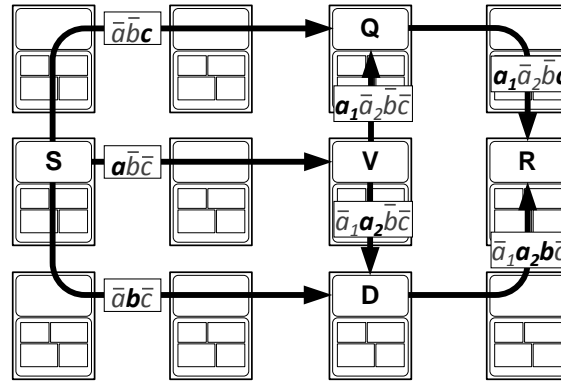


Figure 5-3: Configuring Marking and Acknowledgement Algorithms for Composite-path Routes

As a final step of configuration, buffer space constraints for each VFIFO that is assigned to a PFIFO are specified.

5.9 Minimizing Latency of Virtual FIFOs

As described in Section 5.7, all VFIFOs are guaranteed bandwidth and buffer space during synthesis, but we make no guarantees about latency. Virtual FIFOs with longer paths (many hops) will have greater latency. This will not matter when there are no tight feedback paths.

While we cannot make latency guarantees about all VFIFOs or even a large number of FIFOs, we can provide minimum latencies for a few critical FIFOs, associated with feedback and identified during profiling whose increased latency will directly degrade performance. These FIFOs are given the highest weights during the placement step (cf. Section 5.6), so their lengths are minimized. Prior to the routing LP step, a direct route is chosen for each of these FIFOs, with no splits to avoid packet reordering at the destination. The bandwidth of each of the links in the route is reduced by the corresponding d_i , and the buffer space in each of the n PFIFOs comprising the chosen VFIFO route is reduced by $\max(m_i/n, p_i)$. The two LP's are run as before to produce routes and buffer allocations for the remaining VFIFOs.

Our research group is exploring a combined heuristic bandwidth and buffer allocation algorithm in ongoing work.

Chapter 6

Experimental Results

This section will illustrate the synthesis results of the two examples described in Chapter 3, H.264 decoding and processor performance modeling. The synthesis result of processor performance modeling was also simulated by the diastolic architecture simulator described in Section 4.5.

6.1 H.264 Decoder

The high-level profiling result of H.264 decoder application shows that inter-prediction occupies most of the computation time and has parallelism that can be extracted. Also, the specification shows a tight feedback loop between the intra-prediction module and the deblocking module both of which have relatively little computation time. Therefore, the inter-prediction module was partitioned to enhance throughput by increasing parallelism, and the intra-prediction and the deblocking modules are grouped so the total number of used PEs is 9. The module grouping and partitioning result was shown in Figure 5-2.

After modules are grouped and partitioned, the throughput demand of each VFIFO in the design was determined in the bandwidth profiling step. The profiling assumed the system throughput matches the throughput of HDTV video decoder, and the substrate clock was assumed to be 1 GHz. Figure 6-1 shows the throughput demand.

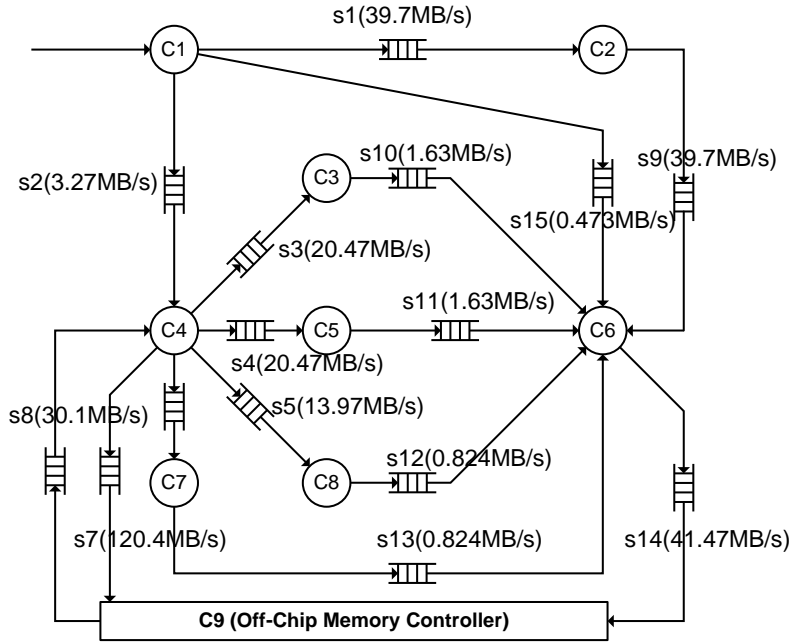


Figure 6-1: Throughput Demand of each VFIFO in H.264 Decoder

A four-by-four two dimensional mesh network was used for the H.264 decoder and a number of candidate placements were generated as described in Section 5.6. For each placement the capacity and the flow conservation constraints were generated and this LP problem was solved by ILOG CPLEX. Figure 6-2 provides routing results for different link bandwidths. The throughput of each route is indicated. When the link bandwidth is 200MB/sec, a feasible route without composite paths was found. Composite paths allow the routing algorithm to fulfill the throughput demand with smaller link bandwidth, such as 100MB/sec (Figure 6-2(b)) and 60MB/sec (Figure 6-2(c)). In Figure 6-2(b), for example, the route from C4 to C9 is split because the link between them cannot deliver more than 100MB/sec.¹ However, if the link bandwidth is too small, the routing algorithm will determine that there is no feasible route, and reports the best route for the given network as shown in Figure 6-2(d).

Of course, different placements result in different routes. For example, Figure 6-3 illustrates how a placement can give a better routing result than another. When there

¹In Figure 6-2, split points are marked by white squares and reconvergent points by white circles.

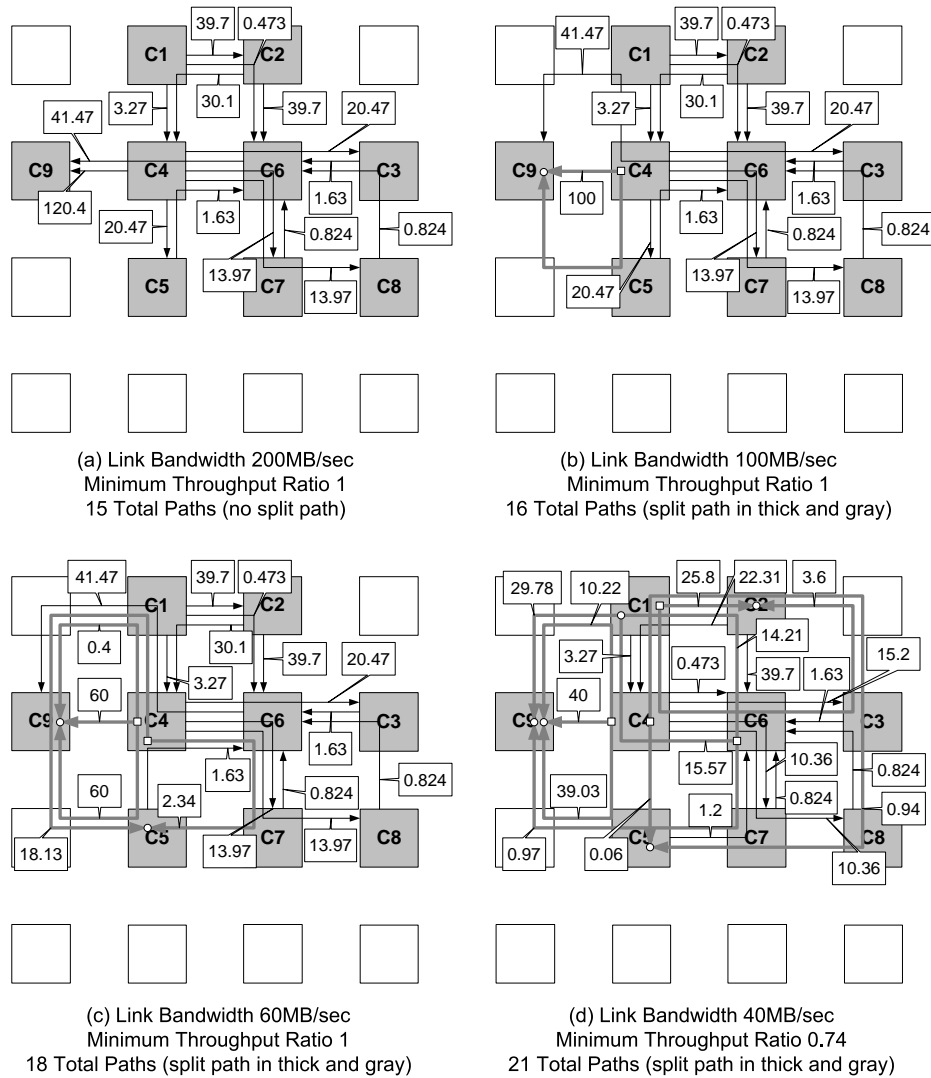


Figure 6-2: Routing results of H.264 decoder for different link bandwidths

is no feasible route as in Figure 6-2(d), the placement that maximizes the minimal fraction of the throughput is chosen from amongst the generated candidate placements (cf. Section 5.6).

The total synthesis time is very fast – a few seconds for this example. The time required to synthesize a Verilog description of H.264 to a FPGA is approximately 46 minutes for logic synthesis and 52 minutes for place and route [14]. Efficient synthesis is enabled because the specification deals with packets rather than bits, because compilation to processors is fast, and because the synthesis algorithms used

here are efficient.

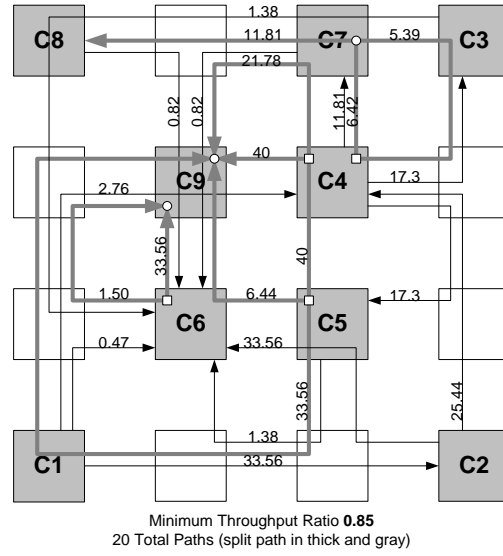


Figure 6-3: Routing Results of H.264 Decoder for a Different Placement and with the Link Bandwidth of Figure 6-2(d).

After finding a feasible or the best route, the synthesis tool allocates buffers for VFIFOs in each PFIFO. Taking the route in Figure 6-2 (c), Table 6.1 summarizes z_i , p_i and m_i values given by the specification and the buffer profiling result as described in Section 5.3.3. ² The result from the buffer allocation step described in Section 5.7.2 is given in Figure 6-4.

virtual FIFO	p_i (bits)	m_i (bits)	z_i (packets)
s1	128	512	1
s2	512	1536	1
s3	680	2024	1
s4	680	2024	1
s5	680	2024	1
s6	680	2024	1
s7	768	1536	1
s8	15552	31104	1
s9	3072	6144	1
s10	1024	2048	1
s11	1024	2048	1
s12	512	1024	1
s13	512	1024	1
s14	3072	6144	1
s15	96	384	1

Table 6.1: Buffer Requirements for VFIFOs in H.264 Decoder

² m_i was obtained from the profiling step, and z_i and p_i from the specification.

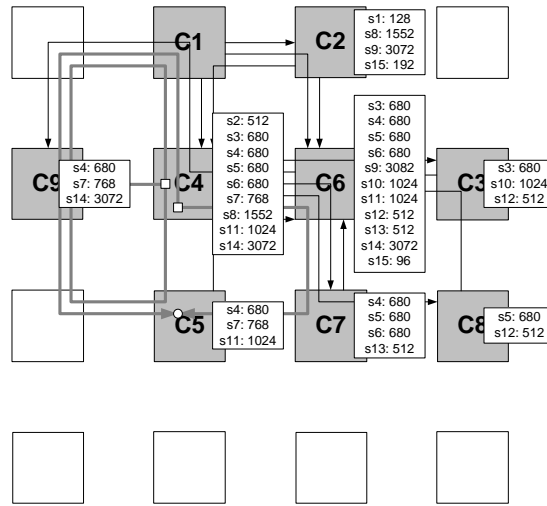


Figure 6-4: Buffer allocation of H.264 decoder for the route of Figure 6-2 (c).

6.2 Processor Performance Modeling

In the particular design of processor performance modeling used in the experiment, data flow in the target processor includes tight feedback between PEs unlike in the H.264 decoder. Hence, the latency of feedback VFIFOs can significantly affect the system throughput. Figure 6-5 shows the application specification with throughput demands determined by bandwidth profiling.

During placement and routing, some VFIFOs corresponding to tight feedback were specified to have minimum latency in order to reduce their impact on system throughput as described in Section 5.9. The result on the same four-by-four mesh network after placement, routing and buffer allocation are shown in Figure 6-6.

As described in Section 5.3.2, bandwidth profiling assumes the VFIFOs are ideal and their latencies are the minimum possible. However, some feedback VFIFOs in Figure 6-6 go through three PFIFOs so their latencies increased. The actual latencies could be worse as many VFIFOs share the same physical links. Because these are tight feedback VFIFOs, these increased latencies may affect system throughput so the actual performance could be degraded even though the synthesis tools guarantee that the network can handle the maximum throughput with the given route.

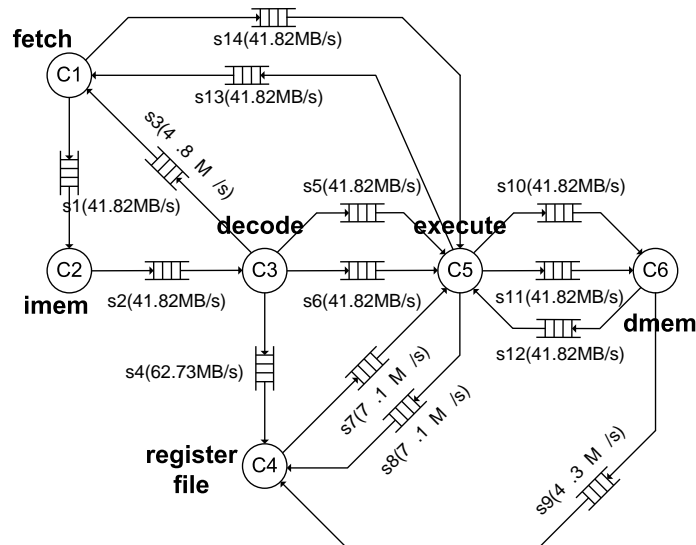


Figure 6-5: Throughput Demand of each VFIFO in Processor Performance Modeling

However, increased latencies in virtual FIFOs corresponding to tight feedback may not immediately degrade the performance because the computation time of each PE can hide those latencies. For example, even if the latency of a tight feedback VFIFO is 10 substrate cycles, the consumer may need to do some computation that costs more than 10 substrate cycles and when it eventually tries to dequeue from the feedback VFIFO data will be ready to be consumed. This gives synthesis tools some margins in dealing with the latencies of tight feedback VFIFOs.

The simulation results show that although the worst-case latency is three times larger than the ideal case, the overall throughput was not affected because the latencies were hidden by the much longer computation time of each PE. Figure 6-7 depicts the maximum and the average latency of each virtual FIFO on the right, and the average number of cycles used for computation per target system cycle on the left. While packets are going through the network, each PE is processing local data and is not blocked. This illustrates that our throughput-driven approach can be used to bind the length of critical paths to be within PE computation times.

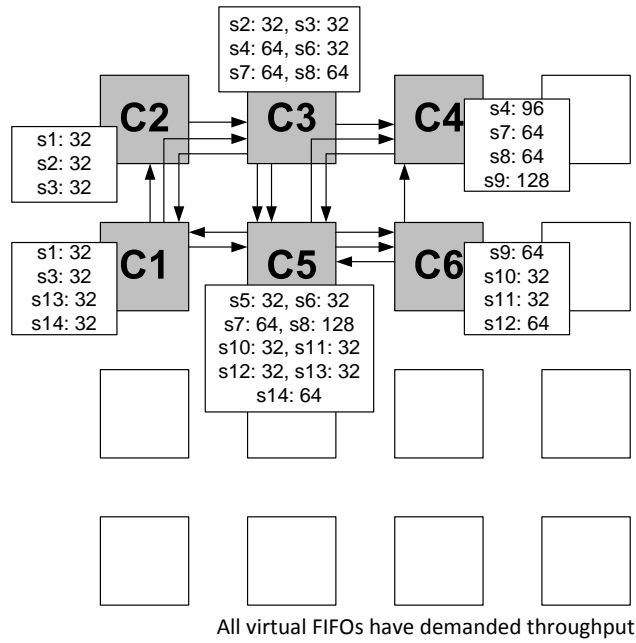


Figure 6-6: Synthesis Result of Processor Performance Modeling

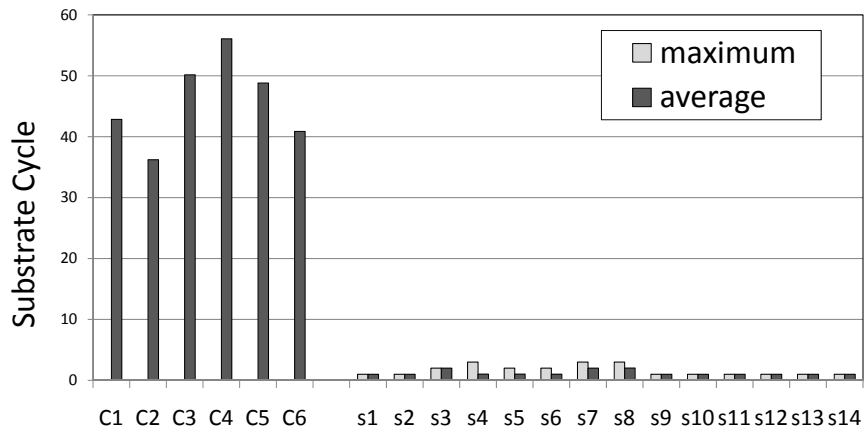


Figure 6-7: Average PE Substrate Cycles per System Cycle and the Maximum and the Average Latencies for each VFIFO

Chapter 7

Conclusion and Future Directions

The synthesis flow for diastolic arrays requires specifications written as functional units communicating via FIFOs connections, and generates configurations for processing elements and physical FIFOs interconnecting them. As illustrated in the previous chapters, this synthesis flow enables significantly easier implementation and optimization than conventional reconfigurable substrate synthesis flows.

Diastolic array architectures provide appropriate hardware mechanisms to ease the tasks in the synthesis flow. A diastolic array architecture provides multiple FIFO connections between processing elements by sharing physical links and data buffers. Processing elements are decoupled from the detailed actions of data communication; all a processing element needs to do is to send or to receive data from its attached physical FIFO unit which orchestrates all data channels the processing unit may have. Computational resources of processing elements are not wasted to manage networking. We also can obtain a fast substrate cycle because processing elements and their corresponding physical FIFOs are close to each other and all data communications within a substrate cycle are between a processing element and a physical FIFO or between adjacent physical FIFOs.

One can implement FIFOs and processors using BRAM and CLBs on an FPGA and use the diastolic array synthesis result. However, FIFOs implemented on FPGAs are quite expensive primarily because a number of long wire connections are required. Therefore, a custom hardware implementation of a diastolic array is necessary to

enable the easier and faster development of high-performance applications.

Before implementing such a custom hardware implementation of a diastolic array and a complete synthesis flow that can be applied to various types of applications, we first need to characterize what applications are readily and naturally expressible as finite state machines interacting through FIFOs. Automatic methods for partitioning based on conventional parallelism extraction methods will enlarge the class of designs that are efficiently synthesizable onto diastolic arrays. Applications where average throughput varies significantly for internal FIFOs will likely require reconfiguration and incur increased overhead.

Second, we need to evaluate the variants of synthesis algorithms applied to the various applications. For example, we have described a synthesis flow with several steps and there is clearly interaction between the steps. It may be better to heuristically solve a more complex problem that integrates the multicommodity flow and buffer allocation LPs, than optimally solve each of the problems in sequence as described. A more integrated strategy of dealing with low-latency feedback is also desirable. For example, computations involving low-latency feedback paths can be grouped together into a PE, so only a few low-latency paths need to be handled by the placement step.

Another interesting topic relates to the static configuration of the VFIFO network. The static configuration that the synthesis tools generate heavily depends on the profiling results, trying to satisfy the system throughput observed by profiling steps. However, it may be difficult to represent the characteristics of some applications through simple profiling. In this case, adaptively switching between multiple configurations can help improve the overall performance. Adaptive switching will require augmentation to the diastolic array architecture.

The next step of the project is to more comprehensively evaluate candidate architectures on different applications such as parallel stochastic simulation and detailed processor performance modeling, prior to undertaking a hardware implementation. The architectural tradeoffs will be fully explored so the microarchitecture of the first diastolic array architecture can be fixed. This exploration includes the tradeoffs corresponding to supporting composite-path routes or only supporting single-path routes,

support for “multicast” virtual FIFOs, hardware optimizations such as timestamps, and also varying the ISA, FIFO or memory sizes.

Bibliography

- [1] Christoph Albrecht. Global routing by new approximation algorithms for multicommodity flow. *IEEE Trans. on CAD of Integrated Circuits and Systems*, 20(5):622–632, 2001.
- [2] J. Becker and M. Vorbach. Coarse-grain reconfigurable XPP devices for adaptive high-end mobile video-processing. In *Proceedings of the International SOC Conference*, pages 165–166, 2004.
- [3] Michael Butts, Anthony Mark Jones, and Paul Wasson. A Structural Object Programming Model, Architecture, Chip and Tools for Reconfigurable Computing. In *FCCM '07: Proceedings of the 15th Annual IEEE Symposium on Field-Programmable Custom Computing Machines*, pages 55–64, 2007.
- [4] Mike Butts. Synchronization through Communication in a Massively Parallel Processor Array. *IEEE Micro*, 27(5):32–40, Sept/Oct 2007.
- [5] Antonio Capone and Fabio Martignon. A Multi-commodity Flow Model for Optimal Routing in Wireless Mesh Networks. *Journal of Networks*, 2(3), June 2007.
- [6] Hongyu Chen, Bo Yao, Feng Zhou, and Chung-Kuan Cheng. Physical Planning Of On-Chip Interconnect Architectures. In *Proceedings of the International Conference on Computer Design*, 2002.
- [7] Derek Chiou, Dam Sunwoo, Joonsoo Kim, Nikhil A. Patil, William H. Reinhardt, D. Eric Johnson, and Zheng Xu. FAST Methodology for High-Speed SoC/Computer Simulation. In *International Conference on Computer-Aided Design*, November 2007.
- [8] Thomas H. Cormen, Charles E. Leiserson, Ronald L. Rivest, and Clifford Stein. *Introduction to Algorithms*. MIT Press/McGraw-Hill, 2001.
- [9] CoWare. CoWare Signal Processing Worksystem (SPW).
- [10] William J. Dally and Charles L. Seitz. Deadlock-Free Message Routing in Multiprocessor Interconnection Networks. *IEEE Trans. Computers*, 36(5):547–553, 1987.

- [11] W.J. Dally. Virtual-Channel Flow Control. *IEEE Transactions on Parallel and Distributed Systems*, 03(2):194–205, 1992.
- [12] David Wentzlaff et al. On-Chip Interconnection Architecture of the Tile Processor. *IEEE Micro*, 27(5):15–31, Sept/Oct 2007.
- [13] Andrew Duller, Gajinder Panesar, and Daniel Towner. Parallel Processing – the picoChip way! In *Communicating Process Architectures*, pages 299–313, 2003.
- [14] Kermin Fleming, Chun-Chieh Lin, Nirav Dave, Arvind, Gopal Raghavan, and Jamey Hicks. H.264 Decoding: A Case Study in Late Design-Cycle Changes. In *Proceedings of the Sixth ACM-IEEE International Conference on Formal Methods and Models for Codesign (MEMOCODE'2008)*, 2008.
- [15] Michael I. Gordon, William Thies, and Saman Amarasinghe. Exploiting Coarse-Grained Task, Data, Pipeline Parallelism in Stream Programs. In *International Conference on Architectural Support for Programming Languages and Operating Systems*, 2006.
- [16] Thomas Gross and David R. O'Hallaron. *iWarp: anatomy of a parallel computing system*. MIT Press, Cambridge, MA, USA, 1998.
- [17] Yuanfang Hu, Yi Zhu, Hongyu Chen, Ronald Graham, and Chung-Kuan Cheng. Communication latency aware low power NoC synthesis. In *Proceedings of the 43rd Design Automation Conference*, pages 574–579, 2006.
- [18] Yuanfang Hu, Yi Zhu, Michael B. Taylor, and Chung-Kuan Cheng. FPGA Global Routing Architecture Optimization Using a Multicommodity Flow Approach. In *Proceedings of the International Conference on Computer Design*, 2007.
- [19] D. Jones and D. M. Lewis. A Time-Multiplexed FPGA Architecture for Logic Emulation. In *Proceedings of the 1995 IEEE Custom Integrated Circuits Conference*, 1995.
- [20] Nachiket Kapre, Nikil Mehta, Michael deLorimier, Raphael Rubin, Henry Barnor, Michael J. Wilson, Michael Wrighton, and Andre DeHon. Packet Switched vs. Time Multiplexed FPGA Overlay Networks. In *IEEE Symposium on Field-Programmable Custom Computing Machines (FCCM 2006)*, 2006.
- [21] Stavros G. Kolliopoulos and Clifford Stein. Improved approximation algorithms for unsplittable flow problems. In *38th Annual Symposium on Foundations of Computer Science*, page 426, 1997.
- [22] H. T. Kung. Why Systolic Architectures? In *Computer Magazine*, January 1982.
- [23] H. T. Kung. Systolic Communication. In *International Conference on Systolic Arrays*, May 1988.

- [24] I. Kuon and J. Rose. Measuring the Gap Between FPGAs and ASICs. *Computer-Aided Design of Integrated Circuits and Systems, IEEE Transactions on*, 26(2):203–215, Feb. 2007.
- [25] Edward A. Lee and David G. Messerschmitt. Static Scheduling of Synchronous Data Flow Programs for Digital Signal Processing. *IEEE Trans. Computers*, 36(1):24–35, 1987.
- [26] Tom Leighton, Clifford Stein, Fillia Makedon, Éva Tardos, Serge Plotkin, and Spyros Tragoudas. Fast approximation algorithms for multicommodity flow problems. In *Proceedings of the 25th Annual ACM Symposium on the Theory of Computing*, pages 101–111, 1991.
- [27] MathStar. Field Programmable Object Array.
- [28] Ethan Mirsky and Andre DeHon. MATRIX: A Reconfigurable Computing Architecture with Configurable Instruction Distribution and Deployable Resources. In *IEEE Symposium on Field-Programmable Custom Computing Machines (FCCM 1996)*, 1996.
- [29] D. Mitra, J.A. Morrison, and K.G. Ramakrishnan. Virtual private networks: joint resource allocation and routing design. *INFOCOM '99. Eighteenth Annual Joint Conference of the IEEE Computer and Communications Societies*, 2:480–490, 21-25 Mar 1999.
- [30] John Oliver, Ravishankar Rao, Paul Sultana, Jedidiah R. Crandall, Erik Czernikowski, Leslie W. Jones IV, Diana Franklin, Venkatesh Akella, and Frederic T. Chong. Synchrosalar: A Multiple Clock Domain, Power-Aware, Tile-Based Embedded Processor. In *ISCA*, pages 150–161, 2004.
- [31] M. Pellauer, M. Vijayaraghavan, M. Adler, J. Emer, and Arvind. Quick Performance Models Quickly: Timing-Directed Simulation on FPGAs. In *International Symposium on Performance Analysis of Systems and Software (ISPASS 2008)*, April 2008.
- [32] Michael Pellauer, Muralidaran Vijayaraghavan, Michael Adler, Arvind, and Joel Emer. A-Ports: an efficient abstraction for cycle-accurate performance models on FPGAs. In *FPGA '08: Proceedings of the 16th international ACM/SIGDA symposium on Field programmable gate arrays*, pages 87–96, 2008.
- [33] Prabhakar Raghavan and Clark D. Thompson. Randomized rounding: a technique for provably good algorithms and algorithmic proofs. *Combinatorica*, 7(4):365–374, 1987.
- [34] K. Sankaralingam, R. Nagarajan, H. Liu, J. Huh, C. K. Kim, D. Burger, S. W. Keckler, and C. R. Moore. Exploiting ILP, TLP, and DLP using polymorphism in the TRIPS architecture. In *International Symposium on Computer Architecture (ISCA)*, pages 422–433, June 2003.

- [35] William Thies, Michal Karczmarek, and Saman Amarasinghe. StreamIt: A Language for Streaming Applications. In *International Conference on Compiler Construction*, 2002.
- [36] S. Trimberger. Scheduling Designs into a Time-Multiplexed FPGA. In *Proceedings of the ACM/SIGDA International Symposium on Field Programmable Gate Arrays*, pages 153–160, 1998.
- [37] E. Waingold, M. Taylor, D. Srikrishna, V. Sarkar, W. Lee, V. Lee, J. Kim, M. Frank, P. Finch, R. Barua, J. Babb, S. Amarasinghe, and A. Agarwal. Baring it all to Software: Raw Machines. In *IEEE Computer*, pages 86–93, September 1997.
- [38] Xilinx. Xilinx Core Generator.
- [39] Zhiyi Yu. *High Performance and Energy Efficient Multi-core Systems for DSP Applications*. PhD thesis, U. C. Davis, 2007.
- [40] Zhiyi Yu, Michael Meeuwsen, Ryan Apperson, Omar Sattari, Michael Lai, Jeremy Webb, Eric Work, Tinoosh Mohsenin, Mandeep Singh, and Bevan Baas. An Asynchronous Array of Simple Processors for DSP Applications. In *Proceedings of 2006 IEEE International Solid-State Circuits Conference (ISSCC)*, February 2006.