

# Data Caches for Superscalar Processors\*

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## Abstract

As the number of instructions executed in parallel increases, superscalar processors will require higher bandwidth from data caches. Because of the high cost of true multi-ported caches, alternative cache designs must be evaluated. The purpose of this study is to examine the data cache bandwidth requirements of high-degree superscalar processors, and investigate alternative solutions. The designs studied range from classic solutions like multi-banked caches to more complex solutions recently proposed in the literature. The performance tradeoffs of these different cache designs are examined in details. Then, using a chip area cost model, all solutions are compared with respect to both cost and performance. While many cache designs seem capable of achieving high cache bandwidth, the best cost/performance tradeoff varies significantly depending on the dedicated area cost, ranging from multi-banked cache designs to hybrid multi-banked/multi-ported caches or even true multi-ported caches. For instance, we find that an 8-bank cache with minor optimizations perform 10% better than a true 2-port cache at half the cost, or that a 4-bank 2 ports per bank cache performs better than a true 4-port cache and uses 45% less chip area.

## 1 Introduction

Currently, processor performance is improved through higher clock rates and increasing the number of instructions executed in parallel. This latter trend raises several issues, among which is the necessity to design data and instruction caches which can tolerate several accesses per cycle. Most processors now achieve high throughput with instruction caches by loading one or several cache lines at the same time, thus exploiting instruction stream spatial locality. To a large extent, the effect of branches on instruction stream locality can be hidden by using branch prediction to drive instruction prefetching [YMP93]. Multiple-access data caches

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are more difficult to design because load/store requests sent in parallel share no obvious locality properties. The difficulty is to propose a design that can cope with increasing degree of instruction parallelism. The solutions presently implemented in processors can be classified as:

- *True multi-porting.* With respect to performance *true multi-porting* is clearly an ideal solution, but its chip area cost is high. Cost can be partly reduced by accepting a certain degradation of cache access time that would reduce the performance.

- *Multiple Cache Copies.* For  $n$  accesses, the cache must be replicated  $n$  times with no benefit to storage space. Moreover, store requests are sent simultaneously to all cache copies for coherence and thus no other cache request can be sent in parallel. Since about 30% of memory accesses are store requests [HP96], this solution is severely limited. The DEC 21164 [Dig94] has a dual-ported cache implemented with two copies of the cache array.

- *Virtual Multiporting.* In the Power2 [Mic93], virtual dual-porting is used: the cache SRAM is twice as fast as the processor clock allowing two processor requests in a single processor cycle. The new Alpha 21264 [Dig96] also uses this technique. Again, it is unlikely a cache SRAM  $n$  times as fast as the processor clock can become a standard solution.

- *Multi-banking.* The cache is divided in several banks, each bank can be accessed independently of the others. The cost of multi-banking is a crossbar to route requests from load/store units to cache banks and another one from banks back to ports. The crossbar area size as well as the cache access time increase with the number of banks. However, the main issue are the *bank conflicts* as shows the experience of multi-banked memories in vector processors [OL85]. Bank conflicts occur when two or more requests need to access the same bank simultaneously. While bank conflicts could be partially eliminated by using a very large number of memory banks in vector processors (512 in the Hitachi S-3800 [KIS<sup>+</sup>94]), this solution may not be practical for caches. Increasing the number of banks also implies deeper crossbar and thus longer cache access time, even though smaller banks are faster and could partially compensate for cache access time degradation. The Pentium data cache [Int93] has 8 banks, while the MIPS R8000 [MIP94] uses a dual-banked data cache.

Thus, to design a data cache that can accept multiple requests simultaneously there are many cost/performance tradeoffs to address. The purpose of this study is to expose these tradeoffs for different cache structures and to provide performance hints for each structure. In Section 2 the superscalar processor architecture used in this study is

described, its performance, cache bandwidth requirements and the characteristics of its cache requests are analyzed in Section 3. True multi-ported caches are examined in Section 4 and these results are used as performance references throughout the study. Multi-banked caches are examined in Section 5, and several alternative designs to both multi-ported and multi-banked caches are discussed in Section 6. These different solutions are first compared in terms of performance throughout the study, and in Section 7 the area cost model developed by Mulder et al. [MQF91] is used to determine the best overall cost/performance tradeoffs. Finally, Section 8 presents some related work.

## 2 Methodology

As processor issue rate increases and the sustained number of instructions executed per cycle (IPC) is closer to the peak IPC, the number of memory requests per cycle is naturally going to increase. To mimic this increased processor pressure on data caches, we have used a superscalar processor with high issue rate. As issue rate increases, more sophisticated branch prediction techniques and a larger number of functional units can be expected. Though it is feasible to add functional units, elaborating on future branch prediction techniques is out of the scope of this article. To still take these future improvements into account and also to exhibit maximal data cache pressure, we have removed these two processor bottlenecks by using perfect branch prediction and a large number of functional units. We acknowledge these assumptions affect the data address trace. Mainly the distribution of data cache requests over time (which cache requests are sent in the same cycle) is changed, but the address sequence is less affected since instruction dependencies are considered. In spite of the imprecision, we still find this tracing methodology to be the best tradeoff for obtaining high data cache pressure and an accurate address trace. A similar approach of using perfect branch prediction was used in a recent study by Jourdan et al. [JSL95] which aimed at dimensioning functional units of future superscalar processors.

### Simulated Architecture

We defined a processor architecture close to that of the HP-8000 which we found to be both aggressive at extracting ILP and simple enough to scale up well.<sup>1</sup> Present processors issue 4 to 6 instructions per cycle. We found that increasing processor degree beyond 8 does not bring significant improvements for most codes. So, except for this section, we use a degree 8 processor. Like the HP-8000, the processor architecture includes an instruction queue playing the role of both reservation stations and commit buffer.<sup>2</sup> Instructions are sent in-order to the queue, dispatched to functional units, executed out-of-order, and committed in-order again. Commits are performed in-order to preserve the coherence of store requests, enable easy squashing of instructions and recovery after exceptions. The instruction queue is split into a load/store queue and a scalar instruction queue as in the HP-8000. A scalar instruction queue entry contains operands and/or sources of operands (functional units identifiers). The load/store queue contains the same information plus the data address. This address is used to maintain coherence between load/store instructions. A load can be sent

to cache only if the addresses of all older store instructions are known and distinct. If there exists a store with same address, the load is not sent to cache and the data is directly read from the load/store queue. Stores execute only when they retire. The main processor parameters are the number of instructions fetched together, i.e., the *degree* of the superscalar processor, the number of instructions the processor attempts to commit every cycle, the functional units configuration (number, types, latencies and issue rates) and the instruction window size (the size corresponds to the sum of the load/store queue size and the scalar queue size; both queues have identical size). To restrict the number of combinations, several configurations have been defined which correspond to different scales of the same design, see Table 1. In Section 3, all configurations are used, but in the other sections, only configuration 2 is used.

Configuration	1	2	3	4
Degree (Nb. of inst. fetched per cycle)	4	8	16	32
Nb of inst. attempted to be committed per cycle	4	8	16	32
Instruction window size	64	128	256	512

Table 1: *Processor Configurations.*

As mentioned above, we assume perfect instruction fetch. To reduce the impact of resource conflicts on processor performance, the number of functional units of each type is equal to the processor degree for each configuration. The functional units latencies are 1 cycle for all ALU operations, 2 cycles for floating-point ADD, 4 cycles for floating-point MULT and 20 cycles for floating-point DIV. All functional units are fully pipelined except for floating-point DIV.

### Cache memory parameters

In the next sections, we seek to define and dimension cache designs that can cope with such processor architectures. A few cache/memory parameters remain fixed. In this study, we essentially consider a fast first-level on-chip data cache. Since cache access time is one of our main concerns, the cache is direct-mapped. The cache is also write-back, write-allocate. The cache size is equal to 32 Kbytes, i.e., within the current range of 8 Kbytes to 256 Kbytes, and the line size is equal to 32 bytes. This cache configuration is called the *Baseline* cache throughout the text and figures. Unless otherwise mentioned, the cache is non-blocking. The miss latency to the next memory level is 5 cycles, the access to this lower memory level is pipelined and one miss request can be sent every cycle with at most 5 pending requests, i.e., as if a close second-level cache is used. However, this lower memory level is not simulated and all requests are considered hits to restrict the number of parameters and focus on the first-level cache.

In the remainder of the text it is necessary to distinguish between the number of *processor-to-cache* ports which corresponds to the number of data paths between the processor and the cache, and the number of *cache ports* or *cell ports* which corresponds to the number of ports of each cache SRAM cell. An  $n$ -bank cache may have only  $p$  processor-to-cache ports with  $p < n$ . For example, the Pentium data cache [Int93] has 2 processor-to-cache ports, 8 banks and 1 cell port, i.e.,  $n = 8$  and  $p = 2$ . It is assumed that a

<sup>1</sup>The HP-8000 is a superscalar processor of degree 4.

<sup>2</sup>This instruction queue corresponds to the *instruction window* mentioned above and in [JSL95].

$p$ -port cache is always associated with a processor having  $p$  processor-to-cache ports.

## Benchmarks

Ten benchmarks were used for the study, five SPECint92 codes and five SPECfp92 codes listed in Table 2. SPEC92 was preferred over SPEC95 because simulation time restricts trace length. With SPEC95, a small trace length is likely to only correspond to a very small fraction of the whole code. Since this study is focused on bandwidth rather than latency, having representative ILP performance, i.e., traversing many different code constructs, was considered more important than having large data sets. No particular criterion drove the selection of these SPEC92 benchmarks. We picked the five first SPECfp92 and SPECint92 that ran successfully with Spy [G. 91], the tracer used in this study. For each benchmark, 100-million instruction traces were simulated which correspond to 5%-10% of most benchmarks. The first 10 million instructions were ignored. Benchmarks were compiled on Sun Sparc processors using `-O4` optimization. No software optimization is used to exhibit more ILP except for loop unrolling as provided in the Sun compilers.

Code	21164 IPC	Superscalar Degree				Mem. Inst.	Miss Ratio
		4	8	16	32		
wave5	0.83	2.49	2.92	3.22	3.22	14%	0.01
tomcatv	0.92	1.55	1.60	1.61	1.61	46%	0.08
swm256	1.60	1.62	1.62	1.62	1.62	21%	0.05
su2cor	0.80	1.91	2.08	2.10	2.10	38%	0.12
hydro2d	0.72	1.95	2.06	2.09	2.10	42%	0.07
Avg FP	0.91	1.91	2.06	2.13	2.14	32%	0.07
espresso	1.00	3.74	5.75	7.14	7.75	25%	0.01
li	0.89	4.00	7.15	8.03	8.09	31%	0.01
eqntott	0.95	3.91	6.85	9.26	11.0	23%	0.03
compress	0.64	3.85	4.88	5.00	5.02	23%	0.16
gcc	0.77	3.46	5.01	5.74	6.04	28%	0.02
Avg INT	0.85	3.79	5.93	7.03	7.58	26%	0.05
Avg All	0.88	2.85	3.99	4.58	4.85	29%	0.06
Mem IPC	N.A.	0.79	1.11	1.25	1.31	N.A.	N.A.

Table 2: Alpha 21164 IPC, IPC with perfect cache for different superscalar degrees, Percentage of memory operations in each benchmark and Miss Ratio with the baseline cache.

## 3 Performance Thresholds and Nature of Cache Requests

In order to get a performance bound for our superscalar processor, simulations were first run for each of the 10 benchmarks assuming a perfect cache, i.e., no cache miss and unlimited number of cache ports, so that each load/store reference is serviced in a single cycle. Table 2 shows the performance measured in instructions committed per cycle, denoted IPC (Instruction Per Cycle), for the four different processor configurations with a perfect cache. The best average IPC is equal to 4.85 for a processor of degree 32. Though this figure is not so high, the actual sustained IPC of current processors is much lower. In [CB96], the IPC of the Alpha 21164 for the same benchmarks were collected and are shown in Table 2. The Alpha 21164 is a 4-way issue processor and it achieves an average IPC of 0.88 for the selected benchmarks. Therefore, even if the IPC for the MIPS R10000 or the HP 8000, which use out-of-order execution unlike the DEC 21164, are 2 or 3 times higher, these results show that significantly higher IPC can be achieved with higher issue rate under optimal hypotheses (perfect

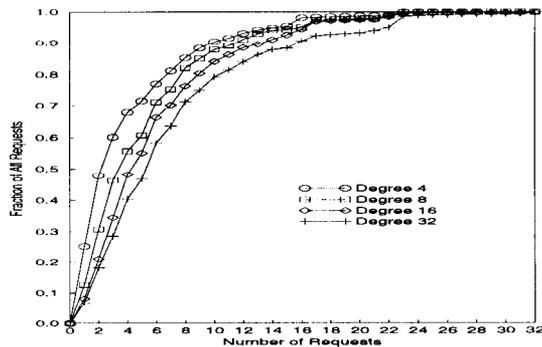


Figure 1: Distribution of Number of Cache Requests Sent Simultaneously (cumulated) with perfect cache.

branch prediction, no resource conflict). Also, the best average floating-point IPC (2.14) is lower than the best average integer IPC (7.58). Because branch prediction is one of the major bottlenecks of integer codes, it is natural that using perfect branch prediction boosts integer codes performance. These numbers do not reflect the theoretical intrinsic instruction-level parallelism indicated in [HP96] but they are consistent with the detailed experiments by Jourdan et al. [JSL95]: about 7.5 IPC for integer codes and about 4.5 for floating-point codes in average<sup>3</sup>. Though floating-point IPC is also lower than integer IPC in the latter study, we observed lower floating-point IPC but we used a different instruction set: Sparc processor and code compiled on a SuperSparc 20 while Jourdan et al. used the MIPS instruction set compiled on a R4600 SGI. Table 2 also provides the miss ratio of the benchmarks with the baseline cache (32-Kbyte cache and 32-byte line). Finally, in table 2, the percentage of load/store requests of each benchmark is indicated to get a hint at the average number of memory requests sent per cycle. Because the average IPC is bounded by 4.85 even when 32 instruction slots and a window size of 512 are used,<sup>4</sup> the average number of load/store requests per cycle, i.e., *memory IPC*, remains bounded by 1.31. However, cache performance is not only affected by global volume of data transactions but also by the distribution of the number of requests sent simultaneously.

Figure 1 shows the cumulated distribution<sup>5</sup> of cache request size, i.e., the number of cache requests sent at the same time. For example, for an 8-degree processor, 45% of cache requests are sent by groups of 4 requests or more. 87% cache requests are sent along with one or more requests for a processor of degree 8, with a maximum of 93% for a processor of degree 32. It even appears that 25% of load/store requests are sent by blocks larger than 8 for an 8-degree processor, for example. Though a superscalar processor of degree 8 can fetch or commit no more than 8 instructions together, the instruction window has 128 entries in our case. Thus, it is possible to have more than 8 load/store instructions ready to execute in the same cycle. The concentration of requests partly lays in the way instructions are committed. In Figure 2 the non-cumulated distribution<sup>6</sup> of the number of instructions committed per cycle is shown. All instructions are considered in this figure. Moreover, cycles where

<sup>3</sup> All the Spec92 benchmarks were used in this study.

<sup>4</sup> A 512-entry window is unlikely to be implemented. These parameters are used to find the upper-bound IPC.

<sup>5</sup> Note that cycles where no request is sent to cache are not considered in this figure

<sup>6</sup> In this case, the non-cumulated distribution is used to better highlight its irregularity

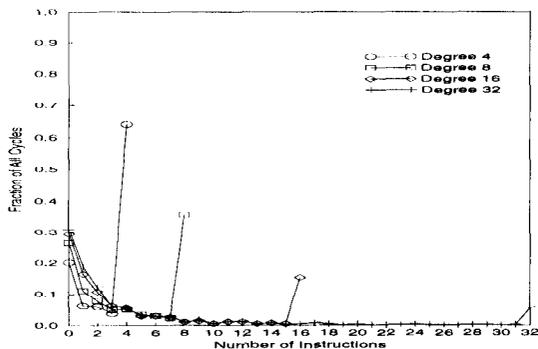


Figure 2: *Distribution of Number of Instructions Committed Per Cycle with perfect cache.*

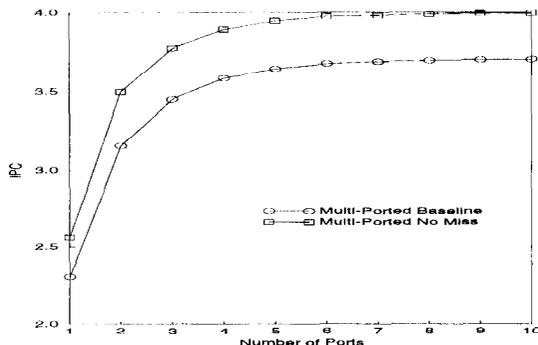


Figure 3: *IPC for different multi-ported cache configurations.*

no instruction was committed are taken into account, unlike in Figure 1. It appears that *commits* mostly occur by bursts, as if it often happens that one instruction locks the commit buffer and prevent all dependent instructions from committing. When an instruction that blocks the commit buffer can finally complete, a large set of preceding instructions can then commit together, hence the burst. Such bursts also breed load/store instruction bursts. Note also the high fraction of cycles where no instruction is committed, i.e., 25% for an 8-degree processor. As a consequence, we found that for an 8-degree processor no cache request is sent within more than 60% of the cycles.

#### 4 Multi-Ported Caches

In this section we examine the performance tradeoffs of true multi-ported caches to determine how many cache ports are needed. Because of the burst requests described above, the best number of ports is not correlated to the average number of cache requests sent per cycle. In Figure 3 the average IPC is plotted for different numbers of ports and different cache configurations which are described below. While in average 1.16 cache requests are sent every cycle (see Table 2: 29% load/store instructions and 3.99 IPC), the average IPC for 2 ports corresponds to 85% of the 8-port IPC, see Figure 3 graph *Multi-Ported Baseline*. This percentage raises to 97% for 4 ports which corresponds to a reasonable cost/performance tradeoff. Increasing the number of cache ports beyond 8 brings no improvement. With 3.70 IPC, an 8-port cache is still 0.30 IPC below the performance of a perfect cache. The remaining performance gap with respect to a perfect cache is due to misses, and an 8-port cache where all requests are considered hits achieves 3.99 IPC, see graph *Multi-Ported No Miss* in Figure 3.

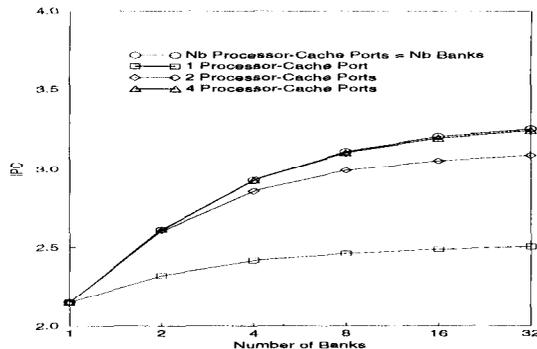


Figure 4: *Influence of the number of processor-to-cache ports for a processor of degree 8.*

#### 5 Multi-Banked Caches

A multi-banked cache consists of several banks connected to processor-to-cache ports via a crossbar. All banks of a multi-banked cache are considered blocking in this study. To investigate multi-banked caches, two new components must be considered: the crossbar which increases cost and cache access time, and the data layout among banks. The crossbar cost is discussed below. With respect to data layout, the straightforward distribution which consists in storing consecutive cache lines into consecutive banks is used as a performance reference in this section. This distribution is used in the Intel Pentium [Int93]. Alternative distributions are examined in Section 6.

To decrease the crossbar cost and its impact on cycle time, either its fan-in or its fan-out can be reduced. Reducing the fan-out means reducing the number of banks and possibly increasing the number of bank conflicts. Reducing the fan-in means reducing the number of processor-to-cache ports which is then smaller than the number of banks. In Figure 4, multi-banked cache performance is reported for different numbers of processor-to-cache ports. In spite of burst requests, we found a small fan-in of 4 processor-to-cache ports is sufficient to exploit most of the performance potential of a multi-banked cache. Thus, we use 4 processor-to-cache ports in the remainder of this section and in the next sections, unless otherwise specified.

In Figure 5, the performance of multi-ported caches is reported along with that of multi-banked caches as a function of the number of banks. While reasonable performance is obtained with multi-banking, a maximum IPC of 3.24 is reached with 32 banks which is significantly lower than the 3.70 IPC of a true 8-port cache. Even with 32 banks, performance remains lower than what is obtained with a true 4-port cache.

Excluding cache access time issues, the main limitation to multi-banking is bank conflicts. The occurrence and nature of bank conflicts are analyzed in details at the end of this Section. To isolate the impact of bank conflicts on performance, it is assumed in Figure 5, graph *Multi-Banked No Miss*, that all requests hit. Thus, performance degradations are only due to bank conflicts. *Multi-Banked No Miss* results should be confronted with *Multi-Banked Baseline* results, in Figure 5. The performance difference varies between 0.28 IPC and 0.42 IPC. Though this difference is significant, it is not as important as the large fraction of bank conflicts suggests, see paragraph on bank conflicts below. Firstly, a bank conflict does not necessarily result in a processor slowdown, especially using dynamic execution ordering. Secondly, the drawbacks of multi-banked caches are

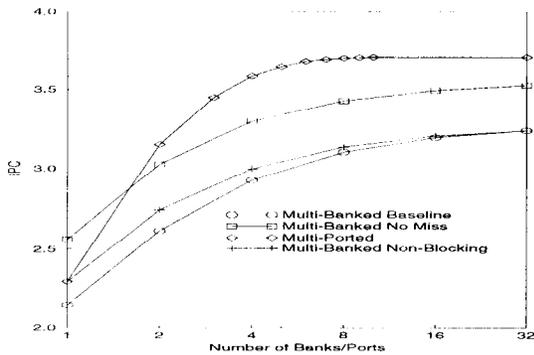


Figure 5: IPC for different multi-banked cache configurations with 4 processor-to-cache ports.

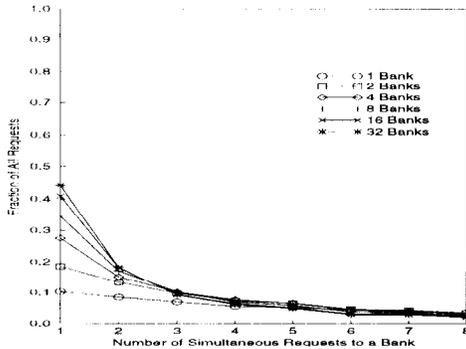


Figure 6: Distribution of number of simultaneous requests to a bank.

partly compensated by a few minor assets. One of the main point is that multi-banked caches are naturally non-blocking because banks operate in a decoupled manner. Thus, a miss in one bank does not stall other banks. In Figure 5, the performance of blocking multi-banked caches (Baseline graph) is compared with non-blocking multi-banked caches (up to 5 outstanding misses) Multi-Banked Non-Blocking graph. As the number of banks increases, the number of simultaneous misses that can occur in a blocking multi-banked cache also increases (one per bank), and thus performance difference tends to 0. Similarly, multi-banked caches with large numbers of banks are better capable of limiting the cache bandwidth wasted by writes.

The second main performance bottleneck of multi-banked caches is crossbar routing delay. In order to examine the impact of crossbar on performance, several simulations were run where cache access time is increased by one or two cycles. The results are reported in [JNT96].

### Nature of bank conflicts

Bank conflicts are shown in Figure 6 which indicates the distribution of the number of simultaneous requests to a bank. These statistics have been collected by counting each cycle the number of cache requests in the load/store queue which are both ready to execute and mapped to the same bank; these statistics were averaged over all banks. For instance with 4 banks, 28% of requests never experience bank conflicts, 18% conflict with another request, 12% conflict with two other requests, . . . and the remaining 42% conflict with at least 3 other requests. The number of conflicts is very high, see Figure 6, starting with 81% of requests experiencing a conflict in a 2-bank cache, and still more than 60% in a 16-bank or 32-bank cache. Past 16 banks, increasing

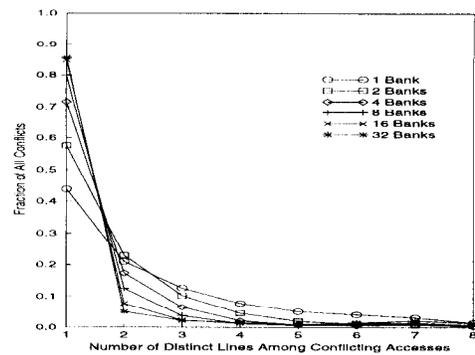


Figure 7: Distribution of number of distinct lines among conflicting requests.

the number of banks is rather inefficient at removing bank conflicts.

We now wish to further analyze the nature of bank conflicts. Spatial locality suggests consecutive many closely spaced requests can target the same line and thus the same bank. To determine what fraction of conflicts correspond to requests to the same line, the distribution of the number of distinct lines among conflicting requests is reported in Figure 7. For instance with 4 banks, 71% of pending requests target the same line. This result should be confronted to the 28% of requests which do not conflict in a 4-bank cache, see Figure 6. This means 43% requests experienced conflicts with one or more requests that referenced the same line. This difference is still equal to 43% for 32 banks. Also, Figure 7 indicates there are few cases where 3 distinct lines are involved in a bank conflict when 4 or more banks are used.

Not only multiple simultaneous requests to banks occur frequently, but we also found that conflicts are not evenly distributed over banks, certain banks standing significantly more stress than others with an average fourfold difference between the bank with fewest conflicts and the bank with most conflicts for an 8-bank cache (27% versus 7%).

## 6 Alternative Cache Designs

The previous sections were dedicated to the two most straightforward techniques for improving data cache bandwidth, i.e., multi-ported and multi-banking. In this section, we explore several alternative designs that attempt to address the main flaws of each solution, i.e., cost and cache access time for multi-ported or bank conflicts and cache access time for multi-banking.

### 6.1 Hybrid Design

A first alternative is a combination of both designs i.e., a multi-banked cache where each bank has several ports. Using multiple banks provides additional bandwidth at a low cost, and multiple ports help removing bank conflicts. Fixing the number of processor-to-cache port to 4,<sup>7</sup> the performance of several bank/port configurations has been measured for 1,2,4 and 8 banks and is reported in Figure 8 as a function of the number of ports per bank. The banks are here considered non-blocking for the sake of comparison with multi-ported caches. We find that a true 4-port cache performs only slightly better than a 4-bank 2-port cache.

<sup>7</sup>More exactly, we use  $\min(4, \text{number of banks} \times \text{number of ports per bank})$ .

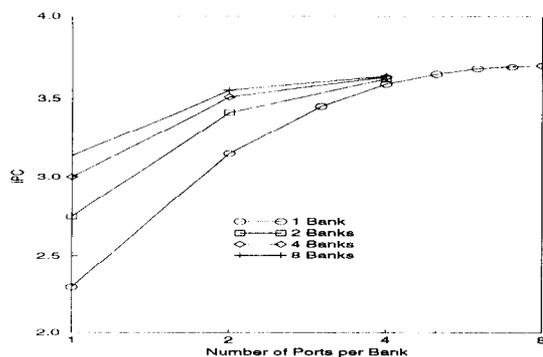


Figure 8: Performance of hybrid designs.

Since the cost of a crossbar for a 4-bank cache is fairly low, hybrid designs seem to provide interesting cost/performance tradeoffs.

## 6.2 Two-Level Multi-Ported Cache

Multi-level cache hierarchies is a well known technique for achieving low average memory access time together with low cycle time. We experimented the idea of two-level cache hierarchies for achieving high data cache bandwidth. Level-0, i.e., closest to the processor, is a small highly true multi-ported cache, whereas Level-1 is a larger cache with the same characteristics as the baseline cache mentioned in Section 3 and a small number of ports. The role of Level-0 is to provide high cache bandwidth at a small cost, thanks to its reduced size, and the role of Level-1 is to provide low miss ratio for the overall two-level hierarchy. Level-0 will mostly exploit spatial locality while Level-1 will exploit both spatial and temporal locality.

Level-1 is designed to have the same access time as Level-0 to compensate for the reduced amount of temporal locality exploited by Level-0. Moreover, Level-0 is fully-associative to avoid conflict misses associated with small sized caches, but random replacement is used to cut down chip area cost. Level-1 only has 1 or 2 ports that are connected to Level-0 through a high bandwidth bus, so it can refill one cache line per port each cycle. Level-0 to Level-1 miss latency is equal to 1 cycle. Level-1 only allows hit under miss while Level-0 is non-blocking (4 pending misses).

The main parameters are Level-0 size and the number of ports between Level-0 and Level-1. In Figure 9 the average IPC is indicated for different configurations and a processor of degree 8. As can be seen, Level-0 filters most of the data traffic and adding more ports from Level-0 to Level-1 does not significantly increase performance. However, performance remains significantly worse than true multi-ported caches, unlike the same design applied to TLBs, see [AS96]. Performance is close to that of multi-banked caches.

## 6.3 Alternative Data Layout

Bank conflicts are one of the two performance bottlenecks of multi-banked caches. The data distribution in banks can have a strong impact on the occurrence of bank conflicts. Word distribution can be an alternative to the cache line distribution used in Section 5. With word distribution, consecutive words of the same cache line, are stored in consecutive banks. For vector processors multi-bank memories, 1-word wide memory banks were used thus limiting the probability of conflict. In a cache, this solution is costly because each banked data must be tagged so that if the

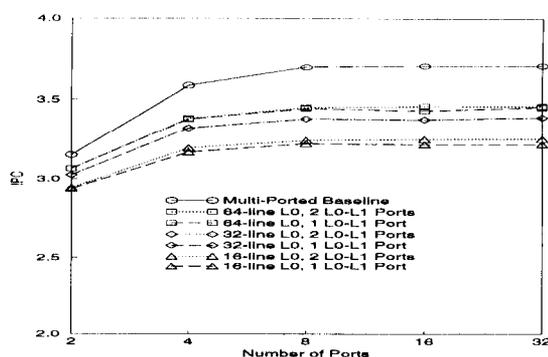


Figure 9: Performance of several two-level configuration compared with true multiporting.

bank width is divided by  $n$  the number of tags is multiplied by  $n$ . The HP-8000 [Gwe94] uses an intermediate but still expensive solution which consists in dual-portioning the tag for its dual-banked cache.<sup>8</sup> For its floating-point cache, the MIPS R8000 [MIP94] implements word distribution.

Spatial locality suggests word distribution since two consecutive references of a given load/store are often to consecutive addresses. Loop unrolling particularly favors this data layout since consecutive references of a load/store instruction then occur at short time intervals. However, the main flaw of this concept is tag area: a line is split in several pieces, each assigned to a different bank. Thus, the line tag must be replicated as many times as the number of banks or the tags must have as many ports as the number of banks. To compensate for tag area increase, the line size must be increased.<sup>9</sup> This, in turn, may increase cache miss ratio and degrade overall performance.<sup>10</sup> In Figure 10, experiments were run using this scheme, see graph Adjusted Line Size. The baseline structure is a 1-bank 32-byte line cache, and the cache line size of an  $n$ -bank cache is  $32 \times n$  bytes. 4 processor-to-cache ports are used. Up to 4 banks, the miss ratio of several codes is decreased by the larger cache line while the miss ratio of other codes is not significantly increased. With 8 banks, poorer average miss ratio is compensated by fewer bank conflicts. Beyond that threshold, average cache miss ratio increases by 30% and word distribution eventually performs worse than line distribution.

## 6.4 Hiding Bank Conflicts

While optimizing data layout can remove bank conflicts, it is also possible to partially hide their effect. If the processor can issue requests without delay in case of bank conflicts, part of the delay is hidden. In vector processors, fifos are used to buffer conflicting requests to memory banks [RR95]. We applied the same technique to cache banks by inserting a small fifo above each bank. Thus, several requests can be sent simultaneously to the same bank, store requests can be committed earlier so that some load/store queue entries can be released, and processor-to-cache ports are more efficiently used over time. 4-entry fifos placed above each bank improve the baseline multi-banked configuration performance by 0.20 IPC in average, see Figure 10.

These fifos can be used to implement further optimizations. For multi-banked TLBs, Austin et al. [AS96] have

<sup>8</sup>The HP-8000 primary cache is located off-chip so chip area is less a concern.

<sup>9</sup>128-byte lines are used in the MIPS R8000 floating-point cache.

<sup>10</sup>The dual-banked floating-point cache of the MIPS R8000 is 1-Mbyte to 16-Mbyte large.

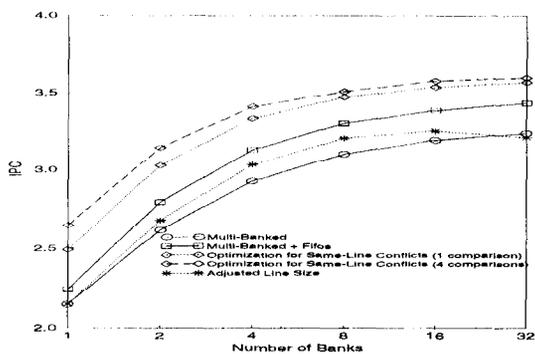


Figure 10: Performance of conflict hiding techniques.

proposed to compare pending TLB requests because of bank conflicts to the request currently processed by the bank. When this request completes, all matching pending requests use the result and complete simultaneously. We have evaluated a similar design for multi-banked caches using the fifo placed above each bank. One or several fifo entries can be compared to the address of the request in process. Wilson et al. [WOR96] have proposed a similar scheme for single-banked caches where multiple pending requests can be checked against the request in process. Such schemes can only remove conflicts between requests to the same cache line but, in Section 5, we show that such conflicts correspond to a significant share of all bank conflicts. The design cost essentially depends on the number of fifo entries that can be simultaneously compared to the request processed by the bank (1 up to 4 in our case). Performance for 1 and 4 simultaneous comparisons are indicated in Figure 10 (4 processor-to-cache ports). Hiding same-line conflicts brings an overall performance improvement of 0.15 IPC, i.e., about half the performance difference between a true 8-port cache and a 32-bank cache. Hiding bank conflicts reduces the number of banks necessary to achieve reasonable performance and thus lessens cache access time degradations.

## 7 A Cost/Performance Comparison

One of the main motivations for this work is the prohibitive cost of true multi-ported caches. After examining the performance of several alternative designs, we wish to show that, for a given transistor count, some of these alternatives provide better performance than true multi-porting. For that purpose, we use the area model for on-chip memories by Mulder et al. [MQF91] where each cache memory component cost is measured in *register-bit equivalent* (rbe) cells. This is a technology-independent metric corresponding to a 6-transistor static area cell with high bandwidth. A single such 6-transistor SRAM cell has a cost of 0.6 rbe. The rbe of control logic, comparators, sense amplifiers and all other basic blocks is also provided. Layout and aspect ratio are assumed to have no effect on area count. Though this is an approximation, we believe that the layout impact can be made similar for all proposed designs and thus can be ignored. Moreover, the area model is used to sort cache designs according to the area cost and not to compute an accurate area cost value.

In Figure 11 the relative cost/performance of most cache designs evaluated in this study is plotted. The x-axis corresponds to the relative cost with respect to baseline cache (1 port, 1 bank), and the y-axis to the IPC. The x-axis uses a logarithmic scale. Each category of design is associated with a character reported in the legend (P for multi-ported

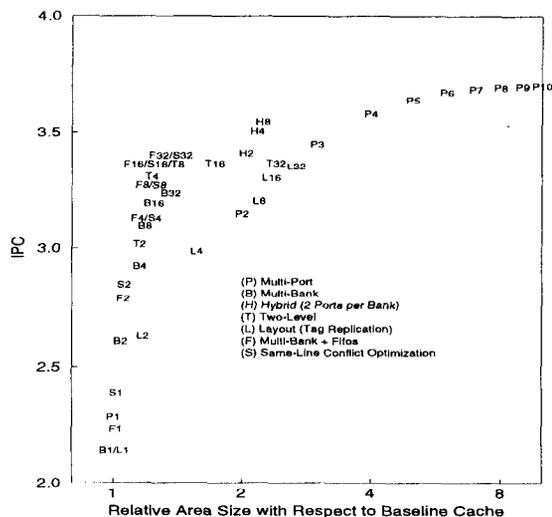


Figure 11: Cost/Performance tradeoffs between different cache designs.

for instance), and the number next to this character is the design configuration. This number corresponds to the number of banks for all designs, except for Multi-Port where it corresponds to the number of ports, and for Two-Level where it corresponds to the number of Level-0 ports.

95% of the maximal performance is achieved with an 8-bank cache using same-line optimization, see Section 6.4. On the other hand standard multi-bank caches usually do not represent a good cost/performance tradeoff. Hybrid designs perform well but for comparable performance their cost is usually two times that of a multi-bank design with conflict optimizations. None of the design studied can reach more than 95% of the performance of true multi-ported caches. However, many designs can achieve 75% or more of the maximal performance at a very small cost. For instance a 2-bank cache using fifos above each bank reaches 75% of the maximal performance with only a 10% area overhead. Other designs like two-level caches perform well but for a narrow interval of performance: to get 90% of the maximal performance, a two-level hierarchy with an 8-port Level-0 cache represents the best cost/performance tradeoff.

In Figure 11, it was assumed the same cycle time can be achieved for all designs. In [JNT96], some experiments introduce delay cycles and can be used to determine a more accurate order of each design.

## 8 Related Work

While many studies have dealt with improving memory hierarchy performance, most have focused on memory latency issues. This trend is now changing, with several recent studies dealing with cache bandwidth issues. Sohi et al. [SF91] evaluated non-blocking caches as a means to increase memory hierarchy bandwidth. They also suggest multi-ported, duplicate or inter-leaved caches as solutions to cache bandwidth issues, but do not evaluate these different solutions in details. Burger et al. [BKG96] have isolated the respective impact of latency and bandwidth on global memory hierarchy performance, concluding cache bandwidth is a major performance issue in current superscalar processors. They further outline that latency tolerating techniques can degrade cache bandwidth. Wilson et al. [WOR96] have proposed and evaluated several mechanisms to obtain more than one memory access per cycle from a single cache port

using buffering techniques to increasing port width. Their motivation also lays in the prohibitive cost of multiported caches, with respect to both area cost and cache access time. Finally, Austin et al. [AS96] examine in details several TLB designs for physically tagged caches that can achieve high bandwidth. Though most of these designs were also examined in the present study, conclusions diverge significantly because cache and TLB locality properties are different.

## 9 Conclusions and Future Work

In this paper, several techniques for improving data cache bandwidth have been evaluated. Because of the prohibitive cost of multi-ported SRAM cells, most designs based on this technique, i.e., true multi-ported caches, two-level caches with highly multi-ported first-level cache or hybrid designs (multi-bank + multi-port) are usually too costly for the performance obtained. Best solutions are based on multi-banked caches. Raw multi-banked caches usually perform poorly, but simple hardware enhancements to hide or remove conflicts can significantly improve overall performance, and the chip overhead for such add-ons is only 10-15% of the raw multi-banked cache cost. Besides deciding the best cost/performance tradeoff for achieving high data cache bandwidth, these results also provide a hierarchy of the different techniques for improving cache bandwidth, both with respect to performance (IPC) and chip area cost.

In this study, the influence of access time was modeled by increasing the cache pipeline length. We intend to use a time model to improve the accuracy of the comparison between the different cache designs. Ultimately, this comparison will be based on three parameters: IPC, cycle time and chip area cost.

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