

Fetch-Directed Instruction Prefetching Revisited

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Abstract—Prior work has observed that fetch-directed prefetching (FDIP) is highly effective at covering instruction cache misses. The key to FDIP’s effectiveness is having a sufficiently large BTB to accommodate the application’s branch working set. In this work, we introduce several optimizations that significantly extend the reach of the BTB within the available storage budget. Our optimizations target nearly every source of storage overhead in each BTB entry; namely, the tag, target address, and size fields.

We observe that while most dynamic branch instances have short offsets, a large number of branches has longer offsets or requires the use of full target addresses. Based on this insight, we break-up the BTB into multiple smaller BTBs, each storing offsets of different length. This enables a dramatic reduction in storage for target addresses. We further compress tags to 16 bits and avoid the use of the basic-block-oriented BTB advocated in prior FDIP variants. The latter optimization eliminates the need to store the basic block size in each BTB entry. Our final design, called FDIP-X, uses an ensemble of 4 BTBs and always outperforms conventional FDIP with a unified basic-block-oriented BTB for equal storage budgets.

I. INTRODUCTION

Contemporary server applications feature deeply layered software stacks and massive instruction working sets far exceeding the capacity of the instruction cache found in current processors. This causes a large number of front-end stall cycles due to frequent instruction cache misses, motivating research into front-end prefetching.

Existing research on instruction prefetching has introduced several schemes that use the BTB and the branch predictor to drive front-end prefetching. These schemes effectively allow the instruction address generation logic to run ahead of the actual fetch stream by predicting and resolving future branches, and issuing prefetches to the generated candidate addresses. This idea, called Fetch Directed Instruction Prefetching (FDIP), was pioneered by Reinman et al. [7]. Subsequent works extended FDIP to also prefetch into the branch target buffer (BTB) [6], and, most recently, introduced a compressed BTB design to maximize instruction footprint coverage with a limited BTB storage budget [5].

A key conclusion reached by recent front-end prefetching research is that FDIP is highly effective at covering L1-I misses, and – given a sufficiently large BTB – is competitive with storage-intensive front-end prefetchers such as temporal streaming [2]–[4]. The reason why the BTB plays a key role in FDIP and its derivatives is that the BTB is used to identify branches, which – if taken – redirect the control flow to a *target address*. For each branch tracked in the BTB, its target

address is also stored there. Thus, the number of branches tracked in BTB plays a key role in FDIP’s effectiveness because any branch evicted from the BTB (e.g., due to contention) may lower FDIP’s effectiveness by impeding its ability to identify control flow discontinuities.

However, naively increasing the BTB size to track more branches results in massive storage overhead. Therefore, this work focuses on optimizing the BTB entry organization to reduce its storage requirements; thus maximizing number of branches captured in a given storage budget.

Our proposed BTB organization leverages the insight that branch offset lengths are unequally distributed. Conditional branches have shorter offsets than unconditional branches, which require full target addresses. Moreover, within the conditional branch category, many targets are very close to the branch itself, requiring very few bits to encode the offset. Based on this insight, we partition the BTB into several smaller BTBs, each storing branches whose targets fall within a certain distance of the branch itself. Because the target field accounts for over half of each entry’s storage budget in a baseline BTB design (see Figure 2), this optimization brings significant storage savings.

We further observe that a full tag is not necessary to identify branches and, instead, use a shorter, hashed tag. Through empirical studies, we find that a 16-bit tag achieves a significant reduction in storage cost compared to the full 39-bit tag¹ with negligible performance impact.

Lastly, we eschew a basic-block-oriented BTB used in all prior FDIP-based designs and opt for a conventional BTB. This provides further storage savings by avoiding the need to track basic block size in each BTB entry. While this optimization carries no performance cost, in practice it may increase BTB bandwidth requirements and its power consumption.

Our final FDIP design, called *FDIP-X*, uses 4 separate BTBs with each containing only 16-bit hashed tags and no basic block size information. The 4 BTBs only differ in the number of bits they allocate to store branch target offsets. Our evaluation shows that FDIP-X significantly outperforms FDIP under stringent storage budget on both server and client traces. However, when the storage budget restriction are relaxed both designs perform similar.

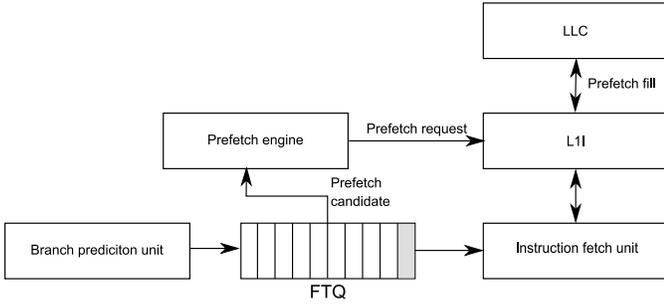


Fig. 1. The FDIP microarchitecture

II. FDIP BASICS

The baseline for this implementation is fetch directed instruction prefetch, FDIP [7]. FDIP, sketched in Figure 1, is an instruction prefetching method that predicts future control flow based on the information contained within the branch-prediction unit, encompassing the branch predictor, BTB, and return address stack. The key innovation pioneered by FDIP is the decoupling of the branch-prediction unit and the fetch engine via the *fetch target queue (FTQ)*. This decoupling allows the branch prediction unit to run ahead of the fetch engine and predict future control flow. The head of the FTQ, shaded in Figure 1, is the fetch point, while subsequent entries can be used for issuing prefetches as described below.

The original FDIP proposal relies on a basic block-oriented BTB, which stores the start and length of basic blocks rather than branch instruction addresses. Here, a basic block is defined as straight-line code ending in a branch instruction. On every cycle, the branch prediction unit predicts the next basic block and inserts it into the FTQ. In this way, the FTQ contains a stream of predicted basic blocks to be fetched. An FTQ entry contains information about the basic block corresponding to the current fetch entry. The head of the FTQ is consumed by the fetch engine which issues N demand-fetch requests where N is the fetch-width.

Since the non-head entries of the FTQ contain addresses that will be fetched by the fetch engine in the future, they represent ideal prefetch candidates. The prefetch engine is the component responsible for scanning the contents of the FTQ to look for new prefetch candidates. For every candidate discovered, the prefetch engine issues a prefetch probe, which checks if the L1-I block corresponding to the FTQ entry is present in the L1-I. If not, FDIP issues a prefetch request to bring the block from higher cache levels into the L1-I. Requests to the L1-I are prioritized such that demand fetches from the fetch engine are processed before prefetch probes.

III. FDIP-X

FDIP-X deploys several optimizations, all aimed at maximizing BTB reach. To motivate the design, we refer the reader to Figure 2, which shows a conventional BTB and the

¹Assuming a 48-bit virtual address space, 128-set BTB, and word (32-bit) aligned instructions.

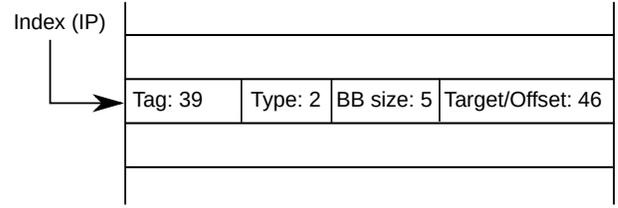


Fig. 2. The composition of entries in a basic-block-based BTB. The numbers are the number of bits used to encode each field.

composition of each entry. The following sections describe optimizations aimed at reducing or eliminating the storage cost of the three costliest fields making up each BTB entry: offset/target, tag, BB size.

A. Partitioned BTB

As Figure 2 shows, the single largest contributor to storage cost is the offset/target field, which stores the branch offset or the target address – up to 46 bits long. Our key insight is that most branches use offsets shorter than 46 bits. Figure 3 plots the distribution of offsets² in the branch working sets of our workload traces. The X-axis shows the number of bits required to encode the offset, while the Y-axis plots the frequency with which the given offset size occurs in each trace. Note that, in addition to bits for encoding the offset, an additional bit is required for the direction of the offset (forward/backward).

As the figure shows, shorts offsets dominate. Indeed, very few branches have an offset requiring more than 23 bits to encode. Note that the data includes both conditional branches and unconditional jumps, hence it comprehensively covers the full branch working set for these traces.

Based on the insights gleaned from Figure 3, we propose to partition a single logical BTB into multiple physically-separate BTBs. The BTBs differ amongst themselves only in the size of the offset/target field. When the branch prediction unit queries an address, all BTB partitions are queried in parallel, hence presenting a logical equivalent of a monolithic BTB.

Figure 4 shows the partitioning used in this implementation. We use four different BTBs with offset field sizes of 8-bits, 13-bits, 23-bits and 46-bits. Branches are allocated entries in one of these BTBs based on the minimum number of bits required to encode their target offsets. For example, if a branch requires 10 bits for encoding its target offset, it is allocated an entry in the BTB with target offset field of 13-bits.

We also leverage the insights from Figure 3 to size the different BTBs. For example, as very few branches require more than 23 bits to encode their target offsets, the BTB with 46-bit offset field is allocated the least number of entries. Also, the remaining three BTBs (8-, 13-, and 23-bit offset) are allocated similar number of entries, as the frequency of 0-8 bit, 9-13 bit, and 14-23 bit offsets is about same.

²In our traces, all the instructions are word (32-bit) aligned as the traces are generated on ARMv8. Therefore, the branch target offset is calculated as the distance to target in instructions rather than in bytes.

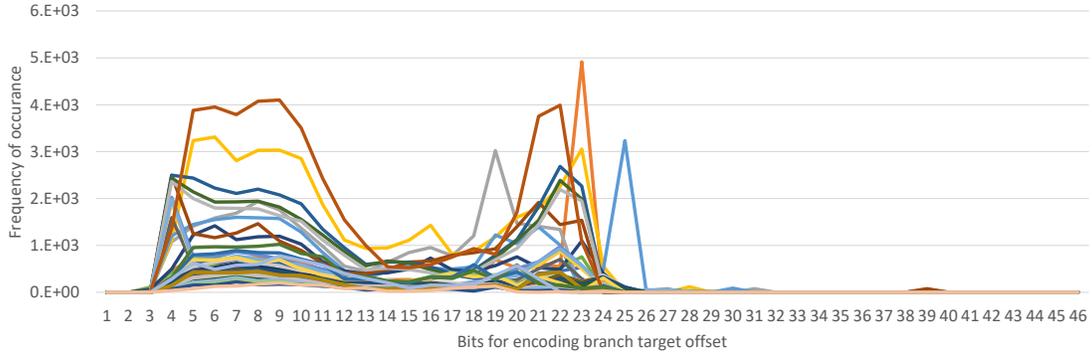


Fig. 3. Distribution of branch target offsets.

Tag: 16	Type: 2	Offset: 8
Tag: 16	Type: 2	Offset: 13
Tag: 16	Type: 2	Offset: 23
Tag: 16	Type: 2	Offset: 46

Fig. 4. The FDIP-X BTB organization.

B. Tag compression

Tags comprise the second largest source of storage overhead in each BTB entry, requiring 39 bits in the baseline design. To further reduce the BTB storage requirement, FDIP-X uses a compressed 16-bit tag in all of its BTBs. Our compression scheme maintains the 8 low-order bits same as in the full tag. The remaining bits of the full tag are folded, using the XOR operator, in blocks of 8 to get the 8 higher-order bits for the compressed tag. The performance impact of this scheme is negligible as the hashing function (folded XOR) preserves most of the entropy found in the high-order bits.

C. Block based or conventional BTB?

Prior incarnations of FDIP used some variant of a block-based BTB as described in Section II. The advantage of using such a BTB is that each entry contains the location of the next branch. This reduces the number of times the BTB has to be queried to locate the next branch, which saves BTB bandwidth and power. The disadvantage of a block-based BTB, however, is that each BTB entry needs to store the size of the associated basic block.

To reduce BTB storage requirements, FDIP-X deploys a conventional instruction-based BTB. Such a BTB is accessed with an instruction address and a hit in the BTB indicates that the address corresponds to a branch instruction. In addition,

BTB provides information about the branch type (conditional, call, etc.) and the target of the branch. If a branch is predicted to be taken (or in the case of an unconditional branches), address generation resumes from the branch target. If a branch is not found in a BTB, addresses continue to be generated sequentially.

The space saving of an instruction-based BTB (compared to a block-based one) is directly proportional to the number of entries in the BTB. For example, with a 8K-entry BTB, not needing the block size field (which requires 5 bits per entry) saves 5KB of storage. Furthermore, empirically, we could not observe a performance difference between the two BTB organizations.

D. Prefetch Throttling

A key design parameter of an instruction prefetcher is prefetch throttling. Uncontrolled wrong-path prefetching can be detrimental for performance as it wastes on-chip bandwidth and may evict useful instructions from the instruction cache.

FDIP-X throttles prefetches by maintaining a list of recently issued prefetches. This list is used to filter the prefetch requests by suppressing the prefetches for cache blocks that have been recently requested. FDIP-X uses a 10-entry fully-associative table to track recently issued prefetches.

In addition, the FTQ itself acts as a throttling mechanism. This is because no new addresses can be generated once the FTQ is full.

IV. EVALUATION

We evaluate FDIP-X on the traces and simulation infrastructure provided by IPC-1 [1]. First, we breakdown the BTB storage requirements, followed by a performance comparison between FDIP-X and FDIP for different BTB storage budgets. Our performance comparison also includes PIF [2], a state-of-the-art temporal stream prefetcher. Finally, we evaluate the performance impact of tag compression.

A. Storage break-down

The storage requirements for a conventional basic-block-oriented BTB for different number of BTB entries are presented in Table I assuming a 48-bit virtual address space.

TABLE I
STORAGE BREAKDOWN FOR BASIC-BLOCK-ORIENTED BTB

Entries	Organization	Entry size (bits)	Total (bytes)
1K	128-set, 8-way	92	11.5K
2K	256-set, 8-way	91	22.75K
4K	512-set, 8-way	90	45K
8K	1024-set, 8-way	89	89K
16K	2048-set, 8-way	88	176K
32K	4096-set, 8-way	87	348K

TABLE II
STORAGE BREAKDOWN FOR FDIP-X BTB

Budget (KB)	Distribution				Used (KB)
	BTB	Entry size	Entries	Storage	
11.5	8-bit offset	26-bit	768	2.44KB	10.06
	13-bit offset	31-bit	768	2.9KB	
	23-bit offset	41-bit	768	3.84KB	
	46-bit offset	64-bit	112	0.88KB	
22.75	8-bit offset	26-bit	1.5K	4.88KB	20.12
	13-bit offset	31-bit	1.5K	5.81KB	
	23-bit offset	41-bit	1.5K	7.68KB	
	46-bit offset	64-bit	224	1.75KB	
45	8-bit offset	26-bit	3K	9.75KB	40.25
	13-bit offset	31-bit	3K	11.63KB	
	23-bit offset	41-bit	3K	15.37KB	
	46-bit offset	64-bit	448	3.5KB	
89	8-bit offset	26-bit	6K	19.5KB	80.5
	13-bit offset	31-bit	6K	23.25KB	
	23-bit offset	41-bit	6K	30.75KB	
	46-bit offset	64-bit	896	7KB	
176	8-bit offset	26-bit	12K	39KB	161
	13-bit offset	31-bit	12K	46.5KB	
	23-bit offset	41-bit	12K	61.5KB	
	46-bit offset	64-bit	1.75K	14KB	
348	8-bit offset	26-bit	24K	78KB	322
	13-bit offset	31-bit	24K	93KB	
	23-bit offset	41-bit	24K	123KB	
	46-bit offset	64-bit	3.5K	28KB	

We increase the number of sets in the BTB to increase the number of entries while keeping the associativity same (8-way). Notice that the entry size reduces by one bit while doubling the number of entries. This is because the size of tag reduces as more bits are needed to index the BTB.

Table II presents the distribution of storage budget of a basic-block-oriented BTB among different BTBs (8-bit, 13-bit, 23-bit, and 46-bit offsets) in FDIP-X. Like basic-block-oriented BTB, we double the number of sets to double the BTB capacity while maintaining the associativity (6-way). Also notice that since the number of sets have to be a power of 2, we are not able to precisely match the storage of basic-block-oriented BTB and FDIP-X BTB. In fact, basic-block-oriented BTB gets a higher storage budget especially with more entries. Yet, FDIP-X BTBs together provide about 2.36x entries than basic-block-oriented BTB.

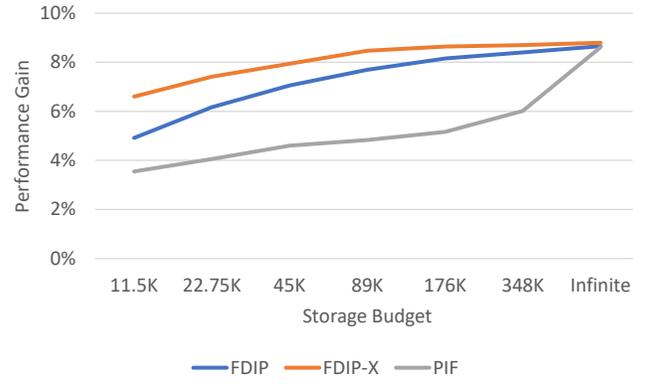


Fig. 5. FDIP, FDIP-X, and PIF performance gain, over no-prefetch baseline, across client traces. X-axis is storage budget for a 1K-, 2K-, 4K-, 8K-, 16K-, 32K-, and infinite-entry basic-block-oriented BTB.

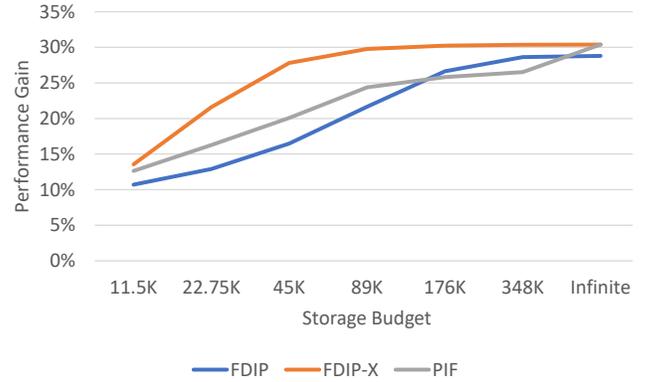


Fig. 6. FDIP, FDIP-X, and PIF performance gain, over no-prefetch baseline, across server traces. X-axis is storage budget for a 1K-, 2K-, 4K-, 8K-, 16K-, 32K-, and infinite-entry basic-block-oriented BTB.

B. Performance

Figures 5 and 6 compare the performance gains of FDIP, FDIP-X, and PIF, over a no-prefetch baseline, for different storage budgets across client and server traces respectively. The storage budgets correspond to 1K-, 2K-, 4K-, 8K-, 16K-, 32K-, and infinite-entry basic-block-oriented BTB.

As the figures show, FDIP-X comprehensively outperforms FDIP and PIF for practical storage budgets of few tens of kilobytes. The performance advantage of FDIP-X is especially visible on server traces as they put high pressure on instruction cache due to their massive instruction footprints. As Figure 6 shows FDIP-X needs only 45KB of storage to reach within 2.5% of the performance offered by an infinite BTB (27.8% vs 30.3%). In contrast, FDIP with its basic-block-oriented BTB requires nearly 200KB of storage to reach similar performance level. Similarly, PIF also requires significantly higher storage budget than FDIP-X to deliver similar performance in a practical storage budget range.

The figures also show that the client traces offer much less performance opportunity compared to the server traces due to their smaller instruction footprints. As a result, the performance gap between FDIP-X and FDIP narrows down

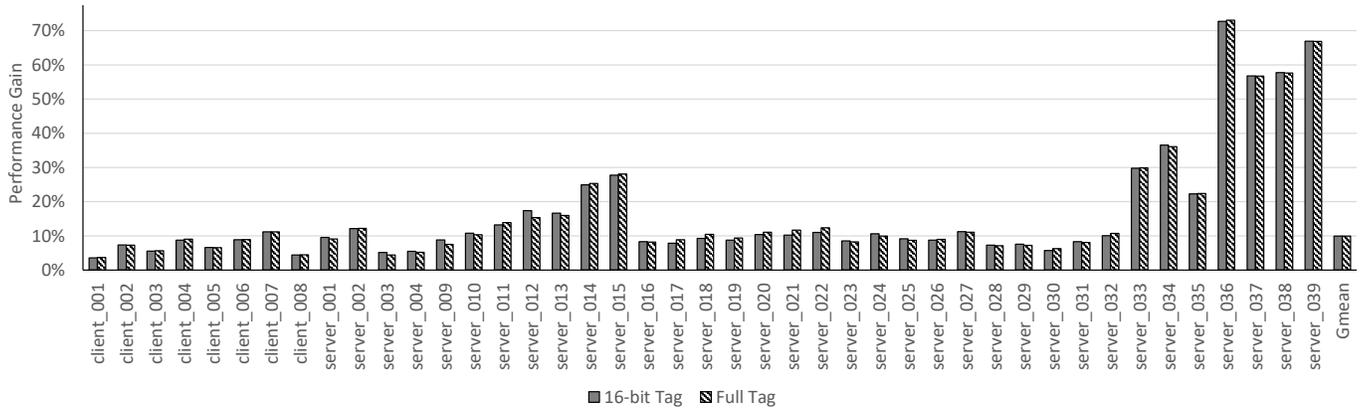


Fig. 7. FDIP-X performance gain with 16-bit tags and full tags in BTB.

quickly as the BTB storage budget increases. PIF, in contrast, falls significantly behind both FDIP-X and FDIP at practical storage budgets.

Figures 5 and 6 also show that, for storage budgets of up to 89KB, PIF outperforms FDIP on server traces; however, it lags behind FDIP on client traces. This is because the client workloads feature shorter streams (that are used by PIF for prefetching) which causes PIF to reset often and loose performance. Our analysis shows that PIF experiences 1.5x more resets on client traces than on the server ones.

C. Impact of tag compression

For assessing the performance loss due to compressed tags, we compare FDIP-X performance with 16-bit tags to full tags for the smallest BTB size. We choose the smallest BTB as it would suffer highest aliasing because of tag compression. As the results presented in Figure 7 show, full tags provide 9.96% performance gain over the baseline compared to 9.92% with compressed tags, a difference of only 0.04%. This result shows that our tag compression mechanism is able to preserve the entropy of the higher order bits.

Overall, the results presented in this section show that by partitioning the BTB into several smaller BTBs, compressing tags, and avoiding the use of a block-based BTB, FDIP-X drastically increases in number of entries in a given BTB storage budget. This enables FDIP-X to deliver much higher performance than the conventional FDIP especially with stringent storage budgets.

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