

HIGH PERFORMANCE BRANCH PREDICTORS FOR SOFT PROCESSORS

by

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Abstract

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Branch prediction has been extensively studied in the context of application specific custom logic (ASIC) implementations. Since the tradeoffs are different for reconfigurable logic, naïvely porting ASIC-based branch predictors to FPGAs may prove slow and/or resource-inefficient. Accordingly, this work studies the FPGA implementation of several commonly used branch predictor designs and does so in the context of simple pipelined processors, the most commonly used general purpose soft processor architecture due to its excellent balance of performance and resource cost. For this purpose, it assumes a pipelined processor implementation representative of Altera’s Nios II-f [4] and investigates the performance and resource cost of various branch predictors. The analysis confirms that existing designs are not efficient nor high-performing on reconfigurable logic. Accordingly, this work proposes FPGA-specific modifications that improve accuracy, resource cost, or both.

Acknowledgements

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Chapter 1

Introduction

Field Programmable Gate Arrays (FPGAs) are increasingly being used in embedded and other systems. Such designs often employ one or more embedded microprocessors, and there is a trend to migrate these microprocessors to the FPGA platform primarily for reducing costs. While these soft processors cannot typically match the performance of hard processors, soft processors are flexible allowing designers to implement the exact number of processors desired and to customize them to efficiently fit the application’s requirements.

Current commercial soft processors such as Altera’s Nios II [4] and Xilinx’s Microblaze [19] use in-order pipelines with five to six pipeline stages. These processors are often used for less computation-intensive applications such as system control tasks. To support more compute-intensive applications, a key performance improving technique is branch prediction. Without branch prediction, a branch has to execute completely before the processor can fetch the instructions that follow. Branch prediction eliminates these stalls by guessing the target address of branches. Current state-of-the-art branch prediction techniques, e.g., TAGE [2], rely on dynamically collected information about past branch behaviour. Such techniques have been proven to be very effective even in deeply pipelined, highly speculative, high-performance custom processor designs.

Branch prediction has been extensively studied, mostly in the context of application specific custom logic (ASIC) implementations. However, naïvely porting ASIC-based branch predictors to FPGAs results in slow and/or resource-inefficient implementations as the tradeoffs are different for reconfigurable compared to custom logic. Accordingly, this work studies the FPGA implementation of several commonly used and advanced branch predictor designs and does so in the context of simple pipelined processors, the most commonly used general purpose soft processor architecture due to its excellent balance of performance and resource cost. For this purpose, it assumes a pipelined processor implementation representative of Altera’s highest performing soft-processor Nios II-f and investigates the performance and resource cost of various branch predictors. The analysis confirms that existing designs are not efficient nor high-performing on reconfigurable logic. Accordingly, this work proposes FPGA-specific modifications that improve accuracy, resource cost, or both.

This work proposes branch predictors for Nios II-f. In more detail, this work makes the following contributions:

- (1) It studies the FPGA-implementation of Branch Target Buffers (BTB), including designs that fuse the BTB and the direction predictor and shows that, contrary to ASIC implementations, it is best to

avoid a BTB and instead to calculate branch target addresses on-the-fly.

(2) It studies the FPGA implementation of the three most commonly used branch direction predictors (DIR): bimodal [11], gshare, and gselect [13]. The analysis corroborates the results of past studies showing that gshare achieves the best accuracy among the three for practical table sizes, but also shows that unlike an ASIC implementation, frequency suffers with gshare on FPGAs. It proposes *gRselect*, an FPGA-friendly gselect implementation that uses a simple indexing scheme to outperform gshare by 11.4%.

(3) It studies the FPGA implementation of two advanced branch predictors: the Perceptron [10] and TAGE [2] predictors. It optimizes Perceptron’s maximum operating frequency by introducing (i) a complement weight table to simplify the multiplication that is otherwise necessary at prediction time, and (ii) Low Order Bit (LOB) Elimination for faster summation. It finds that TAGE is too slow for single-cycle access which negates its advantage in accuracy. Accordingly, this work proposes an overriding predictor O-TAGE-SC that uses a simple base predictor to provide an initial prediction in the first cycle which can be overridden in the second cycle should TAGE disagree with relatively high confidence. O-TAGE-SC achieves 5.2% better instruction throughput over gRselect.

The rest of the thesis is organized as follows. Chapter 2 reviews branch prediction basics and introduces the branch prediction schemes considered in this work. It also details the goals of this work. Chapter 3 discusses the design of a minimalistic branch predictor that uses a hardware budget on par with that of Nios II-f. Chapter 4 presents the study on two more advanced branch predictors: the Perceptron and TAGE predictors. Chapter 5 presents the experimental evaluation results and finally Chapter 6 concludes.

Chapter 2

Background and Goals

This chapter covers the background of branch prediction and the goal of this thesis.

2.1 Why Branch Prediction?

In modern microprocessors, instruction pipelining is a key feature to improve performances. At each cycle, a new instruction is read from the memory at the location indicated by the program counter (PC). The pipeline works ideally when there is no transfer of control, i.e., PC is incremented by a constant at each cycle to fetch the next instruction. However, when there is a transfer of control (e.g. a taken branch instruction), the next instruction to fetch is unknown at this point. The processor has to stall the pipeline to wait until the branch is resolved to fetch the correct instruction, hence severely impacts performance.

Branch prediction is a technique to improve performance by guessing the branch target (i.e. the next instruction) to allow the processor to run speculatively. The processor fetches the predicted target, and compares the prediction with the actual target when the branch is resolved several cycles later. If the prediction was correct, the processor fetched the correct instructions without stalling the pipeline, as if the instruction stream were not disrupted. On the other hand, if the prediction was incorrect, the processor fetched wrong instructions, and the intermediate results related to those wrong instructions has to be squashed, possibly with an extra maintenance penalty. Therefore, prediction accuracy is the key to high performance.

2.2 Branch Prediction Scheme

Branch prediction has two aspects, i.e., direction prediction and target prediction. Branch direction prediction predicts whether a branch instruction will be taken or not, while branch target prediction predicts the target instruction address if the branch is taken.

Fig. 2.1 shows the organization of a typical branch predictor comprising: (1) a direction predictor (DIR), (2) a Branch Target Buffer (BTB), and (3) a Return Address Stack (RAS).

The predictor operates in the fetch stage where it aims to predict the program counter (PC), i.e., the memory address, of the instruction to fetch in the next cycle using the current instruction's PC and other dynamically collected information. The DIR guesses whether the branch will be taken or

not. The BTB and the RAS guess the address for “predicted as taken” branches and function returns respectively. The multiplexer at the end selects based on the branch type and the direction prediction whether the target is the fall through address ($PC+4$ in Nios II), the target predicted by the BTB, or the target provided by the RAS. Since, at this point in time, the actual instruction is not available in a typical ASIC implementation, it is not directly possible to determine whether the instruction is a return, a branch, or some other instruction. Accordingly, a Selection Logic block uses either pre-decode information or a PC-based, dynamically populated lookup table to guess which target is best to use. With the latter scheme, when no entry exists in the lookup table, some default action is taken until the first time a branch is encountered. Once the branch executes, its type is stored in the lookup table where it serves to identify the branch type on subsequent encounters. This scheme is not perfectly accurate due to aliasing.

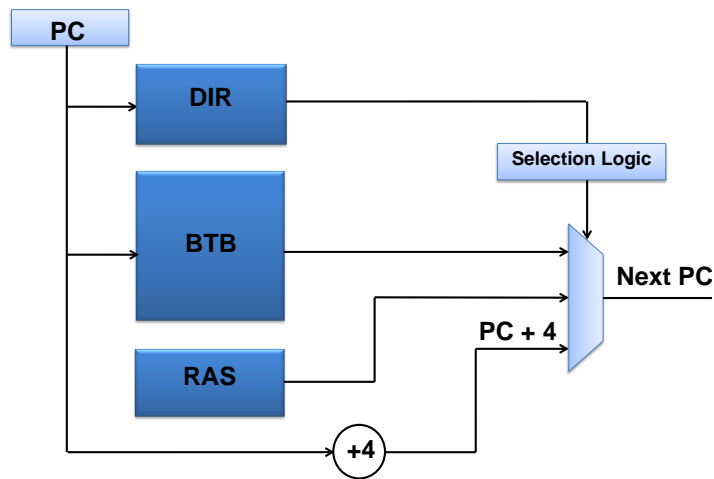


Figure 2.1: Canonical Branch Predictor.

2.3 Branch Target Predictors

Branch Target Prediction usually requires a Branch Target Buffer (BTB), a cache-like structure that records the addresses of the branches and their target addresses. If a branch is predicted to be taken and there is also a BTB hit, then the next PC is set to be the predicted target. A BTB can be set-associative to reduce aliasing.

Another common structure used for branch target prediction is the Return Address Stack (RAS), a stack-like structure that predicts the target address of function returns. When a call instruction executes, the return address of that call is pushed onto the RAS. When the processor executes the corresponding return instruction, RAS pops the return address and provides a prediction. The prediction is accurate as long as the RAS' size is less than the current call depth. Most modern processors have a shallow RAS because typical programs generally do not have very deep call depths.

2.4 Branch Direction Predictors

This section describes the branch direction predictors considered in this thesis.

2.5 Static Predictor

Static branch direction predictors statically predicts a branch to be taken or non-taken. This strategy is based on the observation that most branches are taken. The main weakness of static branch predictors is its inability to adapt to various applications. There are some other variations of static branch predictors such as “backward-taken forward-not-taken”. However, the improvements in accuracy is not significant. As the pipeline in modern processors becomes deeper, the misprediction penalties increases, which necessitates more accurate *dynamic* branch predictors.

2.5.1 Bimodal, Gshare and Gselect Predictor

Bimodal, Gshare and Gselect [13] are some of the simplest dynamic direction prediction schemes. Fig. 2.2 shows the organization of these three predictors. Each of these predictors has a *Pattern History Table* (PHT). The entries of a PHT are called *2-bit saturating counters*, which are used to record the directions of the previously seen branches. The 2-bit saturating counters are incremented/decremented when their corresponding branch is taken/not taken, and the high order bit is used as direction prediction.

The PHT in bimodal is indexed by selected bits of PC. Since not all bits of PC are used to index the PHT, multiple different branches can be assigned to the same 2-bit saturating counter. This *aliasing* can be destructive to the direction records, hence degrades performance.

Gshare and gselect utilize a structure called a *Global History Register* (GHR). The GHR is a shift register that stores recently resolved branch directions. The only difference between bimodal, gshare and gselect is the indexing of the PHTs. Bimodal uses partial PC, gshare uses partial PC XORed with GHR, and gselect uses partial PC concatenated with GHR. Gshare and gselect has better accuracy over bimodal because it reduces aliasing by correlating local history (i.e. PC) and global history (i.e. GHR).

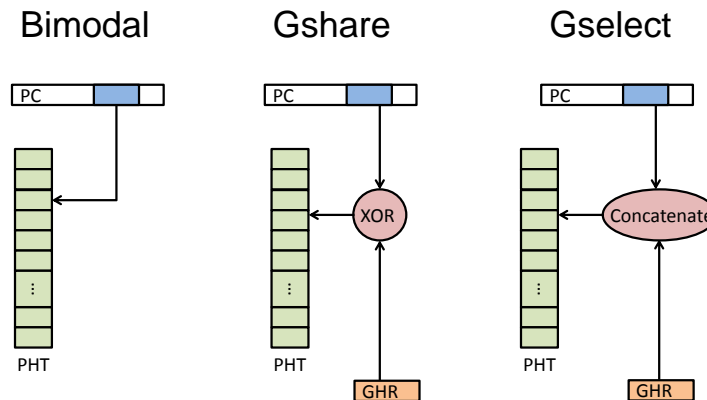


Figure 2.2: Bimodal, Gshare and Gselect.

2.5.2 Perceptron Predictor

The Perceptron predictor uses vectors of weights (i.e., perceptrons) to represent correlations among branch instructions [10]. Fig. 2.3 shows the structure of a Perceptron predictor. It produces a prediction through the following steps: (1) A *perceptron* is read from the table. (2) The weights are multiplied with factors chosen based on the the corresponding global history bits. The weights are 1 for taken and -1 for not-taken. (3) The resulting products are summed up and a prediction is made based on the sign of the result; predict taken if the sum is positive, and not-taken otherwise. Formally, for a Perceptron predictor using h history bits G_i where $i = 1 \dots h$, each weight vector has h weights $w_0 \dots h$, where the bias constant $w_0 = 1$. The predictor has to calculate $y = w_0 + \sum_{i=1}^h G_i w_i$, and predict taken if y is positive and not-taken otherwise.

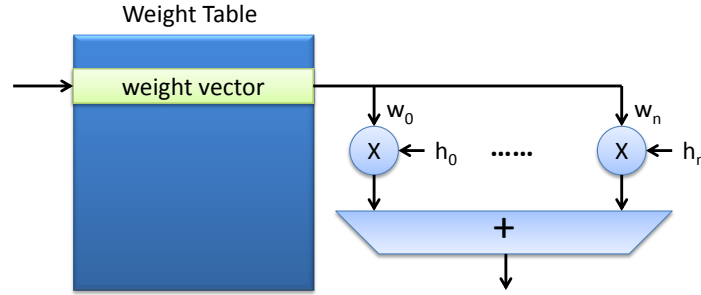


Figure 2.3: The preceptron branch predictor.

2.5.3 Tagged Geometric History Length Branch Predictor (TAGE)

The TAGE predictor features a bimodal predictor as a base predictor T_0 to provide a basic prediction and a set of M tagged predictor components T_i [2]. These tagged predictor components T_i , where $1 \leq i \leq M$, are indexed with hash functions of the branch address and the global branch/path history of various lengths. The global history lengths used for computing the indexing functions for tables T_i form a geometric series, i.e., $L(i) = (int)(\alpha^{i-1} \times L(1) + 0.5)$. TAGE achieves its high accuracy by utilizing very long history lengths judiciously. Essentially, the base predictor captures the bulk of branches that tend to be biased, while the remaining components capture exceptions by recording specific history events that lead to exceptions that foil the base predictor. Fig. 2.4 shows a 5-component TAGE predictor. Each table entry has a 3-bit saturating counter *ctr* for the prediction result, a *tag*, and a 2-bit useful counter *u*. The table indices are produced by hashing the PC and the global history using different lengths per table $L(i)$. All tables are accessed in parallel and each table provides a valid prediction only on a tag match and provided that the corresponding useful counter is saturated. The final prediction comes from the matching tagged predictor component that uses the longest history.

2.6 Field Programmable Gate Arrays (FPGAs) and Soft Processors

Field Programmable Gate Arrays (FPGAs) are chips that can be reconfigured by designers. Modern FPGAs such as Altera's Stratix IV [5] have large number of logic blocks connected by reconfigurable

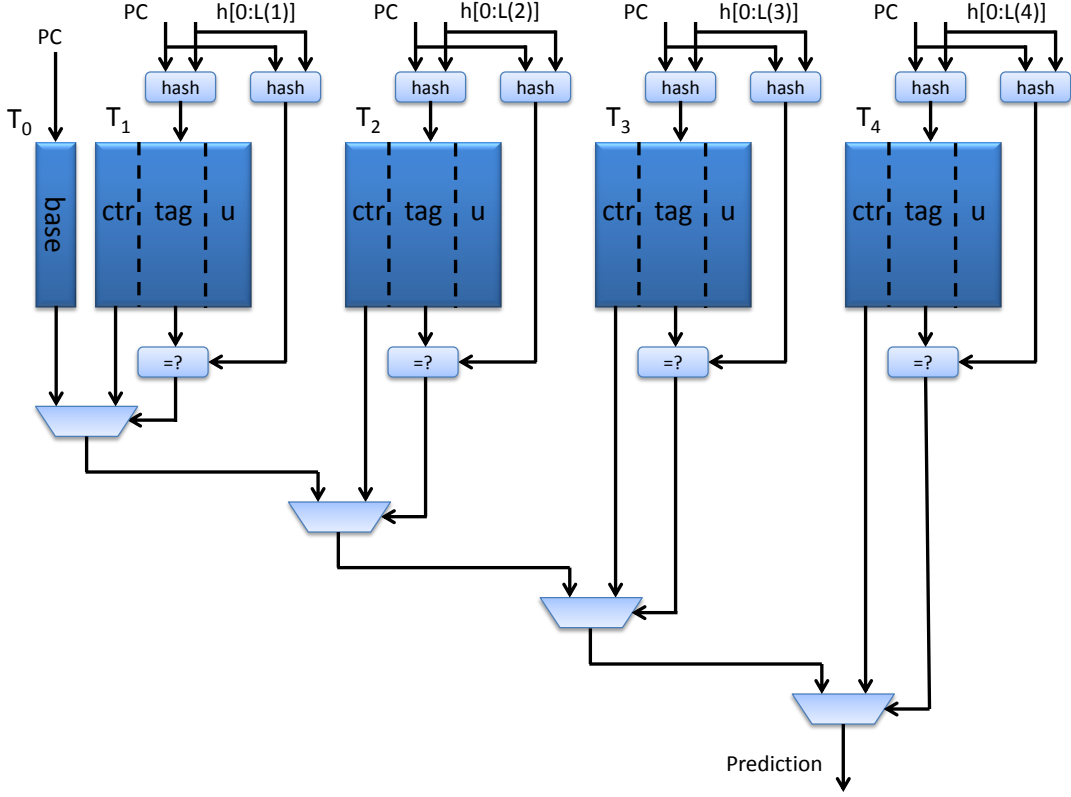


Figure 2.4: A 5-component TAGE branch predictor.

interconnects. The logic blocks usually consist of Look-up Tables (LUTs), registers and Block RAMs (BRAMs) etc. Designers program digital circuits with Hardware Description Languages (HDLs) such as Verilog and VHDL, and then use CAD tools provided by the FPGA vendors to synthesize the design.

FPGAs can be reconfigured to fit specific requirements of various applications, therefore they are popular choices for hardware acceleration. Due to the increasing cost and time of designing ASIC, an increasing number of embedded systems are being built using FPGA platforms [20]. These systems usually contain one or more embedded processors, necessitates high-performance FPGAs-based *soft processors*.

Since an FPGA platform is significantly different than ASIC, hard and soft processors have distinct design tradeoffs. Commercial soft processors such as Alteras's Nios II-f [8] and Xilinx's MicroBlaze [19] usually have shallow pipelines, mostly because the relative speed gap between memory and logic is much smaller than on ASIC. Accordingly, branch predictor designs for soft processors also have to be re-evaluated.

2.7 Design Goals

This work aims to design branch predictors that (1) operate at a high operating frequency while (2) achieving high accuracy so that they improve execution performance.

This work proposes a minimalistic branch predictor for Altera's highest performing soft-processor Nios II-f. Since Nios II-f uses three BRAMs in total and only one BRAM is used for branch prediction [8],

the proposed minimalistic branch predictor has a limited resource budget of one BRAM; each additional BRAM would represent a more than 1/3 overhead in terms of BRAM resources. The design of the minimalistic predictor considers the most commonly used direction predictors, bimodal, gshare and gselect. These predictors use a single lookup table and map relatively well onto a single BRAM.

This work also implements more advanced Perceptron and TAGE predictors. As Chapter 4 will show, a single-cycle TAGE is prohibitively slow. Therefore, this work considers an overriding TAGE predictor [12] that produces a base prediction in one cycle while overriding that decision with a better prediction in the second cycle if necessary. Perceptron and TAGE both require large tables. Accordingly, this work investigates how their accuracy and latency vary with the amount of hardware resources they are allowed to use.

Chapter 3

The Minimalistic FPGA-Friendly Branch Predictors

This chapter discusses the architecture of the various minimalistic FPGA-friendly branch predictors considered. Section 3.1 discusses target prediction, while Section 3.2 discusses direction prediction.

3.1 Target Prediction

A conventional method to predict branch targets is to use Branch Target Buffers (BTB). A BTB is a table that caches branch target addresses. When a branch executes for the first time, the BTB stores the target address so that it can be used on subsequent encounters of the branch. Ideally, the BTB would be large enough so that each branch can use a separate entry. In a practical implementation, however, aliasing will occur reducing prediction accuracy.

The simplest BTB design does not use an address tag per entry and directly predicts the target address for all instructions. Not using a tag results in a fast design that uses one direct SRAM lookup. In addition, not filtering non-branch instructions is desirable since at the time of access the instruction opcode is not available. Unfortunately, as Section 5.2 shows, when all instructions use the BTB, high destructive aliasing results in poor accuracy. To reduce aliasing, a small decode logic can prevent non-branches from updating the BTB. However, as Section ?? shows, while this solution increases target prediction accuracy by 30%, the additional logic reduces the maximum frequency by 35%. An alternative is to calculate the target address during the fetch cycle.

3.1.1 Target Address Pre-calculation

ASIC processor implementations use a BTB since the cache latency dominates the clock cycle leaving no room for further action. This is not true in an FPGA implementation where memory is generally faster than logic. This creates an opportunity to pre-calculate the target address for branches and thus eliminate the BTB. In this scheme the processor fetches the instruction from the cache and then, during the same cycle, calculates the instruction's taken address. As an added benefit, address pre-calculation may improve accuracy since, if possible, it is always correct. Unfortunately, it is not possible to pre-calculate the target address for all branches. The Nios II ISA includes two types of branches: *direct*

and *indirect*. The target of a direct branch can be calculated using the current PC and an offset that is embedded in the instruction. Indirect branch targets are read from the register file.

This work proposes enhancing target prediction with *Full Address Calculation* (FAC), which as Fig. 3.1 shows, calculates the target address for all direct branches and uses a BTB or some other storage for indirect branches. A selection logic identifies direct branches which can benefit from FAC. FAC selects among four possible addresses depending on the branch type. The Nios II ISA supports two schemes for direct branch target addresses, one uses a 16-bit offset (IMM16) and the other a 26-bit range (IMM26). Combined with the fall-through address (i.e., $PC + 4$) and the predicted address coming from the BTB, BTB+FAC uses a four-way multiplexer to select among these four possible addresses. Unfortunately, this multiplexer falls into the critical path.

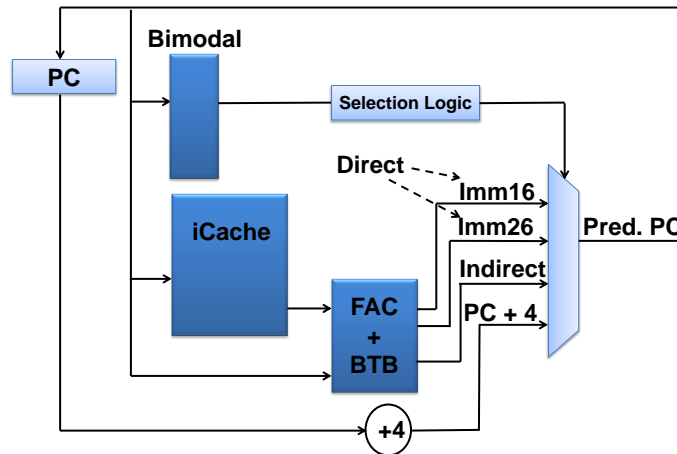


Figure 3.1: BTB with Full Address Calculation.

A lower cost and faster alternative to FAC is *Partial Address Calculation* (PAC) which relies on typical program behavior to reduce the number of choices for the final address multiplexer. Fig. 3.2 reports the relative frequency of the various branch types (see Section 5.1 for the methodology). Since IMM26 branches are far less frequent than IMM16 branches, PAC precalculates IMM16 branches and uses the BTB for IMM26 and indirect branches.

3.1.2 Return Address Stack

The RAS is a hardware, stack-like structure that accurately predicts the target address of function returns. When a call instruction executes, it also pushes its return address onto the RAS. Upon fetching a return instruction, the branch predictor can pop the top value from the RAS accurately predicting the return address. As long as the RAS has enough entries, it will accurately predict all return instructions. Since the call depth of typical workloads is not deep, virtually all high performance processors incorporate a shallow RAS. For the workloads studied a 16-entry RAS proves sufficient. The RAS for a simple pipeline is simple to implement on an FPGA. Deeper pipelines may require support for speculative RAS insertions and deletions complicating its design.

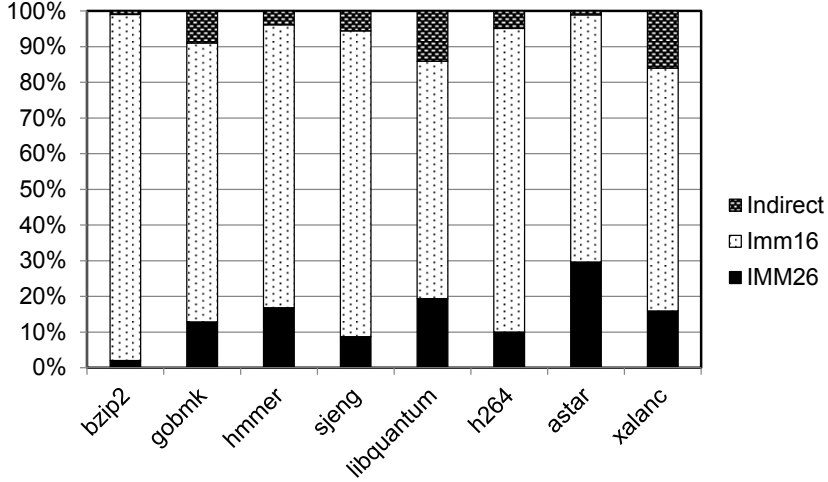


Figure 3.2: Branch Target Type Distribution.

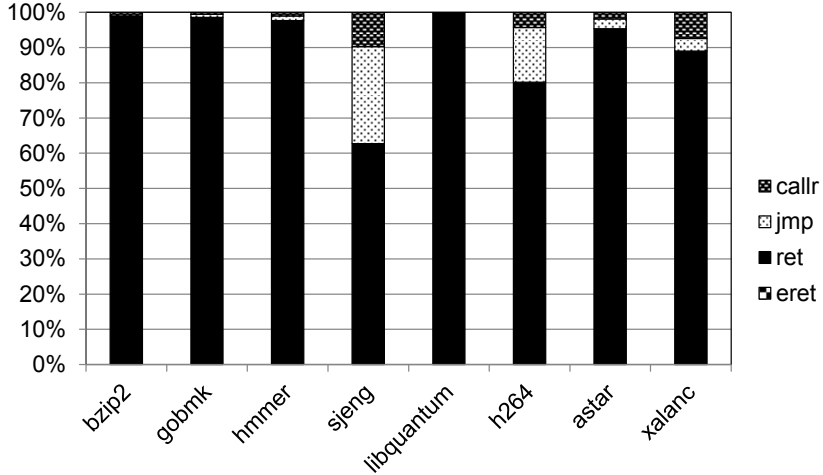


Figure 3.3: Indirect Branch Instruction Type Distribution.

3.1.3 Eliminating the BTB

Fig. 3.3 shows that for the workloads studied in this work, 97% of the indirect branches are returns (other workloads, e.g., those using virtual functions, may behave differently). Once a RAS is included along with FAC, the BTB ends up being used for only less than 1% of all branches. Accordingly, the BTB can be eliminated, and instead use a static, not-taken predictor for all indirect branches other than returns. Section 5.2 shows that removing the BTB in the presence of RAS reduces accuracy negligibly. Section 3.3.1 explains that lower-level FPGA related considerations also favor eliminating the BTB.

3.2 Direction Prediction

A bimodal branch direction predictor is a table of two-bit saturating counters that is indexed with a portion of the PC [11]. The counters are updated up or down depending on whether the branch is

taken or not respectively. The lower bit provides hysteresis to changes while the upper bit provides the prediction. As Section ?? corroborates, increasing the number of bimodal entries does not proportionally improve accuracy. Eventually, using a larger bimodal ceases to provide any improvement since bimodal is fundamentally limited on the branch prediction patterns it can predict.

Gshare is a pattern-based predictor which uses a combination of the PC and a global direction history register (GHR) to index the counter table [13]. GHR stores the direction of the last few branches in a bit vector. Each GHR bit stores the direction (taken or not) of a previous branch. Section ?? shows that gshare is far more accurate than bimodal. However, as Section 3.3 explains, latency suffers with gshare due to its more complex indexing scheme. Gselect, an alternative to gshare, indexes the counter table using a simple concatenation of the GHR and the PC [13]. For practical table sizes, gshare proves more accurate than gselect. Section 3.3.2 explains that with proper modification, gselect proves faster than gshare on an FPGA while sacrificing little in accuracy.

3.3 FPGA implementation optimizations

This section discusses additional FPGA-specific implementation optimizations. While this section assumes a modern, Altera FPGA, the optimizations presented should be broadly applicable.

3.3.1 Eliminating the BTB

As Section 2.7 explained, this work aims to use one M9K BRAM. An M9K BRAM can be configured as wide as 36 bits with 256 rows [6], and it can be used to implement a fused BTB and direction predictor. Specifically, each BRAM row can store one BTB entry along with up to three direction prediction entries for a total of 768 direction entries and 256 target entries. This fused BTB+DIR predictor works well with a bimodal DIR. The PC indexes a row which contains a single target prediction entry and up to three direction prediction entries. Another portion of the PC selects one of these direction prediction entries. The target is used only from taken branches.

Unfortunately, it is not possible to use one BRAM for both a BTB and the most accurate of the direction predictors considered, gshare. There are two reasons why: (1) gshare uses a different indexing scheme than the BTB, and (2) there is a limited number of ports per BRAM [6]. As Section 3.3.1 discussed, the BTB can be eliminated when address precalculation and a RAS are used. Eliminating the BTB frees up the entire BRAM for direction prediction.

3.3.2 FPGA-Friendly Direction Predictor Indexing

This section investigates which of the three branch direction predictors is best to use on an FPGA. Focusing just on accuracy gshare would be the best. However, performance is not the highest with gshare since its indexing scheme results in low clock frequency. Fig. 3.1 depicts why the predictor's indexing scheme, when implemented on an FPGA, falls into the critical path. At every clock cycle the predicted PC is used to index the direction predictor table for the next instruction. Since BRAMs are synchronous, their index must arrive before the clock edge and thus it cannot be a registered signal of the Predicted PC [6]. Moreover, the setup time for the BRAM is longer than that of simple registers. Therefore, the entire path starting from the BRAM data output, through the prediction logic and back into the lookup address of the BRAM forms the critical path. This is especially a concern with gshare

that uses the exclusive-or of the global history register (GHR) with Predicted PC to index the BRAM. This extra XOR logic prolongs the critical path, reducing the operating frequency.

Contrary to gshare, gselect has a simpler indexing scheme. Specifically, gselect uses a simple *concatenation* of the GHR with Predicted PC as index. Not only is gselect’s indexing fast, but it can also be tailored to map well onto FPGAs. This work proposes *gRselect* which breaks the BRAM-to-BRAM critical path by breaking the BRAM access into two parts the first of which does not need to be “predicted PC”. It uses GHR, which is a registered signal, to index the BRAM to retrieve one wide row of counters. Fig. 3.4 shows the gRselect scheme in more detail.

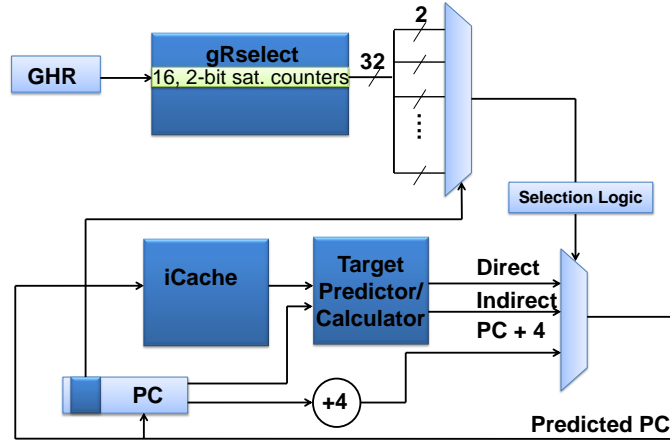


Figure 3.4: FAC with gRselect.

3.3.3 Instruction Decoding

To be able to select the appropriate target, the predictor needs to determine whether an instruction is a branch and if so, what kind of branch it is. This information is needed to select the corresponding predicted target through the output multiplexer. However, the decode logic lies in the critical path. To eliminate this delay, the predictor pre-decodes the instructions prior to installing them in the instruction cache. The pre-decode information is stored along with the instruction. This is similar to typical ASIC implementations.

Chapter 4

The Advanced FPGA-Friendly Branch Predictors

Chapter 3 proposes gRselect as the best performing minimalistic design that has a hardware budget limited to one M9K BRAM. In this chapter, we relax the constraint on hardware budget and consider more advanced and accurate branch prediction technologies to achieve better performance.

4.1 Perceptron Implementation

Section 2.5.2 explained that the Perceptron predictor maintains vectors of weights in a table and produces a prediction through three steps. Each of these steps poses difficulties to map to an FPGA substrate. The rest of this section addresses these problems.

Perceptron Table Organization

Each weight in a perceptron is typically 8-bit wide, and Perceptron predictors usually use at least a 12-bit global history [10]. The depth of the table, on the other hand, tends to be relatively shallow (e.g., 64 entries for 1KB hardware budget). This requires a very wide but shallow memory, which does not map well to BRAMs on FPGAs. For example, the widest configuration of a M9K BRAM on Altera Stratix IV is 36-bit wide times 1K entries [6]. If we implement the 1KB Perceptron as proposed by Jiménez et al. [10], which uses 96-bit wide perceptrons with 12-bit global history, it will result in a huge resource inefficiency as shown in Fig 4.1. Stratix IV chips have another larger but slower and fewer M144K BRAM on Stratix IV chips [6], which can be configured as wide as 72-bit times 2K entries, clearly the inefficiency problem persists and it would impact maximum operating frequency.

Since typically the Perceptron table does not require large storage space, the proposed Perceptron implementation uses MLABs as storage, which are fast fine-grain distributed memory resources. Since 50% of all LABs can be configured as MLAB on Altera Stratix IV devices, using MLABs does not introduce routing difficulty.

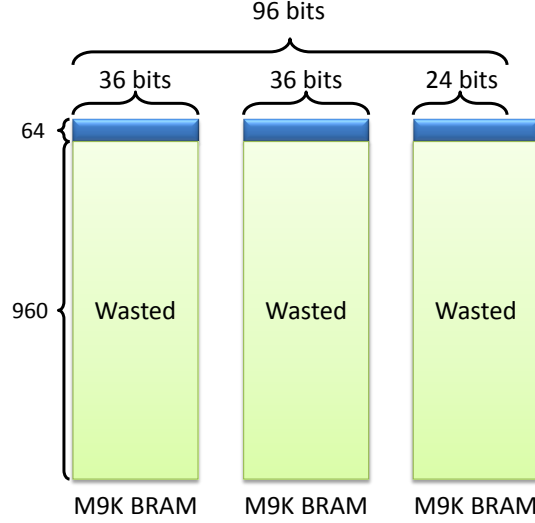


Figure 4.1: Inefficient use of M9K BRAMs to implement wide but shallow perceptron tables.

Multiplication

The multiplication stage calculates the products of weights in a perceptron and their global direction histories. Since the value of the global direction history can only be either 1 or -1, the “multiplication” degenerates to two cases, i.e., each product can either be the true form or the 2’s complement (i.e., negative) form of each weight. A straightforward implementation calculates the negative of each weight and uses a mux to select, using the corresponding global history bit, the appropriate result, as Fig. 4.2(a) shows. To improve operating frequency, when updating the perceptron in the execution stage where the branch is resolved, both positive and negative forms of the updated weight can be pre-calculated, and the negatives can be stored on a complement perceptron table. This way, the multiplication stage at prediction time requires only a 2-to-1 mux, as Fig. 4.2(b) shows. This optimization trade offs increased resources (it requires extra storage for the negative weights) for improved speed.

Adder Tree

The adder tree sums the products from the multiplication stage. As Section ?? will show, a global history of at least 16 bits has to be used to achieve sufficient accuracy. Implementing a 16-to-1 adder tree for 8-bit integers naïvely degrades maximum frequency severely. The maximum frequency has to be improved for Perceptron to be practical.

This work employs *Low Order Bit (LOB) Elimination* that was proposed by Aasaraai et al. [3]. LOB elimination ignores the Low Order Bits (LOBs) of each weight and only use the High Order Bits (HOBs) during prediction, while still using all the bits for updates. Section ?? shows that eliminating five LOB bits reduces accuracy by less than 1% compared to using all eight bits, but summing fewer bits results in 14.6% higher maximum frequency. Section ?? will show that using three HOB for prediction achieves the best overall performance.

Cadenas et al. [9] proposed a method to rearrange the weights stored in the table in order to reduce the number of layers of the adder tree. Assuming a Perceptron predictor uses h history bits, instead of storing h weights w_i where $i = 1 \dots h$, a new form of weights \tilde{w}_i : $\tilde{w}_i = -w_i + w_{i+1}$; $\tilde{w}_{i+1} = -w_i - w_{i+1}$, for $i = 1, 3, \dots, h - 1$ is used. The perceptron prediction can now be computed by $y = w_0 +$

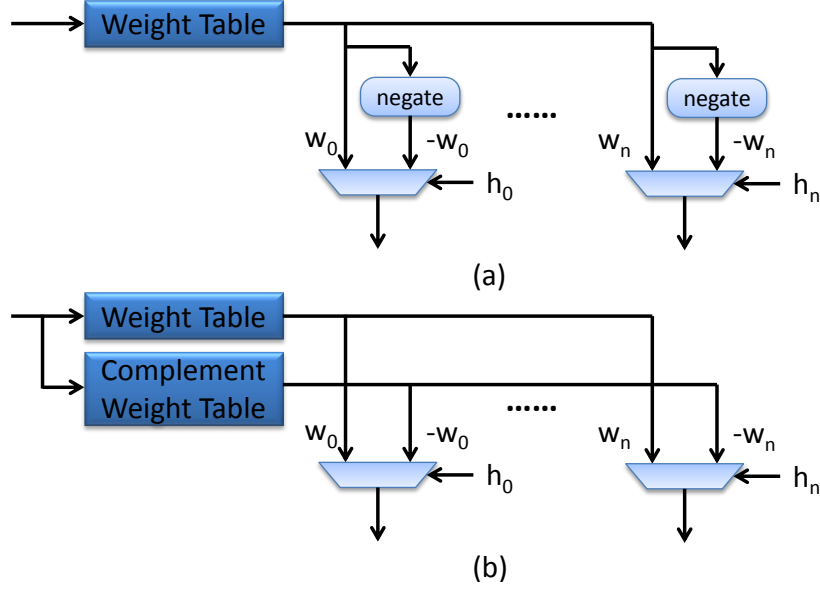


Figure 4.2: Perceptron multiplication implementation.

$\sum_{i=1}^{h/2} (-G_{2i-1}) \tilde{w}_{2i+G_{2i-1}G_{2i}}$. This work applies this new arrangement because it pushes part of the calculation to the less time critical update logic of the Perceptron predictor so that only $h/2$ additions have to be performed, hence reduces the number of adders required by 50%.

Using fast adders such as carry-lookahead adders does not help to reduce the adder tree latency. This is because that the problem is not summing a few very wide numbers, but many narrow numbers. Most of the latency comes from going through layers of adders rather than propagating the carry bits. To further improve maximum frequency, this work adapts the implementation of a Wallace Tree [17]. A Wallace tree is a hardware implementation of a digital circuit that efficiently sums the partial products when multiplying two integers, which is similar to the situation that a Perceptron predictor is facing. The Wallace tree implementation proves to be 10.5% faster than a naïve binary reduction tree implementation.

4.2 TAGE Implementation

Section ?? shows that TAGE is the most accurate amongst all the direction predictors considered in this work when they use the same hardware budget. However, TAGE uses multiple tables with tagged entries that require comparator driven logic which does not map well onto FPGAs. Section ?? shows that the maximum frequency slowdown of TAGE is not amortized by the resulting accuracy gains. Accordingly, TAGE is best used as an overriding predictor.

The critical path of TAGE is as follows: (1) It performs an elaborate PC-based hashing to generate multiple table indices one per table. (2) It accesses the tables and in parallel compares the tags of the read entries to determine whether they match. (3) Finally each decision has to pass through cascaded layers of multiplexers to select the longest matching prediction. Although the latency of these operations is high, the path can be easily pipelined to achieve much higher operating frequency. Based on this observation, this work explores an overriding branch predictor implementation using TAGE.

Overriding branch prediction is a technique to leverage the benefits of both fast but less accurate, and slow but more accurate predictors. This technique has been used commercially, e.g., in the Alpha

EV8 microprocessors [15]. In an overriding predictor, a faster but less accurate base predictor makes a base prediction quickly, and then a slower but more accurate predictor overrides that decision if it disagrees with the base prediction.

In this work, the base predictor is the simple bimodal predictor included in TAGE itself, i.e., T_0 in Fig. 2.4. The bimodal predictor provides a base prediction in the first cycle, and TAGE provides a prediction at the second cycle. Section ?? and ?? show that the overriding TAGE outperforms all the other branch prediction schemes in terms of both accuracy and maximum frequency.

4.3 Branch Target Predictor

Chapter 3 has shown that when using one M9K BRAM – a hardware budget on par with that of Nios II-f – eliminating the BTB and using *Full Address Calculation* (FAC) together with a RAS results in better performance [18]. It has also shown that direct branches and returns comprise over 99.8% of all branches. Implementing FAC with RAS can cover these branches with 100% accuracy, therefore having a BTB to cover all branches results in negligible improvement in target prediction accuracy.

Since, this chapter investigates how branch prediction accuracy can improve when additional hardware resources are used, adding a BTB for better target prediction coverage could improve target prediction accuracy. Accordingly, we consider reintroducing a BTB. However, simulations show that accuracy is still better without a BTB. This is because when the target predictor only has FAC and RAS, it never predicts indirect branches that are not returns because it is not capable to do so. As a result, the destructive aliasing in the *direction* predictor is alleviated because fewer branches are being predicted. Based on this observation, the Perceptron and TAGE predictors in this chapter also uses FAC with a 16-entry RAS as the branch target predictor.

Chapter 5

Evaluation

This section presents the experimental evaluation of the proposed branch predictors. Section 5.1 details the experimental methodology. Section 5.2 evaluates the accuracy of target address schemes showing that using a RAS with FAC is best. Sections 5.3 and 5.5 reports the accuracy of various direction predictors, their resource usage and maximum operating frequency, and finally the overall performance of the minimalistic and the advance branch predictors respectively.

5.1 Methodology

To compare the predictors this work measures: (1) Accuracy as Mispredictions Per Kilo Instructions (MPKI), which has been shown to correlate better with performance compared to prediction accuracy alone. (2) The Instruction Per Cycle (IPC) instruction execution rate, a frequency agnostic metric that better reflects the accuracy of each predictor factoring away their latency, (3) Instructions Per Second (IPS), a true measure of performance which takes the operating frequency into account, (4) Operating frequency, and (5) Resource usage.

Simulation measures MPKI and IPC using a custom, cycle-accurate, full-system Nios II simulator. The simulator boots ucLinux [1], and runs a representative subset of SPEC CPU2006 integer benchmarks with reference inputs [16].

The evaluation of the minimalistic predictor uses a baseline predictor (BASE) with a fused BTB and bimodal, as discussed in Section 3.3.1 both with 256 entries. BASE does not decode instructions and thus uses the BTB and the bimodal for all instructions.

The baseline predictors considered for the Perceptron and TAGE predictors are: (1) bimodal, (2) gshare and (3) gRselect.

All designs were implemented in Verilog and synthesized using Quartus II 13.0 on a Stratix IV EP4SE230F29C2 chip in order to measure their maximum clock frequency and area cost. The maximum frequency is reported as the average maximum clock frequency of five placement and routing passes with different random seeds. Area usage is reported in terms of ALUTs used.

5.2 Target Prediction

This section measures the accuracy of target predictors. by using the baseline direction predictor while considering combinations of BTB, PAC, FAC, RAS, and larger BTBs. Fig. 5.1 reports the reduction in target address mispredictions when using various target prediction mechanisms compared to BASE. Using a decode logic to filter non-branches from the BTB (BTB-256) reduces mispredictions by 30%. However, increasing the BTB size to 512 (BTB-512) or 1024 (BTB-1024) entries does not improve accuracy noticeably. In the rest of this section, all BTB configurations except for BASE use instruction filtering.

Using PAC or FAC with a 256-entry BTB reduces mispredictions by 81% and 90% respectively, whereas using just FAC reduces mispredictions by 84%. Finally, using FAC with a RAS (FAC+RAS) proves best. In conclusion, eliminating the BTB and relying instead on a RAS+FAC is best in terms of accuracy. An added benefit of RAS+FAC is that it allows for a standalone, thus larger and more flexible direction predictor.

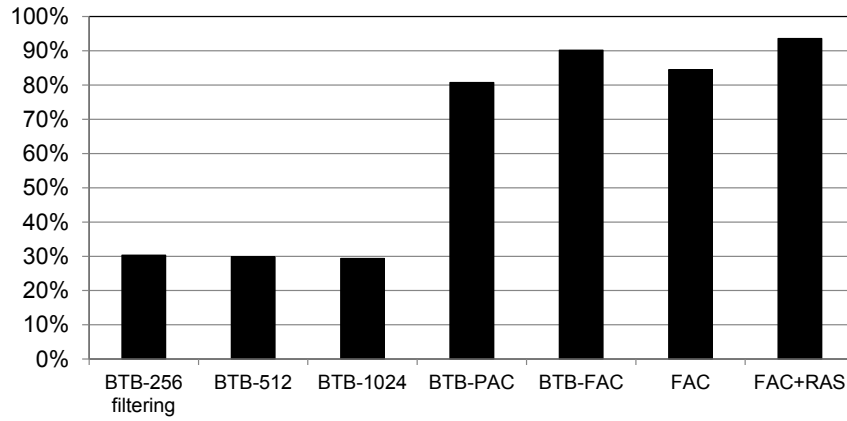


Figure 5.1: Target Address Prediction Schemes: Reduction in target address misprediction over BASE.

5.3 The Minimalistic FPGA-Friendly Branch predictor

5.3.1 Direction Prediction

Fig. 5.2 reports the improvement in MPKI for various direction predictors relative to BASE. Decoding the instructions and performing prediction only for branches improves MPKI by 17% (bimodal-256). Using a larger bimodal with 4K entries further improves MPKI by only 8% suggesting that bimodal is fundamentally limited in the branch sequences it can predict. However, using a 256- or a 4K-entry gshare improves MPKI by 79% and 82% respectively.

Section ?? explained why gselect may be better to implement on an FPGA. Fig. 5.2 show that a conventionally indexed 4K-entry gselect results in competitive accuracy, improving BASE by 80%. Section ?? explained that the desired number of entries for the direction predictor is either 768 or 4K when fused with a BTB or not respectively. The figure shows that a conventionally indexed 4K-entry gselect improves MPKI by 80%, while the proposed FPGA-friendly organization, gRselect, improves MPKI by 79%. In conclusion, gshare achieves the best accuracy with gselect and gRselect offering

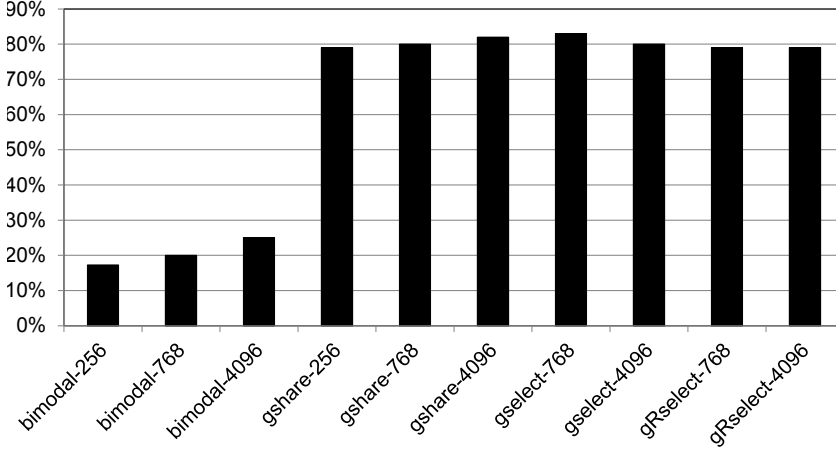


Figure 5.2: Direction Predictors: MPKI improvement over BASE.

competitive accuracies.

5.4 Area and Frequency

Fig. 5.3 shows the maximum frequency and area utilisation for each predictor design. All configurations use one BRAM. As expected, BASE is the fastest and least expensive. Adding instruction filtering reduces f_{max} from 353 MHz to 287 MHz, a 18% drop. By adding address calculation, frequency drops even further. However, removing the BTB partially recovers from this frequency drop. Finally, adding a RAS to a gRselect with pre-decoding, results in a predictor that operates at 259 MHz and that uses only 147 ALUTs.

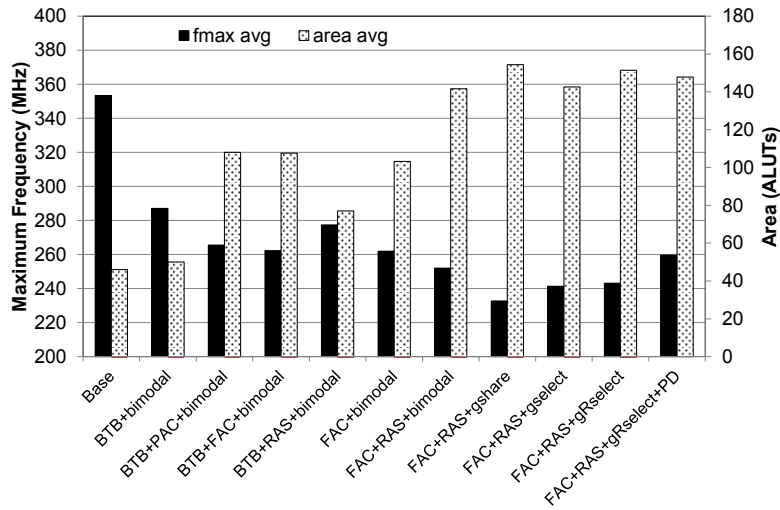


Figure 5.3: Maximum frequency and area utilisation. (PD = pre-decoding)

5.4.1 Performance

Fig. 5.4 reports average IPC gain compared to BASE. The bimodal predictor results in the lowest IPC while gselect performs almost as well as gshare.

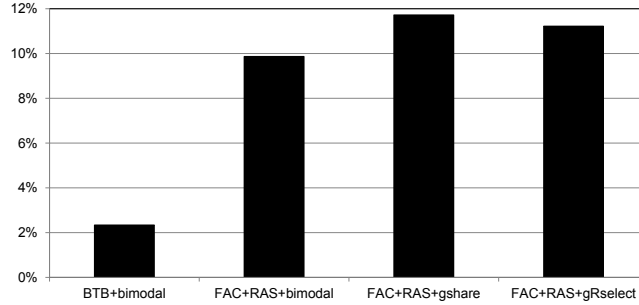


Figure 5.4: Improvement in IPC over BASE.

IPC is proportional to performance only when the clock frequency remains the same. Actual performance depends on IPS, the product of IPC and clock frequency. Fig. 5.5 reports overall performance in IPS. This experiment assumes a 250MHz maximum clock speed for the processor, the maximum clock frequency of Nios-II-f on the Stratix IV [7]. The best performing predictor is a 4K-entry gRselect with FAC+RAS, no BTB, and that uses pre-decoded instructions.

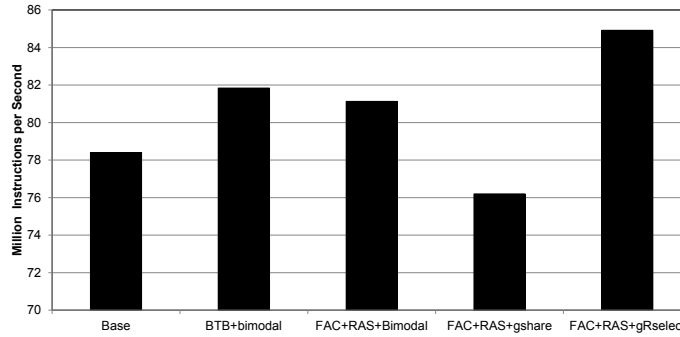


Figure 5.5: IPS comparison of processors with various predictors.

5.5 Advanced Branch predictors

5.5.1 Branch Prediction Accuracy

This section first presents data that justify the final design of Perceptron and TAGE configurations, then a comparison with bimodal, gshare and gRselect is presented.

Perceptron

This work considers Perceptron predictors with a hardware budget ranging from 1KB to 32KB. For each hardware budget, the number of global history bits is varied and the best performing one is chosen. Fig. 5.6 shows the most accurate Perceptron configuration for each hardware budget. All of these

configurations uses 16 history bits. As Section 5.5.3 will show, although the 32KB Perceptron is 3.2% more accurate than the 16KB Perceptron, its IPC saturates at the 16KB budget, therefore for the rest of this work the 16KB Perceptron predictor is used.

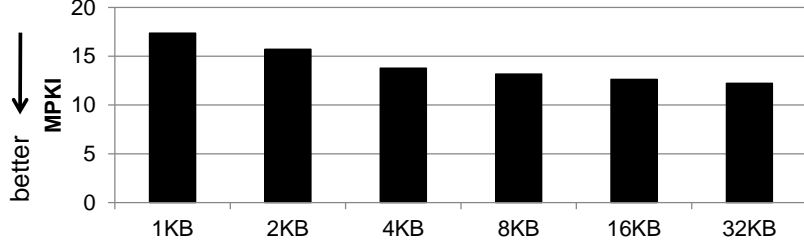


Figure 5.6: Perceptron: MPKI of the most accurate Perceptron configuration with various hardware budgets.

To determine how many HOBs the predictor should use, we took the most accurate Perceptron configuration and experimented with all possible numbers of HOBs used. Fig. 5.7 shows the MPKI of this Perceptron when different number of HOBs are used. The data shows that using three HOBs degrades accuracy by less than 1% compared to using all eight bits. However, the MPKI doubles when using only two HOBs. Therefore the implemented Perceptron designs use three HOBs to improve operating frequency without affecting accuracy.

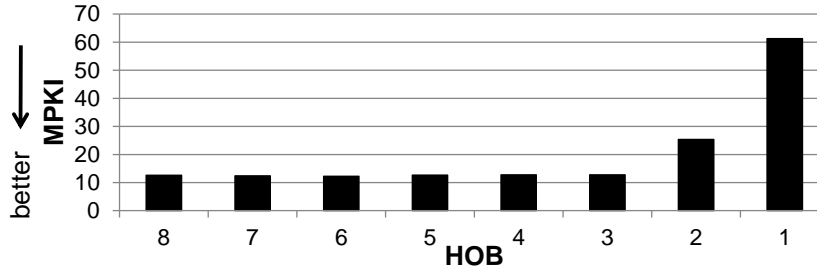


Figure 5.7: Perceptron: MPKI when using different number of HOBs for the most accurate perceptron configuration.

The best performing Perceptron uses 16 global history bits. It has a 16KB perceptron table, which stores 1K perceptrons. Each perceptron contains 16 8-bit weights with the arrangement discussed in Section ?? . It also has a 6KB complement table that stores three HOBs per weight in its 2's complement form to improve frequency. Therefore the total storage required for this Perceptron is 22KB on FPGA. In the remaining sections of this paper, the hardware budgets for Perceptron only include the perceptron table without the FPGA implementation overhead for simplicity.

TAGE

This work uses the TAGE predictor introduced by Seznec et al. [2]. This work proposes four designs incorporating TAGE: (1) the single-cycle TAGE, which requires TAGE to provide a prediction in one cycle (i.e., in the fetch stage), (2) the Overriding TAGE (O-TAGE), which uses just the bimodal predictor (i.e., T_0) to provide a base prediction in the first cycle, and *always* overrides the base prediction if TAGE disagrees at the end of the second cycle, (3) the single-cycle TAGE with a Statistical Corrector (single-cycle TAGE-SC), which forces the predictor to use the base prediction unless TAGE consistently

disagrees over several encounters of the same event, and (4) the Overriding TAGE with a Statistical Corrector (O-TAGE-SC), which is similar to the single-cycle TAGE-SC except that TAGE overrides the base prediction in the second cycle.

Specifically, O-TAGE-SC is motivated by Seznec’s observation that TAGE fails at predicting branches that are statistically biased towards a direction but not correlated to the history path [14]. On some of these branches, TAGE often performs worse than a simple PC-indexed table, e.g., a bimodal predictor. This may result in many miss-overrides on these type of branches. More importantly, in Nios II-f where the branch resolution latency is only two cycles, the overriding TAGE saves one cycle for each correct override, but loses two cycles for each incorrect override. Hence, the overriding TAGE must be very confident to make an overriding decision, which necessitates the statistical corrector.

The statistical corrector we implemented is a small table with 256 entries that is indexed by eight bits from the PC. Each entry is a 10-bit saturating counter. If TAGE correctly overrides a decision, the corresponding counter is incremented by one, otherwise the counter is *reset* to zero. TAGE only overrides when the counter is saturated. All TAGE configurations studies use 32KB and Seznec’s original table configurations. Adjusting TAGE’s size is a non-trivial task, moreover, the results of this work show that the 32KB O-TAGE-SC outperforms the other predictors. Accordingly, we do not vary TAGE’s size in this work. Fig. 5.8 shows the MPKI of the four designs that incorporate TAGE. It shows that the single-cycle and overriding predictors have virtually identical MPKI, the statistical corrector improves MPKI by $\sim 2.4\times$.

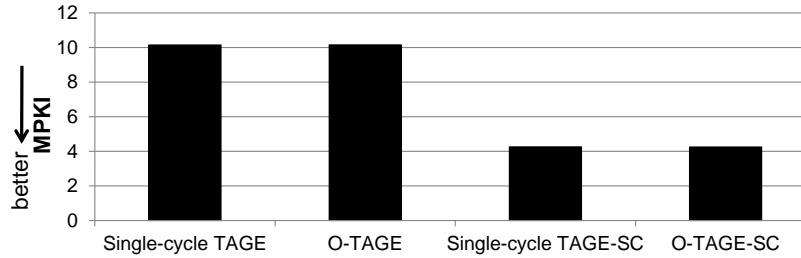


Figure 5.8: TAGE: MPKI and IPC of the four TAGE variations.

Accuracy Comparison

For fair comparisons, we scale bimodal, gshare and gRselect from 1KB to 32KB, which is the same hardware budget as TAGE and the largest Perceptron considered in this work. Fig. 5.9 shows the MPKI of various direction predictors. The TAGE variations use 32KB. All the branch predictors get more accurate as the hardware budget increases. The single-cycle TAGE-SC is the most accurate, followed by O-TAGE-SC with less than 0.06% difference. The single-cycle TAGE-SC is $\sim 2.3\times$ more accurate than the 32KB gRselect and the 32KB gshare.

5.5.2 Frequency

Fig. 5.10 shows the maximum operating frequency for each branch prediction scheme and for various hardware budgets.

The fastest predictors are O-TAGE-SC and O-TAGE, both of them are capped at 270 MHz, the maximum clock frequency for Nios II-f on Altera Stratix IV C2 speed grade devices [7]. The 1KB

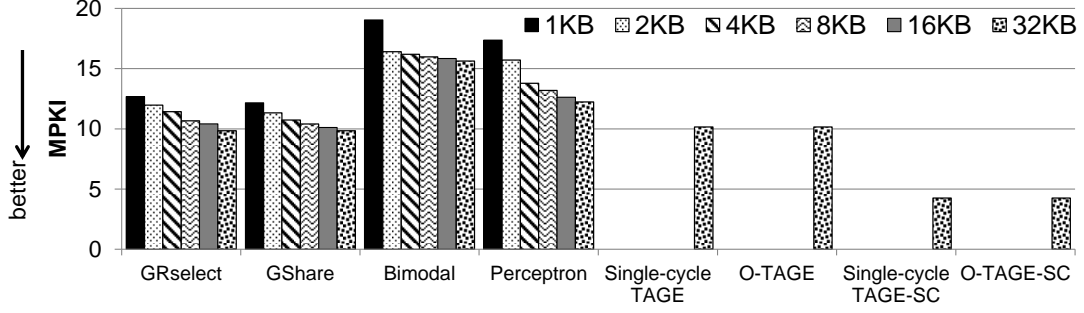


Figure 5.9: MPKI of the direction predictors.

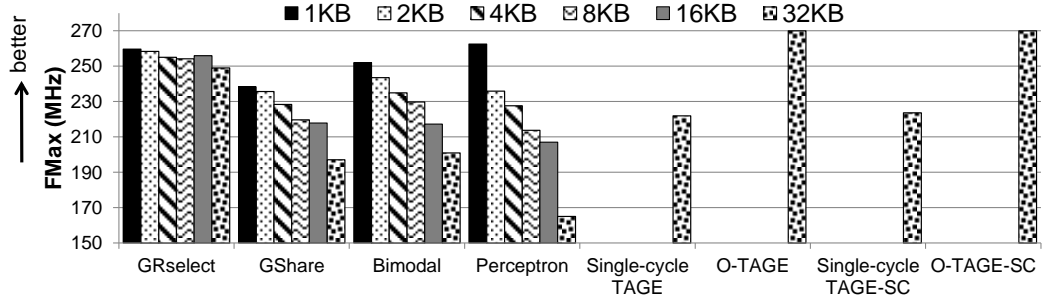


Figure 5.10: Maximum operating frequency of the considered branch prediction schemes with various hardware budget.

Perceptron and the 1KB gRselect follow the overriding TAGE variations. The maximum frequency of gshare, bimodal and Perceptron drop rapidly with increasing size, while gRselect's frequency does not suffer too much. Despite that the logic is larger and more difficult to place and route, the table indexing of gRselect comes from the GHR register. GRselect reads a wide entry and then using bits from the PC to select the appropriate ones. The indexing of gshare, bimodal and Perceptron uses the predicted PC. The PC is both the input and the output of the branch predictor. This loop forms the critical path of gshare, bimodal and Perceptron, which quickly gets slower as the size of the predictors increase. The single-cycle TAGE-SC operates at 223.7MHz, which is 14.8% slower than the 1KB gRselect and 17.2% slower than O-TAGE-SC.

5.5.3 Performance and Resource Cost

Fig. 5.11 shows the IPC of the predictors. Although the MPKI of the 32KB Perceptron is higher than the 16KB Perceptron, they deliver identical IPC, therefore the 16KB version is selected as the final Perceptron implementation. The single-cycle TAGE-SC has the highest IPC, however, as this section shows, its high IPC cannot amortize the slowdown in operating frequency. O-TAGE is much faster, but its IPC drops significantly. Finally, the IPC of O-TAGE-SC is within 0.5% of the single-cycle TAGE-SC.

IPC is a measurement that does not take operating frequency into consideration. The actual performance of a processor is measured by Instructions Per Second (IPS), which is the product of IPC and the maximum operating frequency. Fig. 5.12 reports the overall performance in terms of IPS.

The IPS of gRselect, gshare, bimodal and perceptron drops as they scale, therefore we chose the smallest configurations of these schemes to maximize IPS. The best performing predictor is O-TAGE-SC,

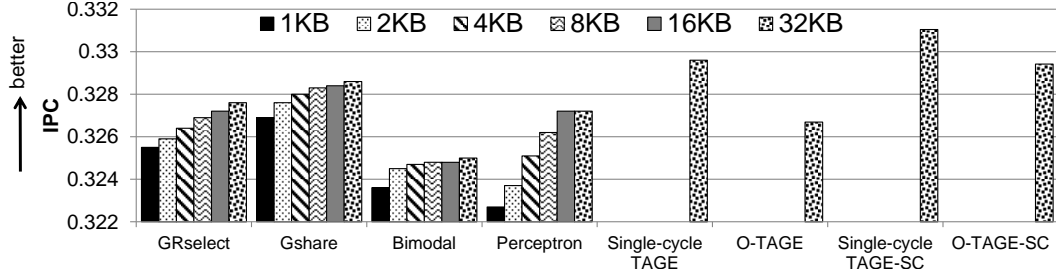


Figure 5.11: IPC of the considered branch predictors.

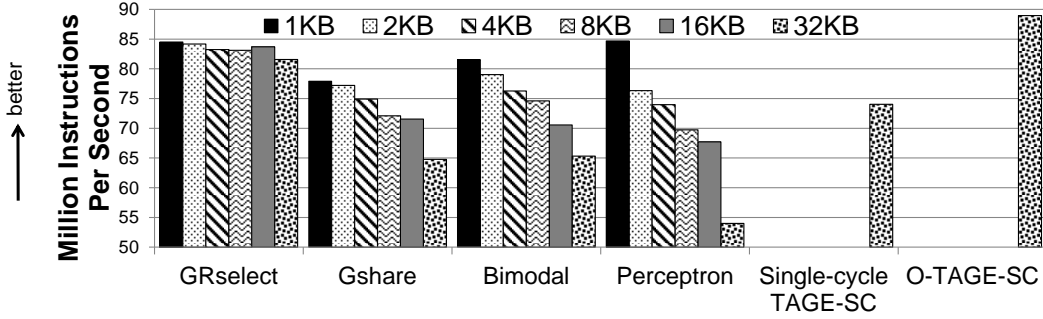


Figure 5.12: Processor IPS comparison with various predictors.

which delivers 5.2% higher IPS than the previously proposed 1KB gRselect. Although the single-cycle TAGE-SC is the most accurate, its IPS is lower than the best performing predictor in all other prediction schemes because its latency is too high. The 1KB Perceptron ends up being 0.2% better than the 1KB gRselect, because of the optimization efforts into improving its frequency.

Finally, Fig. 5.13 shows the resource usage in term of ALUTs used. O-TAGE-SC uses 2.93x ALUTs and Percpetron uses 6.45x ALUTs as the 1KB gRselect.

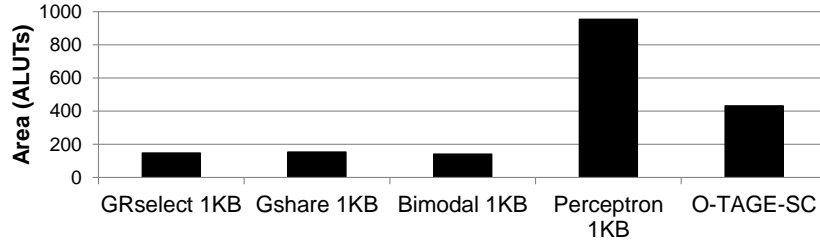


Figure 5.13: ALUTs usage comparison with various predictors.

Chapter 6

Conclusion

This work studied the implementation of branch predictors for general purpose soft processors. This work targeted high frequency, low area overhead branch predictors for pipelined processors, and explored various branch predictor designs. These designs were combinations of a branch target buffer, a return address stack, three commonly used direction predictors, pre-decoding, in-fetch instruction decoding, and target address calculation. Several FPGA-specific optimizations were proposed resulting in a branch predictor that is FPGA-friendly in that it offers high accuracy, high operating frequency with few resources. Future work may consider more elaborate processor designs and/or other workloads that may benefit from more elaborate branch direction predictors than the ones considered in this work.

This work studied the implementation of Perceptron and TAGE branch predictors for general purpose soft processors. It explored the designs tradeoffs of Perceptron and TAGE, and proposed O-TAGE-SC, an overriding predictor that delivers 5.2% better instruction throughput over the best performing previously proposed predictor, gRselect. Several FPGA implementation optimization techniques were proposed to achieve high operating frequency. Although O-TAGE-SC is $\sim 3\times$ more accurate than the 1KB gRselect, the IPS improvement is smaller due to the processor's simple in-order pipeline. Future work may consider investigating the benefits of implementing O-TAGE-SC for more elaborated soft processors, e.g., an Out-of-Order soft processor.

Bibliography

- [1] Arcturus Networks Inc., uClinux. <http://www.uclinux.org/>.
- [2] A. Seznec and P. Michaud. A case for (partially) tagged geometric history length predictors. In *Journal of Instruction Level Parallelism* (<http://www.jilp.org/vol7>), April 2006.
- [3] Kaveh Aasaraai and Amirali Baniasadi. A power-aware alternative for the perceptron branch predictor. In Lynn Choi, Yunheung Paek, and Sangyeun Cho, editors, *Advances in Computer Systems Architecture*, volume 4697, pages 198–208. 2007.
- [4] Altera Corp. Nios II Processor Reference Handbook v9.0. 2009.
- [5] Altera Corp. *Stratix IV Device Handbook*, Feb. 2011.
- [6] Altera Corp. *TriMatrix Embedded Memory Blocks in Stratix IV Devices*, Dec. 2011.
- [7] Altera Corp. *Nios II Performance Benchmarks*, Nov. 2013.
- [8] Altera Corporation. *Nios II Processor Reference*, May 2011.
- [9] O. Cadenas, G. Megson, and D. Jones. A new organization for a perceptron-based branch predictor and its fpga implementation. In *Proc. IEEE Computer Society Annual Symposium on VLSI*, pages 305–306, May 2005.
- [10] D. A. Jimenez and C. Lin. Dynamic Branch Prediction with Perceptrons. In *Intl’ Symposium on High-Performance Computer Architecture*, January 2001.
- [11] J. E. Smith. A study of branch prediction strategies. In *Annual Symposium on Computer Architecture*, June 1981.
- [12] Daniel A Jiménez, Stephen W Keckler, and Calvin Lin. The impact of delay on the design of branch predictors. In *Proceedings of the 33rd annual ACM/IEEE international symposium on Microarchitecture*, pages 67–76. ACM, 2000.
- [13] S. McFarling. Combining Branch Predictors. TN-36, Digital Western Research Laboratory, June 1993.
- [14] André Seznec. A 64 kbytes isl-tage branch predictor. In *JWAC-2: Championship Branch Prediction*, 2011.

- [15] André Seznec, Stephen Felix, Venkata Krishnan, and Yiannakis Sazeides. Design tradeoffs for the alpha ev8 conditional branch predictor. In *Proc. 29th Annual International Symposium on Computer Architecture.*, pages 295–306. IEEE, 2002.
- [16] Standard Performance Evaluation Corporation. SPEC CPU 2006. <http://www.spec.org/cpu2006/>.
- [17] C. S. Wallace. A suggestion for a fast multiplier. *Electronic Computers, IEEE Transactions on*, EC-13(1):14–17, Feb 1964.
- [18] Di Wu, K. Aasaraai, and A. Moshovos. Low-cost, high-performance branch predictors for soft processors. In *Field Programmable Logic and Applications (FPL), 2013 23rd International Conference on*, Sept 2013.
- [19] Xilinx Inc. *MicroBlaze Processor Reference Guide*, July 2012.
- [20] Peter Yiannacouras, Jonathan Rose, and J Gregory Steffan. The microarchitecture of fpga-based soft processors. In *Proceedings of the 2005 international conference on Compilers, architectures and synthesis for embedded systems*, pages 202–212. ACM, 2005.