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PaCo: Probability-based Path Confidence Prediction

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We show that PaCo significantly outperforms threshold-and-count predictors in pipeline gating and SMT fetch prioritization. In pipeline gating, while the best conventional predictor can reduce badpath instructions executed by 7% with a small loss in performance, PaCo can reduce badpath instructions by 32% without any performance loss. In SMT fetch prioritization, using PaCo instead of conventional path confidence predictors improves performance by up to 23%, and 5.5% on average.

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Abstract

A path confidence estimate indicates the likelihood that the processor is currently fetching correct path instructions. Accurate path confidence prediction is critical for applications like pipeline gating and confidence-based SMT fetch prioritization. Previous work in this domain uses a threshold-and-count predictor, where the number of unresolved, low-confidence branches serves as an estimate of path confidence. This approach is inaccurate since it implicitly assumes that all low-confidence branches have the same mispredict rate, and that high-confidence branches never mispredict. We propose an alternative path confidence predictor designed from first principles, called PaCo, that directly estimates the probability that the processor is on the goodpath, and considers contributions from all branches, both high and low confidence. Even though it uses only modest hardware, PaCo can estimate the processor's goodpath likelihood with very high accuracy, with an RMS error of 3.8%.

We show that PaCo significantly outperforms threshold-and-count predictors in pipeline gating and SMT fetch prioritization. In pipeline gating, while the best conventional predictor can reduce badpath instructions executed by 7% with a small loss in performance, PaCo can reduce badpath instructions by 32% without any performance loss. In SMT fetch prioritization, using PaCo instead of conventional path confidence predictors improves performance by upto 23%, and 5.5% on average.

1 Introduction

Branch confidence predictors [8, 18, 7] identify branches that have a relatively high likelihood of misprediction. Branch confidence prediction can be used to derive a path confidence estimate, which indicates the likelihood that the processor is fetching correct path instructions. Path confidence prediction has a number of applications. For example, SMT processors can use it to allocate fetch bandwidth to threads that are more likely to fetch goodpath instructions [12, 13]. Path confidence estimates can also be used to reduce power by gating instruction fetch when the processor is unlikely to be on the correct path [14, 3], and to reduce cache pollution caused by mispredicted instructions [4]

Conventional path confidence predictors use the count of unresolved, low-confidence branches as an estimate of path confidence. In other words, it is implicitly assumed that all low-confidence branches have the same misprediction rate, while high-confidence branches never mispredict at all. We find that because of these two approximations, the same path confidence can represent vastly different goodpath likelihoods across different benchmarks, and across different phases of the same benchmark.

The contributions of this paper include, first, *the proposal of using misprediction probabilities of branches to compute path confidence.* We show that a path confidence predictor can directly produce the probability that the processor is on goodpath.

Second, *we present a simple yet highly accurate hardware implementation of such a path confidence predictor, called PaCo.* PaCo uses logarithms to convert floating point multiplication and division into integer addition and subtraction. It uses less than 60 bytes worth of small counters, and a 10-bit shift register to produce goodpath likelihood estimates. We find that for the SPEC2000 integer benchmarks, the goodpath likelihood provided by PaCo is highly accurate, with an RMS error of 3.8%.

Third, *we evaluate PaCo's performance in two applications of path confidence: pipeline gating and SMT fetch prioritization, and compare it with the performance of conventional counter-based predictors. We show that PaCo performs significantly better than traditional predictors in both these applications.* In pipeline gating, PaCo can reduce the number of badpath instructions executed by the processor by 32%, with only a 0.01% reduction in performance. On the other hand, the best conventional path confidence predictor can only reduce the number of badpath instructions by 7%, with a 0.1% loss in performance. With respect to SMT fetch prioritization, using PaCo instead of traditional threshold-and-count predictors improves performance by upto 23%, and 5.5% on average.

2 Motivation

This section describes the current state of the art in branch confidence prediction and path confidence prediction. While current branch confidence predictors are good at qualitatively classifying branches as high or low confidence, they do not do a good job of estimating the probability that a particular branch will be predicted correctly. Similarly, while current path confidence predictors qualitatively classify the current state of the fetch unit, they do not estimate the important metric: the probability with which the fetch unit is fetching instructions that will eventually retire.

2.1 Branch Confidence Prediction

Modern processors use branch prediction to speculate past control hazards. *Branch confidence prediction* is the process of qualitatively classifying particular dynamic predictions made by a branch predictor as likely correct (high confidence) or likely incorrect (low confidence) [8].

Branch confidence prediction is useful for a number of purposes. For example, it has been proposed that multipath processors [19, 11] fetch instructions from both targets of a low-confidence branch, to eliminate misprediction penalties. Additionally, checkpoint-repair based processors could create checkpoints of the processor's register alias table (RAT) only when low-confidence branches are renamed [1].

Jacobsen et al [8] proposed the JRS branch confidence predictor, which leverages the insight that most mispredicts can be attributed to a relatively small set of branches; a majority of branches almost never mispredict. In particular, if a branch was mispredicted in the recent past, it is likely to be mispredicted again. To identify branches that were mispredicted in the recent past, the JRS predictor uses a table of 4-bit saturating *miss-distance counters* (MDCs). The table entry corresponding to a particular branch is found by XOR-ing the branch PC with the global branch history. The table entry (an MDC) is incremented every time the branch is correctly predicted, and is reset to zero when the branch is mispredicted. Thus, the MDC stores the number of consecutive correct predictions seen by a branch. For example, an MDC value of 10 indicates that the corresponding branch has seen 10 correct predictions, which were preceded by a mispredict.

The MDC value of a branch is indicative of its predictability. The higher the MDC value, the more predictable the branch. Branches whose MDC value is at or above a certain threshold (say, 3) are classified as high-confidence (unlikely to mispredict), while branches with a MDC value less than the threshold are classified as low-confidence (likely to mispredict). Thus, with a threshold of 3, branches need to be predicted correctly three consecutive times before they are considered high-confidence. Among other branch confidence predictors, Grunwald et al [7] proposed the enhanced JRS predictor, where the global history used to hash into the MDC table also includes the predicted direction of the branch in question. This predictor was shown to be superior to the original JRS predictor.

2.2 Path Confidence Prediction

The applications mentioned previously, like multi-path processing and register file checkpointing, use branch confidence predictors directly: they require information about a *particular* branch being low-confidence. Other applications, however, require *aggregate information about all the branches that are outstanding in the machine*. In particular, these applications require the likelihood that the processor is fetching correct-path instructions. The probability that a processor is on the goodpath is indicated by a *path confidence estimate*.

Applications of path confidence include pipeline gating [14], which conserves power by completely stopping instruction fetch when the path confidence estimate is very low (i.e, the processor is very likely to be fetching badpath instructions). Selective throttling [3] improves pipeline gating by slowly reducing instruction fetch bandwidth as path confidence decreases. In the context of simultaneously multi-threaded (SMT) processors, Luo et al [12, 13] proposed giving fetch bandwidth to the thread that has higher path confidence (and thus more likely to be fetching goodpath instructions). Path confidence can also be used to reduce cache-pollution caused by wrong-path instructions [4].

While branch confidence prediction is a mature field that has been researched extensively, path confidence prediction has not been investigated deeply. Applications like pipeline gating, selective throttling, SMT fetch prioritization and cache-pollution reduction have simply used a count of unresolved low-confidence branches to classify the current path as high or low confidence. In the next section, we explain why this rough estimation of path confidence is sub-optimal.

Figure 1 shows a conventional, threshold-and-count path confidence predictor. When a branch is fetched, the MDC value corresponding to the branch is read from the JRS table. A thresholding function converts this MDC value in a 1 bit high/low-confidence estimate. If the branch is low-confidence, a counter is incremented. The output of the counter, which is the number of unresolved, low-confidence branches is used as a measure of Path Confidence. The higher the counter value, the lower the likelihood that the processor is on the goodpath.

2.3 Inefficiencies with threshold-and-count predictors

Threshold-and-count predictors coarsely map a 4-bit MDC values to a 1 bit confidence prediction, without considering the misprediction rate that an MDC value corresponds to. In the next section, we show that as a result of this coarseness,

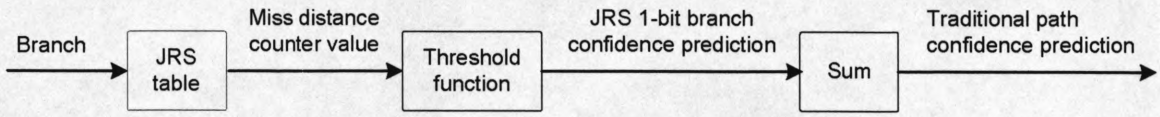


Figure 1: Conventional threshold-and-count Path Confidence prediction

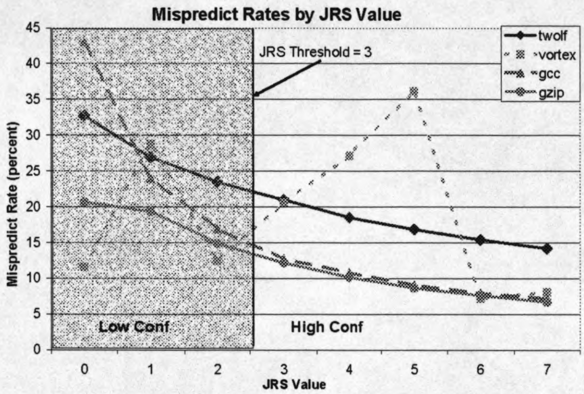


Figure 2: Misprediction Rates of branches with different MDC values

the number of unresolved low-confidence branches is not an accurate measure of the probability that the processor is on the goodpath.

Coarseness

Threshold-and-count predictors make the implicit assumption that all low-confidence branches have the same mispredict rate, while none of the high-confidence branches ever mispredict. Both of these approximations can lead to inaccuracies in path confidence estimation.

Treating all low-confidence branches the same can lead to inaccuracies in path confidence: depending on the MDC value, different low-confidence branches can have vastly different misprediction rates, as shown in Figure 2. Assume that a confidence threshold of 3 was being used. [1]All branches in the gray area in Figure 2 would be considered low-confidence. However, the misprediction rates of these branches vary significantly, both across benchmarks, and for the same benchmark. For example, the mispredict rate of a low confidence branch could be as high as 43% (for gcc, with MDC value 0) or as low as 15%(gcc, with MDC value 2), or 12% (vortex, with MDC value 2). With a fixed threshold based approach to path confidence, these branches with very different misprediction rates are considered equal.

As an example of how this can be detrimental, consider SMT fetch prioritization. Assume that gcc and vortex were being executed together. Further, assume that two branches in vortex with MDC values of 2 were unresolved, while one branch with a MDC value of 1 was unresolved in gcc. A counter-based path confidence estimator would indicate that gcc has a higher likelihood of being on the goodpath, and thus, more fetch bandwidth should be allocated to gcc. In reality, however, vortex is much more likely (probability of goodpath = 0.88^2, or 0.78) to fetch goodpath instructions than gcc (probability of goodpath 0.55)!

Moreover, none of the high-confidence branches affect path confidence, even though they can have significant misprediction rates. With a threshold of 3, there are high-confidence branches (twolf and vortex, MDC value 3) that have a mispredict rate of 21% but don't affect the processor's path confidence.

To summarize, binary branch-confidence mechanisms classify branches into two categories. Generating path confidence estimates by just using this coarse classification is not enough.

Counter value does not indicate Goodpath Probability

As a result of the coarseness introduced by the thresholding mechanism, the count of low-confidence branches is not a direct measure of the likelihood that the processor is on the goodpath. This makes it difficult to choose a counter value for pipeline gating (since the optimal value varies across benchmarks, and across phases of a single benchmark), or to compare counter values of different threads in an SMT processor to find which one is more likely to be on goodpath. Figure 3(a) shows, for a few SPEC2000 benchmarks, the probability of being on the goodpath when 5 low-confidence branches are outstanding.

As can be seen, a low-confidence branch count of 5 corresponds to quite different goodpath probabilities, from very low (10% for vpr-route) to reasonably high (40% for gzip). If pipeline gating was employed, and the processor was gated when 5 low-confidence branches were outstanding, gating would be too aggressive for gzip (thus leading to significant performance degradation), and too conservative for vpr-route (would not significantly reduce power) [2]. Similarly, an SMT processor might allocate equal fetch bandwidth to vpr-route and gzip when 5 low-confidence branches were outstanding in both applications, even though gzip would be four-times more likely to fetch goodpath instructions.

The same counter value can represent different goodpath probabilities not only across applications, but also for different phases of the same application. Figure 3(b) shows the goodpath likelihood for a counter value of 5, for two differ-

[1]3 is a good threshold to use for for path confidence,as indicated by our experiments and previous research [2]

[2]Section 5.1 shows that optimally, the processor should be gated when goodpath probability is 20%

(a) Across different benchmarks

(b) Across phases of the same benchmark

Figure 3: Goodpath Likelihood when 5 low-confidence branches are outstanding.

ent phases of mcf and gcc. This figure indicates that the best counter-value for pipeline gating (for example) changes not only across benchmarks, but also between different phases of the same benchmark.

To summarize, the previous two sections indicate that using low-confidence branch count as a surrogate for path confidence is inaccurate because of coarseness in classification. As a result of this coarseness, counter values don't correspond directly to goodpath probabilities. Hence, it is difficult to accurately compare goodpath probabilities of two different threads, and to select counter values for pipeline gating.

2.4 Probability-based Path Confidence Estimation

In this paper, we propose PaCo, which is a path confidence predictor that tries to address the shortcomings of conventional predictors. Instead of keeping a count of low confidence branches, PaCo *directly* outputs the probability that the processor is on the goodpath. In doing so, PaCo considers contributions from both low-confidence and high-confidence branches (in fact, there is no concept of a confidence threshold in PaCo). Even though PaCo can predict goodpath probability with remarkable accuracy, it only adds a small amount of hardware to the existing JRS predictor. Since PaCo addresses fundamental shortcomings in conventional path confidence predictor, it significantly outperforms counter-based predictors in both Pipeline Gating and SMT fetch prioritization.

In the next section, we present the design of the PaCo predictor. We evaluate the accuracy of PaCo's goodpath probability prediction in Section 4. Finally, we compare the performance of PaCo against conventional path confidence predictors in pipeline gating and SMT fetch prioritization in Section 5.

3 Designing a Probability-based Path Confidence Predictor

The probability-based path confidence predictor that we propose was designed from first principles. We describe the theory behind PaCo, and then present a realizable hardware implementation.

3.1 Finding Goodpath Probability

The probability that the processor is on the goodpath is the same as the probability that every unresolved branch was correctly predicted. Assuming that branch predictions are independent [3], this probability is given by Equation 1.

An important practical issue with using Equation 1 is estimating the term inside the product, the correct prediction probability for a *particular* branch. We use the MDC table of the JRS predictor for this purpose. As shown by Figure 2, the MDC table classifies branches into buckets by their MDC values, where the buckets have very different misprediction rates. PaCo *measures* the misprediction rate for each MDC bucket by using hardware counters, and assigns a correct prediction probability to each branch depending on the MDC bucket that the branch belongs to. In other words, the branch confidence predictor is used as a *stratifier*, which allows us to distinguish between branches with different probabilities of misprediction. Figure 4 pictorially represents the process of arriving at a path confidence estimate, contrasted with the conventional threshold-and-count technique.

Dynamically calculating the misprediction rate for each MDC value is not the only way to estimate the correct-prediction probability for a branch.Other approaches include both more hardware-intensive (using a per-branch misprediction rate table, indexed by a hash of the branch PC and the global history), and simpler (using static, profile-driven misprediction rates for each MDC value) techniques to estimate misprediction rates for a branch. Appendix A shows that dynamically measuring the misprediction rates of each MDC bucket strikes the right balance between accuracy and hardware complexity.

Unlike conventional path confidence predictors, the goodpath probability in Equation 1 includes contributions from all branches, low confidence and high confidence.

[3] Branches may actually be correlated. We show in Section 4 that this assumption doesn't affect the estimation of path confidence appreciably.

$$\text{Goodpath Probability} = \prod_k (\text{CorrectPredictionProbability}_k) \quad \forall k \text{ in Unresolved Branches} \tag{1}$$

$$\log_2(\text{Goodpath Probability}) = \sum_k (\log_2(\text{CorrectPredictionProbability}_k))\ \forall k \text{ in Unresolved Branches} \tag{2}$$

$$\text{Encoded Correct Prediction Probability} = \lfloor -1024 * \log_2(\text{Correct Prediction Probability}) \rfloor \tag{3}$$

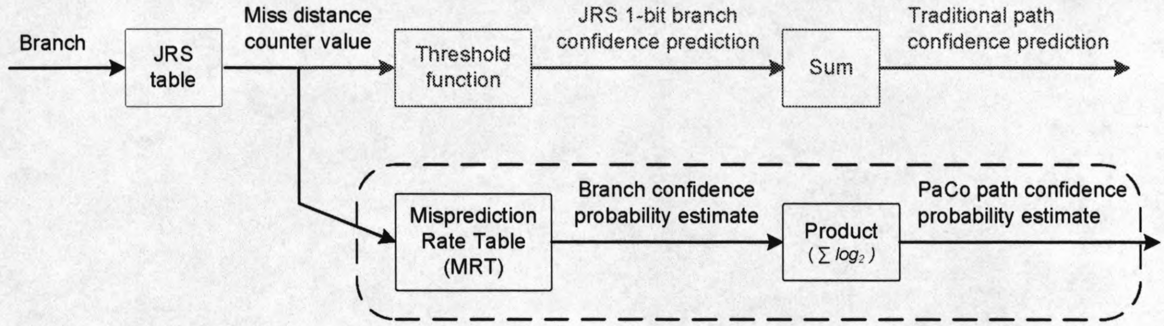


Figure 4: The PaCo path confidence predictor contrasted with the conventional threshold-and-count predictor.

Moreover, the weight assigned to a branch is directly related to its mispredict rate.

Note that equation 1 requires a floating point multiplication whenever a branch is fetched: the current goodpath probability is multiplied with the correct-prediction probability of the branch being fetched. Conversely, a floating point division is required whenever a branch is executed. Floating point multiplication and division are complex operations that take multiple clock cycles. In the next section, we present a hardware implementation that measures path confidence using integer addition and subtraction.

3.2 Hardware Implementation

To remove the need for multiplication and division, the PaCo predictor calculates the *log* of the goodpath probability, instead of directly calculating the goodpath probability. Taking the log of both sides of Equation 1 results in Equation 2, which requires addition of the (logs of) correct prediction probabilities of branches, instead of multiplication. However, note that the correct prediction probability of a branch is a number between 0 and 1, and thus, its log will still be a (negative) floating point number. To remove the need for floating point addition, we scale this number appropriately (by multiplying it with -1024), and round off to the closest integer. In other words, the PaCo predictor works with an encoded version of the correct prediction probability of branches, as shown by Equation 3.

If the encoded probability is greater than 2^{12}, it is converted to 2^{12}. [4] Thus, the encoded probability of the correct prediction rate of a branch is a positive 12-bit integer, with higher values indicating higher mispredict probabilities.

Computing the logarithm of the correct prediction rate of a branch and scaling it is a computationally complex operation. However, as we will describe, this operation is performed very infrequently. The cost of logarithmizing and scaling the correct prediction probability is amortized over a large number of cycles where floating point multiplication/division is converted into integer addition/subtraction in the path confidence predictor.

Figure 5 shows the two components of PaCo: a path confidence calculator, and a Mispredict Rate Table (MRT). The MRT uses information about executed branches (whether or not the branch was mispredicted) to calculate the correct prediction probability corresponding to each MDC value. For each MDC value, the MRT keeps two counters: a 10-bit counter stores the number of correct predictions observed, and a 6-bit counter stores the number of mispredictions. Whenever either of these counters overflows, both counters are halved, thus preserving the overall mispredict rate.

Periodically [5], a logarithmizing and scaling circuit takes the values in the MRT counters, and converts them into 12-bit integer encoded probabilities, which are stored in the path confidence calculator. The MRT counters are reset to zero at this point.

Logarithms with base 2 can be calculated with a very simple circuit consisting of a shift register and a counter [15].The path confidence calculator consists of 12-bit registers storing encoded probabilities calculated above,

[4] An encoded probability greater than 2^{12} represents a branch with a *misprediction* rate greater than 93.5%. No such branches were found while executing the Spec2000 integer benchmark suite

[5] For the experiments in this paper, we chose a period of 200,000 cycles. Thus, the log-circuit is invoked so rarely that its power consumption and complexity are not an issue. PaCo's performance is not very sensitive to this period.

and a counter which computes a running sum of the encoded probabilities of all outstanding branches. When a branch is fetched, the encoded probability of its MDC value is added to the path confidence register. Conversely, when a branch is executed, the encoded probability of its MDC value is subtracted from the path confidence register.

To summarize, we replaced floating point multiplication and division that were required to calculate the goodpath probability by integer addition and subtraction. The resulting path confidence predictor works with encoded correct prediction probabilities of branches, and outputs an encoded probability that the processor is fetching goodpath instructions.

Reconverting to real Goodpath Probability

PaCo *never* needs to convert the encoded probability that it calculates into real probabilities. Instead, the target real probability for an application (say, pipeline gating) is converted into encoded probability. For example, if the architect wants instruction fetch to be gated whenever the processor's goodpath probability is less than 10%, PaCo would convert 10% into an encoded probability (which happens to be 3321) just once. Whenever the encoded goodpath probability increases beyond 3321, the processor is gated.

Hardware Complexity

The PaCo predictor uses relatively modest hardware. The MRT contains 32 counters, which use 32 bytes of storage. The encoded probability table has a 12-bit register for each MDC value, or 24 bytes. The log-circuit uses a counter and a shift register to calculate binary logarithms of a 10 bit binary number. To summarize, the PaCo predictor requires less than 60 bytes of counters, and a 10-bit shift register. Next, we evaluate the accuracy of PaCo's path confidence prediction.

4 Evaluation

In this section, we investigate whether PaCo can accurately predict the probability that the processor is fetching goodpath instructions. In Section 5, we compare the performance of PaCo against conventional counter-based predictor in two applications of path confidence, pipeline gating and SMT Fetch prioritization.

4.1 Machine Architecture

For all experiments in this paper (except for SMT Fetch prioritization), we model a 4-wide out-of-order superscalar processor, with parameters shown in Table 6. The SMT processor is an 8-wide machine with parameters specified later.

We use a large, aggressive, tournament branch predictor, and an 8KB enhanced JRS confidence predictor, where the MDCs are 4-bit counters.

4.2 Simulation Methodology

Our experimental evaluation was performed on a fully execution-driven simulator running a variant of the 64-bit MIPS instruction set ISA. It not only simulates timing, but also *executes* instructions out-of-order in the backend, writing results to the register file out of program order. When a branch mispredict is discovered, the simulator immediately reclaims backend resources (ROB and scheduler entries, etc.) and recovers using the rename checkpoint associated with the branch.

We present results from running all the SPEC2000 integer benchmarks except for eon. Eon was not simulated since our toolchain is incapable of compiling C++ benchmarks. All benchmarks were compiled with `gcc` at optimization level O3. The simulator fast forwards through

Parameter	**Value**
Pipeline Width	4 instrs/cycle
Branch Predictor	96KB hybrid, 32KB gshare, 32KB bimodal, 32KB selector, 8 bits of global history
Misprediction Penalty	At least 10 cycles
Reorder Buffer	256 entries, dynamically shared
Scheduler	64 entries, dynamically shared
Functional Units	4 identical general purpose units
L1 I-Cache	32Kbytes, 4-way set assoc., 128 byte lines, 10 cycle miss
L1 D-Cache	32Kbytes, 4-way set assoc., 64 byte lines, 10 cycle miss
L2 Cache	512Kbytes, 8-way set assoc., 128 byte lines, 100 cycle miss

Figure 6: Pipeline parameters.

Benchmark	PaCo RMS Error	Overall Mispredict Rate	Cond. Br. Mispredict Rate
bzip2	0.0545	9.03	10.5
crafty	0.0528	5.43	5.49
gcc	0.0874	3.07	2.61
gap	0.0830	6.05	5.16
gzip	0.0640	2.86	3.17
mcf	0.0447	3.95	4.51
parser	0.0415	3.98	5.26
perlbmk	0.0613	9.73	0.11
twolf	0.0175	11.8	14.8
vortex	0.0332	0.50	0.65
vprPlace	0.0244	9.47	11.7
vprRoute	0.0322	8.85	11.9
mean	0.0377	6.22	6.32

Figure 7: RMS error between Predicted and Actual Goodpath Probabilities. The table also shows Branch Mispredict Rates. The overall mispredict rate represents all control-flow instructions that retire (including conditional branches, jumps, indirect jumps, calls, returns etc.)

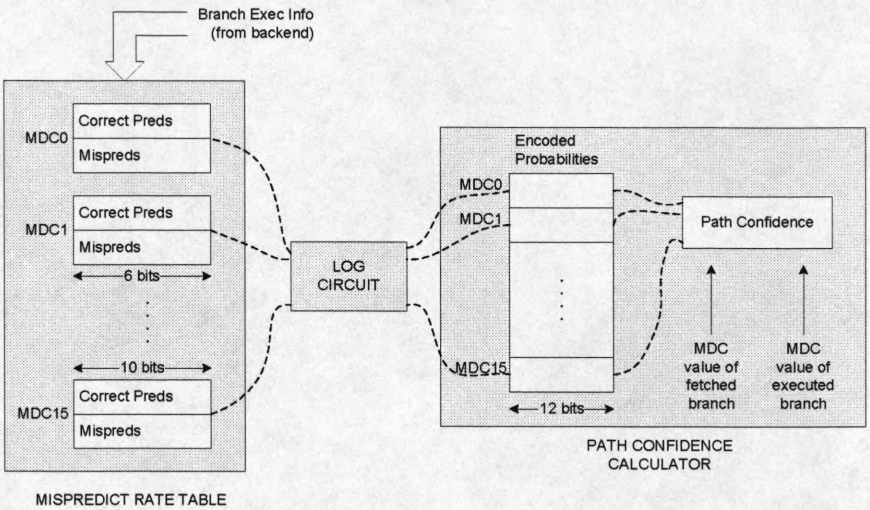


Figure 5: Hardware Implementation of the PaCo predictor

the initialization phase of all benchmarks, and executes 100 million instructions. The mispredict rates observed are shown in Table 7.

4.3 Reliability Diagrams and Correlation

The proposed path confidence predictor falls in the general category of *Probabilistic Forecast Systems.* These systems are used to predict probabilities in binary experiments. For example, weather forecasting systems indicate the likelihood that it will rain on a certain day. Similarly, PaCo outputs a predicted probability that the processor is on the goodpath at any given point in time, given the branches that are as yet unresolved.

The accuracy of Probabilistic Forecast Systems is measured using graphs called Reliability Diagrams [16] [10], which, as the name suggests, are indicative of the reliability of prediction. These diagrams plot predicted probabilities against corresponding observed probabilities. More formally, Reliability Diagrams for a rain forecasting system would plot the predicted precipitation probability, x (output from predictor), against observed probability f, as shown by Equation 4

As an example of what Reliability Diagrams aim to quantify, assume that during the execution of a program, at 1 Million distinct instances, the path confidence predictor claimed that there was a 0.25 probability of the processor being on the goodpath. If the path confidence predictor was accurate, out of these 1 Million instances, 250,000 times the processor would actually be on the goodpath, and 750,000 times the processor would actually be on badpath. In other words, if the *predicted* probability was 0.25 for 1 Million instances, the *observed* probability (Equation 5) for these 1 Million instances would also be 0.25.

A Reliability Diagram plots predicted probability on the x-axis against observed probability on the y-axis. If the Path Confidence predictor is accurate, the reliability diagram would have a slope of 1, i.e, the predicted and observed probabilities would be perfectly correlated.

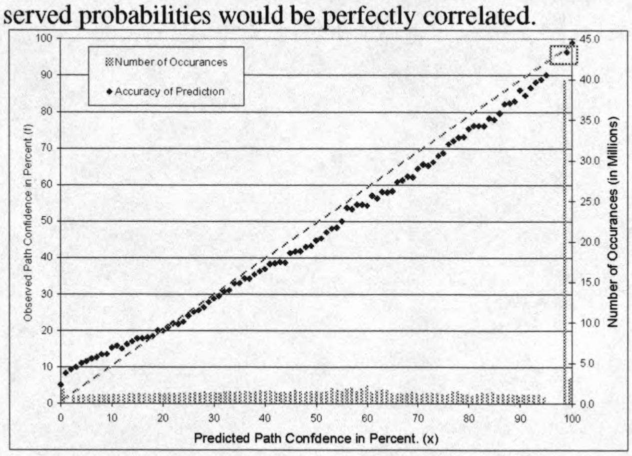


Figure 8: Reliability Diagram for parser. The x-axis plots predicted probability. The left y-axis corresponds to the scatter plot and shows observed probability. The right y-axis corresponds to the histogram and plots percentage of occurance for the corresponding predicted probability. A line with a slope of 1 is also shown for reference

Figure 8 is the reliability diagram for the path confidence predictor, when executing the SPEC benchmark parser for 100 million instructions. The x-axis plots predicted goodpath probability (as a percentage), and the y-axis plots observed goodpath probability (also as a percentage). The curve also shows a bar-graph of the number of instances for each predicted probability. For example, consider the point outlined by a small rectangle, which represents the point (99, 96) on the scatter plot. This point represents a predicted likelihood of 99% (x-axis value). The bar-chart entry for this point is at 40 million, indicating that during

$$f(x) = p(\text{it rained} \mid \text{predicted precipitation probability} = x) \quad (4)$$

$$\text{observedProbability}_{0.25} = p(\text{processor is on goodpath} \mid \text{predicted probability} = 0.25) \quad (5)$$

parser's execution, for 40 Million instances [6], the predicted goodpath probability was 99%. Out of these 40 Million instances, 38.5 Million times the processor was actually on the goodpath, [7] and 1.5 Million times, the processor was on badpath. Hence, the *observed* goodpath probability was about 96% (y-axis value on the scatter plot). As can be seen from the figure, PaCo can predict goodpath likelihood with remarkable accuracy on `parser`. Next, we look at PaCo's performance on different benchmarks.

4.4 Benchmark Behavior

Figure 9 shows Reliability Diagrams for a few representative SPEC integer benchmarks, as well as a cumulative curve with data from all applications. The graphs of twolf and vpr-route show extremely high prediction accuracy, and the graphs of mcf, parser, vortex and place look very similar. On crafty, bzip2 and gzip, PaCo does a very good job, although it is not quite as accurate as it is on twolf etc.

The PaCo predictor does worse on gcc and gap, although it is still relatively accurate. Gcc has a number of short phases, each with different misprediction rates for different JRS buckets. Since PaCo calculates branch mispredict rates periodically, it is unable to adjust when program phases are shorter than this period. On the other hand, gap has highly correlated branches (mispredicts are clustered together, globally). PaCo assumes that branches are independent, and when this assumption is not true, the predictor doesn't do very well. However, overall, PaCo still predicts goodpath probability on gcc and gap with reasonably high accuracy.

The graph for perlbmk is quite different from all other benchmarks. The PaCo predictor is unable to predict goodpath probability with high accuracy on perlbmk. This happens because the JRS predictor assigns MDC values only to conditional branches, while more than 95% of the mispredicts on perlbmk can be attributed to a single indirect function call. Thus, the JRS predictor is unable to identify low-confidence branches on perlbmk. Figure 9(f) shows cumulative data from all benchmarks, which indicates that the PaCo predictor is quite accurate, with predicted probability being very close to observed probability.

While Reliability Diagrams are an excellent tool for visual evaluation of probabilistic predictors, the RMS Error between predicted and observed probabilities is a good quantitative measures for the same. Table 7 shows the RMS error for PaCo. On average, PaCo can predict goodpath probability with very high accuracy, as indicated by the small average RMS error (0.0377). [8] In Section 5, we show that this high accuracy directly results in better performance applications that use path confidence.

4.5 Systematic error at low goodpath probability

Almost all the reliability diagrams show a systematic underestimation of goodpath probability in the very low-confidence region (goodpath probability less than 10%). For example, in Figure 9(f), when PaCo estimates goodpath probability to be 0%, the observed goodpath probability is actually 4%. This underestimation happens because PaCo does not take correlation among branches into account. Grunwald et al [7] showed that globally, branches are correlated. In other words, branches fetched immediately after a misprediction are more likely to mispredict. Conversely, if the last misprediction was seen a long time ago, the branches that are currently being fetched are more likely to be correctly predicted. Now, note that goodpath probability is very low when a large number of branches are outstanding. In other words, the scheduler and the machine's frontend have very high occupancy. This happens only if the machine has not seen a mispredicted branch for a long time. In this case, the branches that are fetched are more likely to be correctly predicted than estimated by PaCo, and hence, PaCo underestimates the processor's goodpath likelihood.

5 Applications

The previous section showed that PaCo is very accurate in estimating goodpath probability. In this section, we evaluate whether this accuracy translates into better performance (compared with conventional predictors) in two applications of path confidence: pipeline gating, and SMT fetch prioritization.

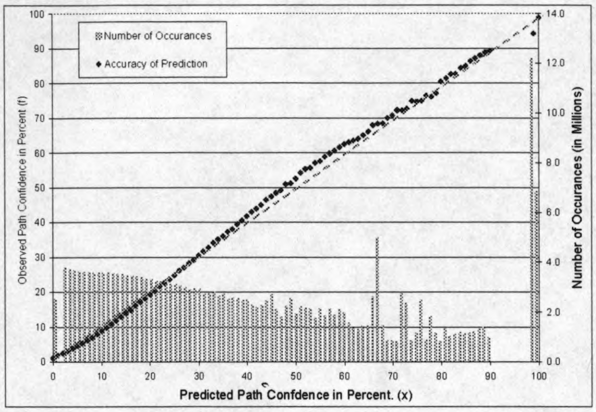
5.1 Pipeline Gating

About 27% of the total power consumed by a superscalar processor is spent on fetching and executing badpath instructions [3]. With multiple processing cores in a single die, reducing this wasteful power has become even more important. Manne et al. [14] proposed pipeline gating as a mechanism to reduce power spent on badpath instructions without reducing performance. Pipeline gating stops fetching instructions when the processor is very likely to be

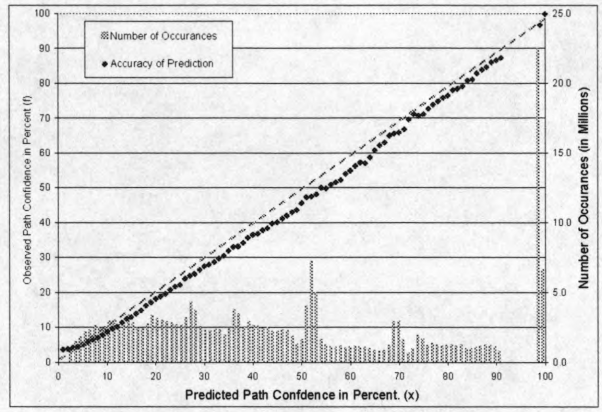
[6] An *instance* refers to an event that can possibly change path confidence. Two such events are fetching an instruction, and executing an instruction

[7] An oracle was used to find when the processor was on the goodpath

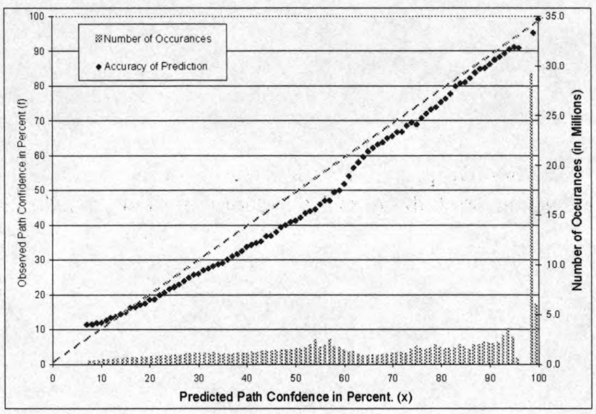
[8] The RMS error is refers to error in goodpath likelihood. An RMS error of 0.0377 implies that when the predicted goodpath probability is 0.20 or 20%, the real goodpath probability is expected to be in the range 0.20 +- 0.0377



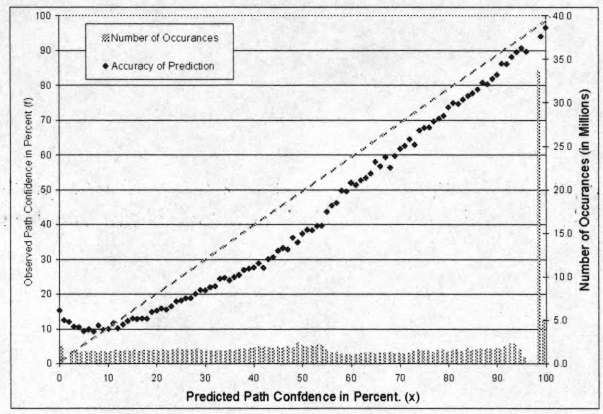
(a) twolf



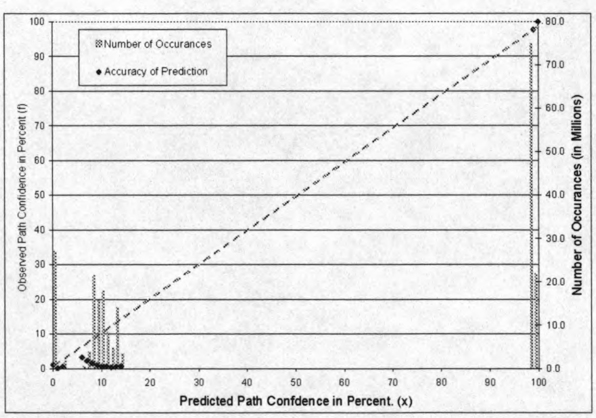
(b) vprRoute



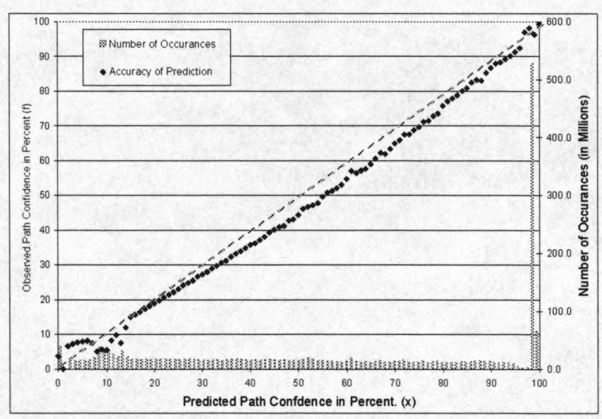
(c) crafty



(d) gcc



(e) perlbmk



(f) cumulative

Figure 9: Reliability Diagrams for a few benchmarks. Twolf and vprRoute show high correlation between observed and predicted probabilities (the graphs for mcf, parser, vortex and place look similar to these two). Crafty shows decent correlation (graphs for bzip2 and gzip are very much like crafty). Goodpath probability is somewhat less predictable for gcc (and for gap). Finally, Figure 9(f) shows data from all benchmarks put together, indicating that the PaCo predictor is accurate across a wide variety of behaviors.

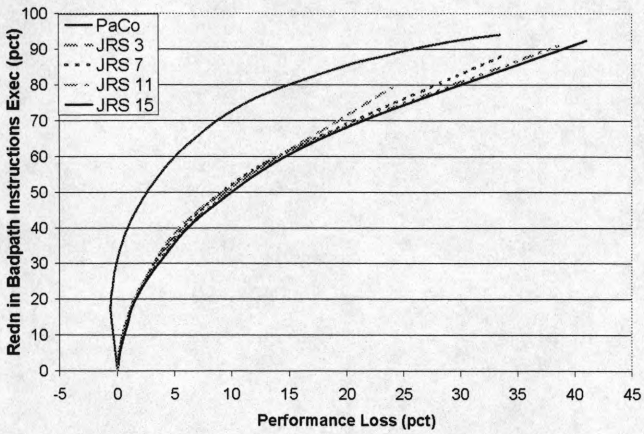


Figure 10: Pipeline gating. The x-axis plots performance loss (in percent) as gating becomes more aggressive. The y-axis shows the corresponding reduction in badpath instructions executed, also in percent.

on badpath, thereby reducing power consumption without significantly affecting performance. The mechanism used to estimate the processor's goodpath likelihood will have a strong effect on the effectiveness of pipeline gating. Conventionally, a count of low-confidence branches is used as an estimate of the processor's badpath likelihood. When this count is above a specified number (called gate-count), instruction fetch is turned off.

In this section, we evaluate the effectiveness of pipeline gating when using two different mechanisms to estimate path confidence: PaCo, and conventional counter-based predictors. To explore the entire design space for the counter-based approach, we performed experiments with four different JRS thresholds: 3, 7, 11 and 15. We also used a number of gate-counts for all these thresholds, from 1 to 10. For PaCo, instead of a gate-count, we specify a target goodpath probability, say 20%. When the predicted goodpath probability false below 20%, instruction fetch is gated. We evaluated different gating probability thresholds, from 2% to 90%, in increments of 4.

Figure 10 shows the results of our experiments, with performance reduction on the x-axis plotted against reduction in badpath instructions executed on the y-axis. The graph shows an average across all benchmarks. All confidence predictors start from the origin, which represents no gating. As we increase the gating probability for PaCo (or decrease the gate-count for conventional predictors below 10), we see increasing reductions in badpath instructions executed, and a corresponding reduction in overall performance. Interestingly, as we start gating with PaCo, performance improves slightly in the beginning. We found that badpath instructions often pollute the data-cache (as in the benchmark gap) and/or the branch-target buffer (BTB) (for example, in perlbmk). Gating very conservatively (at a goodpath probability of 10%, for example) gets rid of these pollution effects, and improves performance slightly, countering the reduction in goodpath instruction fetch. Note that this phenomenon is not seen in conventional counter-based predictors: the performance loss from gating goodpath instructions far outweighs any beneficial effects from reduced cache/BTB pollution.

Parameter	Value
Pipeline Width	8 instrs/cycle
Misprediction Penalty	At least 20 cycles
Reorder Buffer	512 entries
Functional Units	8 identical general purpose units
Number of threads	2

Figure 11: Pipeline Parameters in SMT mode.

Overall, the PaCo predictor does significantly better than threshold-and-count predictors. For example, the PaCo predictor (with a confidence gating threshold of 20%) can reduce badpath instructions executed by 32% with a 0.01% reduction in performance. In comparison, the best counter-based predictor (JRS threshold 3) can only reduce badpath instructions by 7% with a 0.2% loss in performance, which is similar to results in previous research [14] [2].

While a detailed power analysis is required to find how a one-third (32%) reduction in badpath instructions *executed* translates to a reduction in power, note that the reduction in the number of badpath instructions *fetched* is even higher(70%).With badpath instructions (including their fetch, rename, execute etc) consuming 27% of the total power [3], reducing their execution by a third should significantly reduce power consumption, without affecting performance.

5.2 SMT Fetch Prioritization

Luo et al. [12, 13] proposed a fetch prioritization mechanism for an SMT processor that allocates more fetch bandwidth to the thread that is more likely to be fetching goodpath instructions. We compared the PaCo predictor against conventional counter-based predictors in SMT fetch prioritization in an 8-wide SMT processor capable of executing two threads. Processor parameters are shown in Table 11. Other parameters are the same as the 4-wide processor shown in Table 6.

We executed 16 pairs of benchmarks in SMT mode for 100 million instructions. The SMT simulator that we use is incapable of executing parser. Every benchmark is executed in SMT mode with 3 other benchmarks (except for gzip, which is executed with 2 benchmarks). We use the *harmonic mean of weighted IPCs*, or HMWIPC as a measure of SMT performance. HMWIPC has become the metric of choice in SMT fetch prioritization [6] since it has been shown to balance throughput and fairness [13]. HMWIPC is defined in Equation 6, where N is the number of threads, $SingleIPC_i$ is the IPC of a $thread_i$ running by itself, and

IPC_i is the IPC of thread_i when the processor is in SMT mode.

$$\text{HMWIPC} = N / \sum_i (\text{SingleIPC}_i / \text{IPC}_i) \quad (6)$$

Figure 12 shows the performance of 16 pairs of benchmarks for a number of different fetch policies. We used 4 different JRS threshold-and-count predictors (with thresholds of 3, 7, 11 and 15). We compare these against a fetch prioritization scheme that uses PaCo to estimate path confidence. For reference, we also show the performance of the ICount [17]fetch prioritization scheme.

The figure demonstrates that PaCo does a better job than counter-based predictors at allocating fetch bandwidth to the thread that is more likely to fetch goodpath instructions. On average, PaCo shows a 5.4% performance improvement compared to the best counter-based predictor (JRS threshold 3). Figure 12 also indicates that among threshold-and-count predictors, while a threshold of 3 is the best for most applications, higher confidence thresholds sometimes perform better (e.g, gap-mcf). Since PaCo doesn't use a fixed threshold, it automatically adjusts to application behavior and beats the best among the JRS predictors for 14 out of 16 applications.

6 Related Work

All previous work in dynamic path confidence estimation has used a count of low-confidence branches as an indicator of goodpath likelihood.

Aragon[3] and Akkary [2] have proposed dividing low-confidence branches into two buckets, *very* low confidence, and just low-confidence. The branch prediction for very low confidence branches is often inverted [2]. While this technique somewhat alleviates the issue of treating all low-confidence branches as the same, it is unclear how a very-low-confidence branch should affect path confidence (recall that a low-confidence branch increases path confidence by 1). We show in this paper that the correct weight to add to the path confidence for any branch is the log of its mispredict rate.

There has been recent research in branch-confidence predictors based on perceptron [2], which was shown to be better than the enhanced JRS predictor. There has also been some work on 'hybrid' branch confidence predictors that combine branch confidence estimates from more than one predictor [9]. We consider branch confidence prediction to be orthogonal to our work: the PaCo predictor uses the branch-confidence predictor as a 'stratifier'. A better branch confidence predictor would simply provide a better stratifier, hopefully improving PaCo's accuracy.

In the context of pipeline gating, while the original mechanism proposed by Manne is an all-or-nothing mechanism (instruction fetch is completely turned off when more than gate-count low-confidence branches are pending), Aragon et al. [3] have proposed a more sophisticated version that *gradually* reduces instruction fetch bandwidth as the number of unresolved low-confidence branches increase. Gradual reduction of fetch bandwidth should work even better with PaCo, since PaCo gives very fine-grained information about path confidence (as opposed to a counter value provided by conventional branch confidence predictors).

With regard to SMT fetch prioritization, there have been a number of proposals [5] [6] that have been shown to be better than ICount, specially for applications that suffer a lot of cache misses (eg., SPEC floating point benchmarks). A path confidence based scheme that uses PaCo can complement these mechanisms, particularly when integer applications are being executed.

7 Conclusion

We showed that conventional threshold-and-count path confidence predictors do not consider branch misprediction rates, and thus, can lead to inaccurate path confidence estimates. We proposed PaCo, which directly predicts the probability that the processor is on the goodpath. To simplify hardware implementation, PaCo uses logarithms to eliminate the need for floating point multiplication and division, and instead uses integer addition and subtraction.

We found that the path confidence estimate derived from PaCo was very accurate, with a low RMS error. Finally, we showed that PaCo's high accuracy directly leads to much better performance than counter-based predictors in pipeline gating and SMT fetch prioritization.

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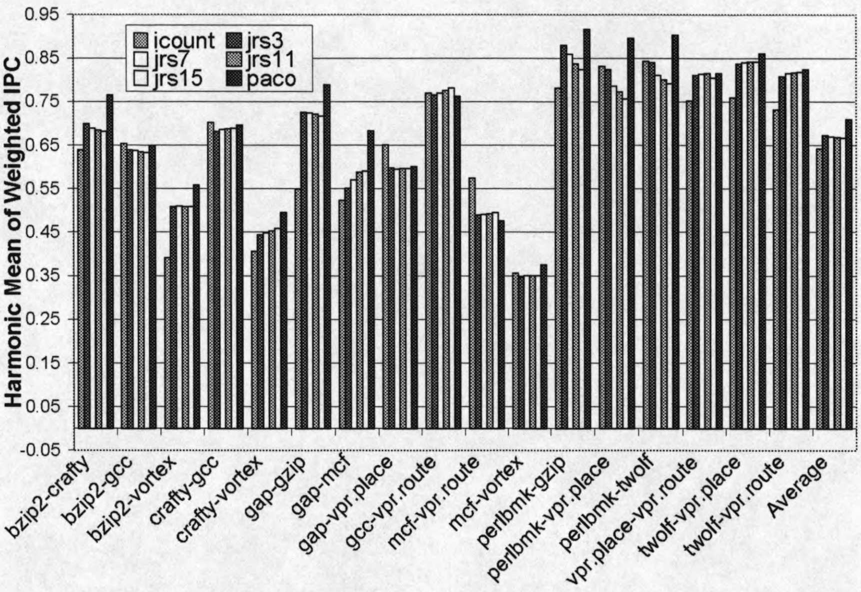

Figure 12: For SMT fetch prioritization, PaCo is better than threshold-and-count predictors.

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A Appendix

We assign a correct-prediction probability to a branch based solely on its MDC value. There are a number of other ways to estimate the misprediction probability for a particular branch. Instead of dynamically calculating the misprediction rate for each MDC value, one could statically assign probabilities to MDC values using profile information, an approach that we call *Static MRT*. This would remove the need for a log circuit, and counters to measure mispredict rates (i.e, the Mispredict Rate Table or MRT), at the cost of some loss in accuracy. Another more hardware-intensive and possibly more accurate technique would be to not use the MDC table at all. Instead, a per-branch mispredict rate table (indexed by a hash of the branch and the global history) is used to estimate the correct-prediction probability for a branch. Figure 13 pictorially shows these two approaches, while Table **??** shows the RMS error. The table indicates that the static MRT approach almost triples the RMS error, with only modest savings in hardware.

A per-branch MRT predictor performs significantly worse than dynamically measuring the mispredict rates of MRT buckets. While this result is surprising, we find that the reason for this is that the per-branch MRT predictor gives the same weight to mispredictions that happened recently, and mispredictions from the more distant past. For example, a branch P that has seen 1 mispredict followed by 100 correct predictions has the same mispredict rate as another branch Q that has seen 100 correct predictions followed by a mispredict; these two branches would be given the same weight w.r.t Path Confidence by a per-branch MRT predictor. However, we know from the work of Jacobsen [8] and Grunwald [7] that these two branches have very different predictabilities.

To summarize, measuring the correct-prediction probability of a branch by using the MDC value ensures that branches that have mispredicted in the recent past are assigned lower correct-prediction probabilities. In other words, PaCo uses the JRS table to leverage correlation information to better indicate the predictability of branches.

Benchmark	MRT	Static MRT	Per-branch MRT
bzip2	0.0545	0.0608	0.0850
crafty	0.0528	0.0498	0.1232
gap	0.0874	0.1103	0.0683
gcc	0.0830	0.1011	0.0770
gzip	0.0640	0.1180	0.2209
mcf	0.0447	0.0779	0.0850
parser	0.0415	0.0467	0.1023
perlbmk	0.0613	0.0389	0.0500
twolf	0.0175	0.3060	0.0739
vortex	0.0332	0.0981	0.8028
vprPlace	0.0244	0.0566	0.0453
vprRoute	0.0322	0.1059	0.0557
Mean	0.0377	0.1038	0.8895

Table 1: RMS error between Predicted and Actual Good-path Probabilities for different approaches to estimating correct-prediction probability of a branch.

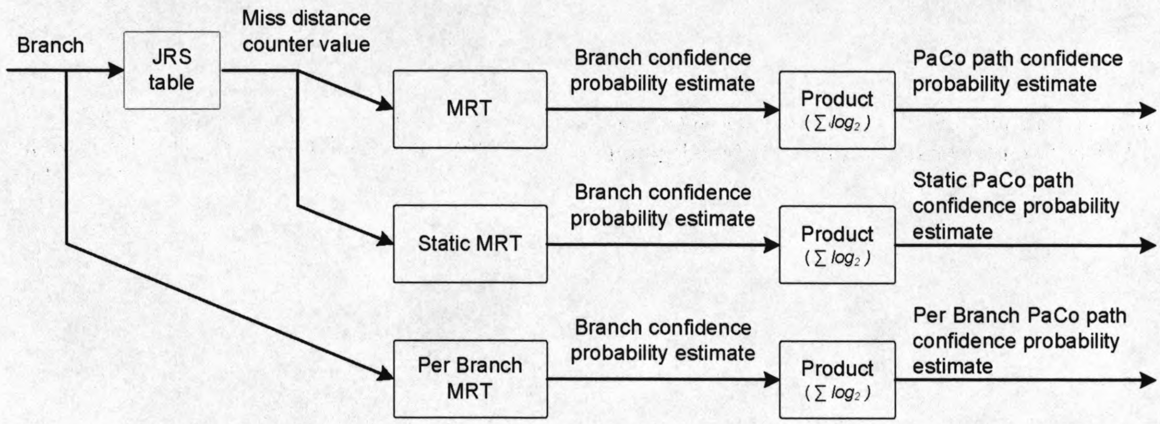

Figure 13: Alternative ways of measuring correct-prediction probabilities for a branch. Static MRT uses profiling to assign fixed probabilities to each MDC value. Per-branch MRT uses a per-branch table