

## Research Article

# An Efficient Segmental Bus-Invert Coding Method for Instruction Memory Data Bus Switching Reduction

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This paper presents a bus coding methodology for the instruction memory data bus switching reduction. Compared to the existing state-of-the-art multiway partial bus-invert (MPBI) coding which relies on data bit correlation, our approach is very effective in reducing the switching activity of the instruction data buses, since little bit correlation can be observed in the instruction data. Our experiments demonstrate that the proposed encoding can reduce up to 42% of switching activity, with an average of 30% reduction, while MPBI achieves just 17.6% reduction in switching activity.

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## 1. Introduction

Designs of portable consumer electronic devices such as mobile phones, PDAs, video games, and other embedded systems are increasingly demanding low power consumption to maximize the battery life, reduce weight, and improve reliability. These types of power sensitive devices are usually equipped with microprocessors as the processing elements and memories as the storage units. With current CMOS technology, a large portion of power consumption is consumed in the form of dynamic power, which in turn is determined by the bit switching and the switched load capacitance. (Leakage power becomes unneglectable in nanoscaled devices. However, leakage power optimization achieves better in low-leakage component design at the physical level, for which paper [1] can be a good reference. In this paper we mainly focus on dynamic power reduction at the system level of the off-chip bus.) Since the microprocessor fetches instructions over the memory bus every clock cycle and bus lines to memory are often much longer than buses within the processor, the power consumed by the bus due to instruction fetch is significant.

So far, research for the instruction data bus switching reduction has generally concentrated on code compression. The compressed code causes less memory access, thus

reducing the bus activity. Compression requires complicated compression/decompression units, which reside in the critical path and can considerably affect the overall system performance. In this paper, we investigate a different approach—bus encoding.

Most of existing bus encoding schemes are effective for address or data memory buses and mainly utilize correlations of transferred data. For example, T0 [2] and Gray encodings [3] use the temporal correlation of data on address buses, while the bus-invert encoding [4] exploits the spatial transition correlation among the data bits. We investigated the data on the instruction data buses and found that the bit switching behavior of the instruction data bus is different from those of the other types of buses. Figure 1 shows an experimental result of the bit transition probability for three different memory buses: instruction memory address bus (*imab*) instruction memory data bus (*imdb*) and data memory data bus (*dmdb*) (all over the 32-bit bus space of the SimpleScalar ISA [5]).

As can be seen from Figure 1, switching activity on the instruction address bus concentrates on the low section of bits, largely due to the sequential access of instruction memory. For the data memory data bus, the switching activity spreads over all bus bits with almost 50% switching probability. But for the instruction data bus, the switching

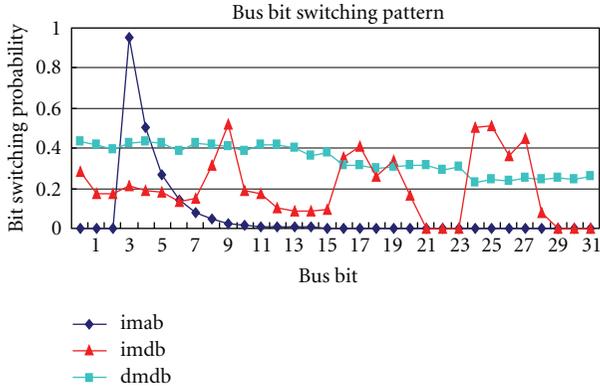


FIGURE 1: Bit switching probability of different buses.

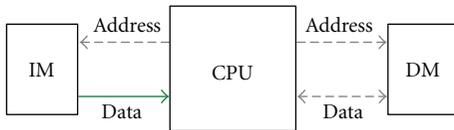


FIGURE 2: System architecture.

probability is not evenly distributed. Some bits show very low switching activity. Therefore, most of existing encodings for address buses and data memory data buses do not suit for encoding of the instruction data buses.

Since there are some bits on the instruction buses with high switching frequency, it is possible to use segmental bus-invert encoding—a set of bus segments are selected and to each segment the traditional bus-invert (BI) encoding is performed such that the bus switching activity can be reduced.

In this paper, we target a system consisting of a processor with Harvard architecture, where the instruction memory (IM) and the data memory (DM) are separated, and each memory has different buses for address and data transmission, as illustrated in Figure 2. We want to reduce switching activity on the instruction data bus, as highlighted in the solid bus line in Figure 2.

We further investigated the bit correlation of the instruction data and found that there is little correlation in the instruction data, as is illustrated by our experimental results shown in Figure 3, which gives the percentage of bit pairs of instruction data buses (and address buses for comparison) in different correlation coefficient ranges. The bigger the coefficient, the higher the correlation of a two-bit pair. The figure shows that over 80% of bits pairs on the instruction data bus are hardly correlated, with the correlation coefficient below 0.3. In comparison, the address bus data are highly correlated, with about 60% of the bus bit pairs having correlation coefficient over 0.3. Therefore, approaches that are based on the correlation of bit pairs are not effective for the instruction data bus switching reduction.

In this paper, we develop a segmental bus-invert (SBI) coding and a fast segment searching algorithm to effectively

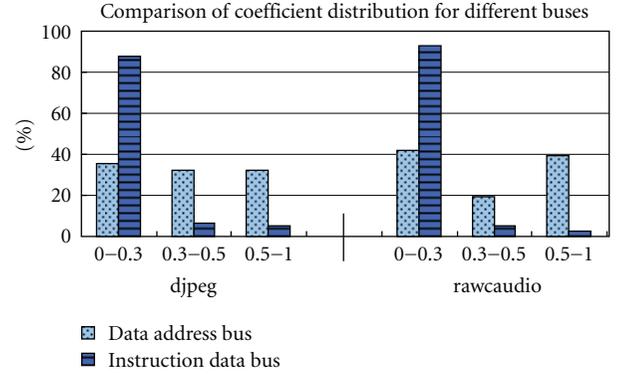


FIGURE 3: Bus bit correlation: instruction data buses versus address buses. X-axis: correlation coefficients range, Y-axis: percentage of bus bit pairs.

reduce the instruction data bus switching with as small hardware overhead as possible. Our main contributions are

- (1) an analytical model of bus switching reduction for bus segments with the bus-invert encoding,
- (2) an efficient segmental bus-invert approach that can achieve a high switching reduction for instruction data buses,
- (3) a fast segment search algorithm using the instruction-field based search space partition and the Hamming distance (HD) of bus segments.

The rest of the paper is organized as follows. Section 2 reviews some existing bus coding schemes for low-power system design. Section 3 analyzes the effect of bus-invert encoding on switching reduction and area cost, based on which we propose the segmental bus encoding design in Section 4. Section 5 presents the experimental setup, followed by the simulation results and related discussions. And finally, the paper is concluded in Section 6.

## 2. Related Work

Bus encoding techniques for low power consumption have been studied in the last couple of decades. The Gray encoding [3] was proposed for the instruction address bus where binary addresses are converted into Gray code for bus transmission. When instructions are sequentially executed, the address bus has only one bit flip per instruction.

Another approach [2] for address bus encoding is the asymptotic zero-transition activity encoding, known as T0. For the instructions of a program to be executed sequentially without any branches, T0 can ideally achieve zero bus switching. An extra control bus line for signalling sequential memory access and a local instruction address counter in memory are required in this encoding approach.

In [6], Henkel and Lekatsas presented an adaptive address bus encoding ( $A^2BC$ ) for low power address buses in the deep submicron design, where the coupling effects of bus lines were considered.

Stan and Burleson [4] proposed the bus-invert (BI) coding. This method uses either the original or the inverted value to encode the data bus. If the current value to be sent over the bus causes more than half of the bus bits to switch, its inverted value will be transferred on the bus. An extra invert control line is required to indicate whether the data are inverted or not. This approach achieves a good switching reduction if the transferred data are random and evenly distributed over the whole data range. For the wide data bus without evenly distributed random data, the same authors proposed a partitioned bus-invert coding, partitioning the wide bus into several narrow subbuses and applying the BI encoding to each subbus. This partitioning approach improves the switching reduction at the cost of extra invert control lines.

The partitioned bus-invert approach has been modified and proposed as partial bus-invert (PBI) coding [7] for the address bus. The approach selects and encodes a subgroup of bus lines that are correlated and frequently switched. In the same paper, they extended this approach to multiway partial bus-invert (MPBI), where highly correlated bus lines were clustered into multiple subbuses and each of them was encoded independently.

In [8], Ramprasad et al. presented an encoding framework where an encoding can be abstracted as a two-step process: decorrelating and encoding. Data to be transferred over the bus are first decorrelated for high entropy, which then leads to small encoding code and reduced bus bit switchings.

A dictionary-based approach to reduce data bus power consumption has been introduced in [9]. This approach exploits frequent data patterns detected from the application trace and uses two synchronized dictionaries on both sides of the bus. The dictionaries cache recently transferred data so that the same data that can be accessed in the local dictionary will not be transferred on the bus to reduce bus switching activity.

For instruction of bus power reduction, most previous researchers have focused on code compression. The pioneer work by Wolfe and Chanin [10] mainly aimed for program memory reduction. With their approach, the total bus switching activity can be reduced via compressed code that are transferred over the bus. A decompression unit is required to restore each instruction before execution.

Scheme in [11] also compresses instructions and compacts more compressed instructions into one bus word to reduce the total number of memory access, hence the total number of bus switches. This code compression scheme was extended in [12] to further reduce switching between consecutive instruction words.

Petrov and Orailoglu [13] introduced an instruction bus encoding, where the major loops are encoded and stored in the memory so that when they are fetched, the switching activity on the bus is minimized. This approach can achieve good switching reduction but requires a complex code transformation and control in the decoding logic.

In this paper, we propose a bus encoding for the instruction data buses. Our approach is similar to the PBI/MPBI approach in that we both apply the bus invert (BI) encoding

to a set of subbuses. But there exists a major difference: their approach to finding bus subsets for BI application is based on the data bit-pair correlations. We found that there is very little bit-pair correlation in the instruction data; therefore, their approach is not effective for the instruction data bus switching reduction. We propose a segment search algorithm based on Hamming distance to achieve a better result, as will be demonstrated in our results in Section 5.

### 3. Bus Invert Encoding

The effectiveness of our approach is closely related to the segments selected for the bus encoding. Therefore, we first study the effect of BI encoding on switching reduction and the hardware overhead, which leads to a search criteria for our design space exploration.

*3.1. Switching Reduction Rate with BI Encoding.* For a sequence of  $w$ -bit code words, assume that their Hamming distances are  $h_1, h_2, \dots, h_n$ ,

$$h_i = \sum_{j=1}^w s_{(i-1)j} \oplus s_{ij}, \quad i = 1, 2, \dots, n, \quad (1)$$

where  $n$  is the length of the code sequence,  $s_{ij}$  the  $j$ th bit of word  $i$  (denoted by  $s_i$ ) in the sequence, and  $\oplus$  the logic XOR operation.

Without any bus encoding, the total number of bit switches (SA) for the sequence of code after it is transferred on the bus is

$$SA = \sum_{i=1}^n h_i. \quad (2)$$

When BI is applied to this sequence, some words will be bit-inverted, if their Hamming distances are larger than  $w/2$ , the half of word width. The associated Hamming distances will be changed accordingly. For example, for a word,  $s_i$ , assume that its preceding word  $s_{i-1}$  has been inverted, then the new Hamming distance of  $s_i$  will be

$$\begin{aligned} \sum_{j=1}^w \overline{s_{(i-1)j}} \oplus s_{ij} &= \sum_{j=1}^w (1 \oplus s_{(i-1)j}) \oplus s_{ij} \\ &= \sum_{j=1}^w (1 - s_{(i-1)j} \oplus s_{ij}) \\ &= w - \sum_{j=1}^w s_{(i-1)j} \oplus s_{ij} \\ &= w - h_i. \end{aligned} \quad (3)$$

Therefore, when BI encoding is taken into account, the Hamming distance of a word,  $s_i$ , can be generalized as

$$\begin{aligned} H_i &= c_{i-1}(w - h_i) + (1 - c_{i-1})h_i \\ &= \begin{cases} h_i, & c_{i-1} = 0, \\ w - h_i, & c_{i-1} = 1, \end{cases} \end{aligned} \quad (4)$$

where  $c_{i-1}$  is the invert control of the previous transfer; when it equals 1, the previous transferred value is bit inverted. For the  $i$ th word transfer, the bit switching saving is  $(2H_i - w)c_i$ , which, from Formula (4), can also be written as

$$(2h_i - w)c_i. \quad (5)$$

Considering the switching from the invert control line, the bit switching saving from transferring word  $s_i$  is

$$(2h_i - w)c_i - c_i. \quad (6)$$

Therefore, the total bit switching saving for the sequence is

$$SA_{\text{save}} = \sum_{i=1}^n ((2h_i - w)c_i - c_i). \quad (7)$$

Based on Formulas (2) and (7), the switching reduction rate ( $r$ ) is

$$r = SA_{\text{save}}/SA = \frac{\sum_{i=1}^n ((2h_i - w)c_i - c_i)}{\sum_{i=1}^n h_i}, \quad (8)$$

where  $c_i = 1$ , when  $h_i > w/2$ ; otherwise,  $c_i = 0$ .

As can be seen from Formula (8), when the Hamming distance of each word in the sequence is close to the maximum value,  $w$ , (namely, the  $c_i$  of most words in the sequence is equal to 1 and  $h_i \rightarrow w$ ), the reduction rate is close to 100%. If the average HD,  $E(HD)$ , is around  $w/2$ , (i.e., about half of words having  $c_i$  equal to 1), the higher the deviation of HD,  $\text{Dev}(HD)$ , the larger the switching savings, hence the higher the reduction rate. If the average HD is small and  $E(HD) + \text{Dev}(HD) \leq w/2$ , (i.e., either small number of words having  $c_i$  equal to 1 and/or the HD of those words is close to  $w/2$ ), the reduction rate becomes very small. Therefore, we use

$$\delta = E(HD) + \text{Dev}(HD) \quad (9)$$

as a criterion parameter in searching instruction word segments for *BI* encoding. For a segment to be selected for *BI* encoding, we want  $\delta > w/2$  and  $\delta$  as big as possible.

**3.2. Bus-Invert Control Logic.** For each segment to be applied with bus-invert encoding, there needs to be some control logic for bus-invert operation as illustrated in Figure 4, where from an  $n$ -bit bus for instruction word transmission,  $w$  bit lines are applied with the bus-invert encoding. Note that the design can be extended to multiple bus segments, with each segment of a different width ( $w_i$ ) and a separate *BI* control line.

The logic checks whether the Hamming distance of current  $w$ -bit data value is larger than half of the segment size and determines the actual bus value to be transferred.

The logic circuit contains several computing components: a  $w$ -bit *inverter* (*INV*) to invert the input data value; a  $w$ -bit *register*, made of  $D$  flip-flops, to store previously transferred data; a  $w$ -bit *logic xor* ( $\oplus$ ) to find bit transitions; an *adder* (+) to calculate Hamming distance of data

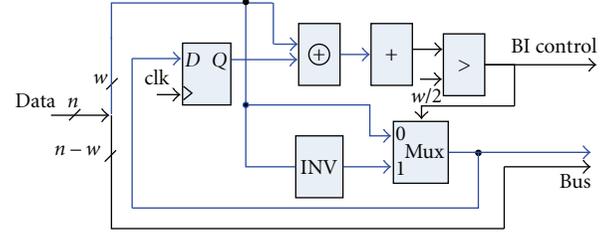


FIGURE 4: Bus invert logic.

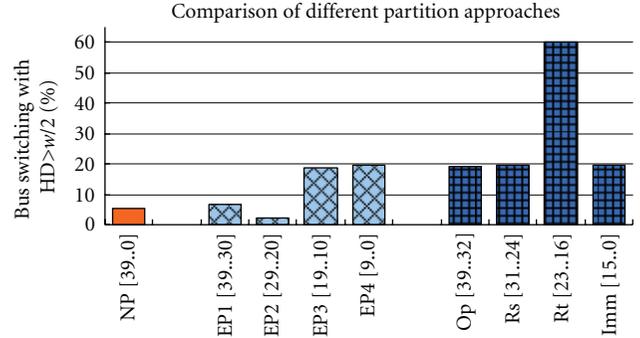


FIGURE 5: HD distribution of different partition methods for 40-bit instruction words.

transition on the  $w$  bit segment; a  $w$ -bit *comparator* ( $>$ ) to compare the Hamming distance with the half of the segment size; and a  $w$ -bit *multiplexer* (*Mux*) to choose between the inverted and uninverted data values.

The area of each component, except for the adder that has  $w \log(w)$  area complexity, is linearly proportional to the number of bits of the input data,  $w$ . Since the area of the adder increases dramatically when its input bit size becomes large, we want the segment size to be small. This will be used as a guide in our instruction word segment search algorithm discussed in the following section.

## 4. Approach for Segmental Bus-Invert Encoding

Full space search of multiple segments for optimal switching reduction is a time consuming process since there are a large number of possibilities. Just for choosing a single segment in an  $n$ -bit instruction space, the number of solutions is  $\sum_{i=2}^n C_n^i$  (note, the segment size can be varied, but at least 2 bits are required for *BI* encoding). These solutions will form a huge search space if  $n$  is large and the space increases exponentially with the word width,  $n$ .

Ideally, each solution in the space needs to be investigated for an optimal solution. To speed up the search process, we propose to partition the instruction word into several bit divisions and perform the *BI* segment search on each of the divisions. Since the segmental search is based on a set of narrower bus segments, its search space is much smaller than that on the full width bus; therefore, the search is fast.

```

get instruction execution trace for a given application;
find frequent basic blocks,  $\mathbb{B}$ ;
find instruction types,  $\mathbb{I}$ , in  $\mathbb{B}$ ;
determine divisions,  $\mathbb{P}$ , based on  $\mathbb{I}$ ;

```

ALGORITHM 1: Search space partition, *partition()*.

*Search Space Partition.* There are many ways for the instruction word bit space partition. We investigated the percentage of transferred segment words whose Hamming distance is greater than half the segment size (hence enabling BI operation to reduce bus switching), for three different partition cases: one, no partition (*NP*); two, evenly partitioned (*EP*); and three, partition based on the instruction fields. For the instruction set architecture used in our investigation, it includes four instruction fields: *Op*, *Rs*, *Rt*, and *Imm*.

The results are presented in Figure 5, where the bit range for a segment is given in the bracket. For the case without partition (hence only one segment), just 5% of bus transmissions have more than half of bus bits switching. In the case of the even partition, the bus is partitioned into four segments of an equal size, the percentage value for each segment is below 20%, on average, and only 10% of transmissions have the BI operation. With the instruction field-based partition, the segment size varies, but all four segments have a higher percentage of BI-enabled transmissions than other two cases, which allows for more bit switching reduction if BI encoding is applied. Thus we base our bit space partition on the instruction fields.

For an application, its execution can be represented with a connection of basic blocks. Instructions within a basic block are executed sequentially. Often, the switching activity is mainly determined by the frequently executed loop blocks (named as *dominant block* in this paper).

To find a partition, we use instruction types in the dominant blocks. Based on those types of instructions, fields that are sensitive to the input are grouped as one division, and the other fields are each treated as a separate division. The partition approach is summarized in Algorithm 1.

*BI Segment Search.* Given a space partition produced by Algorithm 1, we search for a bit segment for BI encoding (henceforth called *BI segment*).

For each bit space division, we investigate all bus segments of different sizes and locations. We use the leftmost bit of the segment to mark the segment location. For each location, we start from the smallest segment of a two-bit window; then we increase the window rightward by 1 bit to form a new segment. We compare the new segment with the one currently deemed as the best. If the following condition is satisfied:

$$\delta_{\text{new}} - \delta_{\text{best}} \geq \frac{(w_{\text{new}} - w_{\text{best}})}{2}, \quad (10)$$

namely, the extra  $w_{\text{new}} - w_{\text{best}}$  bits of the new segment will statistically increase the switching reduction, the new

segment is recorded as the best segment; otherwise, the new segment is discarded. After all possible window sizes are explored for a location, we continue with another segment location starting from the two-bit window again. This time, it is possible that  $\delta_{\text{new}} > \delta_{\text{best}}$  but  $w_{\text{new}} < w_{\text{best}}$  holds. In this case, the new segment with small size  $w$  but large  $\delta$  is always recorded as the best segment. This process is repeated until all possible cases are exhausted. The search approach is given in Algorithm 2. Note that the switching activity of invert control lines is taken into account for the final switching reduction rate.

*BI Segment Merge.* Since a BI segment requires an invert control line, an overhead for BI encoding, we want to merge some *BI segments* that are locally generated within different bit divisions, in order to save the control lines while keeping the same or improving switching reduction.

Figure 6 shows an example of merging two code segment sequences, Seg.1 and Seg.2. To calculate the bit switches, we assume that the initial value on the bus is the first word in the sequence. The bit switches are generated when the following words are sent over the bus. The number of bit switches with and without BI is given below each sequence in the figure. With BI encoding, no bit switching is saved for Seg.1; for Seg.2, five bits of switching are saved. If the two segments are merged (see Merged Seq. in the figure), eight bit switches can be saved; if we apply BI to the subset of the newly merged segment, as highlighted in the shaded area, a further 1 bit switching can be saved. Therefore, for each merge attempt, we rerun the segment search for the merged segment, using Algorithm 2.

Since the large segment may result in large invert control logic as discussed in Section 3.2, we start from small segments for the merge operation so that after merge we have as small number of segments as possible with each segment being not expensive. The merge approach is given in Algorithm 3.

## 5. Experimental Results

To examine the efficiency of our segmental bus-invert coding, we applied this approach to a set of applications from MiBench [14] and compared our approach with the most related encodings: traditional Bus-Invert [4], Partitioned Bus-Invert [4], Partial Bus-Invert [7], and Multiway Partial Bus Invert [7].

*Experimental Setup.* The experiment setup is given in Figure 7. To simulate our design for a given application, we use ASIPMeister [15] to generate a processor VHDL model as the experimental platform for the application. The SimpleScalar PISA [5] has been chosen as the target processor instruction set architecture. The instruction format of this architecture can be extended to 64 bits, but 40 bits are actually used in normal designs. Therefore, our simulations adopt the 40-bit instruction format.

The experiment starts with a given application written in C, which is compiled by the SimpleScalar tool and then

```

BI_seg =  $\Phi$ ;
for each partition,  $p \in \mathbb{P}$  do
   $\delta_{\text{best}} = 0$ ;
   $w_{\text{best}} = 2$ ;
  tmp_seg =  $\Phi$ ;
  for all bit_sub_set,  $bs(w) \in \mathbb{P}$  do
    get  $E(HD)$ ,  $DEV(HD)$  of  $bs(w)$ ;
     $\delta = E(HD) + DEV(HD)$ ;
    if  $\delta > w/2$  then
      if  $\delta \geq \delta_{\text{best}}$  then
        if  $w < w_{\text{best}}$  then
          tmp_seg =  $bs$ ;
           $\delta_{\text{best}} = \delta$ ;
           $w_{\text{best}} = w$ ;
        else if  $\delta - \delta_{\text{best}} \geq (w - w_{\text{best}})/2$  then
          tmp_seg =  $bs$ ;
           $\delta_{\text{best}} = \delta$ ;
           $w_{\text{best}} = w$ ;
        else
          discard  $bs$ ;
        end if
      else
        discard  $bs$ ;
      end if
    else
      discard  $bs$ ;
    end if
  end for
  BI_seg = BI_seg  $\cup$  tmp_seg;
end for
apply BI on BI_seg;
 $r = \text{get\_switching\_reductio\_rate}$ ;

```

ALGORITHM 2: BI segment search, segSearch ( $\mathbb{P}$ ).

```

red_best =  $r$ ;
sort segments BI_seg  $\in \mathbb{S}$  in the size-ascending order [ $\text{seg}_0, \text{seg}_1, \dots, \text{seg}_{n-1}$ ];
for ( $i = 0$ ;  $i < n - 1$ ;  $i++$ ) do
  for ( $j = i + 1$ ;  $j < n$ ;  $j++$ ) do
     $\text{seg}_k = \text{seg}_i \cup \text{seg}_j$ 
     $P = (\text{BI\_seg} - \text{seg}_i - \text{seg}_j) \cup \text{seg}_k$ ;
    segSearch ( $P$ );
    if  $r \not\leq \text{red}_{\text{best}}$  then
      BI_seg =  $P$ ;
      segMerge (BI_seg);
    end if
  end for
end for

```

ALGORITHM 3: BI segment merge, segMerge ( $\mathbb{S}$ ).

simulated on the processor VHDL model generated by ASIPMeister. The instruction trace over the instruction data bus is extracted during the simulation. This instruction trace is used to determine the bus segments for BI encoding based on our encoding design approach proposed in Section 4. The related BI encoding/decoding and control logic is then implemented in the processor VHDL model, which is then

synthesized by Synopsys Design Compiler for area, delay, and power overhead evaluation based on the Tower 0.18-micron standard cells [16].

*Bus Switching Reduction.* Table 1 gives the simulation results obtained for the conventional BI coding (and its extended

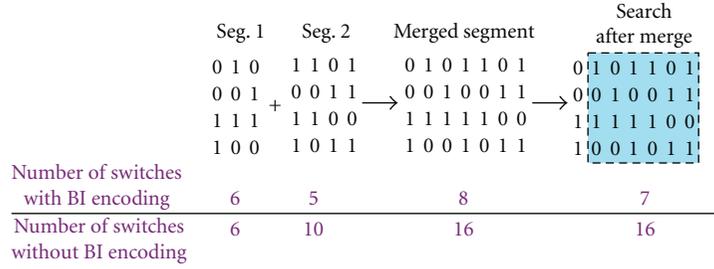


FIGURE 6: Merge example.

TABLE 1: Results for Bus Switchings Reduction.

Application	Total switches	Switches/insn.	BI %Red.	Parti. BI ( $S = 48$ )		PBI ( $I = 1$ )		MPBI			SBI		
				%Red.	$I$	%Red.	$S$	%Red.	$S$	$I$	%Red.	$S$	$I$
crc32	19675453	10.1	0.2	10.1	24	14.9	9	19.4	20	3	22.7	21	3
dijkstra	89941656	11.5	5.1	15.6	12	16.3	15	24.8	28	4	35.8	20	3
qsort	88290717	10.3	6.5	21.4	24	15.0	26	23.7	28	3	42.1	17	3
cjpeg	115662171	14.0	4.2	13.8	12	7.1	8	13.1	28	3	31.9	19	3
djpeg	19505584	9.5	4.6	16.6	12	6.6	7	17.2	32	4	22.5	20	3
rawcaudio	23261730	10.0	1.7	12.6	24	10.9	12	11.0	32	4	33.9	12	2
rawaudio	20425528	10.5	6.5	14.3	12	10.8	15	16.6	30	3	32.5	23	3
rijndael	92029948	10.1	2.3	17.1	12	8.1	7	15.2	33	4	22.3	21	3
stringsearch	4820331	11.4	6.6	17.0	12	13.1	25	18.6	27	4	34.6	24	4
yuv420torgb	191314971	8.4	3.1	10.9	12	9.6	25	16.1	24	4	24.7	15	2
Average	66492809	10.6	4.1	14.9	15.6	11.2	15	17.6	28	4	30.3	19	3

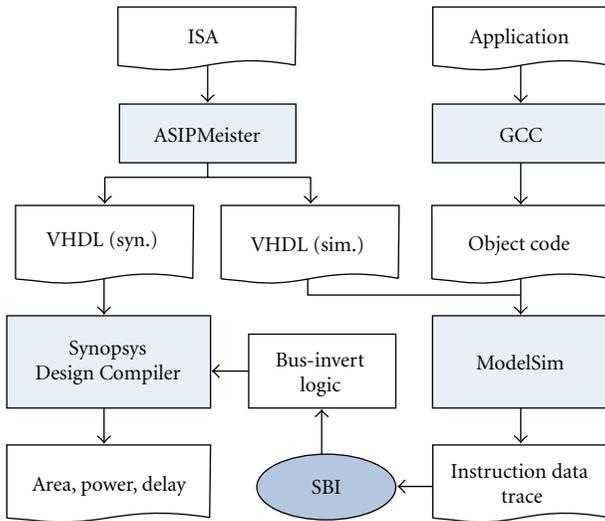


FIGURE 7: Experimental setup.

partitioned BI), the PBI coding (and its extended MPBI), and our proposed SBI coding approach, for each application listed in Column 1.

Columns 2 and 3 provide the number of total bit switches and the average switching bits per instruction for each application without any bus encoding. The percentage of the

switching reduced with the traditional bus-invert encoding (BI) is presented in Column 4. We explored different bus partitions based on the approach proposed in [4]; the best result for each application is shown in Columns 5 and 6 (see label Parti. BI in the table). The switching reduction data from the Partial Bus-Invert encoding (PBI) and Multiple Partial Bus-Invert (MPBI) encoding are shown in Columns 7 and 8, and Columns 9–11, respectively, where %Red stands for the switching reduction rate,  $I$  the number of invert control bus lines incurred, and  $S$  the total number of bus lines to which the the bus-invert encoding is applied. Columns 12–14 give the simulation results from our encoding approach (SBI).

From Table 1, we can see that the traditional BI encoding achieves very little switching reduction (on average, only 4.1%). This ineffectiveness can also be seen from the other existing encodings: with average reduction rates from Partitioned BI, PBI, and MPBI being 14.9%, 11.2%, and 17.6%, respectively; for some application, the reduction rate is as small as just 7.1%. By using our segmental bus-invert encoding approach, however, we can achieve from 22.3% up to 42.1% switching reduction. On average, 30.3% bus switching can be reduced with SBI.

In addition, Column 3 in Table 1 shows that an average of 10 bus bits switches per instruction, which indicates that, on average, the number of total bits to be effectively applied with bus-invert should be around 20. This is because, as already explained right after (2), only when the Hamming

TABLE 2: Area, power, and delay overheads of PBI, MPBI, and SBI VLSI implementation.

Applications	PBI			MPBI			SBI		
	area ( $\mu\text{m}^2$ )	power (mW)	delay (ns)	area ( $\mu\text{m}^2$ )	power (mW)	delay (ns)	area ( $\mu\text{m}^2$ )	power (mW)	delay (ns)
crc32	409	0.30	2.14	1107	1.44	2.40	1114	1.11	1.95
dijkstra	517	0.69	1.81	1488	1.95	1.85	1105	1.52	1.64
qsort	709	1.15	1.87	1266	2.03	2.14	1053	1.27	2.14
cjpeg	393	0.28	2.14	1250	1.62	1.97	1087	1.09	2.14
djpeg	371	0.30	1.95	1545	2.16	2.01	1104	1.39	2.14
rawaudio	463	0.44	1.44	1562	2.36	2.35	711	0.74	1.95
rawaudio	517	0.69	2.86	1297	1.73	1.79	1159	1.35	1.85
rijndael	371	0.37	1.95	1478	1.75	2.57	1120	1.24	2.35
stringsearch	693	1.06	1.95	1482	2.39	1.78	1371	1.66	1.95
yuv420torgb	693	1.05	1.95	1419	2.38	1.72	767	1.07	2.57
Average	514	0.63	2.01	1389	1.98	2.06	1059	1.24	2.07

distance is larger than the half of bus width, bus-invert can be performed to have the switching activity reduced effectively. This is reflected by our SBI encoding, where  $S$  equals 19. In contrast, the average number of bits applied by BI in MPBI and PBI is either relatively too high ( $S = 28$ ) or too small ( $S = 15$ ), reducing chances for BI operation and the switching saving from each BI inversion.

Furthermore, looking at the control lines incurred from each encoding, the table shows that the Partitioned BI is most expensive, requiring an average of 15.6 invert-control lines; in contrast, few control lines are required by the other encodings, including SBI.

*BI Control Logic Overheads.* Switching reduction is achieved at the cost of not only extra control lines but also the associated control logic for each BI segment, thus incurring in area and power overheads. As BI and Partitioned BI either have extremely low switching reduction efficiency or incur too many invert control bus lines which are impractical for the real design and not suitable for the instruction data bus switching reduction, we only compare PBI and MPBI with our approach for encoding/decoding logic overhead in terms of area (in  $\mu\text{m}^2$ ), power (in mW), and delay (in ns) in Table 2, where the area and power values are the total cost, and the delay is the longest delay, of all BI segments for an encoding.

As can be seen from Table 2, PBI is the cheapest and MPBI is the most expensive in terms of area and power. The three encodings have a similar delay incurred from their control logic. Considering their switching reduction rate presented in Table 1, SBI achieves considerable switching reduction at a lower cost than MPBI with respect to area and power. Among the three encodings, PBI is the cheapest to encode, but it is also the least effective.

*Power Savings Estimation.* We use the following formula to estimate the net power savings of SBI, PBI, and MPBI encodings:

$$P_{\text{save}} = 0.5 * C_{\text{bus}} * V_{\text{dd}}^2 * f * (\text{switch./insn.}) * \text{Red\%} - P_{\text{logic}}, \quad (11)$$

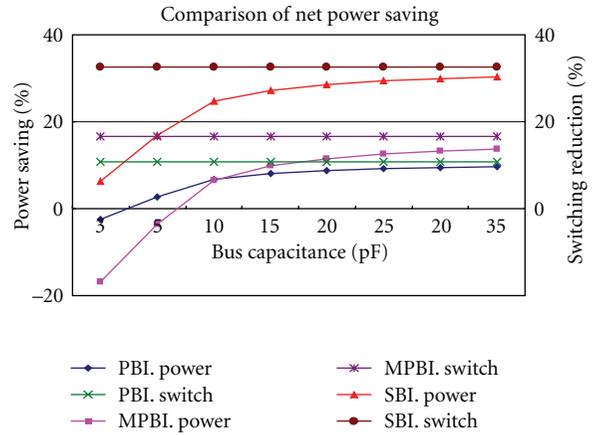


FIGURE 8: Estimated power saving over different bus capacitances.

where  $C_{\text{bus}}$  is the bus load capacitance,  $V_{\text{dd}}$  the supply voltage,  $f$  the frequency, (switch./insn.) the switched bus bits per instruction, Red% the switching reduction rate, and  $P_{\text{logic}}$  the encoding/decoding logic power consumption estimated with the Design Compiler.

The bus capacitance varies with the system architecture and low-level implementation. The load capacitance of the off-chip bus is normally multiple orders of magnitude higher than that of standard cells. Based on the 0.3 pF standard cell capacitance, the supply voltage (1.8 V), and clock frequency (100 Mhz) used in Synopsys DesignPower, we calculate the power savings with different bus capacitances ranging from 3 to 35 pF. We use the *rawaudio* application as an example in this investigation, and the results are plotted in Figure 8.

From the figure, it can be seen that SBI brings higher savings than the other two encodings. With increase of the bus capacitance, the power saving of each encoding reaches to their switching reduction rate, as depicted by the horizontal lines in the figure. For example, when we conservatively assume 30 pF as load capacitance of the off-chip bus, 9.5%, 13.2%, and 29.9% of the total dynamic

power consumption of the instruction data bus can be saved by coding of PBI, MPBI, and SBI, respectively. However, when the bus capacitance is decreased to a certain value (e.g., 3 pF or 10 times of the cell capacitance), SBI still has a power saving of around 6.3%. But for PBI and MPBI, power overhead of the encoding/decoding logic will cancel out the power saving from the bus switching reduction. If we further scale the capacitance value down to around 2 pF and below, it turns out that the logic overhead incurred brings the power savings to negative values in all PBI, MPBI, and our proposed SBI, as the power curves indicate. This means that bus encoding schemes have some limitations and are not always effective for the on-chip buses especially when the bus capacitance is very small. On the other hand, the load capacitance of the off-chip buses are usually very high, and when they reach two orders of magnitude larger than that of on-chip cells, the power reduction rate can be approximately the same as the bus switching activity reduction rate.

Note that our results of power saving by all the bus invert schemes are based on the 180 nm technology, where the dynamic (switching) power is dominant. As technology scales down, leakage power may become significant. However, a large portion (50% for the current 90 nm down to 45 nm technologies) of power still comes from the dynamic power [17]; effective power reduction by bus switching reduction can still be expected.

## 6. Conclusions

In this paper, we have discussed the switching reduction of the instruction memory data bus for lower power processor-based systems with the Harvard architecture.

We found that the data on the instruction data bus have little temporal correlation, and the randomness of the data can be hardly exploited by the existing bus encodings due to its unevenly bit switching distribution. We proposed a segmental bus-invert encoding that can take the simplicity of the encoding approach and at the same time effectively reduce bus switching activity.

Our encoding idea is similar to the multiway partial bus invert. But we use a different search algorithm for bus segments so that by applying the bus invert encoding to each of the segments, we can achieve an average 30% switching reduction on a set of benchmarks, in contrast to the 17.6% obtained by MPBI. The power consumption reduction rate can be achieved approximately the same accordingly when the load capacitance of the off-chip bus reaches two orders of the magnitude of the on-chip cell-capacitance. In addition, compared to the traditional bus invert encoding, our approach comes with the reduced area for encoding/decoding logic, with an average of two more extra control lines. In contrast, MPBI requires three additional bus control lines.

We would restate that the experiment results presented in the paper were based on the designs for individual applications. Our design approach can be extended to find a fixed SBI design for a set/domain of applications, which

may be a practical design issue and will be investigated in the future.

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