Coupling Reduction Analysis of Bus-Invert Coding

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***Abstract*—Theoretical analysis of bus-invert coding for reducing switching activity was previously investigated. In this paper we conduct a theoretical analysis of this method for coupling reduction. Closed-form formulas are derived to compute the number of couplings per bus transfer for a non-partitioned versus a partitioned bus. Our contribution complements the work done previously and helps establish a sound theoretical foundation for bus-invert coding.**

I. INTRODUCTION

Due to significant capacitive coupling between two adjacent lines in deep submicron process technologies, many approaches have been proposed to alleviate bus energy loss and extra bus delay due to coupling. Among them, bus encoding has been widely investigated. In the past, bus encoding focused more on reducing switching activity [1-4]. Recently, many coupling reduction methods have been proposed to lower the energy dissipation or eliminate crosstalk-induced delay. They can be mainly classified into three categories. The methods in the first category [5-9] completely eliminate worst crosstalk coupling (a wire switching oppositely against its two neighboring wires) in order to get rid of crosstalk-induced delay. The methods in the second category [7, 10-17] re-arrange wiring layout for reducing coupling energy based on a priori knowledge about bus switching behavior. These methods can be best applied to an instruction address bus. Those in the third category [18-22] focus on coupling energy reduction without a priori information. In [22], the authors also derive a formula to compute energy dissipation per bus transfer for a given mapping of code words.

Many of the aforementioned methods have either included bus-invert coding [1,2] as a part of the methods or used it as a basis for performance comparison. Bus-invert coding was first proposed by Fletcher [1], later elaborated by Stan and Burleson [2, 3], and recently theoretically analyzed by Lin and Tsai [23]. The previous analysis performed by Lin and Tsai mainly focuses on switching activity and weight reduction. In this paper, an in-depth theoretical analysis was performed for coupling reduction. The main theoretical results included some closed-form formulas for computing the number of couplings on a partitioned and a non-partitioned bus. Using these results along with those presented in [23], we could obtain the following facts:

- Coupling reduction percentage with respect to an un-encoded bus first increases, culminates at 17.5% with a 6-bit bus, and then decreases with increasing bus width.
- Bus energy reduction percentage does not vary noticeably with the ratio of coupling capacitance to self-capacitance when bus width is larger than eight.
- Partitioning a bus into a number of smaller buses, each of which is encoded independently, also brings more coupling reduction. Partitioning a bus into many 2-bit buses results in most coupling reduction.
- Partitioning a bus into smaller buses, each of which has odd number of bits, is not a viable approach to coupling reduction.
- The expected number of couplings per bus transfer on a partitioned bus with clustered invert lines is equal to that with distributed invert lines.

The rest of the paper is organized as follows. Section II gives an overview of energy dissipation on coupled bus lines, bus-invert coding, and the limited-weight code. Section III describes how we derive closed-form formulas for computing couplings. Section IV discusses how energy reduction could vary with bus width and the ratio of coupling capacitance to self-capacitance and examines to what extent energy reduction could be brought about through partitioning a bus. The last section draws a conclusion.

II. PRELIMINARY

A. Bus Line Energy Dissipation

The energy dissipation on a non-terminated line i of an n-bit bus can be formulated as follows:

$$E_i = E_{is} + E_{ic} \qquad (1)$$

where E_{is} and E_{ic} are the energy dissipation due to self-capacitance and coupling capacitance of line i, respectively. *To ease the problem formulation, we assume that E_{ic} for line i includes only the energy dissipation due to the coupling capacitance to line $i+1$.* Although the energy dissipation due to the coupling capacitance to line $i-1$ is not counted in E_{ic}, it will be included in $E_{(i-1)c}$. Herein, the coupling for a particular line i always means the coupling between lines i and i+1. We assume that all bus lines have the same self-capacitance C_s, all-pairs of adjacent lines have the same coupling capacitance[1] C_c, and all signal changes appear on the bus lines at the same time. For $0 \le i \le n-2$,

a). $E_{ic} = 0$ if lines i and i+1 have no transitions or both have transitions in the same direction.

b). $E_{ic} = 0.5\,C_c V^2$ if either line i or i+1 has a transition.

c). $E_{ic} = 2\,C_c V^2$ if lines i and i+1 both have transitions in the opposite direction.

Here V is the voltage swing on the bus. We assume $E_{(n-1)c} = 0$ for line $n-1$. If we define a coupling as an occasion dissipating an

[1] In fact, the left-most (right-most) bus line would have larger self-capacitance than the lines in the middle if it does not have any close neighbors on its left (right) side. Our study also shows that for wires with a large height/width ratio, the coupling to the second nearest line from the line of interest is very small.

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amount of energy equal to $0.5 C_c V^2$, then the number of couplings is 0 for case (a), 1 for case (b), and 4 for case (c). E_{is} can be 0 or $0.5 C_s V^2$ depending on whether there is a transition on line *i*. Then, the energy dissipation of a bus per bus transfer is

$$\xi = \sum_{i=0}^{n-1} E_i \tag{2}$$

Assume $C_c = \lambda C_s$. Then, computing ξ is equivalent to counting the couplings per bus transfer. Although we can easily obtain ξ for a given datum, we are interested in the expected value of ξ.

B. Bus-Invert Methods and Limited-Weight Code

Here we investigate Hamming-distance-based (*HDB*) and weight-based (*WB*) bus-invert methods [23]. We assume that the invert line is numbered as line *n* and placed next to line $n-1$. The *HDB* approach computes the Hamming distance H_d between the next data value and the present bus value (*including the invert line*). The data value is inverted for transmission and the invert line is set to 1 if $H_d > \lfloor n/2 \rfloor$. Otherwise, the data value is unchanged and the invert line is set to zero. To facilitate our discussion, some results from [23] for *HDB* are given below.

For even bus width n:

$$p_v = p_b = \frac{1}{2} - 2^{-(n+1)} C\left(n, \frac{n}{2}\right). \tag{3}$$

$$N(n) = (n+1)\left(\frac{1}{2} - 2^{-(n+1)} C\left(n, \frac{n}{2}\right)\right) \tag{4}$$

For odd bus width n:

$$p_v = 0.5; \quad p_b = \frac{1}{2} - 2^{-n} C\left(n-1, \frac{n-1}{2}\right) \tag{5}$$

$$N(n) = \frac{n+1}{2} - n\, 2^{-n} C\left(n-1, \frac{n-1}{2}\right) \tag{6}$$

where $p_v > 0$ and $p_b > 0$ are the transition probability of the invert line and a bus line, respectively. $N(n)$ is the total number of signal transitions per bus transfer.

The *WB* approach [23] works essentially the same as the *HDB* approach except that the weight of the *next data value*, which is the number of 1's on the next data value, is used to decide whether a data value should be inverted before transmission.

Limited-weight codes (*LWC*s) [2,3] play an important role in deriving closed-form formulas for computing the number of couplings per bus transfer. The *HDB* approach generates code words in terms of *transition signaling*. The weight of a code word is the number of 1's in the code word. A perfect (*k*, *l*) *LWC* consists of all the code words whose length is *l* and whose weights are smaller than or equal to *k*. TABLE I gives the *LWC* generated by the coding process with $n = 4$. Note that the right most bit in a code word is generated by the invert line. The *WB* approach generates code words in terms of *level signaling*. The code words for even bus width are identical to those generated by the *HDB* approach. For example, the code words shown in Table 1 are also the ones generated by the *WB* approach for $n = 4$.

III. BUS COUPLING CHARACTERISTICS

A. Coupling Characteristics of an Un-encoded Bus

Herein, we assume that the un-encoded data are spatially and temporally independent and uniformly distributed. Based on this assumption, we have the following theorem.

Theorem 1: *The expected number of couplings on an un-encoded n-bit bus per bus transfer is*

$$M(n) = n - 1. \tag{7}$$

TABLE I. A PERFECT (2,5) LWC WITH $n = 4$.

00000	00001	00010	00100	01000	10000	00011	00101
01001	10001	00110	01010	10010	01100	10100	11000

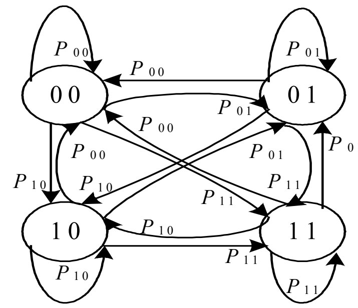

Figure 1. A four-state Markov chain.

To prove this theorem, we first compute the probability $P(X_i)$, i.e., the probability of line *i* with X_i couplings. X_i can be either 0, 1, or 4. For any lines *i* and *i*+1 with $i < n-1$, we can create a four-state Markov chain shown in Fig. 1. States 00, 01, 10, and 11 represent the logic values of the two bus lines being 00, 01, 10, and 11, respectively. The transition probabilities from one state to another are $P_{00} = P_{01} = P_{10} = P_{11} = 0.25$. Hence, each state probability in steady state is 0.25. Therefore,

$$P(X_i = 0) = 0.375,\ P(X_i = 1) = 0.5,\ P(X_i = 4) = 0.125. \tag{8}$$

Consequently, the expected number of couplings on line *i* per bus transfer is equal to 1 and Theorem 1 thus follows.

B. Coupling Characteristics of HDB Approach

Here, we want to find the *expected* number of couplings per bus transfer for even bus width. This can be done by summing up the expected number of couplings on all the lines. Hence, we have to compute $P(X_i)$ for $0 \le i \le n-1$. To compute $P(X_i = 1)$, we count the number of the code words whose bit values at the i^{th} and $(i+1)^{th}$ positions are either 0 and 1 or 1 and 0, and then divide this number by the total number of code words. For example, in TABLE I, the number of distinct code words starting with 01 or 10 is 8 and thus $P(X_0 = 1) = 0.5$. Similarly, we can compute $P(X_i = 4)$ by considering only the code words whose bit values at the i^{th} and $(i+1)^{th}$ positions are 1's. For example, $P(X_i = 4) = 1/32$ for the code words shown in TABLE I. Since the code words for even *n* form a *perfect* $(n/2, n+1)$ *LWC* and occur with equal probability, we have for each line $0 \le i \le n-1$

$$P(X_i = 1) = 2\sum_{h=0}^{n/2-1} C(n-1, h)\, 2^{-n} = 0.5 \tag{9}$$

$$P(X_i = 4) = 2^{-3} - 2^{-n-1} C\left(n-1, \frac{n}{2} - 1\right) \tag{10}$$

$$P(X_i = 1) + 4P(X_i = 4) = 1 - 2^{-n+1} C\left(n-1, \frac{n}{2} - 1\right) \tag{11}$$

The h^{th} term in the series of (9) counts the number of code words, each of which has 0 and 1 (or 1 and 0) respectively at the i^{th} and $(i+1)^{th}$ positions and has *h* 1's at the other $n-1$ positions. Equation (10) is obtained in a similar way.

Theorem 2: *The expected numbers of couplings per bus transfer with even bus width n for the HDB approach is*

$$M(n) = n - n\,2^{-n+1} C\left(n-1, \frac{n}{2}-1\right) \quad (12)$$

Similarly, we have the following theorem for odd bus width.

Theorem 3: *The expected number of couplings per bus transfer with odd bus width n for the HDB approach is*

$$M(n) = n - (2n-1)2^{-n} C\left(n-1, \frac{n-1}{2}\right) \quad (13)$$

C. Coupling Characteristics of WB Approach

An approach similar to that for an un-encoded bus can be used to derive the number of couplings for the weight-based approach. Due to space limitation, only the results are presented.

Theorem 4: *The expected number of couplings per bus transfer with even bus width n for the WB approach is*

$$M(n) = n. \quad (14)$$

Theorem 5: *The expected number of couplings per bus transfer with odd bus width n for the WB approach is*

$$M(n) = n + 8\left(2^{-n-1} C\left(n-1, \frac{n-1}{2}\right)\right)^2. \quad (15)$$

D. Coupling Characteristics of a Partitioned Bus

Here, we would like to investigate to what extent partitioning would help reduce couplings. Suppose the bus lines are partitioned into k equal-sized groups, each of which has $m = n/k$ lines. We consider two possibilities of placing the invert lines. One is to place an invert line immediately next to the right most line in the underlying group as shown in Fig. 2 (left). In this case, the invert lines are said to be distributed among bus groups. The other is to cluster all the invert lines on the right of the k^{th} groups as shown in Fig. 2 (right). We will deal with only the *HDB* approach for it being more effective in reducing couplings.

To obtain the expected number of couplings for a partitioned bus with distributed invert lines, it is yet to know the expected number of couplings between the invert line of group j and the first bus line of group j+1. Since groups are independent of each other, the expected number of couplings can be derived using (3) and (5), i.e., the transition probabilities of the invert line of group j and the first bus line of group j+1. A Markov chain as shown in Fig. 1 with the state transition probability matrix given in (16) can be made to model the transition behavior of the two lines.

$$\begin{array}{c} \\ 00 \\ 01 \\ 10 \\ 11 \end{array} \begin{array}{c} \begin{array}{cccc} 00 & 01 & 10 & 11 \end{array} \\ \begin{bmatrix} (1-p_v)(1-p_b) & (1-p_v)p_b & p_v(1-p_b) & p_v p_b \\ (1-p_v)p_b & (1-p_v)(1-p_b) & p_v p_b & p_v(1-p_b) \\ p_v(1-p_b) & p_v p_b & (1-p_v)(1-p_b) & (1-p_v)p_b \\ p_v p_b & p_v(1-p_b) & (1-p_v)p_b & (1-p_v)(1-p_b) \end{bmatrix} \end{array} \quad (16)$$

Hence, the expected number of couplings between the invert line of group j and the first bus line of group j+1 is simply

$$M_p = p_b + p_v. \quad (17)$$

Theorem 6: *The expected number of couplings per bus transfer on an n-bit bus which is partitioned into k groups with distributed invert lines is*

$$M(n,k) = kM(m) + (k-1)M_p \quad (18)$$

Similarly, we can find out the expected number of couplings per bus transfer for a partitioned bus with clustered invert lines. It is surprising that we have the following theorem.

Theorem 7: *The expected number of couplings per bus transfer on a partitioned bus with clustered invert lines is equal to that on a partitioned bus with distributed invert lines.*

IV. Discussions

A. Coupling Reduction

Fig. 3 gives the average number of couplings per pair of lines per bus transfer in terms of bus width. Because the *WB* approach can not reduce couplings, the discussion in the sequel will solely center around the *HDB* approach. Fig. 4 presents the percentage of transition reduction and coupling reduction on the whole bus per bus transfer with respect to an un-encoded bus. Coupling reduction first increases, reaches its maximum of 17.5% for n=6, and then decreases with increasing bus width. It is interesting to see that the percentage of coupling reduction is closer to that of transition reduction as bus width increases.

B. Total Energy Reduction

The average energy dissipation on the whole bus per bus transfer can be formulated as follows:

$$E(\xi) = (N(n) + \lambda M(n))E_s \quad (19)$$

where $C_c = \lambda C_s$, $E_s = 0.5 C_s V^2$, $M(n)$ is defined as above, and $N(n)$ is the average number of transitions per bus transfer given by (4) or (6). Fig. 5 plots the percentage of energy reduction for the *HDB* approach with different λ and bus width. The value of λ covers a wide range of choices in wire width and spacing. It is interesting to note that the variation in λ has little influence on

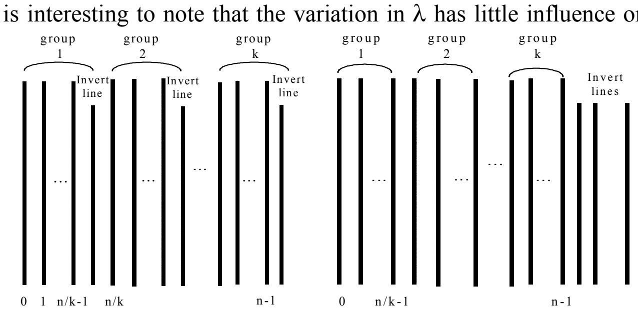

Figure 2. Distributed versus clustered invert lines.

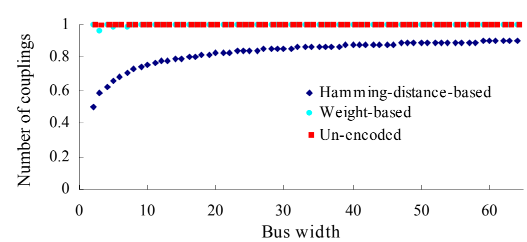

Figure 3. Average couplings per pair of lines per bus transfer.

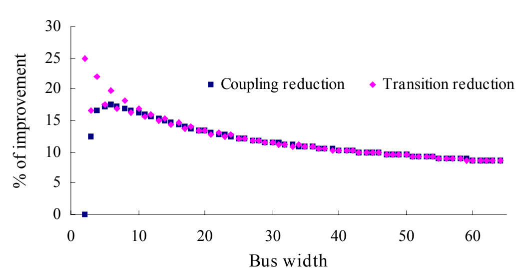

Figure 4. Coupling versus transition reduction.

the energy reduction percentage for a given bus with $n \geq 8$ as more clearly shown in Fig. 6. The reason for this is that, as shown in Fig. 4 when n is sufficiently large, the small difference between transition and coupling reduction percentages makes the total energy reduction percentage insensitive to λ.

C. Energy Reduction of a Partitioned Bus

It was shown that partitioning a bus into a number of smaller buses, each of which has odd number bits, is not a viable approach to switching activity reduction [23]. This property also holds for coupling reduction and can be justified in a way similar to that used in [23]. Its justification can also be observed from TABLE II that gives the results of partitioning a 24-bit bus into different number of groups. Also shown in the table is that partitioning a 24-bit bus into 12 two-bit groups would save 24% of couplings and 25% of transitions with respect to the un-encoded case.

V. CONCLUSIONS

We have performed an in-depth theoretical analysis of the bus-invert method for coupling reduction. The main results include some closed-form formulas for computing the number of couplings per bus transfer. These formulas and those presented in our previous work [23] together establish a sound theoretical foundation for bus-invert coding.

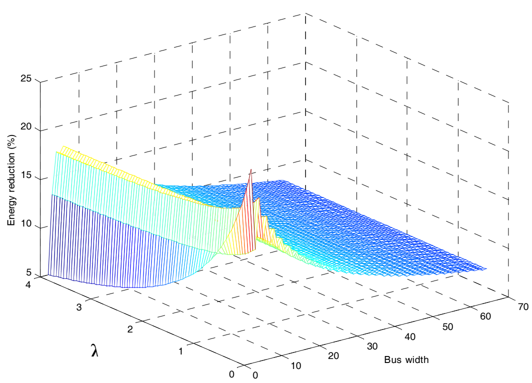

Figure 5. Energy reduction in terms of λ and bus width.

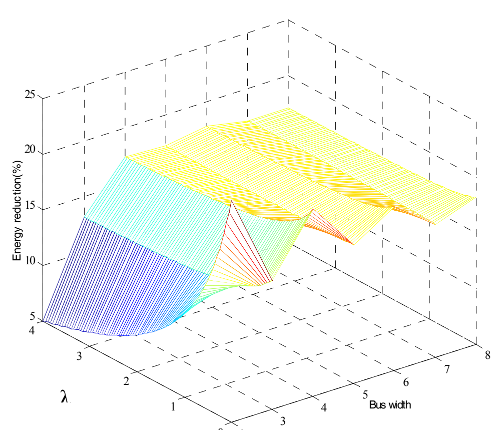

Figure 6. Energy reduction for small bus width.

TABLE II. BUS COUPLING CHARACTERISTICS WITH n=24.

# of bits per group		24	12	8	6	4	3	2
# of groups	0*	1	2	3	4	6	8	12
# of couplings	23	20.13	19.36	18.89	18.56	18.13	19.25	17.5
# of transitions	12	10.49	10.07	9.81	9.63	9.38	10	9

0* indicates bus transfer without coding

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