Simulation Results for a Crosstalk Avoidance and Low Power Coding Scheme for System on Chips

Anitta Thomas and Shinoj J Vattakuzhi

Abstract--- The major problems associated with System-on-Chip buses are Delay problem, Power problem and Reliability problem. Capacitive crosstalk and high power consumption due to various capacitances are the major causes of this problem. So, in order to avoid these problems, a coding scheme is proposed which avoids crosstalk, reduces power consumption and increases reliability. This involves design of encoder and decoder modules. VHDL simulation of encoder and decoder modules are done using GHDL simulator.

Keywords--- Bus-invert, Crosstalk, Correlated Switching, Forbidden Pattern

I. INTRODUCTION

SYSTEM-ON-CHIP is the technology by which different systems that perform various functions are placed on a single silicon chip. This in turn reduces the development cycle, increase product functionality, performance and quality. A system-on-chip is designed to provide full functionality for an application by stitching together multiple stand-alone VLSI designs (cores). The major advantages achieved by SoC devices are lower cost, decreased size and reduced power consumption. System-on-Chips are widely used in embedded systems.

A significant amount of the power dissipated in digital circuits is due to long buses. With the Deep Sub Micron (DSM) technology in CMOS, the interconnect width and spacing reduce, which in turn increases the inter-wire capacitance and interconnect resistance. Such shrinking feature size, makes the power dissipation in data bus more predominant than the power dissipation in other parts of the circuitry.

As the number of multiple function systems in a single chip increases, on-chip global interconnects length are also increasing. This results in large on-chip propagation delay due to increase in interconnect resistance, length, and inter-wire capacitance. The wire delay is becoming a large fraction of the overall delay of a circuit[1]. The wire delay contributes to the major fraction of overall delay.

The system block diagram is given in Figure 1:

Figure 1: System Block Diagram

The system is designed in such a way that it overcomes problems mentioned above.

II. LITERATURE SURVEY

Crosstalk is caused by the interference of one signal with another signal. On chip crosstalk is mainly due to the capacitive coupling of nearby lines. The capacitive crosstalk increases when two adjacent lines are switching simultaneously in opposite direction. Crosstalk in the adjacent wires causes timing violations and extra power dissipation [3].

Two problems [2] can occur due to cross-talk. First, there is a significant delay variation may occur in the victim wire depending on the state of neighboring wires due to crosstalk. Second, loss of signal integrity may occur due to the misinterpretation of the logical state of the wire due to crosstalk of aggressor wire. Chances of correlated switching is also there when two or more neighboring wires make opposite transitions at the same time. For example, the victim wire is switching from high to low while its adjacent wire (aggressor) is switching from low to high at the same time.

Different possibilities of signal transitions in a data bus is analyzed in Figure 2. In type A transitions (Figure 2 (a)), there is no correlated switching and the cross-coupling capacitance is minimum. In type B transitions (Figure 2 (b)), there is one correlated switching. In this case, the effect of coupling capacitance between line 1 and line 2 increases twice due to Miller effect. The type C transition (Figure 2(c)) is the worst possible scenario where there are two correlated switchings between the wire and its two adjacent neighbors. Here the coupling capacitance between both adjacent neighboring wires increases by a factor of 2 due to Miller effect.

Figure 2: Categorization of Signal Transitions in a bus

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A. Terminologies related to Crosstalk

The coupling capacitance of a wire can be classified into four types 1C, 2C, 3C and 4C [4] according to the coupling capacitance (CI) of two wires. Let (v_i, v_{i+1}, v_{i+2}) represent the signal pattern on three wires at any given time, where v_{i+1} is the victim, and v_i, v_{i+2} are the aggressors. j and $j+1$ represents two instants of time.

1.C sequence: A sequence of vectors is called a 1.C sequence [1] if

$$\begin{aligned} & \bullet \quad v_i^{vj} = v_{i+1}^{vj+1} = v1 \text{ and } v_{i+1}^{vj} = v_{i+2}^{vj} = v2 \text{ and} \\ & \quad v_{i+1}^{vj+1} = v_{i+2}^{vj+1} = \overline{v2}, \text{ where } v1, v2, v3 \in \{0,1\} \text{ OR} \dots\dots\dots (2.1) \end{aligned}$$

$$\begin{aligned} & \bullet \quad v_{i+2}^{vj} = v_{i+2}^{vj+1} = v1 \text{ and } v_i^{vj} = v_{i+1}^{vj} = v2 \text{ and} \\ & \quad v_i^{vj+1} = v_{i+1}^{vj+1} = \overline{v2}, \text{ where } v1, v2, v3 \in \{0,1\}. \dots\dots\dots (2.2) \end{aligned}$$

The coupling capacitance for 1.C sequence is CI [4].

2.C sequence: A sequence of vectors is called a 2C sequence if

$$\begin{aligned} & v_i^{vj} = v_{i+1}^{vj+1} = v1 \text{ and } v_{i+1}^{vj} = v2 \text{ and } v_{i+1}^{vj+1} = \overline{v2} \\ & \text{and } v_{i+2}^{vj} = v_{i+2}^{vj+1} = v3 \text{ where } v1, v2, v3 \in \{0,1\}. \dots\dots\dots (2.3) \end{aligned}$$

The coupling capacitance for 2.C sequence is 2CI.

3.C sequence: A sequence of vectors is called a 3C sequence if

$$\begin{aligned} & \bullet \quad v_i^{vj} = v_{i+1}^{vj+1} = v1 \text{ and } v_i^{vj+1} = v_{i+1}^{vj} = \overline{v1} \\ & \quad \text{and } v_{i+2}^{vj} = v_{i+2}^{vj+1} = v2 \text{ where } v1, v2 \in \{0,1\} \text{ OR} \dots\dots\dots (2.4) \\ & \bullet \quad v_{i+1}^{vj} = v_{i+2}^{vj+1} = v1 \text{ and } v_{i+1}^{vj+1} = v_{i+2}^{vj} = \overline{v1} \\ & \quad \text{and } v_i^{vj} = v_i^{vj+1} = v2 \text{ where } v1, v2 \in \{0,1\}. \dots\dots\dots (2.5) \end{aligned}$$

The coupling capacitance of v_{i+1} in this case will be 3CI.

4.C sequence: A sequence of vectors is called a 4C sequence if

The coupling capacitance of v_{i+1} in this case rises to 4CI.

B. Delay Model for the DSM Bus

The delay of line l ($1 < l < n$) of the bus is given by [5]

$$\begin{aligned} & v_i^{vj} = v_{i+1}^{vj+1} = v_{i+2}^{vj} = v \text{ and } v_i^{vj+1} = v_{i+1}^{vj} = v_{i+2}^{vj+1} = \overline{v}, \\ & \text{where } v \in \{0,1\}. \dots\dots\dots (2.6) \end{aligned}$$

$$T_l = \tau_0 [(1+2\lambda)\Delta_l^2 - \lambda\Delta_l (\Delta_{l-1} + \Delta_{l+1})]$$

τ_0 - delay of a crosstalk-free line

λ - ratio of the coupling capacitance to the bulk capacitance Δl - is the transition occurring on line l .

Δl is equal to 1 for 0-to-1 transition, -1 for 1-to-0 transition, and 0 for no transition. The relative delay of a line l is given in Table 1.

Table 1: Relative Delay of Line l

Δ_{l-1}	Δ_l	Δ_{l+1}	Relative Delay
—	—	—	0
↑	↑	↑	1
—	↑	↑	$1+\lambda$
—	↑	—	$1+2\lambda$
↑	↑	↓	$1+2\lambda$
↓	↑	—	$1+3\lambda$
↓	↑	↓	$1+4\lambda$

III. CROSSTALK AVOIDANCE CODING AND DECODING

A. Forbidden Pattern Based Crosstalk Avoidance Coding

The patterns "101" and "010" are forbidden patterns. If there is no forbidden pattern in any three consecutive bits, then the code is said to be forbidden pattern free (FPF). As an example, 1101110 is not forbidden pattern free; 1100110 is FPF.

Table 2 shows a particular mapping which eliminates 3C (and 4C) crosstalk sequences [1], and also eliminates 010 and 101 patterns.

For the particular encoding shown in Table 2, the logic functions are:

$$q1 = d1 \dots\dots\dots (2.7)$$

$$q2 = (d2d3 + d2\overline{d4}) \oplus d1 \dots\dots\dots (2.8)$$

$$q3 = (d2 + d3\overline{d4}) \oplus d1 \dots\dots\dots (2.9)$$

$$q4 = (d3 + d2d4) \oplus d1 \dots\dots\dots (2.10)$$

$$q5 = d4 \oplus d1 \dots\dots\dots (2.11)$$

If a 16-bit bus is considered, the input is divided into four 4-bit groups. The data of each group is encoded using a 4 to 5 encoder. For a 4-bit bus, all $2^4=16$ vectors can be mapped to 16 available 5-bit vectors as shown in Table 2. In practice, forbidden pattern can occur across the group boundaries. To prevent this from occurring, the outputs of the second encoder is inverted if $v_{j,5} \neq v_{j+1,1}$ where j is the group index. To identify this at the decoder end, a group complement bit is also transmitted. The complete set of grouping complement bits are transmitted in a separate group.

Table 2: 4 to 5 Encoder Input-Output Mapping

Input	output
0000	00000
0001	00001
0010	00110
0011	00011
0100	01100
0101	00111
0110	01110
0111	01111
1000	11111
1001	11110
1010	11001
1011	11100
1100	10011
1101	11000
1110	10001
1111	10000

The block diagram of 16-bit Crosstalk Avoidance Coding is shown in Figure 3.

Figure 3: Block Diagram for Crosstalk Avoidance Coding

As in Figure, each group is coded using the boolean expressions discussed (Equations. 2.7 to 2.11). The inversion of inter_data values is determined by decision logic according to XOR gate output. The final encoded value of a particular group is compared with the boundary bits of the next group and so on. The advantage of xor_in input is that any number of 16-bit data busses can be cascaded to form higher bus width. The xor_in can be complement_bit from other group of 16-bit data.

B. Advantages of Crosstalk Avoidance codes

- Crosstalk Avoidance Codes reduces the mutual inter-wire coupling capacitance and hence the energy dissipation of wire segments.
- Reduces the inter-wire crosstalk and hence boosts up the maximum speed on the data bus.
- System reliability can be enhanced and overall energy dissipation can be decreased.
- Less area overhead than shielding techniques [8].

C. Crosstalk Avoidance Decoding

Table 3 shows a 5 to 4 decoder input-output mapping which decodes the data pattern coded using the method discussed in section C.

Table 3: 5 to 4 Decoder Input-Output Mapping

Input	output
00000	0000
00001	0001
00110	0010
00011	0011
01100	0100
00111	0101
01110	0110
01111	0111
11111	1000
11110	1001
11001	1010
11100	1011
10011	1100
11000	1101
10001	1110
10000	1111

For the particular decoding shown in Table 3, the logic functions are:

$$d1=q1 \quad \dots\dots\dots(2.12)$$

$$d2 = (q1 \oplus q2) + \bar{q1} q3 q5 + q2 \bar{q3} \bar{q5} \quad \dots\dots\dots(2.13)$$

$$d3 = \bar{q1} (q2q4 + q3 q4 + q4 q5) + q1 (\bar{q2} \bar{q4} + q3 \bar{q4} + \bar{q4} q5) \quad \dots\dots\dots(2.14)$$

$$d4 = q1 \oplus q5 \quad \dots\dots\dots(2.15)$$

The block diagram for 16-bit Crosstalk Avoidance Decoding is given in Figure 4.

Figure 4: Block Diagram for Crosstalk Avoidance Decoding

The input complement_bit represents whether the final encoded value of group complement bits is inverted or not. The group complement bits are decoded using boolean expressions (Equations 2.12 to 2.15). The data_out values were obtained by using group complement bits and also by decoding using the boolean expressions discussed in this section. The data_out values are same as that of the data given to the crosstalk avoidance coding block.

IV. LOW POWER CODING AND DECODING

Bus Invert Coding is the method applied for obtaining low power. Low power encoding techniques transform the data in such a way that the self-switching activity on buses is reduced.

A. Bus-Invert Coding

In the bus-invert method [6,7], the Hamming distance is computed between the present bus value and the next data value (also counting the present invert line). If the Hamming distance is larger than $n/2$, set 'invert' is equal to '1' and make the next bus value equal to the inverted next data value. Otherwise let 'invert' is equal to '0' and let the next bus value equal to the next data value. At the receiver side the contents of the bus must be conditionally inverted according to the invert line.

The block diagram for bus invert coding is shown in Figure 5. The XOR gate plays a major role in calculating the hamming distance. If the output of XOR logic is one, it means that the corresponding bits of the present data value and the previous bus value differ. The majority voter circuit takes the decision whether to invert the next bus value according to the Hamming distance. The value of the present invert line must be considered by the majority voter. The decision logic outputs the bus value according to the input obtained from the majority voter circuit.

Figure 5: Block Diagram for Bus Invert Coding

B. Bus-Invert Decoding

The block diagram for bus invert decoding is given in Figure 6. The invert bit carries the information about the inversion of data value. The decision logic is the logic which decides whether the input data to this block to be inverted to get the original data value.

Figure 6: Block Diagram for Bus Invert Decoding

V. IMPLEMENTATION

In the proposed coding scheme to address the cross talk and to reduce the power consumption, it was decided to place FPC (for crosstalk avoidance) as the first block to ensure that after performing bus invert coding (for low power) also, the crosstalk avoidance property will be maintained. If the coding scheme is reversed, that is first bus invert coding followed by crosstalk avoidance coding; then the criteria for low power consumption will not be met. The low-power, reliable, crosstalk avoidance coding scheme had been implemented for 8 bits of data as well as for 16 bits of data. The 8-bit data coding scheme has the disadvantage that, it cannot be used for higher bus widths. So, a 16-bit data coding scheme is proposed which can be extended to a higher bus width of 32 bits, 48 bits, 64 bits etc. This can be used as a core in future system-on-chips.

A. Encoder Module

The block diagram for the encoder module is shown in Figure 7. The CAC block and the bus invert coding block were integrated to get the encoder module. The first block eliminates crosstalk and the second block is designed for low power. The input to this integrated block is data_in(15:0) and the output obtained is bus_out(25:0) and invert bit, the coded value given to the bus.

Figure 7: Block Diagram for 16-bit Encoder Module

B. Decoder Module

The block diagram for the decoder module is shown in Figure 8. The bus invert decoding block and the crosstalk avoidance decoding block were integrated to get the decoder module. The input to this integrated block is the output obtained from encoder module. The output of decoder module is denoted as data_out(15:0), which is same as the data given to the encoder module.

Figure 8: Block diagram for 16-bit Decoder Module

VI. SIMULATION RESULTS

Simulation of various blocks was done using GHDL simulator[9]. Waveform viewer used was GTKWave. The simulation results for the encoder module is given in Figure 9 with data_in[15:0] is the input. The data_in[15:0] input is first CAC coded, then the bus invert coding is done for CAC coded output including the group complement bit. bus_out[25:0] and invert are the final outputs of the encoder module. By analyzing the simulation result, it can be concluded that the crosstalk avoidance property is maintained even after combining with bus invert coding which is performed to obtain low power.

Figure 9: Simulation Results for Encoder Module

The simulation results for the decoder module is given in Figure 10. The input to this integrated block is encoded_data[25:0] and invert, which are outputs of the module. The invert bit carries the information about the inversion of data. The output obtained after bus invert decoding is given to crosstalk avoidance decoder block. The decoded output denoted as data_out[15:0], which is same as that of the data given to the encoder module.

Figure 10: Simulation Results for Decoder Module

VII. CONCLUSIONS AND FUTURE WORK

In this work, Forbidden Pattern Condition Codes (FPC) and Bus Invert method was used to address the cross talk and to reduce the power consumption respectively. Here, it was decided to place FPC (for crosstalk avoidance) as the first block to ensure that after performing bus invert coding (for low power) also, the crosstalk avoidance property will be maintained. If the coding scheme is reversed, that is first bus invert coding followed by crosstalk avoidance coding; then the criteria for low power consumption will not be met. The 16-bit coding scheme explained has the advantage that it can be extended to a higher bus width of 32 bits, 48 bits, 64 bits etc. By incorporating crosstalk avoidance and low power coding, the SoC reliability can be enhanced and the overall energy dissipation can be lowered.

In the next phase of this work, it is proposed to include error correction mechanisms also, which further improves the reliability of the system. But the error correction principles should be applied such that it will not alter the properties of forbidden pattern condition codes (which avoids crosstalk) and bus invert coding (which provides low-power).

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