A High-Speed Conditional Carry Select (CCS) Adder Circuit with a Successively Incremented Carry Number Block (SICNB) Structure for Low-Voltage VLSI Implementation

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Abstract—This paper reports a conditional carry select (CCS) adder circuit with a successively-incremented-carry-number block (SICNB) structure for low-voltage VLSI implementation. Owing to the successively-incremented-carry-number block (SICNB) structure, the new 16-bit SICNB CCS adder provides a 37% faster speed as compared to the conventional conditional carry select adder based on the SPICE results.

Index Terms—Carry select adders, high-speed, low-voltage, multipliers.

I. INTRODUCTION

IN A very large scale integration (VLSI) CPU, the adder is an important circuit. The speed performance of a CPU is predominantly determined by its adder circuit. Various adder circuits with improved speed performance have been reported [1]–[8]. Among them, the conditional carry select (CCS) adder [1] has a superior speed performance. As shown in Fig. 1, in a 16-bit CCS adder, the key circuit is the carry select circuit [1]. The principle of the carry select circuit is briefly described here. The carry select circuit is used to process the propagate and generate signals produced by the half adders to generate the carry signals. The function of the carry select circuit is

$$C_i = G_i + C_{i-1} \cdot P_i, \quad \text{for } i = 1 \sim n \quad (1)$$

where n is the bit number. G_i and P_i are the generate and propagate signals ($G_i = X_i \cdot Y_i$, $P_i = X_i + Y_i$) produced from two inputs (X_i , Y_i) to the half adder. From the above equation, if $C_{i-1} = 0$, then $C_i = G_i$. If $C_{i-1} = 1$, then $C_i = P_i$. Therefore, the carry signal can be reorganized as

$$C_i = \overline{C_{i-1}} \cdot G_i + C_{i-1} \cdot P_i. \quad (2)$$

As shown in Fig. 1, the 16-bit conditional carry select circuit is group into four carry blocks. In each carry block, there are

four multiplexers (MUX) controlled by C_{i-1} to produce four output carry signals C_i , C_{i+1} , C_{i+2} , C_{i+3} —the carry number of this conditional carry select circuit is four

$$C_i = \overline{C_j} \cdot C_i(\text{if } C_j = 0) + C_j \cdot C_i(\text{if } C_j = 1) \\ i = j + 1 \sim j + 4; j = -1, 3, 7, 11. \quad (3)$$

For example, in the first block, considering C_0 , if $C_{in} = 1$, the output carry signal

$$C_0 = \overline{C_{in}} \cdot G_0 + C_{in} \cdot P_0 = P_0 \equiv C_0(\text{if } C_{in} = 1).$$

If

$$C_{in} = 0, \quad C_0 = G_0 \equiv C_0(\text{if } C_{in} = 0).$$

As for C_1 , if $C_{in} = 1$

$$C_1 = \overline{C_0} \cdot G_1 + C_0 \cdot P_1 \\ = \overline{P_0} \cdot G_1 + P_0 \cdot P_1 \equiv C_1(\text{if } C_{in} = 1).$$

If $C_{in} = 0$

$$C_1 = \overline{G_0} \cdot G_1 + G_0 \cdot P_1 \equiv C_1(\text{if } C_{in} = 0).$$

As for C_2 , if $C_{in} = 1$

$$C_2 = \overline{C_1} \cdot G_2 + C_1 \cdot P_2 \\ = \overline{\overline{P_0} \cdot G_1 + P_0 \cdot P_1} \cdot G_2 + (\overline{P_0} \cdot G_1 + P_0 \cdot P_1) \cdot P_2 \\ \equiv C_2(\text{if } C_{in} = 1).$$

If $C_{in} = 0$

$$C_2 = \overline{\overline{G_0} \cdot G_1 + G_0 \cdot P_1} \cdot G_2 + (\overline{G_0} \cdot G_1 + G_0 \cdot P_1) \cdot P_2 \\ \equiv C_2(\text{if } C_{in} = 0).$$

As for C_3 , if $C_{in} = 1$,

$$C_3 = \overline{C_2} \cdot G_3 + C_2 \cdot P_3 \\ = \overline{\overline{\overline{P_0} \cdot G_1 + P_0 \cdot P_1} \cdot G_2 + (\overline{P_0} \cdot G_1 + P_0 \cdot P_1) \cdot P_2} \cdot G_3 \\ + (\overline{\overline{P_0} \cdot G_1 + P_0 \cdot P_1} \cdot G_2 + (\overline{P_0} \cdot G_1 + P_0 \cdot P_1) \cdot P_2) \cdot P_3 \\ \equiv C_3(\text{if } C_{in} = 1).$$

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Fig. 1. Block diagram of a 16-bit CCS circuit.

If $C_{in} = 0$

$$\begin{aligned}
 C_3 &= \overline{\overline{G_0} \cdot G_1 + G_0 \cdot P_1 \cdot G_2 + (\overline{G_0} \cdot G_1 + G_0 \cdot P_1) \cdot P_2 \cdot G_3} \\
 &\quad + \overline{\overline{G_0} \cdot G_1 + G_0 \cdot P_1 \cdot G_2} \\
 &\quad + (\overline{G_0} \cdot G_1 + G_0 \cdot P_1) \cdot P_2 \cdot P_3 \\
 &\equiv C_3 \text{ (if } C_{in} = 0 \text{)}.
 \end{aligned}$$

In summary, there are four carry blocks in the 16-bit conditional carry select circuit. Each carry block produces four output carry signals. In the first block, with the multiplexer control signal C_{in} , four output carry signals (C_0, C_1, C_2, C_3) are produced. In the second block, with the multiplexer control signal C_3 , four output carry signals (C_4, C_5, C_6, C_7) are generated. In the third block, with the multiplexer control signal C_7 , four

Fig. 2. Block diagram of the 16-bit SICNB structure CCS circuit.

output carry signals (C_8, C_9, C_{10}, C_{11}) are produced. With the multiplexer control signal C_{11} , four output carry signals ($C_{12}, C_{13}, C_{14}, C_{15}$) are generated. The longest critical path is from X_0 to C_{15} , which occurs at inputs $(X_0 \sim X_{15}) = (1, 0 \sim$

0); $(Y_0 \sim Y_{15}) = (1 \sim 1)$, which involves gate delays of eight stages—one stage of P_0 or G_0 , three stages of multiplexers, and four stages of carry.

II. SUCCESSIVELY INCREMENTED CARRY NUMBER BLOCK (SICNB) CARRY SELECT ADDER

Fig. 2 shows the 16-bit SICNB CCS circuit. As shown in the figure, five carry blocks, as in the conditional carry select circuit, have been used. Different from the conditional carry select circuit, the carry number in each carry block is not always four—not uniform. Instead, in the first carry block, only one output carry signal C_0 is produced

$$C_i = \overline{C_j} \cdot C_i(\text{if } C_j = 0) + C_j \cdot C_i(\text{if } C_j = 1);$$

$$j = -1, i = j + 1. \quad (4)$$

In the second carry block, two output carry signals C_1 and C_2 are generated.

$$C_i = \overline{C_j} \cdot C_i(\text{if } C_j = 0) + C_j \cdot C_i(\text{if } C_j = 1);$$

$$j = 0, i = j + 1, j + 2. \quad (5)$$

In the third carry block, three output carry signals C_3 – C_5 are available

$$C_i = \overline{C_j} \cdot C_i(\text{if } C_j = 0) + C_j \cdot C_i(\text{if } C_j = 1);$$

$$j = 2, i = j + 1 \sim j + 3. \quad (6)$$

In the fourth carry block, four output carry signals C_6 – C_9 are generated.

$$C_i = \overline{C_j} \cdot C_i(\text{if } C_j = 0) + C_j \cdot C_i(\text{if } C_j = 1);$$

$$j = 5, i = j + 1 \sim j + 4. \quad (7)$$

In the fifth carry block, six output carry signals C_{10} – C_{15} are produced

$$C_i = \overline{C_j} \cdot C_i(\text{if } C_j = 0) + C_j \cdot C_i(\text{if } C_j = 1);$$

$$j = 9, i = j + 1 \sim j + 6. \quad (8)$$

As shown in the figure, in the SICNB CCS adder, the number of output carry signals produced in each block is successively incremented from the first block to the last block.

The longest critical path is from X_0 to C_{15} , which occurs at inputs $(X_0 \sim X_{15}) = (1, 0 \sim 0)$; $(Y_0 \sim Y_{15}) = (1 \sim 1)$, which involves gate delays of six stages—one stage of P_0 or G_0 and five stages of multiplexers. Compared to the conventional conditional carry select circuit, the longest critical path is two stages shorter.

Fig. 3 shows the 1-bit pass-transistor-based carry select (PTBCS) circuit [4] used in the SICNB CCS adder of Fig. 2. Instead of P_i in the conventional Manchester CLA circuit, C_{i-1} is used as the control signal in the PTBCS circuit, as shown in Fig. 3. In addition, pass-transistor logic has been

used to replace the multiplexer structure. The operation principle is described here. When $C_{i-1} = 1$, the carry signal ($C_i = G_i + C_{i-1} \cdot P_i$) becomes $C_i = P_i$, hence P_i is used as the input to a transmission gate controlled by C_{i-1} . When $C_{i-1} = 0$, the transmission gate is off. Under this situation, the circuit is similar to a $\overline{G_i}$ -controlled inverter (when $\overline{C_{i-1}}$ is high; hence, the NMOS device MNA is on). Therefore, $C_i = \overline{G_i}$. Similarly

$$\overline{C_i} = \overline{G_i} \cdot (\overline{C_{i-1}} + \overline{P_i}) = \overline{C_{i-1}} \cdot \overline{G_i} + \overline{G_i} \cdot \overline{P_i}.$$

Since

$$\overline{G_i} \cdot \overline{P_i} = (\overline{X_i} + \overline{Y_i})(\overline{X_i} \cdot \overline{Y_i}) = \overline{X_i} \cdot \overline{Y_i} = \overline{P_i}$$

therefore, $\overline{C_i} = \overline{P_i} + \overline{C_{i-1}} \cdot \overline{G_i}$. Similarly, $\overline{C_{i-1}}$ is used as the control signal. When $\overline{C_{i-1}}$ is high, $\overline{C_i} = \overline{P_i} + \overline{G_i} = \overline{G_i}$. Therefore, $\overline{G_i}$ can be used as an input to the transmission gate controlled by C_{i-1} . When $\overline{C_{i-1}}$ is low, the transmission gate is off. Under this situation, the above circuit becomes a P_i -controlled inverter (when C_{i-1} is high, the nMOS device MNB turns on), $\overline{C_i} = \overline{P_i}$. Using the pass-transistor logic in the PTBCS circuit, there are advantages: the output of one stage is connected to the gate of the next stage instead of the source/drain in the conventional Manchester CLA circuit. Therefore, no long serial critical path is involved in the circuit, which is especially useful for low-voltage operation.

III. RESULTS

In order to verify the effectiveness of the new adder, a 16-bit SICNB CCS adder has been designed based on a 0.8- μm CMOS technology. The aspect ratio of the nMOS and the pMOS devices in the test chip is 8 $\mu\text{m}/0.8 \mu\text{m}$ and 16 $\mu\text{m}/0.8 \mu\text{m}$, respectively. Fig. 4 shows the transient waveforms of the 8th and the 16th bit carry signals (C_7 , C_{15}) of the 16-bit SICNB CCS adder at V_{dd} of 1.5 V with two inputs to be added as $(X_0 \sim X_{15}) = (1, 0 \sim 0)$; $(Y_0 \sim Y_{15}) = (1 \sim 1)$, based on SPICE simulation results. As shown in the figure, the propagation delay from the input X_0 to the 16th bit carry out signal ($C_{15,A}$) is 14.56 ns, which is 37% faster as compared to the conventional CCS adder without SICNB structure. Fig. 5 shows the propagation delay of the 16th bit carry signal (C_{15}) versus the power supply voltage used in the SICNB CCS adder. As shown in the figure, the SICNB CCS adder has a consistent improvement over the conventional CCS adder regardless of the power supply voltage. Table I shows the power consumption of a 16-bit adder implemented by conventional CCS technique and the SICNB CCS technique. As shown in the table, using the SICNB CCS technique, the power consumption increases mildly as compared to the adder implemented by the conventional CCS technique.

CCS adders have been well known for their advantages in high speed as compared to Manchester adders. The SICNB CCS adder presented in this paper can provide an even higher speed performance as compared to the CCS adder. The applicability of the SICNB CCS adder is discussed here. In this paper, the

Fig. 3. The 1-bit PTBCS circuit.

adder designed is 16-bit. The SICNB CCS adder is also advantageous for implementing adders with more than 16 bits. The critical path of a 32-bit adder implemented by cascading two conventional 16-bit CCS adders involves 16 stages of logic gates. In contrast, the critical path of a 32-bit adder implemented by cascading two 16-bit SICNB CCS adders involves 12 stages of logic gates, which is 4 stages fewer as compared to the conventional CCS approach. The critical path of a 64-bit adder implemented by cascading four conventional 16-bit CCS adders involves 32 stages of logic gates, which is double as compared to the 32-bit case. On the other hand, the critical path of a 64-bit adder implemented by cascading four SICNB CCS adders, in-

volves 24 stages of logic gates, which is only 50% more as compared to the 32-bit case. Therefore, when the adder is getting bigger, the speed advantages of the SICNB CCS adder over the CCS adder are more noticeable.

IV. CONCLUSION

In this paper, a CCS adder circuit with an SICNB structure for low-voltage VLSI implementation has been described. Owing to the SICNB structure, the new 16-bit SICNB CCS adder provides a 37% faster speed as compared to the conventional CCS adder based on the SPICE results.

Fig. 4. Transients of the 1.5-V 16-bit SICNB structure CCS circuit and the CCS circuit.

Fig. 5. Propagation delay versus supply voltage of the 16-bit SICNB structure and CCS circuit.

TABLE I
POWER CONSUMPTION OF A 16-BIT ADDER IMPLEMENTED BY
CONVENTIONAL CCS TECHNIQUE AND THE SICNB CCS TECHNIQUE

Supply Voltage	Conventional CCS Adder	SICNB CCS Adder
1.5V	0.22 mW	0.39 mW
2V	0.4 mW	0.71 mW
2.5V	0.65 mW	1.13 mW
3V	0.97 mW	1.68 mW

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