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The Correctness of the High Speed Array Multiplier Circuits

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Summary. This article introduces the verification of the correctness for the operations and the specification of the high speed array multiplier. We formalize the concepts of 2-by-2 and 3-by-3 bit Plain array multiplier, 3-by-3 Wallace tree multiplier circuit, and show that outputs of the array multiplier are equivalent to outputs of normal (sequencial) multiplier.

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The article [1] provides the notation and terminology for this paper.

1. Preliminaries

Let x_0, x_1, y_0, y_1 be sets. The functor $\mathrm{MULT}_{210}(x_1,y_1,x_0,y_0)$ yielding a set is defined by:

(Def. 1) $\mathrm{MULT}_{210}(x_1,y_1,x_0,y_0) = \mathrm{AND2}(x_0,y_0)$.

The functor $\mathrm{MULT}_{211}(x_1,y_1,x_0,y_0)$ yielding a set is defined as follows:

(Def. 2) $\mathrm{MULT}_{211}(x_1,y_1,x_0,y_0) = \mathrm{ADD1}(\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$.

The functor $\mathrm{MULT}_{212}(x_1,y_1,x_0,y_0)$ yields a set and is defined as follows:

(Def. 3) $\mathrm{MULT}_{212}(x_1,y_1,x_0,y_0) = \mathrm{ADD2}(\emptyset,\mathrm{AND2}(x_1,y_1),\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$.

The functor $\mathrm{MULT}_{213}(x_1,y_1,x_0,y_0)$ yields a set and is defined as follows:

(Def. 4) $\mathrm{MULT}_{213}(x_1,y_1,x_0,y_0) = \mathrm{CARR2}(\emptyset,\mathrm{AND2}(x_1,y_1),\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$.

One can prove the following proposition

(1) Let x_0, x_1, y_0, y_1, z_0, z_1, z_2, z_3, q_0, q_1, c_1, q_{11}, c_{11} be sets such that NE q_0 iff NE $\mathrm{AND2}(x_0,y_0)$ and NE q_1 iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$ and NE c_1 iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$ and NE q_{11} iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_1,y_1),\emptyset,c_1)$ and NE c_{11} iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_1,y_1),\emptyset,c_1)$ and NE z_0 iff NE q_0 and NE z_1 iff NE q_1 and NE z_2 iff NE q_{11} and NE z_3 iff NE c_{11}. Then

(i) NE z_0 iff NE $\mathrm{MULT}_{210}(x_1,y_1,x_0,y_0)$,

(ii) NE z_1 iff NE $\mathrm{MULT}_{211}(x_1,y_1,x_0,y_0)$,

(iii) NE z_2 iff NE $\mathrm{MULT}_{212}(x_1,y_1,x_0,y_0)$, and

(iv) NE z_3 iff NE $\mathrm{MULT}_{213}(x_1,y_1,x_0,y_0)$.

Let x_0, x_1, x_2, y_0, y_1 be sets. The functor $\mathrm{MULT}_{310}(x_2,x_1,y_1,x_0,y_0)$ yields a set and is defined by:

(Def. 5) $\mathrm{MULT}_{310}(x_2,x_1,y_1,x_0,y_0) = \mathrm{AND2}(x_0,y_0)$.

The functor $\mathrm{MULT}_{311}(x_2,x_1,y_1,x_0,y_0)$ yielding a set is defined by:

(Def. 6) $\mathrm{MULT}_{311}(x_2,x_1,y_1,x_0,y_0) = \mathrm{ADD1}(\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$.

The functor $\mathrm{MULT}_{312}(x_2,x_1,y_1,x_0,y_0)$ yields a set and is defined as follows:

(Def. 7) $\mathrm{MULT}_{312}(x_2,x_1,y_1,x_0,y_0) = \mathrm{ADD2}(\mathrm{AND2}(x_2,y_0),\mathrm{AND2}(x_1,y_1),\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$.

The functor $\mathrm{MULT}_{313}(x_2,x_1,y_1,x_0,y_0)$ yielding a set is defined as follows:

(Def. 8) $\mathrm{MULT}_{313}(x_2,x_1,y_1,x_0,y_0) = \mathrm{ADD3}(\emptyset,\mathrm{AND2}(x_2,y_1),\mathrm{AND2}(x_2,y_0),\mathrm{AND2}(x_1,y_1),\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$

The functor $\mathrm{MULT}_{314}(x_2,x_1,y_1,x_0,y_0)$ yields a set and is defined as follows:

(Def. 9) $\mathrm{MULT}_{314}(x_2,x_1,y_1,x_0,y_0) = \mathrm{CARR3}(\emptyset,\mathrm{AND2}(x_2,y_1),\mathrm{AND2}(x_2,y_0),\mathrm{AND2}(x_1,y_1),\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset$

Let x_0, x_1, x_2, y_0, y_1, y_2 be sets. The functor $\mathrm{MULT}_{321}(x_2,y_2,x_1,y_1,x_0,y_0)$ yields a set and is defined as follows:

(Def. 10) $\mathrm{MULT}_{321}(x_2,y_2,x_1,y_1,x_0,y_0) = \mathrm{ADD1}(\mathrm{MULT}_{312}(x_2,x_1,y_1,x_0,y_0),\mathrm{AND2}(x_0,y_2),\emptyset)$.

The functor $\mathrm{MULT}_{322}(x_2,y_2,x_1,y_1,x_0,y_0)$ yields a set and is defined by:

(Def. 11) $\mathrm{MULT}_{322}(x_2,y_2,x_1,y_1,x_0,y_0) = \mathrm{ADD2}(\mathrm{MULT}_{313}(x_2,x_1,y_1,x_0,y_0),\mathrm{AND2}(x_1,y_2),\mathrm{MULT}_{312}(x_2,x_1,y_1,x_0,y_0),\mathrm{AND2}$

The functor $\mathrm{MULT}_{323}(x_2,y_2,x_1,y_1,x_0,y_0)$ yielding a set is defined by:

(Def. 12) $\mathrm{MULT}_{323}(x_2,y_2,x_1,y_1,x_0,y_0) = \mathrm{ADD3}(\mathrm{MULT}_{314}(x_2,x_1,y_1,x_0,y_0),\mathrm{AND2}(x_2,y_2),\mathrm{MULT}_{313}(x_2,x_1,y_1,x_0,y_0),\mathrm{AND2}$

The functor $\mathrm{MULT}_{324}(x_2,y_2,x_1,y_1,x_0,y_0)$ yielding a set is defined by:

(Def. 13) $\mathrm{MULT}_{324}(x_2,y_2,x_1,y_1,x_0,y_0) = \mathrm{CARR3}(\mathrm{MULT}_{314}(x_2,x_1,y_1,x_0,y_0),\mathrm{AND2}(x_2,y_2),\mathrm{MULT}_{313}(x_2,x_1,y_1,x_0,y_0),\mathrm{AND}$

We now state the proposition

(2) Let x_0, x_1, x_2, y_0, y_1, y_2, z_0, z_1, z_2, z_3, z_4, z_5, q_0, q_1, q_2, c_1, c_2, q_{11}, q_{12}, c_{11}, c_{12}, q_{21}, q_{22}, c_{21}, c_{22} be sets such that NE q_0 iff NE $\mathrm{AND2}(x_0,y_0)$ and NE q_1 iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$ and NE c_1 iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$ and NE q_2 iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_2,y_0),\mathrm{AND2}(x_1,y_1),\emptyset)$ and NE c_2 iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_2,y_0),\mathrm{AND2}(x_1,y_1),\emptyset)$ and NE q_{11} iff NE $\mathrm{XOR3}(q_2,\mathrm{AND2}(x_0,y_2),c_1)$ and NE c_{11} iff NE $\mathrm{MAJ3}(q_2,\mathrm{AND2}(x_0,y_2),c_1)$ and NE q_{12} iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_2,y_1),\mathrm{AND2}(x_1,y_2),c_2)$ and NE c_{12} iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_2,y_1),\mathrm{AND2}(x_1,y_2),c_2)$ and NE q_{21} iff NE $\mathrm{XOR3}(q_{12},\emptyset,c_{11})$ and NE c_{21} iff NE $\mathrm{MAJ3}(q_{12},\emptyset,c_{11})$ and NE q_{22} iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_2,y_2),c_{21},c_{12})$ and NE c_{22} iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_2,y_2),c_{21},c_{12})$ and NE z_0 iff NE q_0 and NE z_1 iff NE q_1 and NE z_2 iff NE q_{11} and NE z_3 iff NE q_{21} and NE z_4 iff NE q_{22} and NE z_5 iff NE c_{22}. Then

(i) NE z_0 iff NE $\mathrm{MULT}_{310}(x_2,x_1,y_1,x_0,y_0)$,

(ii) NE z_1 iff NE $\mathrm{MULT}_{311}(x_2,x_1,y_1,x_0,y_0)$,

(iii) NE z_2 iff NE $\mathrm{MULT}_{321}(x_2,y_2,x_1,y_1,x_0,y_0)$,

(iv) NE z_3 iff NE $\mathrm{MULT}_{322}(x_2,y_2,x_1,y_1,x_0,y_0)$,

(v) NE z_4 iff NE $\mathrm{MULT}_{323}(x_2,y_2,x_1,y_1,x_0,y_0)$, and

(vi) NE z_5 iff NE $\mathrm{MULT}_{324}(x_2,y_2,x_1,y_1,x_0,y_0)$.

2. Logical Equivalence of Wallace Tree Multiplier

One can prove the following proposition

(3) Let x_0, x_1, x_2, y_0, y_1, y_2, z_0, z_1, z_2, z_3, z_4, z_5, q_0, q_1, q_2, q_3, c_1, c_2, c_3, q_{11}, q_{12}, q_{13}, c_{11}, c_{12}, c_{13} be sets such that NE q_0 iff NE $\mathrm{AND2}(x_0,y_0)$ and NE q_1 iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$ and NE c_1 iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$ and NE q_2 iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_2,y_0),\mathrm{AND2}(x_1,y_1),\mathrm{AND2}(x_0,y_2))$ and NE c_2 iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_2,y_0),\mathrm{AND2}(x_1,y_1),\mathrm{AND2}(x_0,y_2))$ and NE q_3 iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_2,y_1),\mathrm{AND2}(x_1,y_2),\emptyset)$ and NE c_3 iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_2,y_1),\mathrm{AND2}(x_1,y_2),\emptyset)$ and NE q_{11} iff NE $\mathrm{XOR3}(q_2,c_1,\emptyset)$ and NE c_{11} iff NE $\mathrm{MAJ3}(q_2,c_1,\emptyset)$ and NE q_{12} iff NE $\mathrm{XOR3}(q_3,c_2,c_{11})$ and NE c_{12} iff NE $\mathrm{MAJ3}(q_3,c_2,c_{11})$ and NE q_{13} iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_2,y_2),c_3,c_{12})$ and NE c_{13} iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_2,y_2),c_3,c_{12})$ and NE z_0 iff NE q_0 and NE z_1 iff NE q_1 and NE z_2 iff NE q_{11} and NE z_3 iff NE q_{12} and NE z_4 iff NE q_{13} and NE z_5 iff NE c_{13}. Then

(i) NE z_0 iff NE $\mathrm{MULT}_{310}(x_2,x_1,y_1,x_0,y_0)$,

(ii) NE z_1 iff NE $\mathrm{MULT}_{311}(x_2,x_1,y_1,x_0,y_0)$,

(iii) NE z_2 iff NE $\mathrm{MULT}_{321}(x_2,y_2,x_1,y_1,x_0,y_0)$,

(iv) NE z_3 iff NE $\mathrm{MULT}_{322}(x_2,y_2,x_1,y_1,x_0,y_0)$,

(v) NE z_4 iff NE $\mathrm{MULT}_{323}(x_2,y_2,x_1,y_1,x_0,y_0)$, and

(vi) NE z_5 iff NE $\mathrm{MULT}_{324}(x_2,y_2,x_1,y_1,x_0,y_0)$.

Let a_1, b_1, c be sets. We introduce $\mathrm{CLAADD1}(a_1,b_1,c)$ as a synonym of $\mathrm{XOR3}(a_1,b_1,c)$. We introduce $\mathrm{CLACARR1}(a_1,b_1,c)$ as a synonym of $\mathrm{MAJ3}(a_1,b_1,c)$.

Let a_1, b_1, a_2, b_2, c be sets. The functor $\mathrm{CLAADD2}(a_2,b_2,a_1,b_1,c)$ yields a set and is defined by:

(Def. 16)[1] $\mathrm{CLAADD2}(a_2,b_2,a_1,b_1,c) = \mathrm{XOR3}(a_2,b_2,\mathrm{MAJ3}(a_1,b_1,c))$.

The functor $\mathrm{CLACARR2}(a_2,b_2,a_1,b_1,c)$ yielding a set is defined as follows:

(Def. 17) $\mathrm{CLACARR2}(a_2,b_2,a_1,b_1,c) = \mathrm{OR2}(\mathrm{AND2}(a_2,b_2),\mathrm{AND2}(\mathrm{OR2}(a_2,b_2),\mathrm{MAJ3}(a_1,b_1,c)))$.

Let a_1, b_1, a_2, b_2, a_3, b_3, c be sets. The functor $\mathrm{CLAADD3}(a_3,b_3,a_2,b_2,a_1,b_1,c)$ yields a set and is defined by:

(Def. 18) $\mathrm{CLAADD3}(a_3,b_3,a_2,b_2,a_1,b_1,c) = \mathrm{XOR3}(a_3,b_3,\mathrm{CLACARR2}(a_2,b_2,a_1,b_1,c))$.

The functor $\mathrm{CLACARR3}(a_3,b_3,a_2,b_2,a_1,b_1,c)$ yielding a set is defined by:

(Def. 19) $\mathrm{CLACARR3}(a_3,b_3,a_2,b_2,a_1,b_1,c) = \mathrm{OR3}(\mathrm{AND2}(a_3,b_3),\mathrm{AND2}(\mathrm{OR2}(a_3,b_3),\mathrm{AND2}(a_2,b_2)),\mathrm{AND3}(\mathrm{OR2}(a_3,b_3$

Let a_1, b_1, a_2, b_2, a_3, b_3, a_4, b_4, c be sets. The functor $\mathrm{CLAADD4}(a_4,b_4,a_3,b_3,a_2,b_2,a_1,b_1,c)$ yielding a set is defined as follows:

(Def. 20) $\mathrm{CLAADD4}(a_4,b_4,a_3,b_3,a_2,b_2,a_1,b_1,c) = \mathrm{XOR3}(a_4,b_4,\mathrm{CLACARR3}(a_3,b_3,a_2,b_2,a_1,b_1,c))$.

The functor $\mathrm{CLACARR4}(a_4,b_4,a_3,b_3,a_2,b_2,a_1,b_1,c)$ yields a set and is defined by:

(Def. 21) $\mathrm{CLACARR4}(a_4,b_4,a_3,b_3,a_2,b_2,a_1,b_1,c) = \mathrm{OR4}(\mathrm{AND2}(a_4,b_4),\mathrm{AND2}(\mathrm{OR2}(a_4,b_4),\mathrm{AND2}(a_3,b_3)),\mathrm{AND3}(\mathrm{OR2}($

We now state the proposition

(4) Let x_0, x_1, x_2, y_0, y_1, y_2, z_0, z_1, z_2, z_3, z_4, z_5, q_0, q_1, q_2, q_3, c_1, c_2, c_3 be sets such that NE q_0 iff NE $\mathrm{AND2}(x_0,y_0)$ and NE q_1 iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$ and NE c_1 iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_1,y_0),\mathrm{AND2}(x_0,y_1),\emptyset)$ and NE q_2 iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_2,y_0),\mathrm{AND2}(x_1,y_1),\mathrm{AND2}(x_0,y_2))$ and NE c_2 iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_2,y_0),\mathrm{AND2}(x_1,y_1),\mathrm{AND2}(x_0,y_2))$ and NE q_3 iff NE $\mathrm{XOR3}(\mathrm{AND2}(x_2,y_1),\mathrm{AND2}(x_1,y_2),\emptyset)$ and NE c_3 iff NE $\mathrm{MAJ3}(\mathrm{AND2}(x_2,y_1),\mathrm{AND2}(x_1,y_2),\emptyset)$ and NE z_0 iff NE q_0 and NE z_1 iff NE q_1 and NE z_2 iff NE $\mathrm{CLAADD1}(q_2,c_1,\emptyset)$ and NE z_3 iff

[1] The definitions (Def. 14) and (Def. 15) have been removed.

NE CLAADD2$(q_3, c_2, q_2, c_1, \emptyset)$ and NE z_4 iff NE CLAADD3(AND2$(x_2, y_2), c_3, q_3, c_2, q_2, c_1, \emptyset)$ and NE z_5 iff NE CLACARR3(AND2$(x_2, y_2), c_3, q_3, c_2, q_2, c_1, \emptyset)$. Then

(i) NE z_0 iff NE MULT$_{310}(x_2, x_1, y_1, x_0, y_0)$,

(ii) NE z_1 iff NE MULT$_{311}(x_2, x_1, y_1, x_0, y_0)$,

(iii) NE z_2 iff NE MULT$_{321}(x_2, y_2, x_1, y_1, x_0, y_0)$,

(iv) NE z_3 iff NE MULT$_{322}(x_2, y_2, x_1, y_1, x_0, y_0)$,

(v) NE z_4 iff NE MULT$_{323}(x_2, y_2, x_1, y_1, x_0, y_0)$, and

(vi) NE z_5 iff NE MULT$_{324}(x_2, y_2, x_1, y_1, x_0, y_0)$.

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