Simultaneous Application of Power Management Scheduling and Operation Delay Selection for Peak Power Minimization

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ABSTRACT

Operation scheduling is the most important task in high-level synthesis. Most conventional operation scheduling algorithms paid attention to the minimization of control steps or the minimization of resources. However, as the design complexity continues to increase, huge peak power may lead to logic errors due to voltage drops or reliability problems due to electromigration. As the popularization of portable and wireless communication, low power design is getting very important. An efficient power management method is to use control logic to shut down unused operations. On the other hand, longer operation delay, which implies smaller peak power, can be selected if no design constraint (timing and resource). In this paper, we present an ILP (integer linear programming) formulation to model the problem of simultaneous application of power management scheduling and operation delay selection for peak power minimization. Benchmark data consistently show that our approach minimizes the peak power within an acceptable run time.

1: INTRODUCTIONS

The peak power is the maximum power consumption of the integrated circuit at any instant during its execution. Huge peak power can cause many reliability problems, such as large voltage drop, large current density, and large heat dissipation. As the design complexity continues to increase, there is a demand to reduce the peak power at higher-level abstraction where the tradeoff is easier to understand. This paper, investigates the reduction of peak power during the stage of high-level synthesis.

Therefore, several operation scheduling approaches [1,2] have been proposed to reduce the peak power. Note that Shiue [1] studied the peak power minimization under single supply voltage, while Mohanty, Ranganathan, and Chappidi [2] studied peak power minimization under multiple supply voltages. However, they [1,2] do not consider power management. Different from them, in this paper, we study the simultaneous application of power management scheduling and operation delay selection for peak power minimization. The basic idea of power management is to shut down unused operations before their executions. On the other hand, longer operation delay, which implies smaller peak power, can be selected if no design constraint (timing and resource). An ILP (integer linear programming) formulation is proposed to model the simultaneous application of power management scheduling and operation delay selection for peak power minimization. Previous work [3,4] ever used the power management to reduce the average power. However, to the best of our knowledge, our paper is the first work that uses the simultaneous application of power management scheduling and operation delay selection to minimize the peak power.

2: MOTIVATION

We use the CDFG shown in Figure 1 to illustrate our motivation. The notation > denotes the control operation, the notation + denotes the addition operations, the notation - denotes the subtraction operations, and the notation * denotes the multiplication operation. Operations o_1 and o_4 are multiplexers. The control operation determines the output of the multiplexer. For example, if the result of operation o_2 is true(T), the output of multiplexer o_1 is the same as the output of operation o_4; otherwise, the output of multiplexer o_1 is the same as the output of operation o_3.

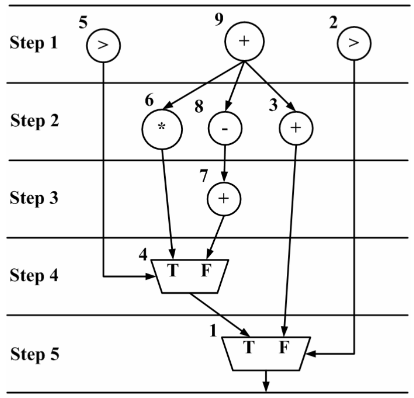

Figure 1: A CDFG.

Assume that the power consumptions of control operation, multiplexer, addition operation, subtraction operation, and multiplication operation are 4, 1, 3, 3, and 20, respectively. The power consumptions at control steps 1, 2, 3, 4, and 5 are 11, 26, 3, 1, and 1 respectively. The peak power is 26.
However, in fact, due to the control operations, the outputs of some operations are not used under certain situations. For example, operation o_6 and operation o_7 are mutually exclusive. If the result of control operation o_5 is 0, the output of operation o_6 is not used; thus, we can add control logics to shut down operation o_6 when the result of control operation o_5 is 0. On the other hand, if the result of control operation o_5 is 1, the output of operation o_7 is not used. thus, we can add control logics to shut down operation o_7 when the result of control operation o_5 is 1.
If the unused operations can be shut down, the power consumption can be reduced. However, due to dependency constraints and resource constraints, not all unused operations can be shut down. An unused operation can be shut down if and only if it is scheduled after the corresponding control operations.
We use the CDFG shown in Figure 2 as an example. We use a dotted line, called soft edge, to denote the control logic that shuts down an operation when the unused condition occurs. The power consumptions at control steps 1, 2, 3, 4, and 5 are 7, 20, 6, 5, and 1, respectively. Therefore, the peak power is 20.

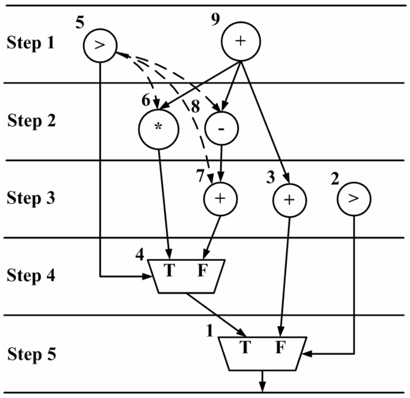

Figure 2: Power Management scheduling

Suppose that the power consumption of a multiplication operation is 20mW. If the multiplication operation is executed within one control step, the power consumption of each control step is 20 mW. On the other hand, if the multiplication operation is executed within two control steps, the power consumption of each control step is 10 mW.
Using Figure 3 as an example, operation o_6 can be delayed one clock cycle violating any design constraint (timing and resource). The power consumption of operation o_6 at control steps 2, and 3 become 10, and 10, respectively. Therefore, the peak power is 10.

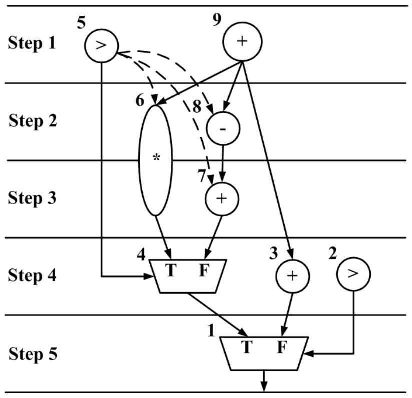

Figure 3: Simultaneous Application of Power Management Scheduling and Operation Delay Selection.

Due to the deep-micron circuit design demand (e.g., reliability issue), we need to consider peak power in high-level synthesis stage. Therefore, in this paper, we propose an ILP formulation to model the problem of simultaneous application of power management scheduling and operation delay selection..

3: ILP FORMULATION

In our ILP formulations, we use the notation $x_{i,j,s}$ to denote a binary variable (i.e., an 0-1 integer variable). Binary variable $x_{i,j,s} = 1$, if and only if operation o_i is scheduled into control step j and the slack of operation o_i is exactly s clock cycles; otherwise, binary variable $x_{i,j,s} = 0$. Clearly, we have $1 \leq i \leq n$, $1 \leq j \leq t$ and $0 \leq s \leq t-1$, where n is the number of operations in the data flow graph and t is the total number of control steps. Thus, intuitively, the total number of binary variables is $n \cdot t^2$. However, in fact, from the ASAP (as soon as possible) and ALAP (as late as possible) schedules, we can find that a lot of binary variables are redundant since their values are definitely 0. Therefore, we can prune these redundant binary variables without sacrificing the accuracy of the solution.
The notations used in our ILP formulation are as below.

(1) We use C_i to denote the set of control operations that can shut down operation o_i when operation o_i is unused.
(2) The value $|A|$ denotes the number of elements in the set A.
(3) The value w_i denotes the power consumption of operation o_i.
(4) We use the notation $Y_{c,i}$ to denote the control dependency from control operation o_c to operation o_i.

If the value $Y_{c,i} = 1$, then there is a soft edge connects from control operation o_c to operation o_i.

(5) We use the notation $Z_{c.i,j}$ to denote the control dependency from control operation o_c to operation o_i and operation o_i is scheduled into control step j. If the value $Z_{c,i,j} = 1$, there is a soft edge from control operation o_c to operation o_i and operation o_i is scheduled into control step j.

(6) We use the notation $Y_{A,i}$ to denote the control dependency from control operations in the set A to operation o_i. If the value $Y_{A,i} = 1$, there are soft edges that connects from control operations in the set A to operation o_i.

(7) We use $Z_{A,i,j}$ to denote the control dependency from control operations in the set A to operation o_i and operation o_i is scheduled into control step j. If the value $Z_{A,i,j} = 1$, there are soft edge that connects control operations in the set A to operation o_i and operation o_i is scheduled into control step j.

(8) The notation H_s denotes the set of unused operations under condition s.

(9) The delay of each operation o_i is D_i.

(10) The value E_i denotes the earliest possible control step of operation o_i. Note that, we can use the ASAP calculation [5] to determine the value E_i for each operation o_i.

(11) The value L_i denotes the latest possible control step of operation o_i. Note that, given the upper bound of number of control steps, we can use the ALAP calculation [5] to determine the value L_i for each operation o_i.

(12) We use FU_k to denote the function unit k, and we say that $o_i \in FU_k$ if and only if operation o_i is assigned to be executed by the function unit FU_k.

(13) The value M_k is the number of function unit k.

The minimal peak power problem can be formulated as the following ILP programming formulations.

Minimize peak_power (Formula 1)

Subject to

For each operation o_i

$$\sum_{j=E_i}^{L_i} \sum_{s=0}^{L_i - j} x_{i,j,s} = 1 \qquad \text{(Formula 2)}$$

For each dependency relation $o_i \rightarrow o_l$

$$\sum_{j=E_i}^{L_i} \sum_{s=0}^{L_i - j} (j + D_i + s - 1) \cdot x_{i,j,s} < \sum_{j=E_p}^{L_p} \sum_{s=0}^{L_p - j} j \cdot x_{p,j,s} \qquad \text{(Formula 3)}$$

For each control step c and each island FU_k

$$\sum_{o_i \in FU_k} \sum_{j=E_i}^{c} \sum_{s=c-(j+D_i-1)}^{L_i - j} x_{i,j,s} \le M_k \qquad \text{(Formula 4)}$$

For each possible control dependency relation $o_i \rightarrow o_l$

$$\sum_{j=E_c}^{L_c} \sum_{s=0}^{L_c - j} (j + D_c + s - 1) \cdot x_{c,j,s} < \sum_{j=E_i}^{L_i} \sum_{s=0}^{L_i - j} j \cdot x_{i,j,s} + (1 - Y_{c,i}) \cdot t \qquad \text{(Formula 5)}$$

For each operation o_l and the set $A \subseteq C_l$

$$\sum_{o_c \in A} Y_{c,i} \le Y_{A,i} + |A| - 1 \qquad \text{(Formula 6)}$$

For each operation o_l and each operation $o_i \in A \subseteq C_l$

$$Y_{A,l} \le Y_{i,l} \qquad \text{(Formula 7)}$$

For each control step j, each operation o_i, and each set $A \subseteq C_i$

$$Y_{A,i} + x_{i,j,s} \le Z_{A,i,j,s} + 1 \qquad \text{(Formula 8)}$$

$$Z_{A,i,j,s} \le Y_{A,i} \qquad \text{(Formula 9)}$$

$$Z_{A,i,j,s} \le x_{i,j,s} \qquad \text{(Formula 10)}$$

For each control step j and each possible condition s

$$\sum_{i=1}^{n} \sum_{s=c-(j+D_i-1)}^{L_i - j} \frac{w_i}{s+1} \cdot x_{i,j,s} - \sum_{i=1}^{n} \sum_{o_i \in H_g} \sum_{A \subseteq C_i} \sum_{s=c-(j+D_i-1)}^{L_i - j} (-1)^{|A|} \cdot \frac{w_i}{s+1} \cdot Z_{A,i,j,s} \le peak\_power \qquad \text{(Formula 11)}$$

Formula 1 defines the objective function. Formula 2 states the constraint that every operation must be scheduled into a control step. Formula 3 ensures that the data dependency relationships are preserved. Formula 4 states the constraint that each function unit k at most executes under the number M_k in any control step. Formula 5, Formula 6, Formula 7, Formula 8, Formula 9, and Formula 10 describe the control dependency relationship due to adding soft edges. Formula 11 describe the peak power constraint for different conditions at each control step.

We use the CDFG given in Figure 1 to illustrate our ILP formulation. Assume that the number of control steps is 4 and the delay of each operation is one control step. Figure 4 (a) and Fig. 4 (b) give the ASAP schedule and the ALAP schedule, respectively. According to the ASAP and ALAP schedules, we can prune all the redundant binary variables. Table 1 gives all the necessary (i.e., irredundant) binary variables associated with each operation. Table 2 gives all the binary variables associated with each possible control dependency. In the following, for each formula, we give an example to explain.

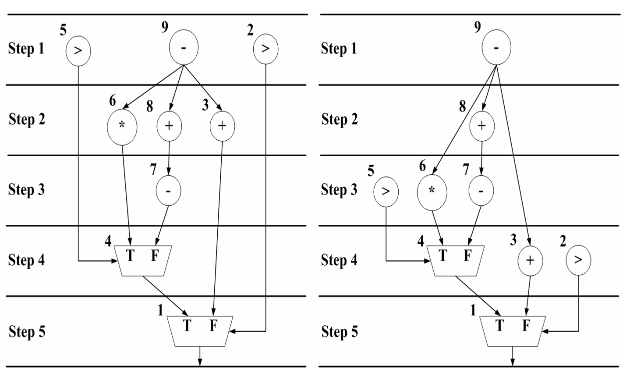

Figure 4 : (a) ASAP schedule. (b) ALAP schedule.

operation	Associated Binary Variables
o_1	$x_{1,5,0}$
o_2	$x_{2,1,0}$, $x_{2,2,0}$, $x_{2,3,0}$, $x_{2,4,0}$, $x_{2,1,1}$, $x_{2,1,2}$, $x_{2,1,3}$, $x_{2,2,1}$, $x_{2,2,2}$, $x_{2,3,1}$
o_3	$x_{3,2,0}$, $x_{3,3,0}$, $x_{3,4,0}$, $x_{3,2,1}$, $x_{3,2,2}$, $x_{3,3,1}$
o_4	$x_{4,4,0}$
o_5	$x_{5,1,0}$, $x_{5,2,0}$, $x_{5,3,0}$, $x_{5,1,1}$, $x_{5,1,2}$, $x_{5,2,1}$
o_6	$x_{6,2,0}$, $x_{6,3,0}$, $x_{6,2,1}$
o_7	$x_{7,3,0}$
o_8	$x_{8,2,0}$
o_9	$x_{9,1,0}$

Table 1: Binary variables associated with each operation.

controller	Associated Binary Variables
o_2	$Y_{\{2\},3}$, $Y_{\{2\},6}$, $Y_{\{2\},7}$, $Y_{\{2\},8}$, $Z_{\{2\},3,2,0}$, $Z_{\{2\},3,2,1}$, $Z_{\{2\},3,2,2}$, $Z_{\{2\},3,3,0}$, $Z_{\{2\},3,3,1}$, $Z_{\{2\},3,4,0}$, $Z_{\{2\},6,2,0}$, $Z_{\{2\},6,2,1}$, $Z_{\{2\},6,3,0}$, $Z_{\{2\},7,3,0}$, $Z_{\{2\},8,2,0}$,
o_5	$Y_{\{5\},6}$, $Y_{\{5\},7}$, $Y_{\{5\},8}$, $Z_{\{5\},6,2,0}$, $Z_{\{5\},6,3,0}$, $Z_{\{5\},6,2,1}$, $Z_{\{5\},7,3,0}$, $Z_{\{5\},8,2,0}$,
$\{ o_2, o_5 \}$	$Y_{\{2,5\},6}$, $Y_{\{2,5\},7}$, $Y_{\{2,5\},8}$, $Z_{\{2,5\},6,2,0}$, $Z_{\{2,5\},6,2,1}$, $Z_{\{2,5\},6,3,0}$, $Z_{\{2,5\},7,3,0}$, $Z_{\{2,5\},8,2,0}$,

Table 2: Binary variables associated with soft edges.

Due to the page limit, we cannot list all the constraints of our ILP formulation for this CDFG. In the following, for each formula, we use an example to explain its meaning.

Formula 2. Using operation o_6 as an example, there is exactly one binary variable is true among all the 3 binary variables associated with operation o_6. Thus, we have $x_{6,2,0} + x_{6,2,1} + x_{6,3,0} = 1$. All the constraints due to Formula 2 are listed in the following.

$x_{1,5,0} = 1;$
$x_{2,1,0} + x_{2,2,0} + x_{2,3,0} + x_{2,4,0} + x_{2,1,1} + x_{2,1,2} + x_{2,1,3} + x_{2,2,1} + x_{2,2,2} + x_{2,3,1} = 1;$
$x_{3,2,0} + x_{3,3,0} + x_{3,4,0} + x_{3,2,1} + x_{3,2,2} + x_{3,3,1} = 1;$
$x_{4,4,0} = 1;$
$x_{5,1,0} + x_{5,1,1} + x_{5,1,2} + x_{5,2,0} + x_{5,2,1} + x_{5,3,0} = 1;$
$x_{6,2,0} + x_{6,3,0} + x_{6,2,1} = 1;$
$x_{7,3,0} = 1;$
$x_{8,2,0} = 1;$
$x_{9,1,0} = 1;$

Formula 3. Using the data dependency relation of $o_9 \rightarrow o_6$ as an example, operation o_6 can be executed if and only if operation o_9 has completed its execution. Thus, we have $2x_{9,1,0} < 2x_{6,2,0} + 2x_{6,2,1} + 3x_{6,3,0}$. All the constraints due to Formula 3 are listed in the following.

$x_{9,1,0} < 2x_{8,2,0};$
$x_{9,1,0} < 2x_{3,2,0} + 3x_{3,3,0} + 4x_{3,4,0} + 2x_{3,2,1} + 2x_{3,2,2} + 3x_{3,3,1};$
$x_{9,1,0} < 2x_{6,2,0} + 2x_{6,2,1} + 3x_{6,3,0};$
$2x_{8,2,0} < 3x_{7,3,0};$
$3x_{7,3,0} < 4x_{4,4,0};$
$2x_{6,2,0} + 3x_{6,2,1} + 3x_{6,3,0} < 4x_{4,4,0};$
$4x_{4,4,0} < 5x_{1,5,0};$
$2x_{3,2,0} + 3x_{3,3,0} + 4x_{3,4,0} + 3x_{3,2,1} + 4x_{3,2,2} + 4x_{3,3,1} < 5x_{1,5,0};$
$1x_{5,1,0} + 2x_{5,1,1} + 3x_{5,1,2} + 2x_{5,2,0} + 3x_{5,2,1} + 3x_{5,3,0} < 4x_{4,4,0};$
$1x_{2,1,0} + 2x_{2,2,0} + 3x_{2,3,0} + 4x_{2,4,0} + 2x_{2,1,1} + 3x_{2,1,2} + 4x_{2,1,3} + 3x_{2,2,1} + 4x_{2,2,2} + 4x_{2,3,1} < 5x_{1,5,0};$

Formula 4. Consider that there are three ALU operations o_3, and o_7 can be scheduled into control step 3. Suppose that we are given two ALUs and one multipliers. Then, we have $x_{3,2,1}+x_{3,2,2}+x_{3,3,0}+x_{3,3,1}+x_{7,3,0} \leq 2$. All the constraints due to Formula 4 are listed in the following.

$x_{3,2,1} + x_{3,2,2} + x_{3,3,0} + x_{3,3,1} + x_{7,3,0} \leq 1;$
$x_{3,2,1} + x_{3,2,2} + x_{3,2,0} + x_{8,2,0} \leq 1;$
$x_{3,2} + x_{7,2} + x_{9,2} \leq 1;$
$x_{9,1,0} \leq 1;$
$x_{6,2,0} \leq 1;$
$x_{6,3,0} \leq 1;$
$x_{6,2,1} \leq 1;$

Formula 5. If control operation o_5 is schedule into control step 2, it is impossible to shut down operations o_8. Thus, we have $1x_{5,1,0} + 2x_{5,1,1} + 3x_{5,1,2} + 2x_{5,2,0} + 3x_{5,2,1} + 3x_{5,3,0} < 2x_{8,2,0} + (1 - Y_{\{5\},8})*5$. All the constraints due to Formula 5 are listed in the following.

$1x_{5,1,0} + 2x_{5,1,1} + 3x_{5,1,2} + 2x_{5,2,0} + 3x_{5,2,1} + 3x_{5,3,0} < 2x_{8,2,0} + (1 - Y_{\{5\},8})*5$
$1x_{5,1,0} + 2x_{5,1,1} + 3x_{5,1,2} + 2x_{5,2,0} + 3x_{5,2,1} + 3x_{5,3,0} < 3x_{7,3,0} + (1 - Y_{\{5\},7})*5$
$1x_{5,1,0} + 2x_{5,1,1} + 3x_{5,1,2} + 2x_{5,2,0} + 3x_{5,2,1} + 3x_{5,3,0} < 2x_{6,2,0} + 2x_{6,2,1} + 3x_{6,3,0} + (1 - Y_{\{5\},6})*5$
$1x_{2,1,0} + 2x_{2,2,0} + 3x_{2,3,0} + 4x_{2,4,0} + 2x_{2,1,1} + 3x_{2,1,2} + 4x_{2,1,3} + 3x_{2,2,1} + 4x_{2,2,2} + 4x_{2,3,1} < 2x_{3,2,0} + 3x_{3,3,0} + 4x_{3,4,0} + 3x_{3,2,1} + 4x_{3,2,2} + 4x_{3,3,1} + (1 - Y_{\{2\},3})*5$
$1x_{2,1,0} + 2x_{2,2,0} + 3x_{2,3,0} + 4x_{2,4,0} + 2x_{2,1,1} + 3x_{2,1,2} + 4x_{2,1,3} + 3x_{2,2,1} + 4x_{2,2,2} + 4x_{2,3,1} < 2x_{8,2,0} + (1 - Y_{\{2\},8})*5$
$1x_{2,1,0} + 2x_{2,2,0} + 3x_{2,3,0} + 4x_{2,4,0} + 2x_{2,1,1} + 3x_{2,1,2} + 4x_{2,1,3} + 3x_{2,2,1} + 4x_{2,2,2} + 4x_{2,3,1} < 3x_{7,3,0} + (1 - Y_{\{2\},7})*5$
$1x_{2,1,0} + 2x_{2,2,0} + 3x_{2,3,0} + 4x_{2,4,0} + 2x_{2,1,1} + 3x_{2,1,2} + 4x_{2,1,3} + 3x_{2,2,1} + 4x_{2,2,2} + 4x_{2,3,1} < 2x_{6,2,0} + 2x_{6,2,1} + 3x_{6,3,0} + (1 - Y_{\{2\},6})*5$

Formula 6, Formula 7, Formula 8, Formula 9, and Formula 10. Both control operation o_2 and control operation o_5 may shut down operation o_7. Due to Formula 6, we have $Y_{\{2\},7} + Y_{\{5\},7} \leq Y_{\{2,5\},7} + 2 - 1$. Due To Formula 7, we have $Y_{\{2,5\},7} \leq Y_{\{2\},7}$ and $Y_{\{2,5\},7} \leq Y_{\{5\},7}$. In other words, we have $Y_{\{2,5\},7} = 1$ if and only if both $Y_{\{2\},7} = 1$ and $Y_{\{5\},7} = 1$. Due to Formula 8, we have $Y_{\{2,5\},7} + x_{7,3,0} \leq Z_{\{2,5\},7,3,0} + 1$. Due to Formula 9, we have $Z_{\{2,5\},7,3,0} \leq Y_{\{2,5\},7}$. Due to Formula 10, we have $Z_{\{2,5\},7,3,0} \leq x_{7,3,0}$. In other words, we have $Z_{\{2,5\},7,3,0} = 1$ if and only if both $Y_{\{2,5\},7}$ and $x_{7,3,0} = 1$. All the constraints due to Formula 6, Formula 7, Formula 8, Formula 9, and Formula 10 are listed in the following.

$Y_{\{2\},7} + Y_{\{5\},7} \leq Y_{\{2,5\},7} + 1;$
$Y_{\{2,5\},7} \leq Y_{\{2\},7};$

$Y_{\{2,5\},7} \le Y_{\{5\},7}$;
$Y_{\{2\},8} + Y_{\{5\},8} \le Y_{\{2,5\},8} + 1$;
$Y_{\{2,5\},8} \le Y_{\{2\},8}$;
$Y_{\{2,5\},8} \le Y_{\{5\},8}$;
$Y_{\{2\},6} + Y_{\{5\},6} \le Y_{\{2,5\},6} + 1$;
$Y_{\{2,5\},6} \le Y_{\{2\},6}$;
$Y_{\{2,5\},6} \le Y_{\{5\},6}$;
$Y_{\{2,5\},7} + x_{7,3,0} \le Z_{\{2,5\},7,3,0} + 1$;
$Z_{\{2,5\},7,3,0} \le Y_{\{2,5\},7}$;
$Z_{\{2,5\},7,3,0} \le x_{7,3,0}$;
$Y_{\{2,5\},8} + x_{8,2,0} \le Z_{\{2,5\},8,2,0} + 1$;
$Z_{\{2,5\},8,2,0} \le Y_{\{2,5\},8}$;
$Z_{\{2,5\},8,2,0} \le x_{8,2,0}$;
$Y_{\{2,5\},6} + x_{6,3,0} \le Z_{\{2,5\},6,3,0} + 1$;
$Z_{\{2,5\},6,3,0} \le Y_{\{2,5\},6}$;
$Z_{\{2,5\},6,3,0} \le x_{6,3,0}$;
$Y_{\{2,5\},6} + x_{6,2,0} \le Z_{\{2,5\},6,2,0} + 1$;
$Z_{\{2,5\},6,2,0} \le Y_{\{2,5\},6}$;
$Z_{\{2,5\},6,2,0} \le x_{6,2,0}$;
$Y_{\{2,5\},6} + x_{6,2,1} \le Z_{\{2,5\},6,2,1} + 1$;
$Z_{\{2,5\},6,2,1} \le Y_{\{2,5\},6}$;
$Z_{\{2,5\},6,2,1} \le x_{6,2,1}$;

Formula 11. Consider all the possible conditions at control step 2. If the output of control operation o_2 is 0 and the output of control operation o_5 is 0, we have $4x_{2,2,0} + 2x_{2,2,1} + 2x_{2,1,1} + 1.3x_{2,1,2} + 1x_{2,1,3} + 0.8x_{2,1,4} + 3x_{8,2,0} + 20x_{6,2,0} + 10x_{6,2,1} + 4x_{5,2,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 2x_{5,1,1} + 1.5x_{3,2,1} + 3x_{3,2,0} + 1x_{3,2,2} - 20Z_{\{2\},6,2,0} + 10Z_{\{2,5\},6,2,1} + 20Z_{\{2,5\},6,2,0} - 10Z_{\{2\},6,2,1} - 20Z_{\{5\},6,2,0} - 10Z_{\{5\},6,2,1} - 3Z_{\{2\},8,2,0} \le peak\_power$. If the output of control operation o_2 is 0 and the output of control operation o_5 is 1, we have $4x_{2,2,0} + 2x_{2,2,1} + 2x_{2,1,1} + 1.3x_{2,1,2} + 1x_{2,1,3} + 0.8x_{2,1,4} + 3x_{8,2,0} + 20x_{6,2,0} + 10x_{6,2,1} + 4x_{5,2,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 2x_{5,1,1} + 3x_{3,2,0} + 1x_{3,2,2} 1.5x_{3,2,1} - 20Z_{\{2\},6,2,0} - 10Z_{\{2\},6,2,1} - 3Z_{\{2\},8,2,0} - 3Z_{\{5\},8,2,0} + 3Z_{\{2,5\},8,2,0} \le peak\_power$. If the output of control operation o_2 is 1 and the output of control operation o_5 is 0, we have $4x_{2,2,0} + 2x_{2,2,1} + 2x_{2,1,1} + 1.3x_{2,1,2} + 1x_{2,1,3} + 0.8x_{2,1,4} + 3x_{8,2,0} + 20x_{6,2,0} + 10x_{6,2,1} + 4x_{5,2,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 2x_{5,1,1} + 3x_{3,2,0} + 1.5x_{3,2,1} + 1x_{3,2,2} - 3Z_{\{2\},3,2,0} - 1.5Z_{\{2\},3,2,1} - 1Z_{\{2\},3,2,2} - 20Z_{\{5\},6,2,0} - 10Z_{\{5\},6,2,1} \le peak\_power$. If the output of control operation o_2 is 1 and the output of control operation o_5 is 1, we have $4x_{2,2,0} + 2x_{2,2,1} + 2x_{2,1,1} + 1.3x_{2,1,2} + 1x_{2,1,3} + 0.8x_{2,1,4} + 3x_{8,2,0} + 20x_{6,2,0} + 10x_{6,2,1} + 4x_{5,2,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 2x_{5,1,1} + 3x_{3,2,0} + 1.5x_{3,2,1} + 1x_{3,2,2} - 3Z_{\{2\},3,2,0} - 1.5Z_{\{2\},3,2,1} - 1Z_{\{2\},3,2,2} - 3Z_{\{5\},8,2,0} \le peak\_power$. All the constraints due to Formula 11 are listed in the following.

Control step 1:
$4x_{5,1,0} + 2x_{5,1,1} + 1.3x_{5,1,2} + 4x_{2,1,0} + 2x_{2,1,1} + 1.3x_{2,1,2} + 1x_{2,1,3} + 3x_{9,1,0} \le peak\_power$;
Control step 2:
$o_2 = 0$ and $o_5 = 0$
$4x_{2,2,0} + 2x_{2,2,1} + 2x_{2,1,1} + 1.3x_{2,1,2} + 1x_{2,1,3} + 3x_{8,2,0} + 20x_{6,2,0} + 10x_{6,2,1} + 4x_{5,2,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 2x_{5,1,1} + 1.5x_{3,2,1} + 3x_{3,2,0} + 1x_{3,2,2} - 20Z_{\{2\},6,2,0} - 10Z_{\{2\},6,2,1} + 20Z_{\{2,5\},6,2,0} + 10Z_{\{2,5\},6,2,1} - 20Z_{\{5\},6,2,0} - 10Z_{\{5\},6,2,1} - 3Z_{\{2\},8,2,0} \le peak\_power$;
$o_2 = 0$ and $o_5 = 1$
$4x_{2,2,0} + 2x_{2,2,1} + 2x_{2,1,1} + 1.3x_{2,1,2} + 1x_{2,1,3} + 3x_{8,2,0} + 20x_{6,2,0} + 10x_{6,2,1} + 4x_{5,2,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 2x_{5,1,1} + 3x_{3,2,0} + 1x_{3,2,2} + 1.5x_{3,2,1} - 20Z_{\{2\},6,2,0} - 10Z_{\{2\},6,2,1} - 3Z_{\{2\},8,2,0} - 3Z_{\{5\},8,2,0} + 3Z_{\{2,5\},8,2,0} \le peak\_power$;
$o_2 = 1$ and $o_5 = 0$
$4x_{2,2,0} + 2x_{2,2,1} + 2x_{2,1,1} + 1.3x_{2,1,2} + 1x_{2,1,3} + 3x_{8,2,0} + 20x_{6,2,0} + 10x_{6,2,1} + 4x_{5,2,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 2x_{5,1,1} + 3x_{3,2,0} + 1.5x_{3,2,1} + 1x_{3,2,2} - 3Z_{\{2\},3,2,0} - 1.5Z_{\{2\},3,2,1} - 1Z_{\{2\},3,2,2} - 20Z_{\{5\},6,2,0} - 10Z_{\{5\},6,2,1} \le peak\_power$;
$o_2 = 1$ and $o_5 = 1$
$4x_{2,2,0} + 2x_{2,2,1} + 2x_{2,1,1} + 1.3x_{2,1,2} + 1x_{2,1,3} + 3x_{8,2,0} + 20x_{6,2,0} + 10x_{6,2,1} + 4x_{5,2,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 2x_{5,1,1} + 3x_{3,2,0} + 1.5x_{3,2,1} + 1x_{3,2,2} - 3Z_{\{2\},3,2,0} - 1.5Z_{\{2\},3,2,1} - 1Z_{\{2\},3,2,2} - 3Z_{\{5\},8,2,0} \le peak\_power$;
Control step 3:
$o_2 = 0$ and $o_5 = 0$
$4x_{2,3,0} + 1.3x_{2,2,1} + 1x_{2,2,2} + 1x_{2,1,3} + 1.3x_{2,1,2} + 3x_{7,3,0} + 20x_{6,3,0} + 10x_{6,2,1} + 4x_{5,3,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 1.5x_{3,2,1} + 3x_{3,3,0} + 1x_{3,2,2} - 20Z_{\{2\},6,3,0} - 10Z_{\{2\},6,2,1} + 20Z_{\{2,5\},6,3,0} + 10Z_{\{2,5\},6,2,1} - 20Z_{\{5\},6,3,0} - 10Z_{\{5\},6,2,1} - 3Z_{\{2\},7,3,0} \le peak\_power$;
$o_2 = 0$ and $o_5 = 1$
$4x_{2,3,0} + 1.3x_{2,2,1} + 1x_{2,2,2} + 1x_{2,1,3} + 1.3x_{2,1,2} + 3x_{7,3,0} + 20x_{6,3,0} + 10x_{6,2,1} + 4x_{5,3,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 1.5x_{3,2,1} + 3x_{3,3,0} + 1x_{3,2,2} - 20Z_{\{2\},6,3,0} - 10Z_{\{2\},6,2,1} - 3Z_{\{2\},7,3,0} - 3Z_{\{5\},7,3,0} + 3Z_{\{2,5\},7,3,0} \le peak\_power$;
$o_2 = 1$ and $o_5 = 0$
$4x_{2,3,0} + 1.3x_{2,2,1} + 1x_{2,2,2} + 1x_{2,1,3} + 1.3x_{2,1,2} + 3x_{7,3,0} + 20x_{6,3,0} + 10x_{6,2,1} + 4x_{5,3,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 1.5x_{3,2,1} + 3x_{3,3,0} + 1x_{3,2,2} - 3Z_{\{2\},3,3,0} - 1.5Z_{\{2\},3,2,1} - 1Z_{\{2\},3,2,2} - 20Z_{\{5\},6,3,0} - 10Z_{\{5\},6,2,1} \le peak\_power$;
$o_2 = 1$ and $o_5 = 1$
$4x_{2,3,0} + 1.3x_{2,2,1} + 1x_{2,2,2} + 1x_{2,1,3} + 1.3x_{2,1,2} + 3x_{7,3,0} + 20x_{6,3,0} + 10x_{6,2,1} + 4x_{5,3,0} + 2x_{5,2,1} + 1.3x_{5,1,2} + 1.5x_{3,2,1} + 3x_{3,3,0} + 1x_{3,2,2} - 3Z_{\{2\},3,3,0} - 1.5Z_{\{2\},3,2,1} - 1Z_{\{2\},3,2,2} - 3Z_{\{5\},7,3,0} \le peak\_power$;
Control step 4:
$o_2 = 0$
$1x_{4,4,0} + 3x_{3,2,2} + 1.5x_{3,3,1} + 1x_{3,4,0} + 4x_{2,4,0} + 2x_{2,3,1} + 1.3x_{2,2,2} + 1x_{2,1,3} - 1Z_{\{2\},4,4,0} \le peak\_power$;
$o_2 = 1$
$1x_{4,4,0} + 3x_{3,2,2} + 1.5x_{3,3,1} + 1x_{3,4,0} + 4x_{2,4,0} + 2x_{2,3,1} + 1.3x_{2,2,2} + 1x_{2,1,3} - 3Z_{\{2\},3,4,0} - 1.5Z_{\{2\},3,3,1} - 1Z_{\{2\},3,2,2} \le peak\_power$;
Control step 5:
$1x_{1,5,0} \le peak\_power$;

After solving the ILP formulation, we have that $x_{1,4,0} = x_{2,4,0} = x_{3,4,0} = x_{4,4,0} = x_{5,1,0} = x_{6,2,1} = x_{7,3,0} = x_{8,2,0} = x_{9,1,0} = Y_{5,6} = Y_{5,7} = Y_{5,8} = Z_{\{5\},6,2,1} = Z_{\{5\},7,3,0} = Z_{\{5\},8,2,0} = 1$, and the values of other binary variables are 0.

4: EXPERIMENTAL RESULTS

The ILP solver is the Extended LINGO Release 8.0 running on a personal computer with P4-3.3GHz CPU and 1024M Bytes RAM. Seven benchmark circuits are used to test the effectiveness of our approach. Benchmark circuits

GCD [6], Jian [7], Mult [8], G2 [9], G5 [10] are popular DSP applications and widely used in the high-level synthesis community, while benchmark circuits Dist1 and Dist2 are the representative functions adopted from the MediaBench suite [11]. In our experiments, the CPU time of each benchmark circuit is only few minutes.

Table 3 gives the characteristics of benchmark circuits. The column # denotes the number of multiplexers. The column > denotes the number of comparison operations. The column + denotes the number of addition operations. The column - denotes the number of subtraction operations. The column * denotes the number of multiplication operations.

Circuit	#	>	+	-	*
GCD	3	3	2	0	0
Jian	3	3	10	0	0
Mult	2	2	7	3	0
G2	3	3	9	0	9
G5	2	2	16	8	0
Dist1	16	16	48	48	0
Dist2	3	3	192	64	64

Table 3: Characteristics of benchmark circuits.

Table 4 gives our experimental results. For the purpose of comparisons, we also implement the power management scheduling approach proposed in [1]. The column *Resources* denotes the resource constraints. The column *Steps* denotes the number of control steps. The column [1] denotes the minimum peak power obtained by the approach of [1] (i.e., the minimum peak power achieved by operation scheduling). The column Ours denotes the minimum peak power obtained by our approach (i.e., the minimum peak power achieved by the simultaneous application of operation scheduling and power management). The column Imp% denotes the percentage of improvement.

Circuit	Constraints		Peak Power		
	Resources	Steps	[1]	Ours	Imp%
GCD	2 ALUs	5	6	5	17%
Jian	3 ALUs	6	10	8	20%
		7	9	7	22%
Mult	3 ALUs	6	9	7	22%
G2	2 MULs	8	46	38	17%
	2 ALUs	9	43	22	49%
G5	4 ALUs	8	12	9	25%
		9	10	7	30%
Dist1	3 ALUs	38	13	10	23%
		39	10	8	20%
Dist2	5 ALUs	99	22	18	18%
	2 MULs	100	20	15	20%

Table 4: Experimental results.

5: CONCLUSIONS

In this paper, we present an ILP formulation to model the peak power minimization problem via the combination of power management scheduling and operation delay selection. Benchmark data consistently show that our approach has significant peak power reduction. Compared with the peak power reduction via only operation scheduling, our average improvement achieves 27.2%.

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