A Detailed Routing Algorithm for Switch Boxes

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Abstract: A k-side switch box with W terminals on each side is said to be hyper universal, denoted by \((k, W)\)-HUSB, if it is routable for any global routing with density at most \(W\). In [5], we have proposed a switch box design strategy and designed a near optimum \((4, W)\)-HUSB \(F(W)\) with 6.6\(W\) switches. In this paper, we design, analyze and implement an efficient detailed routing algorithm for the S-box \(F(W)\). This router can accommodate all routing requirement topologies.

1. Introduction

Field Programmable Gate Array (FPGA) is one of the fast developed product type of VLSIs in last decade, and has been used in a great amount of digital equipment today.

A typical 2D-FPGA architecture is shown in Figure 1. The functional blocks (or logic cells) are marked by \(L\), which are separated by vertical and horizontal channels. There are \(W\) (called channel density) prefabricated parallel wire segments running between each pair of adjacent \(L\)-cells in both vertical and horizontal channels. There are C-boxes in the channel between adjacent \(L\)-cells. A Switch Box (S-box), located at each intersection of a vertical channel and a horizontal channel, contains programmable switches to connect wire segments running from its surrounding C-boxes.

![Diagram of 2D-FPGA architecture](image)

Figure 1. The architecture of a 2D-FPGA.

Conventionally, the routing process is divided into two subsequent steps, global routing and detailed routing. Global routing specifies the connection topologies for all nets, while the detailed routing decides the exact assignment of wire segments and switches used to materialize the complete routing. A global routing is called routable if there is a detailed routing for it.

There are two important issues in the design of FPGAs: the area and time efficiency and the routability. Switch boxes, which are the main programmable component and have great effects on the two issues of FPGA chips, have been the crucial part in the FPGA architecture designs [1], [2], [4].

In [5], we have proposed a switch box design strategy and designed a near optimum \((4, W)\)-HUSB \(F(W)\), and proved theoretically that \(F(W)\) reflects a good balance of the area efficiency and routability issues. Therefore, it would be desirable if we provide an efficient detailed routing algorithm for the S-box \(F(W)\). This is the purpose of this paper.

2. The S-box \(F(W)\)

We first briefly describe the terminology and notations we used in the designing of HUSBs in [5], [6].

A k-side switch box with \(W^k\) terminals on each side is denoted by \((k, W^k)\)-SB. We label the \(k\) sides by \(1, \ldots, k\) respectively. Then a net connecting the sides \(i_1, \ldots, i_r\), can be represented as a set \{\(i_1, \ldots, i_r\}\). A k-way (balanced) global routing of density \(d\), or briefly \((k, d)\)-GR \((k, d)\)-GGR, is a collection \(\{N_i|i = 1, \ldots, v\}\) of subsets of \{1, 2, \ldots, \(k\)\} such that each \(i\) (1 \(\leq i \leq k\)) appears at most \(d\) (exactly \(d\)) sets in \(\{N_i|i = 1, \ldots, v\}\); \(N_i\) is also referred to as a net of the global routing. Let \(R\) be a \((k, d)\)-GR and \(R'\) be a sub-collection of \(R\). If \(R'\) is a \((k, d')\)-GR with \(d' < d\), \(R'\) is called a sub-global routing of \(R\). \(R\) is said to be minimal or an MGR if it does not contain sub-global routings. A \((k, d)\)-GR is called primitive \((k, d)\)-PGR if it does not contain two unequal nets of size one. A \((k, d)\)-PGR stands for a k-way primitive minimal balanced global routing.

We represent the \(j\)-th terminal on the \(i\)-th side of a \((k, W)\)-SB by a vertex \(v_{i,j}\), and let \(v_{i,j}v_{p,q}\) represent the switch joining the two terminals represented by the vertices \(v_{i,j}\) and \(v_{p,q}\), then the \((k, W)\)-SB can be viewed as a \(k\)-partite graph \(G = ((V_1, V_2, \ldots, V_k), E)\) where \(V_i = \{v_{i,j}|j = 1, \ldots, W\}\) for \(i = 1, \ldots, k\), and \(E\) is the set of switches. A detailed routing of a \((k, W)\)-GR \(\{N_i|i = 1, \ldots, v\}\) in \(G\) is a set of mutually disjoint subgraphs \(\{T(N_i)|i = 1, \ldots, v\}\) of \(G\) satisfying: (1) \(T(N_i)\) is a tree of \(|N_i|\) vertices, and (2) \(|V_j \cap V(T(N_i))| = 1\) if \(j \not\in N_i\), for \(i = 1, \ldots, v\). \(T(N_i)\) is called a detailed routing of \(N_i\).

A \((k, W)\)-SB is called hyper universal or a \((k, W)\)-HUSB if it has a detailed routing for every \((k, W)\)-GR.
This is equivalent to that it has a detailed routing for every \((k, W)\)-PBGR since a \((k, W)\)-GR can be converted to a \((k, W)\)-PBGR by adding in some singletons and combining different singletons.

Figure 2(a) shows a global routing and Figure 2(b) shows a detailed routing of the global routing (a) in the S-box \(H_4\) (see Figure 4).

![Diagram](image)

**Figure 2.** Examples of a global routing, a detailed routing and the disjoint union of two S-boxes.

Let \(GR_1\) and \(GR_2\) be two \(k\)-way global routings and \(m\) a positive integer. The disjoint union of \(GR_1\) and \(GR_2\) as a multiple set is denoted by \(GR_1 + GR_2\), and the disjoint union of \(m\) copies of \(GR_1\) is denoted by \(mGR_1\). Figure 2 (c) shows the disjoint union of a \((4, 2)\)-SB and a \((4, 3)\)-SB.

It is shown in [5] that a 4-PBGR can always be decomposed into 4-PMBGRs. Figure 3 provides the complete list of 4-PMBGRs. Let \(PMBGR\) denote the collection of all 4-PMBGRs in Figure 3.

In [5], we have designed the following \((4, W)\)-HUSB \(F(W)\).

\[
F(W) = \begin{cases} 
    hH_6 & \text{if } W = 6h, \\
    (h - 1)H_6 + H_7 & \text{if } W = 6h + 1, \\
    hH_6 + H_2 & \text{if } W = 6h + 2, \\
    hH_6 + H_3 & \text{if } W = 6h + 3, \\
    hH_6 + H_4 & \text{if } W = 6h + 4, \\
    hH_6 + H_5 & \text{if } W = 6h + 5,
\end{cases}
\]

where the \(H_s\)s are shown in Figure 4.

The detailed routing problem associated with \(F(W)\) is:

**Input:** A \(4\)-GR \(R = \{N_i | i = 1, \ldots, v\}\) and \(W\).

**Problem:** Find a detailed routing of \(R\) in \(F(W)\).

### 3. The Detailed Routing Algorithm

#### The Algorithm

A Calculate the density of \(R\) and make it balanced and primitive.

### B Decompose \(R'\) into minimal global routings.

Let \(R' = \{N_1, \ldots, N_l\}\).

Repeat Step 1 to Step 3 until \(R' = \emptyset\) or \(PMBGR = \emptyset\).

**Step 1** For any \(M \in PMBGR\), let \(T_1, \ldots, T_m\) be all different nets in \(M\). For \(i = 1\) to \(m\), let \(t_i\) be the number of replications of \(T_i\) in \(M\) and set \(x_i = 0\). Set \(M = \emptyset\).

**Step 2** For \(i = 1\) to \(l\), \(j = 1\) to \(m\), if \(N_i = T_j\), set \(x_j = x_j + 1\).

**Step 3** If \(x_j \geq t_j\) for all \(j = 1\) to \(m\), then set \(M = M \cup M\), and set \(GR' = GR' - M\). Else, set \(PMBGR = PMBGR - M\).

**C** Group the sub-global routings in \(M\).

Let \(d = 6h + r\), where \(r\) takes a value from \(\{0, 2, 3, 4, 5, 7\}\)
4 primitive global routings which is a union of a density 3 and a density 1 minimal global routings in Figure 3. There are 40 detailed routings in $D_4$.

$D_6$ is the database for detailed routings in $H_6$ of density 6 primitive global routings which is a union of two densities 3 minimal global routings in Figure 3. There are 25 detailed routings in $D_6$.

For each $GR_i$, find a detailed routing in $G_6$ if $i \leq h$:
- Find a detailed routing $DR_i$ of $GR_i$.
- If $GR_i = GR_1 + GR_2 + GR_3$ is of the form $2^2 + 2^2$, then search for $D_2$ to find detailed routings $DR_1$, $DR_2$, and $DR_3$. Set $DR_i = DR_1 \oplus DR_2 \oplus DR_3$.
- Else ($GR_i$ is of the form $3 + 3^2$), then search for $D_6$ to find a detailed routing $DR_i$.

If $r \neq 0$, find a detailed routing $DR_{h+1}$ of $GR_{h+1}$ in $H_r$.

$$D_1: r = 1$$ Find for $D_1$ to find a detailed routing $DR_{h+1}$ for $GR_{h+1}$.

$$D_2: r = 2$$ Find for $D_2$ to find a detailed routing $DR_{h+1}$ for $GR_{h+1}$.

$$D_3: r = 3$$ If $GR_{h+1} = GR_1 + GR_2$ is of the form $a + 2^2$, then search for $D_1$ to find a detailed routing $DR_1$ for $GR_1$, and search for $D_2$ to find a detailed route for $GR_2$. Set $DR_{h+1} = DR_1 \oplus DR_2$.

Otherwise, search for $D_6$ to find a detailed routing $DR_{h+1}$ of $GR_{h+1}$.

$$D_4: r = 4$$ If $GR_{h+1} = GR_1 + GR_2$ is of the form $2 + 2^2$, then search for $D_2$ to find detailed routings $DR_1$ and $DR_2$ for $GR_1$ and $GR_2$, respectively. Set $DR_{h+1} = DR_1 \oplus DR_2$.

Otherwise, search for $D_4$ to find a detailed routing $DR_{h+1}$ for $GR_{h+1}$.

$$D_5: r = 5$$ We must have $GR_{h+1} = GR_1 + GR_2$ is of the form $2 + 3^2$. Search for $D_2$ to find a detailed routing $DR_1$ for $GR_1$, and apply the procedure $(D_3 r=3)$ to find a detailed routing $DR_2$ for $GR_2$. Set $DR_{h+1} = DR_1 \oplus DR_2$.

$$D_7: r = 7$$ We have $GR_{h+1} = GR_1 + GR_2$ is of the form $3 + 4^2$. Apply the procedure $(D_3 r=3)$ to find a detailed routing $DR_1$ for $GR_1$, and apply the procedure $(D_4: r=4)$ to find a detailed routing $DR_2$ for $GR_2$. Set $DR_{h+1} = DR_1 \oplus DR_2$.

Set $G = DR_1 \oplus \cdots \oplus DR_{h+1}$ if $r \neq 0$, and $G = DR_3 \oplus \cdots \oplus DR_h$ otherwise.

**E Find a detailed routing of $R$.**

For each 2-pin set $\{i,j\} \in D$, delete a detailed routing of $\{i,j\}$ in $G$.

Search the cells in $G$ which represent the $i$-th and $j$-th sides. If there is a cell $(p_i,q_j)$ such that $g_{p_i,q_j} = 1$, and the $p_i$-th row and $q_j$-th column are all 0s except $g_{p_i,q_j} = 1$, then set $g_{p_i,q_j} = 0$.

**F Output $G$.**

We note that the output $G$ is an incidence matrix of a graph which is a subgraph of $F(W)$.

### 4. Analysis of the algorithm

**Part A:** Given the input $R$ and $W$, the algorithm calculates the density $d$ of $R$ in $O(W)$ basic operations.
$d \leq W$, the algorithm also constructs a balanced primitive $(4, W)$-GR $R'$ based on $R$ in $O(W)$ operations.

**Part B:** This step decomposes $R'$ into minimal sub-global routings. The algorithm compares the nets in $R'$ with the nets of minimal global routing in $PMGR$. Since $PMGR$ contains only 35 elements, it takes $O(l) = O(W)$ comparisons.

**Part C:** The algorithm groups the decomposition of $R'$ obtained in Part B into $h$ $(4, 6)$-GRs and one $(4, r)$-GR if $r \neq 0$. If we store the results in Part B using three vectors $V_1$, $V_2$, and $V_3$, such that $V_i$ contains global routings of density $i$, then it is easy to get the desired groups if we start from $V_4$. We need a linear time, that is $O(W)$ to finish this task.

**Part D:** For each sub-global routing produced in Part C, we need search for certain data base(s) to find a detailed routing. As the data bases contains all detailed routings for primitive, minimal 4-way global routings, therefore, we can always find a detailed routing for each sub-global routing obtained in Part C. Combing all these detailed routings for the sub-global routings in Part C, we obtain a detailed routing of the global routing $GR'$. Upon deleting the detailed routings for the 2-pin nets in $D$, we obtain a detailed routing for the original input $GR$. Therefore, the algorithm produces a correct detailed routing for any input global routing $GR$. Note that in Part D, we need $O(W)$ basic operations.

**Part E:** In this step, we need search for $O(W^2)$ cells of $G$ in the worst case.

Summing up, we have that the time complexity of the above detailed routing algorithm is $O(W^2)$.

### 5. Implementation of the algorithm

We develop a single switch box router to implement the above detailed routing algorithm in C++ with the output graphical user interface in JAVA. We use string of numbers $0, 1, 2, 3, 4$ as a data structure to represent global routings, where 0 is used as the separator of nets. For instance, “12302340234” represents $(4, 3)$-GR $\{1, 2, 3\}, \{2, 3, 4\}, \{2, 3, 4\}$. Figure 5 shows the detailed routing of “12302340234" in F(3). In Figure 6, the channel density ($W$) is 4 and the Global Routing string is “1234012302340134”. There are 4 nets where the first net connects all 4 different sides of the switch box.

### 6. Conclusions

An efficient detailed routing algorithm for the $(4, W)$-HUSB $F(W)$ is described in this paper. A detailed algorithmic analysis of the router is also included in the paper. From the theory and experiments we conducted, this router is able to complete any given routing topologies as long as the density is no more that $W$. Moreover, we conclude that if the S-boxes in the FPGA (shown in Figure 1) are replaced by $F(W)$, then with the detailed routing algorithm designed in this paper as a sub-module, it is possible to design an efficient detailed router for the whole chip.

### References