On Optimum Switch Box Designs for 2-D FPGAs

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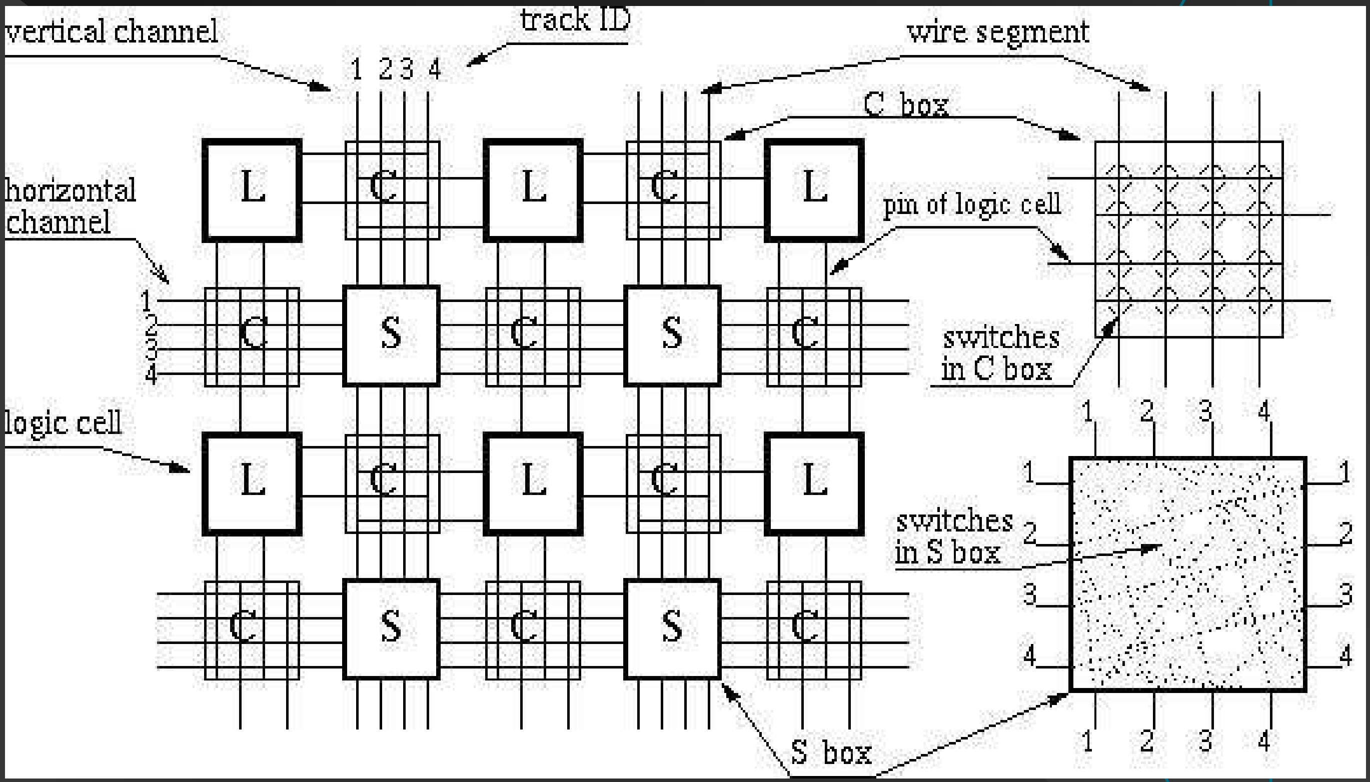
Outline

- Switch box design problem of 2D-FPGA
- Hyper-univsersal switch box (HUSB)
- Reduction design method
  - Hypergraph model for routing requirement
  - Graph models for switch box
  - Decomposition theory
  - Reduction design scheme
- Now optimum HUSB designs and verification
- Experimental results on HUSB

Switch box design problem in 2D-FPGA



Design Goal: to find Switch Boxes (SB) with higher routability and fewer switches.

Routability specifications

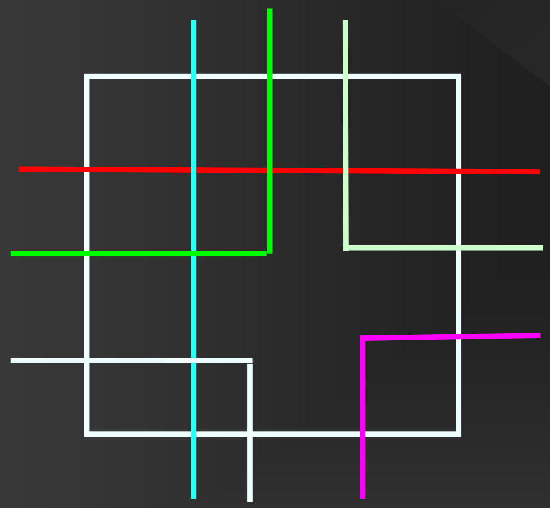
1. Probability model (by J. Rose and S. Brown):
   Flexibility, average probability of completing a connection

2. Universal Switch Block (USB)
   (by Y.W. Chang, D.F. Wong, C.K. Wong)
   routable for every set of 2-pin nets routing requirement

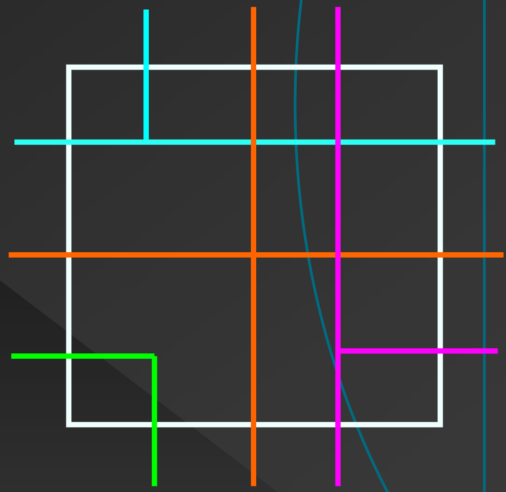
3. Hyper-Universal Switch Box (HUSB) :
   routable for every set of multi-pin nets routing requirement

The differences between HUSB and USB:

- HUSB is a generalization of USB
- USB is for all 2-pin nets; HUSB is for multi-pin nets
- HUSB => USB



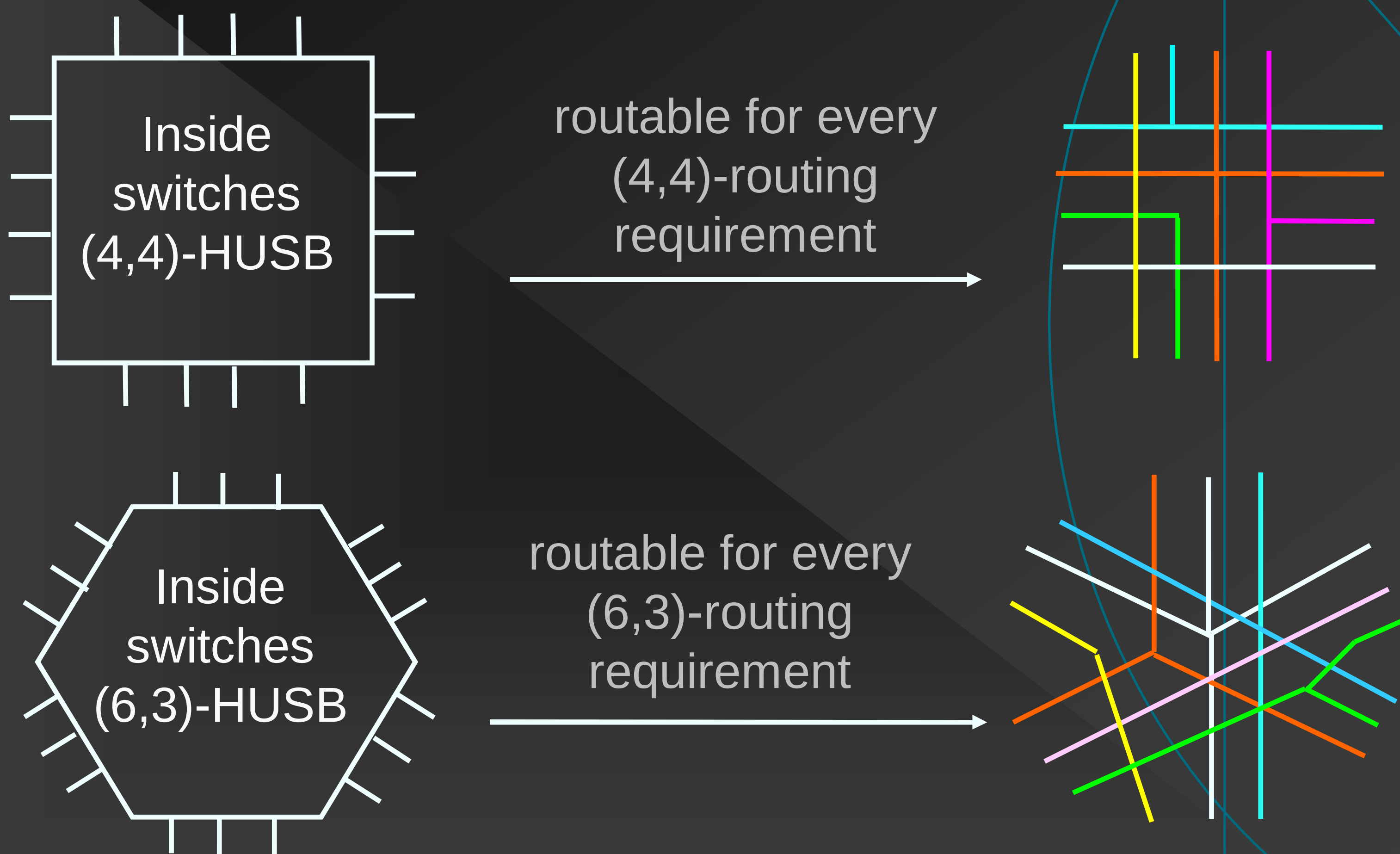
A 2-pin nets routing requirement



A multi-pin nets routing requirement

(k, w)-HUSB :

the HUSB of k-way and W terminals on each way

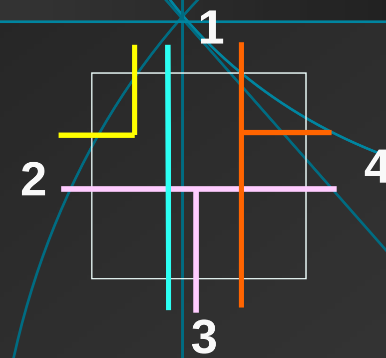


Hyper-Universal (k, w)-Design Problem:

- **For each pair of k and W, to design a (*k, w*)-HUSB with the minimum number of switches, optimum (k, w)-HUSB**
- ***e(k, w)* = the number of switches in an optimum (*k, w*)-HUSB.**
- **Optimum (k, w)-designs for k =2, 3 are known.**
  - **E(2, W) = w**
  - **e(3, W) = 3w**
- **This paper is aimed for optimum (4, w)-designs.**
- **The hard part of the problem is to verify a given design is hyper-universal**

Routing Requirement Modeling:

For (4, w)-SB, label the sides *1, 2, 3, 4*.



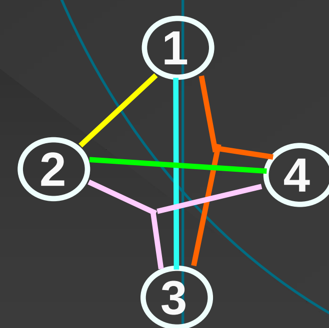
A net <=> a subset of {1, … , 4 }
Routing requirement <=>collection of subsets
Global Routing (GR)

{1, 2} {2, 3, 4}
{1, 3} {1, 3, 4}

Balanced Global Routing, (4, w)- GR

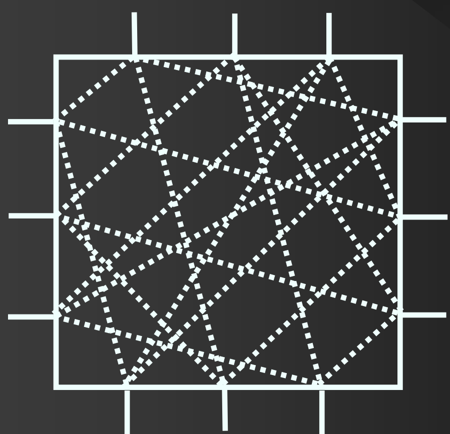
{1, 2} {2, 3, 4}
{1, 3} {1, 3, 4} {2, 4}

W - regular hypergraph

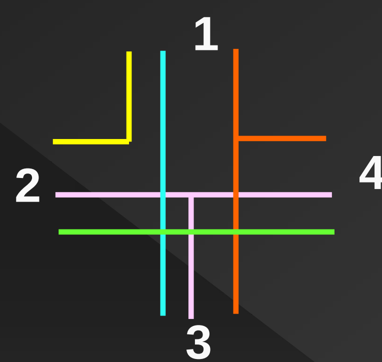


Graph Model of Switch Boxes

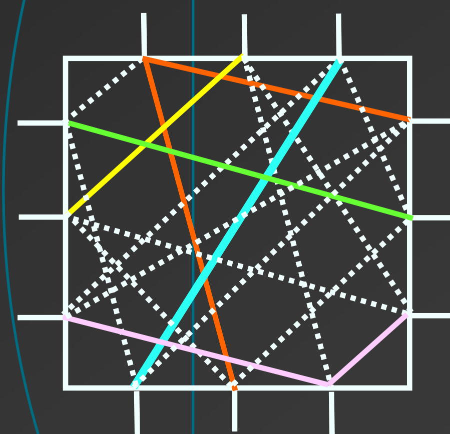
- **(k, W) - SB <=>** graph: terminals as nodes; switch as edges
- **A detailed routing <=>** a spanning forest



A (4, 3) - HUSB view as a graph



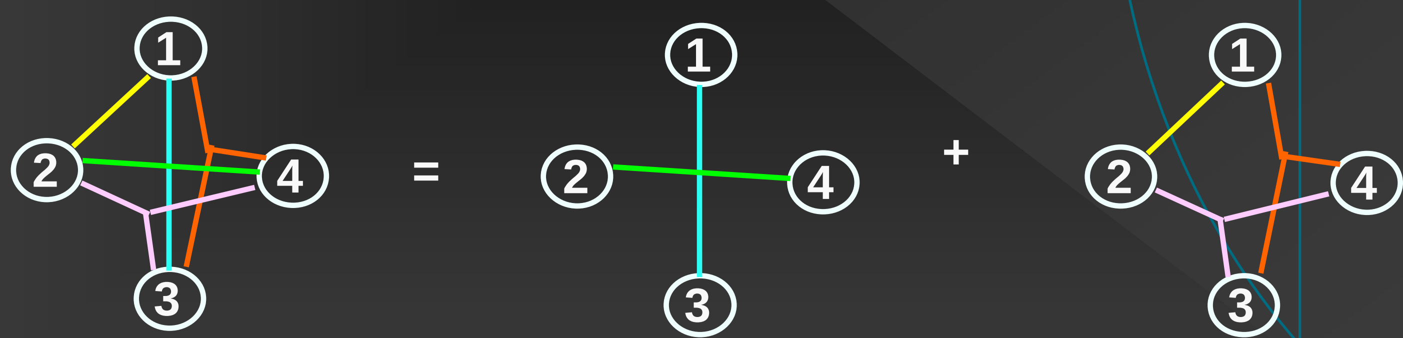
A (4, 3) - GR



A detailed routing as a spanning forest

Decomposition Theorem

- Minimal BGR (MBGR) : non decomposable 4-way BGR (regular hypergraph with four nodes)
  - For a fixed *k,* there are finite number of k-MBGRs.
  - Every BGR can be decomposed into the union of MBGRs.
- *f(k)* = maximum density of all k-MBGRs.
  - f(4) = 3
  - all 4-way MBGRs are obtained



Hyper-universal decomposition theorem

- **Let *p(k)* be the least common multiple of minimal densities of k-MBGRs. Then for each *W*, there exists r such that $r < f(k)\,(p(k) - 1) + 1$ and every *(k, W)*-BGR can be decomposed into the union of some *(k, p(k))*-BGRs and a *(k, r)*-BGR**
- **$K_{m,n}$: the complete *(m, n)-SB***
- **$K_{k,\,p(k)} + \ldots K + {}_{k,\,p(k)} + K_{k,\,r}$ is a (k, W)-HUSB**
- ***when k is fixed, then e(k, W) = O(W)***

Design scheme for (k, w)-HUSBs

1. Compute the set of all *k*-MPBGRs.
2. Compute $p(k)$, determine all $d_1, \ldots, d_n$ such that for each *W*, there is an d_j such that any (k, W)-BGR can be decomposed into a union of some $(k, p(k))$-BGRs and a (k, d_j)-BGR.
3. Design (k, $p(k)$)-HUSB H(k, $p(k)$) and (k, d_j)-HUSB H(k, d_j) for each $j = 1, \ldots, n$.
4. (W- d_i)/p(k) $(k, p(k))$-HUSBs + (k, d_i)-HUSB

Hyper-Universal (4, W)-Designs

- *f(4) = 3,   p(4) = 6*
- *e(4, w) >= 6w*
- To design (4, *i*)-HUSBs H_i for $i = 1, \dots, 7$:
- $$F(4, W) = \begin{cases} h \quad H_6\text{'s} & \text{if } W = 6h, \\ (h-1) \quad H_6\text{'s} + H_7 & \text{if } W = 6h+1 \\ h \quad H_6\text{'s} + H_2 & \text{if } W = 6h+2 \\ h \quad H_6\text{'s} + H_3 & \text{if } W = 6h+3 \\ h \quad H_6\text{'s} + H_4 & \text{if } W = 6h+ \\ h \quad H_6\text{'s} + H_5 & \text{if } W = 6h+5 \end{cases}$$

  gives a hyper-universal (4, w)-design.
- If |F(4, W)| = 6w, then it is an optimum design.
- With above design, detailed routing at the box can be done in polynomial time.

New hyper-universal (4, W)-design

$|E(H_1)| = 6$,

$|E(H_2)| = 12$,

$|E(H_3)| = 18$,

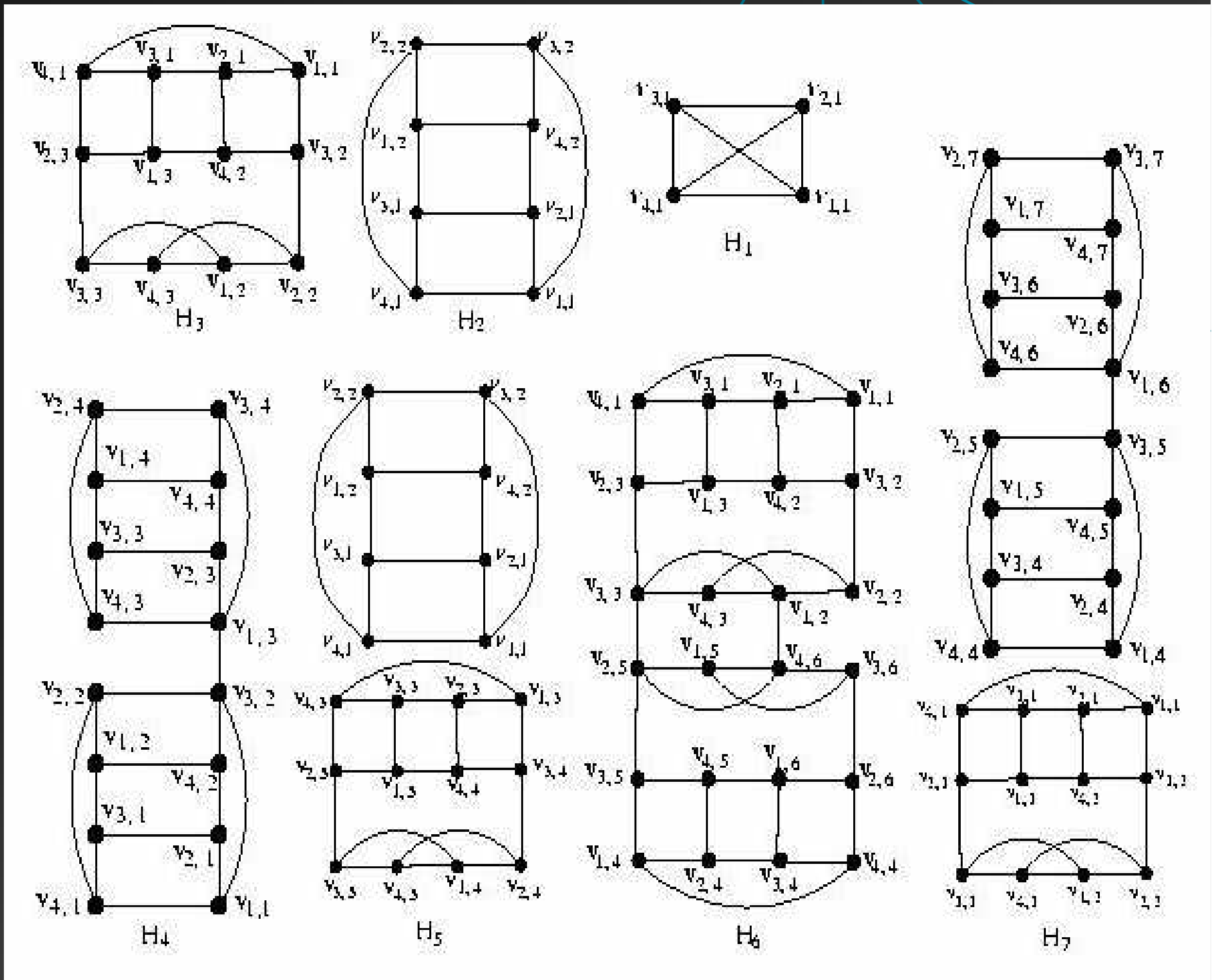
$|E(H_4)| = 25 > 24$,

$|E(H_5)| = 30$,

$|E(H_6)| = 37 > 36$,

$|E(H_7)| = 43 > 42$.

$|F(4, w)| = 6.3w$



Which are optimum designs

$|E(H_1)| = 6 = e(4, 1)$, H_1 is optimum.

$|E(H_2)| = 12 = e(4, 2)$, H_2 is optimum.

$|E(H_3)| = 18 = e(4, 3)$, H_3 is optimum !

$|E(H_4)| = 25 = e(4, 4)$, H_4 is optimum !

$|E(H_5)| = 30 = e(4, 5)$, H_5 is optimum !

$|E(H_6)| = 37$, H_6 is optimum ? Unknown !

$|E(H_7)| = 43$, H_7 is optimum ? Unknown !

$|F(4, w)| = 6.3w$, $F(4, w)$ is optimum ? Unknown !

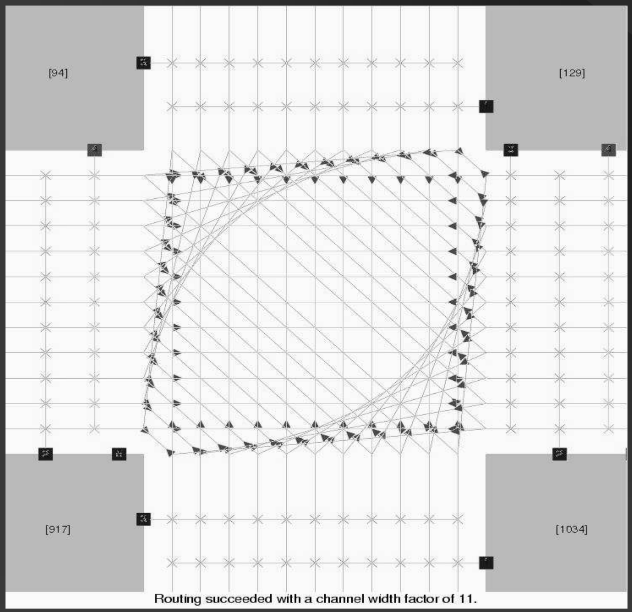
The verification of HUSBs

This is the most technical part of the paper:

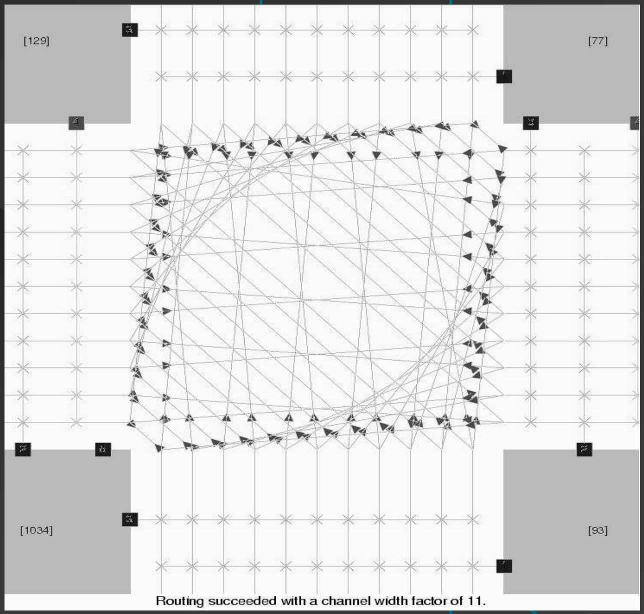
1. Verification for H_3
   1. find detailed routings in H_3 for all (4, 3)-BGRs formed by the union of 4-way MBGRs
2. Verification for H_4
   1. show that no (4,4)-SB with 24 switches is hyper-universal
   2. find detailed routing in H_4 for every (4, 4)-BGRs formed by the union of 4-way MBGRs
3. Verification for H_5 , H_6 , H_7 and $F(4, w)$
   1. use decomposition theorems
4. A data base and a detailed routing algorithm

Experiment with HUSBs

- Run "VPR" on FPGAs with a reduced HUSBs
  - two switches are deleted from F(4, w) to meet the flexibility requirement F_s = 3 for VPR
  - use MCNC benchmark circuits
- Compare the number of tracks required to route the circuits on FPGAs with disjoint S-Box (XC4000 type)



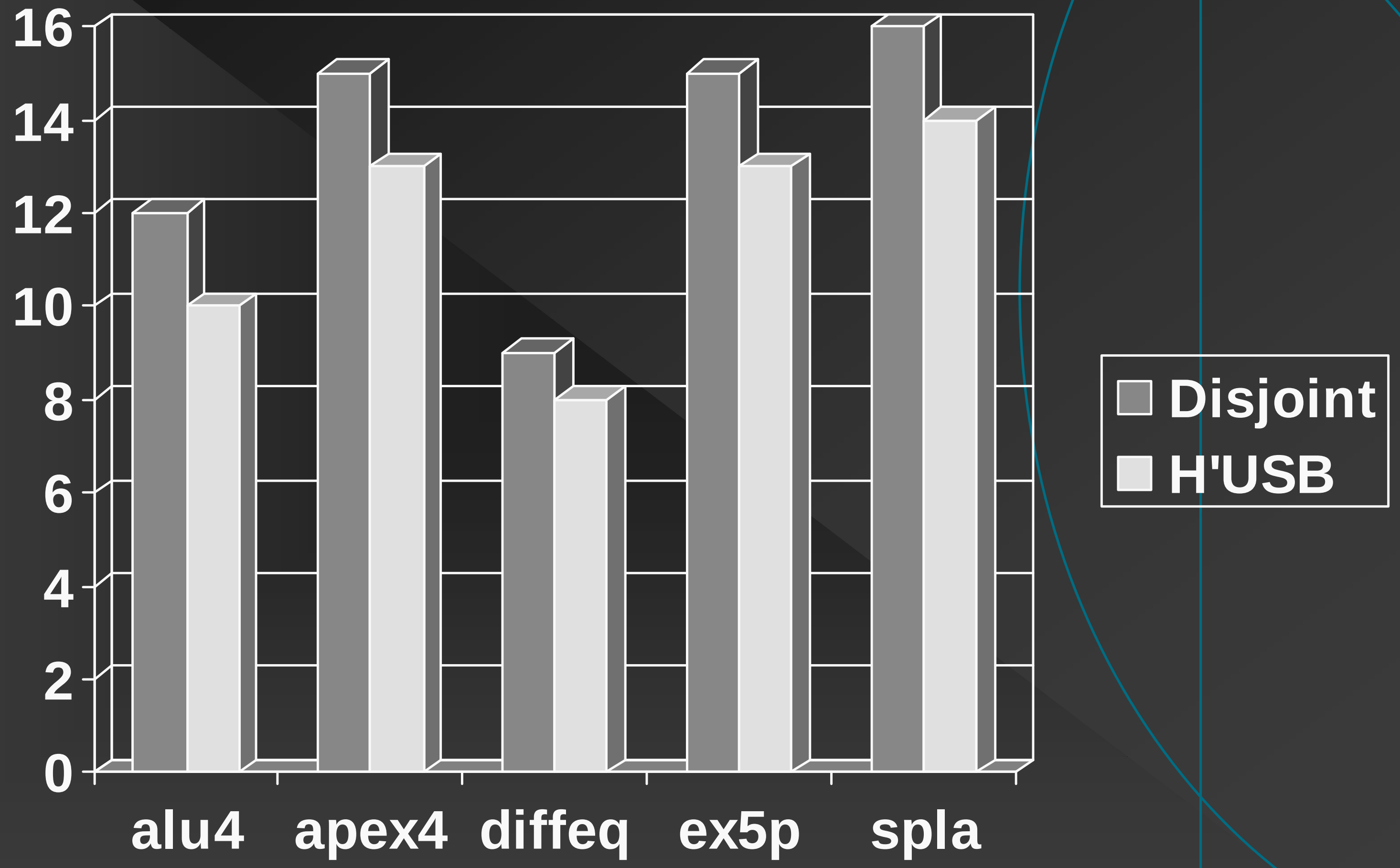
Disjoint (4, 11)-SB



Reduced (4, 11)-HUSBs

Experimental Results

- The H’USB FPGAs use about 10% less tracks than Disjoint S-box.



Experimental Results

Circuit Name	Disjoint	H'USB
alu4	12	10
apex2	12	11
apex4	15	13
bigkey	8	7
des	9	8
diffeq	9	8
dsip	7	7
elliptic	11	11
ex5p	15	13
misex3	13	12
seq	12	12
spla	16	14
tseng	8	7
e64	9	8
Total	156	141 (-9.62%)

Conclusion:

1. The graph models and systematic design method for FPAG like configurable switch boxes are presented.
2. Derive a series of new hyper-universal (4, w)-designs including optimum (4, w)-designs for w = 3, 4, 5, and a nearly optimum (4, w)-designs for w >= 6, 7.
3. An efficient routability verification is used, which leads to an efficient detailed routing algorithm.
4. The hyper-universal switch box is locally optimal with respect to the routing capability. Experimental shows that the hyper-universal switch box can also improve the global routing capacity.