Estimating Routing Congestion using Probabilistic Analysis

Jinan Lou **Shankar Krishnamoorthy** **Henry S. Sheng**

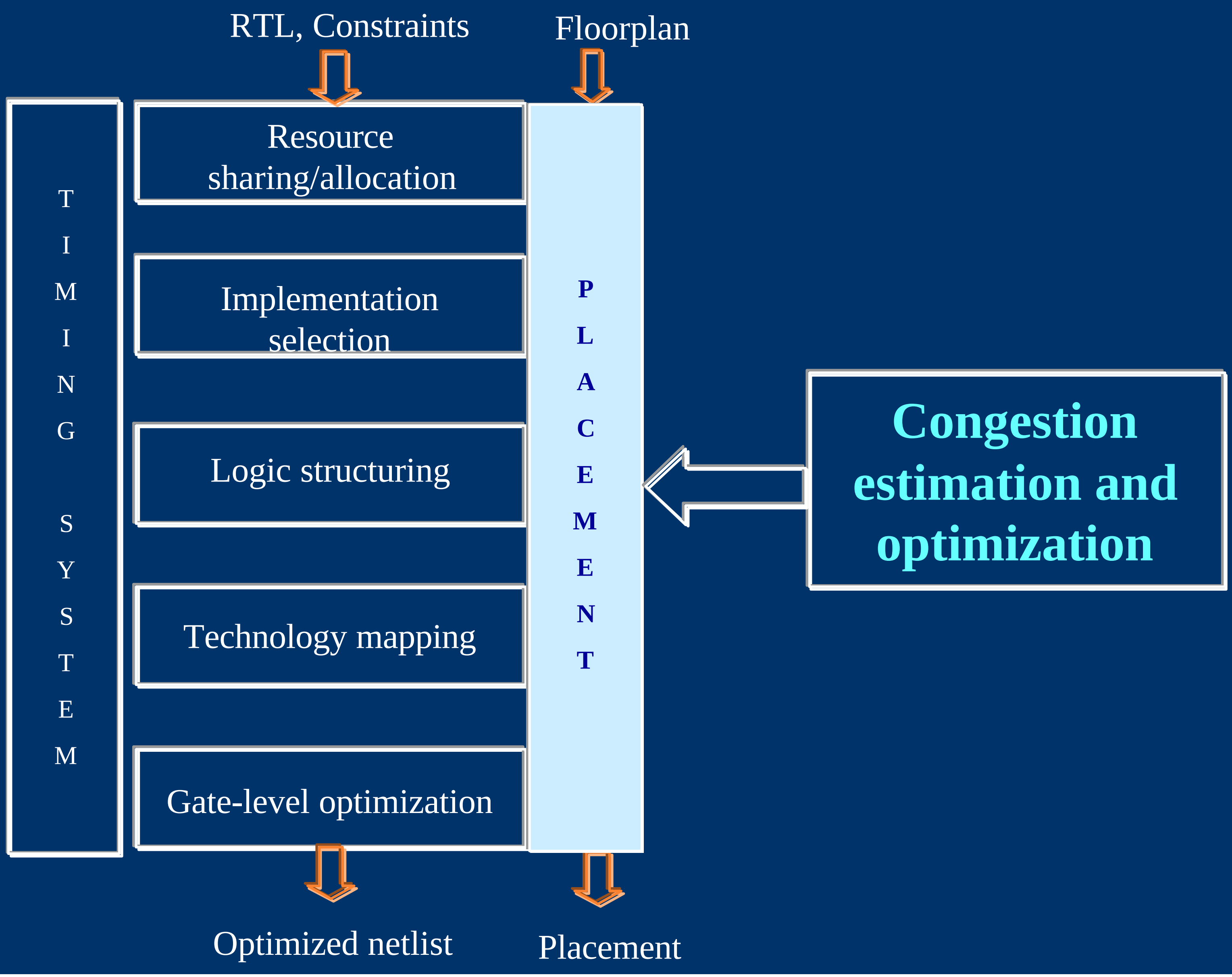
Synopsys Inc.

{jlou, shankar, hsheng}@synopsys.com

Congestion Problem

- **Wiring congestion is a key metric to predict routability & performance of a design**
  - **A good timing result is useful only if routing can be completed**
  - **Congestion increases delay uncertainty**
  - **Congestion deteriorate signal integrity**
- **Congestion optimization must be performed early in design cycles**
  - Synthesis adds many new gates to the design increasing cell density and wiring demand
  - Timing-driven placement has to keep critical gates closer
  - Users would like to close timing in same or smaller floorplans
- **Requires a fast and accurate estimator**

Physical Synthesis Flow

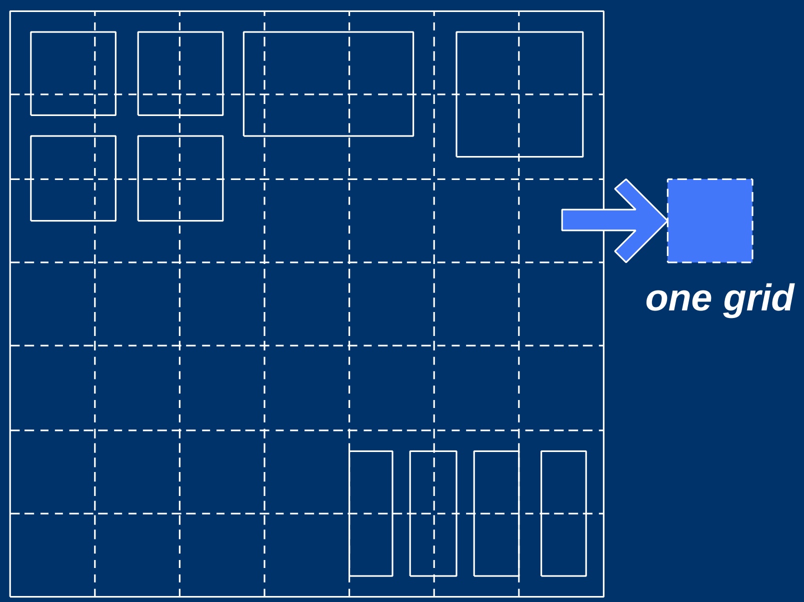


Summary of Our Contributions

- Proposed a probabilistic based congestion estimator
- Based on supply and demand analysis of routing resources
- Independent of implementation details of downstream routing algorithms
- Blockage aware
- Fast and yet accurate
- Congestion optimization based on this algorithm demonstrates its effectiveness

Congestion Analysis

- Divide the core area of the design into congestion grids
- Analyze the supply and demand for routing resources in each congestion grid



Routing Supply of a Grid

- N_h : number of horizontal routing layers
- N_v : number of vertical routing layers
- L_{hi} : minimum pitch for the i^{th} horizontal layer
- L_{vi} : minimum pitch for the i^{th} vertical layer

$$horizontal\_capacity = H \times \sum_{i=1}^{N^h} \left(1 / L^h{}_i \right)$$

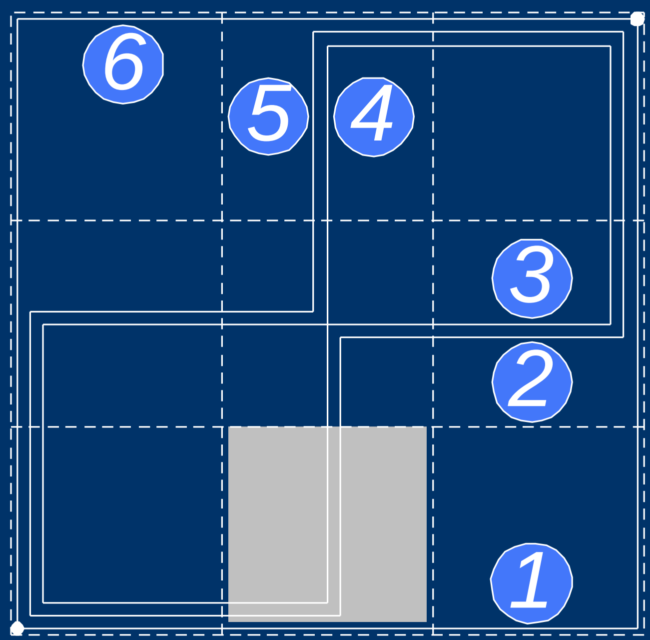
$$vertical\_capacity = W \times \sum_{i=1}^{N^v} \left(\frac{1}{L^v{}_i} \right)$$

Routing Demand of a Grid

- Empirical model
  - Design dependent
  - Hard to correlate to the real congestion
- Global router
  - Slow
  - Introduce problems for 3rd party routers
- Probabilistic analysis
  - Fast
  - Router independent

An Example

Estimate a 2-pin nets covering a 3´3 mesh



Total number of possible routes: 6

Horizontal usage = 0.5 + 0.5 + 1.0 = 2.0
Vertical usage = 1.0 + 1.0 = 2.0

$$\frac{1}{6}\times\begin{bmatrix} \begin{pmatrix}1 & 1\end{pmatrix} & \begin{pmatrix}2 & 2\end{pmatrix} & \begin{pmatrix}3 & 3\end{pmatrix} \\ \begin{pmatrix}2 & 2\end{pmatrix} & \begin{pmatrix}2 & 2\end{pmatrix} & \begin{pmatrix}2 & 2\end{pmatrix} \\ \begin{pmatrix}3 & 3\end{pmatrix} & \begin{pmatrix}2 & 2\end{pmatrix} & \begin{pmatrix}1 & 1\end{pmatrix} \end{bmatrix}$$

Number of Possible Routes

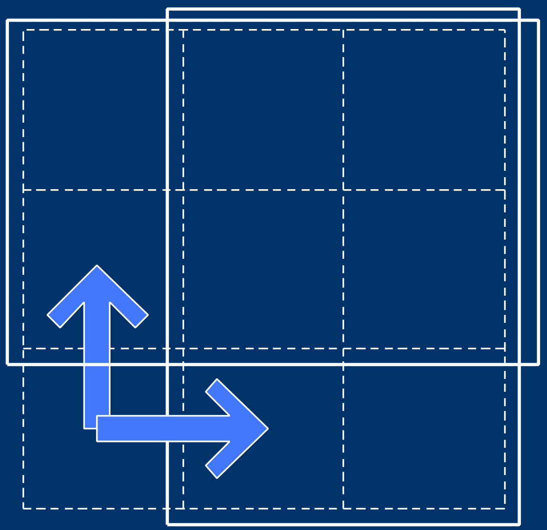
For a 2-pin net covering a *m´ n* mesh,
denote the number of possible routes as *F*(*m*, *n*) :

$$F(m,n) = F(m-1,n) + F(m,n-1)$$

$$F(m,n) = F(n,m)$$

$$F(m,n) = \begin{cases} 1 & n = 1 \\ m & n = 2 \\ \displaystyle\sum_{i_{n-2}=1}^{m} \sum_{i_{n-3}=1}^{i_{n-2}} \cdots \sum_{i_1=1}^{i_2} i_1 & n \geq 3 \end{cases}$$

***F*(*m*-1, *n*)**



***F*(*m*, *n*-1)**

F(*m*,*n*) up to 10´10

$$
\begin{bmatrix}
1 & 10 & 55 & 220 & 715 & 2002 & 5005 & 11440 & 24310 & 48620 \\
1 & 9 & 45 & 165 & 495 & 1287 & 3003 & 6435 & 12870 & 24310 \\
1 & 8 & 36 & 120 & 330 & 792 & 1716 & 3432 & 6435 & 11440 \\
1 & 7 & 28 & 84 & 210 & 462 & 924 & 1716 & 3003 & 5005 \\
1 & 6 & 21 & 56 & 126 & 252 & 462 & 792 & 1287 & 2002 \\
1 & 5 & 15 & 35 & 70 & 126 & 210 & 330 & 495 & 715 \\
1 & 4 & 10 & 20 & 35 & 56 & 84 & 120 & 165 & 220 \\
1 & 3 & 6 & 10 & 15 & 21 & 28 & 36 & 45 & 55 \\
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1
\end{bmatrix}
$$

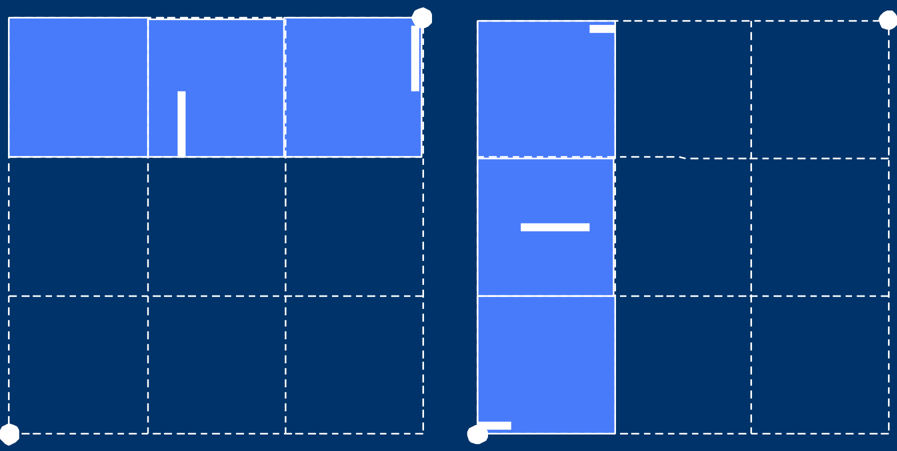
Probabilistic Usage Matrix

$$P(m,n) = \begin{bmatrix} \left(P_x(m,1) \quad P_y(m,1)\right) & \cdots & \left(P_x(m,n) \quad P_y(m,n)\right) \\ \vdots & \cdots & \vdots \\ \left(P_x(1,1) \quad P_y(1,1)\right) & \cdots & \left(P_x(1,n) \quad P_y(1,n)\right) \end{bmatrix}$$

$$P_{x|y}(i,j) = P_{x|y}(m-i+1,\ n-j+1)$$

$$\sum_{j=1}^{n} P_y(i,j) = 1 \quad \forall i$$

$$\sum_{i=1}^{m} P_x(i,j) = 1 \quad \forall j$$

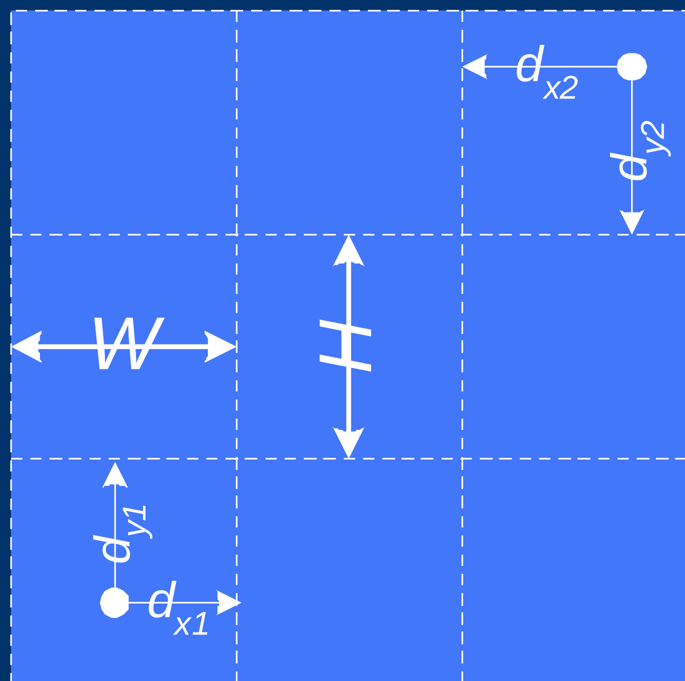


Computing the Probabilities

$$P_x(i,j)=\frac{1}{F(m,n)}\times\begin{cases} F(m,n-1) & \text{case } a\text{: } i=1,\ j=1 \\ 1 & \text{case } b\text{: } i=1,\ j=n \\ F(m-i+1,n-1) & \text{case } c\text{: } 1<i<m,\ j=1 \\ \dfrac{F(m,n-j+1)+F(m,n-j)}{2} & \text{case } d\text{: } i=1,\ 1<j<n \\ \dfrac{F(i,j)F(m-i+1,n-j)+F(i,j-1)F(m-i+1,n-j+1)}{2} & \end{cases}$$

$$P_y(i,j)=\frac{1}{F(m,n)}\times\begin{cases} F(m-1,n) & \text{case } a\text{: } i=1,\ j=1 \\ 1 & \text{case } b\text{: } i=1,\ j=n \\ \dfrac{F(m-i+1,n)+F(m-i,n)}{2} & \text{case } c\text{: } 1<i<m,\ j=1 \\ F(m-1,n-j+1) & \text{case } d\text{: } i=1,\ 1<j<n \\ \dfrac{F(i,j)F(m-i,n-j+1)+F(i-1,j)F(m-i+1,n-j+1)}{2} & \end{cases}$$

Off-grid Pins



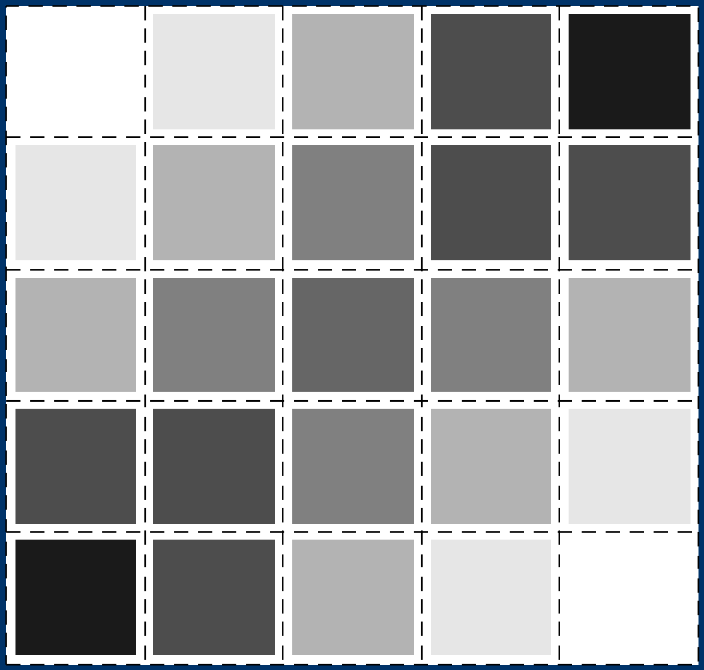
Horizontal Usage with Off-grid Pins

$$P_x(i,j) = \frac{1}{F(m,n)} \times \begin{cases} F(m,n-1)\times {}^{d_{x1}}\!/_{W} & \text{case } a: i=1, j=1 \\ F(m,n-1)\times {}^{d_{x2}}\!/_{W} & \text{case } \tilde{a}: i=m, j=n \\ {}^{d_{x2}}\!/_{W} & \text{case } b: i=1, j=n \\ {}^{d_{x1}}\!/_{W} & \text{case } \tilde{b}: i=m, j=1 \\ F(m-i+1,n-1)\times {}^{d_{x1}}\!/_{W} & \text{case } c: 1<i<m, j=1 \\ F(i,n-1)\times {}^{d_{x2}}\!/_{W} & \text{case } \tilde{c}: 1<i<m, j=n \\ \dfrac{F(m,n-j+1)+F(m,n-j)}{2} & \text{case } d: i=1, 1<j<n \\ \dfrac{F(m,j)+F(m,j-1)}{2} & \text{case } \tilde{d}: i=m, 1<j<n \\ \dfrac{F(i,j)F(m-i+1,n-j)+F(i,j-1)F(m-i+1,n-j+1)}{2} & \end{cases}$$

Vertical Usage with Off-grid Pins

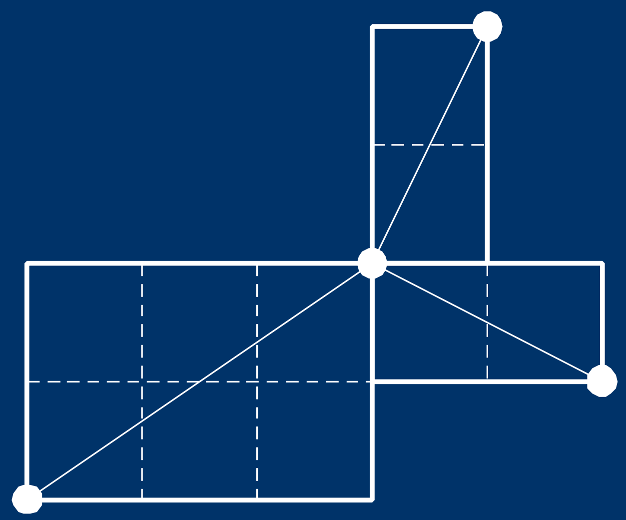
$$P_y(i,j) = \frac{1}{F(m,n)} \times \begin{cases} F(m-1,n)\times {d_{y1}}/{H} & \text{case } a\text{: } i=1,\ j=1 \\ F(m-1,n)\times {d_{y2}}/{H} & \text{case } \tilde{a}\text{: } i=m,\ j=n \\ {d_{y1}}/{H} & \text{case } b\text{: } i=1,\ j=n \\ {d_{y2}}/{H} & \text{case } \tilde{b}\text{: } i=m,\ j=1 \\ \dfrac{F(m-i+1,n)+F(m-i,n)}{2} & \text{case } c\text{: } 1<i<m,\ j=1 \\ \dfrac{F(i,n)+F(i-1,n)}{2} & \text{case } \tilde{c}\text{: } 1<i<m,\ j=n \\ F(m-1,n-j+1)\times {d_{y1}}/{H} & \text{case } d\text{: } i=1, 1<j<n \\ F(m-1,j)\times {d_{y2}}/{H} & \text{case } \tilde{d}\text{: } i=m, 1<j<n \\ \dfrac{F(i,j)F(m-i,n-j+1)+F(i-1,j)F(m-i+1,n-j+1)}{2} & \end{cases}$$

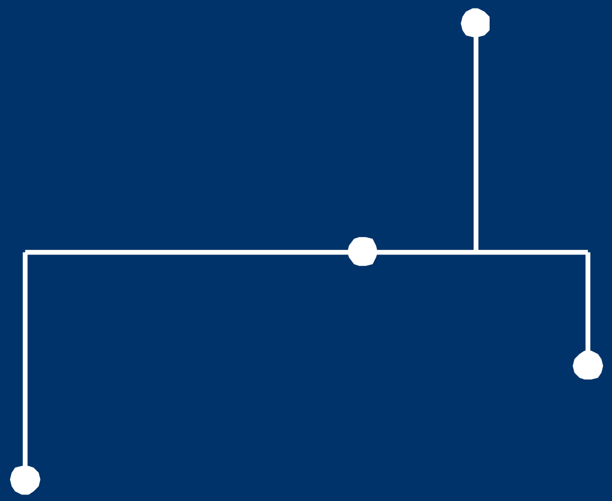
Track Usages for a 5´5 Mesh



- Darker color represents higher probability of usages

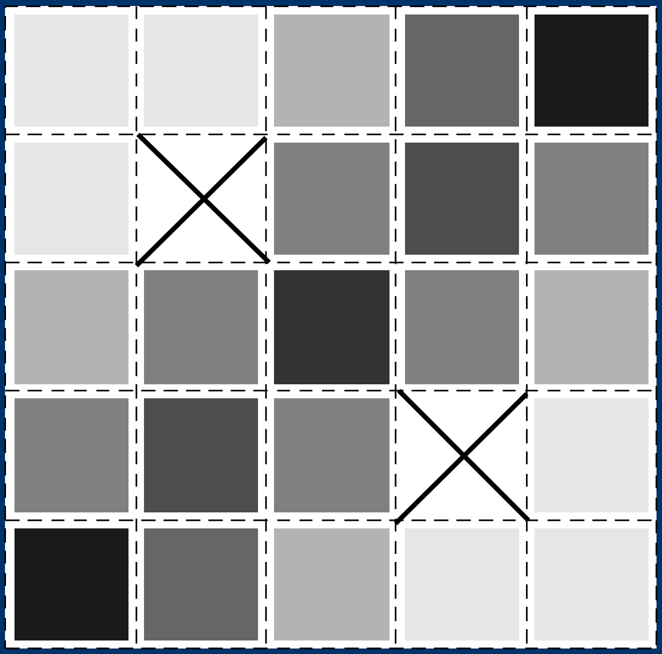
Multi-pin Nets





- MST based algorithm in early stages
- RST based algorithm in later stages

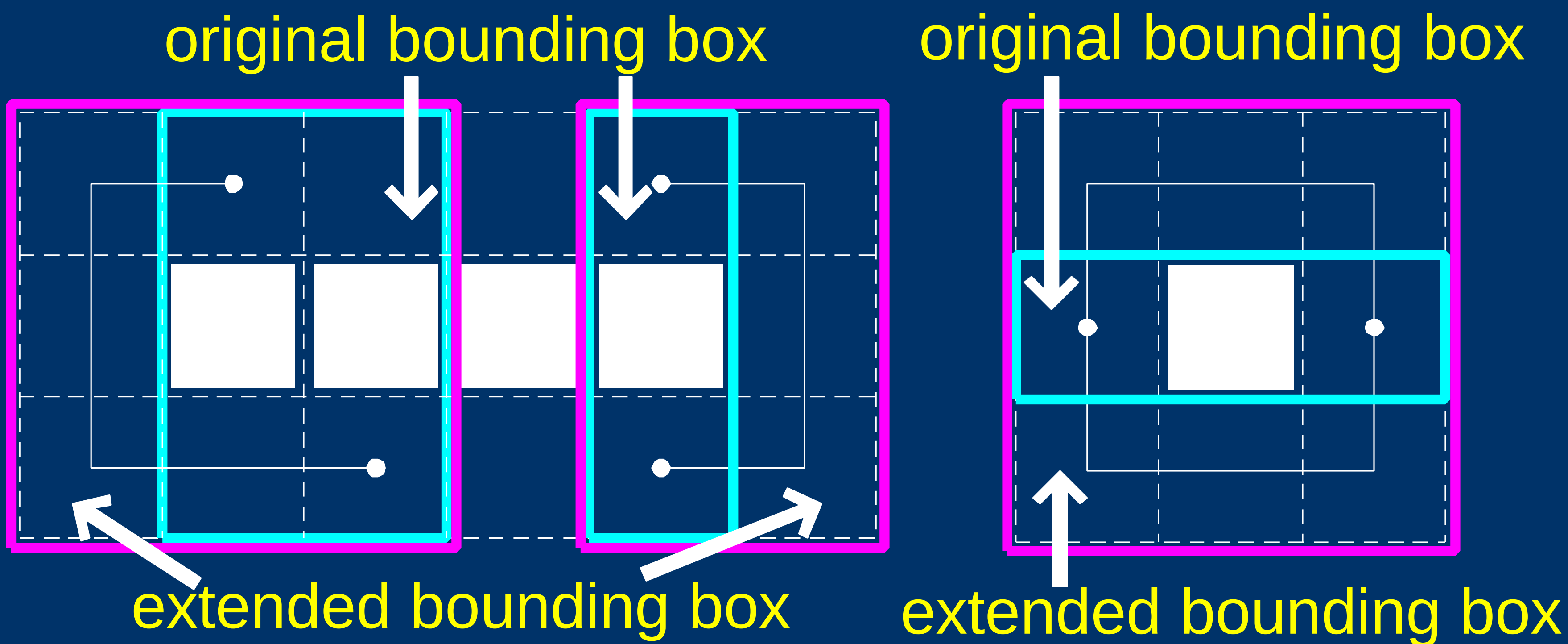
Simple Routing Blockages



Distribute the usage of a blocked grid to its neighboring grids based on the distance *d* and number of unblocked neighbors *n*:

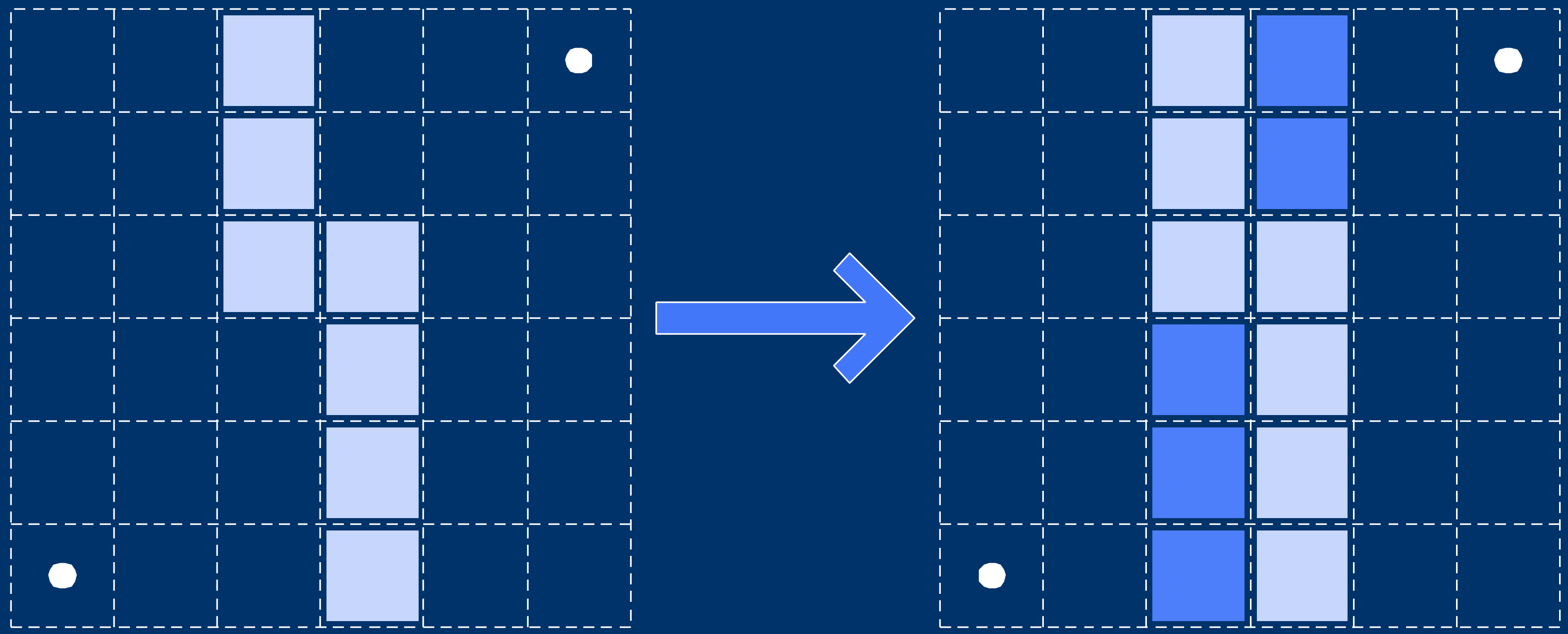
$$w = 2^{-d} \times n$$

Line Blockages



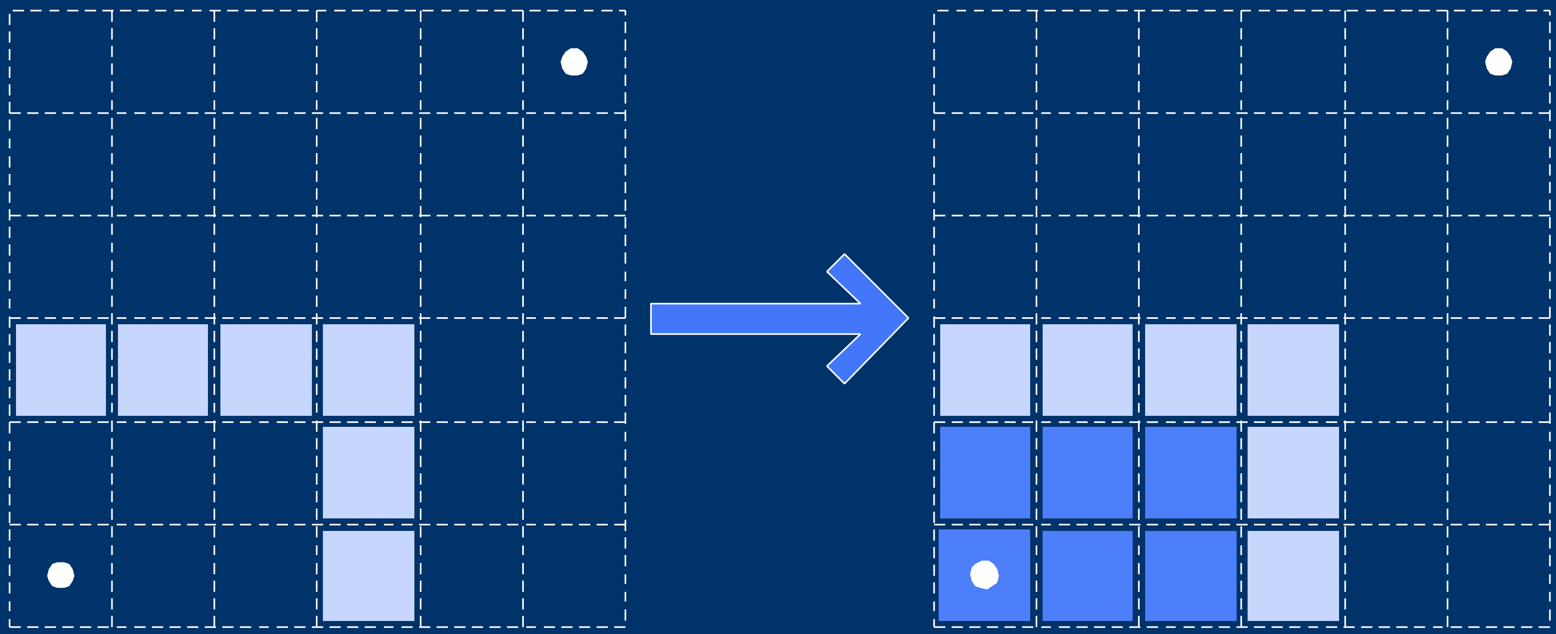
- **Extend the bounding box of the net**

Adjacent Blockages



• **Find the bounding box of the blockages**

Complex Blockages

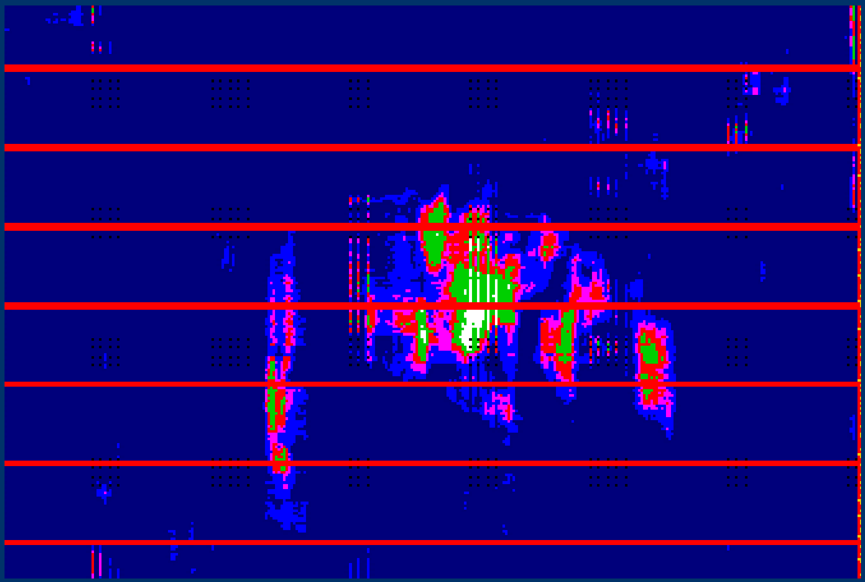


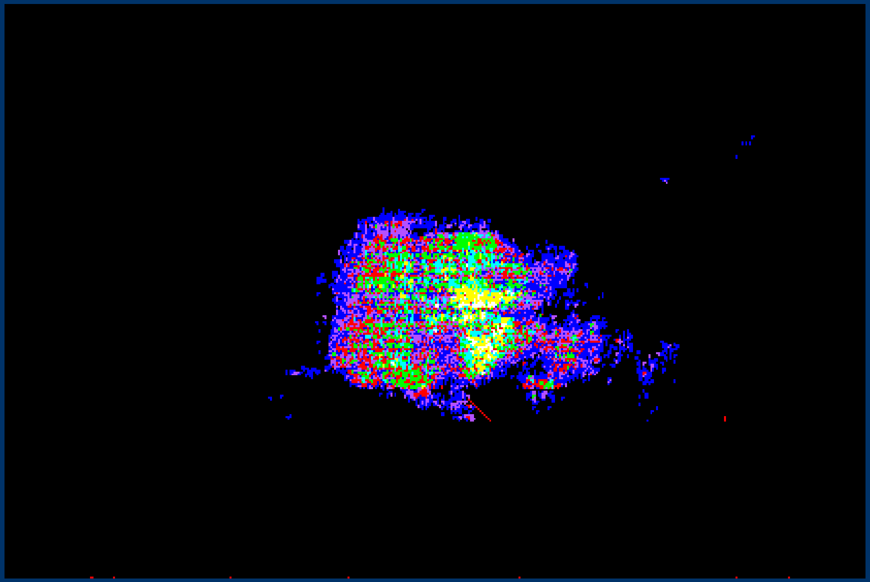
- Maze router needed
- How often do you see this?

Runtime for two Testcases

	# of instances	# of nets	CPU time
Design1	316K	332K	70s
Design2	347K	374K	110s

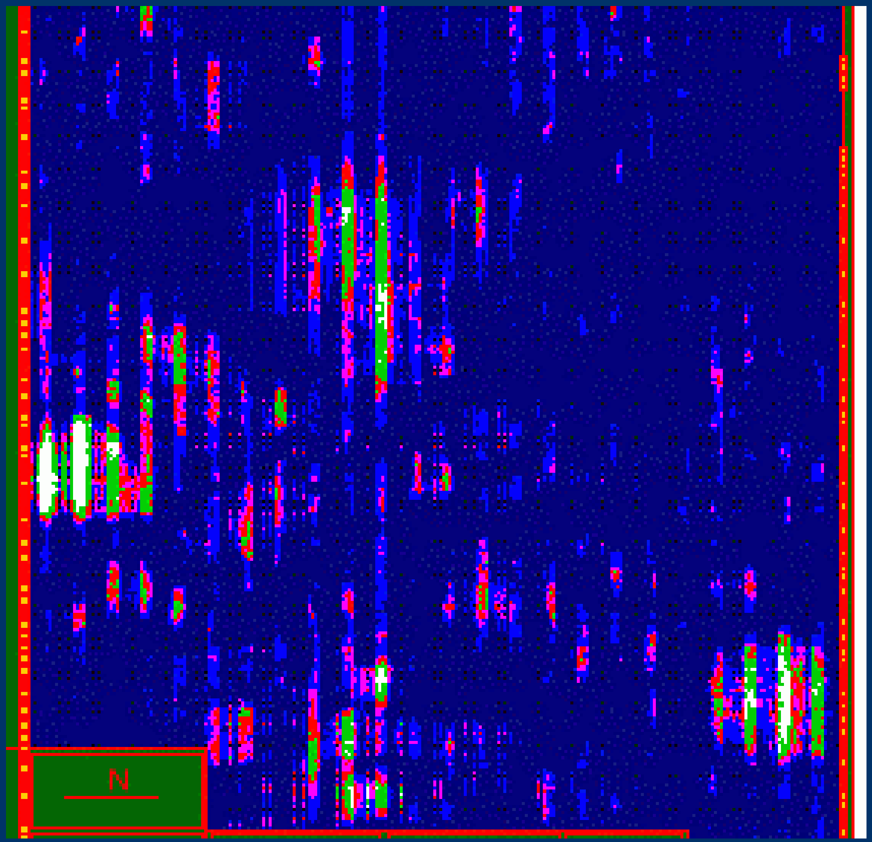
Testcase I: Congestion Correlation



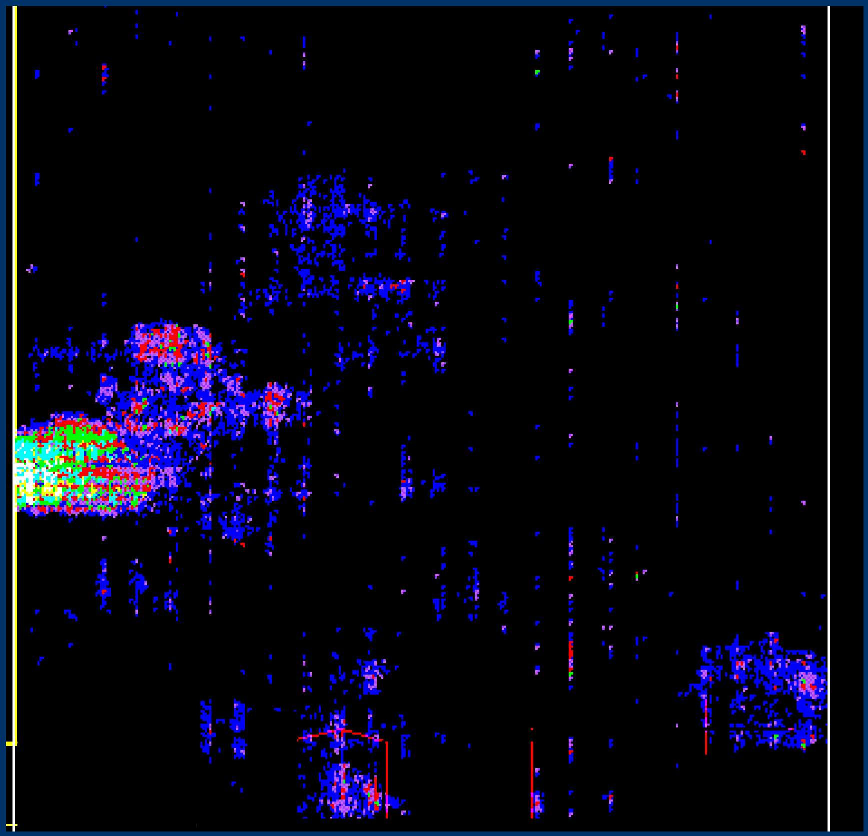


Estimated congestion **Post-route congestion**

Testcase II: Congestion Correlation

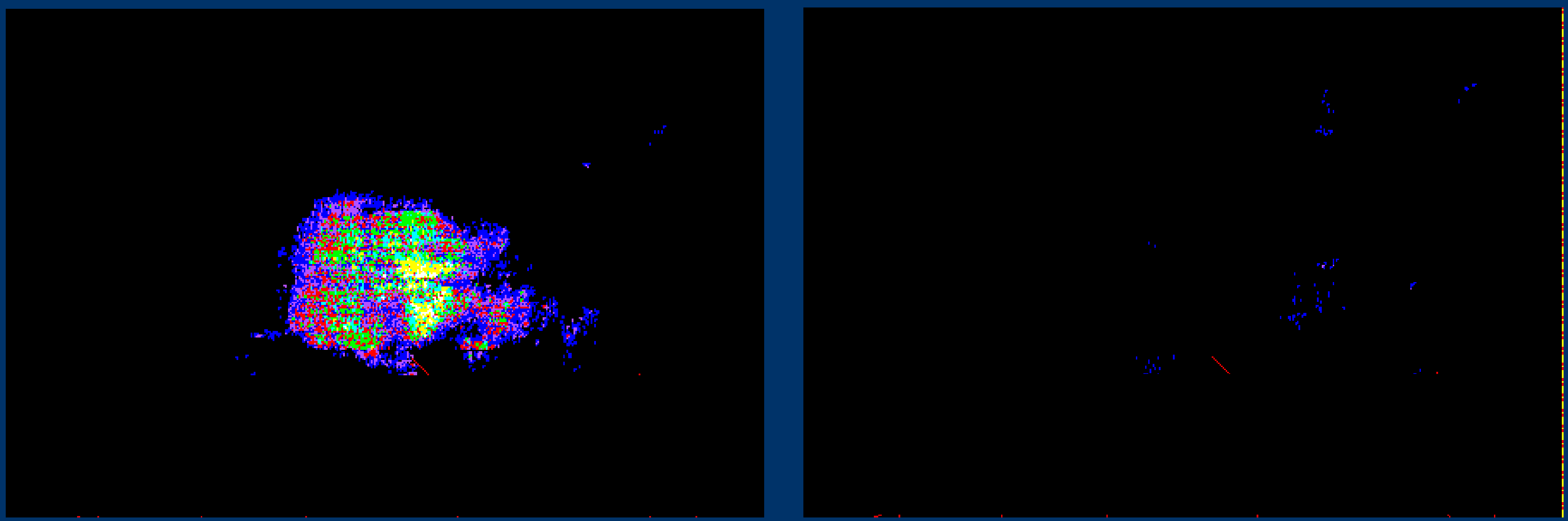


Estimated congestion



Post-route congestion

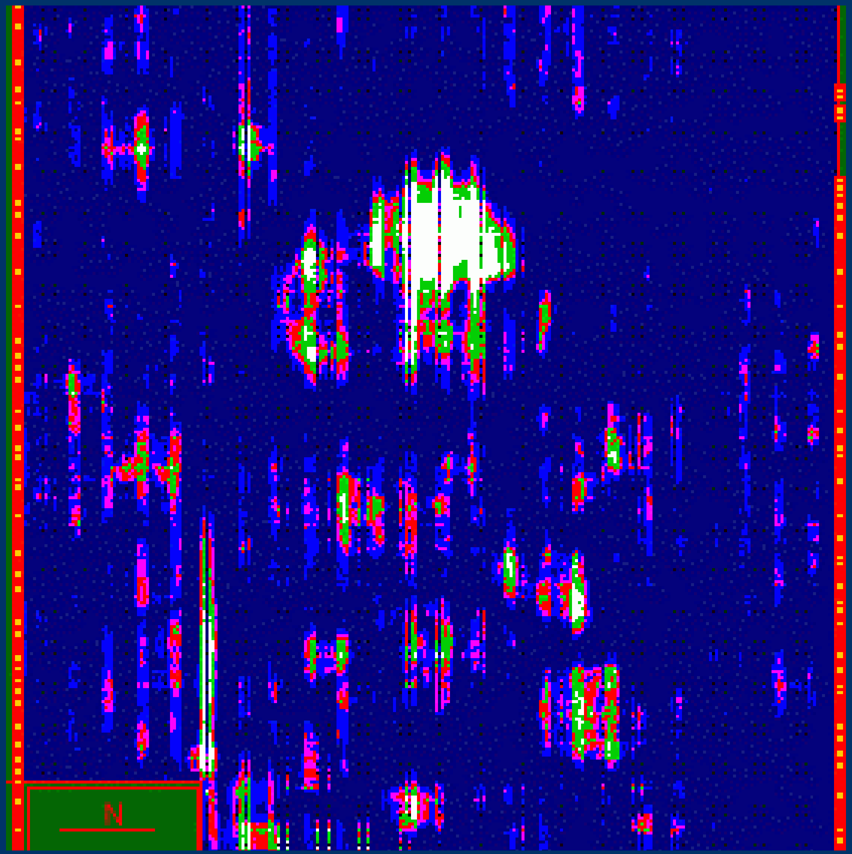
Testcase I: Congestion Removal



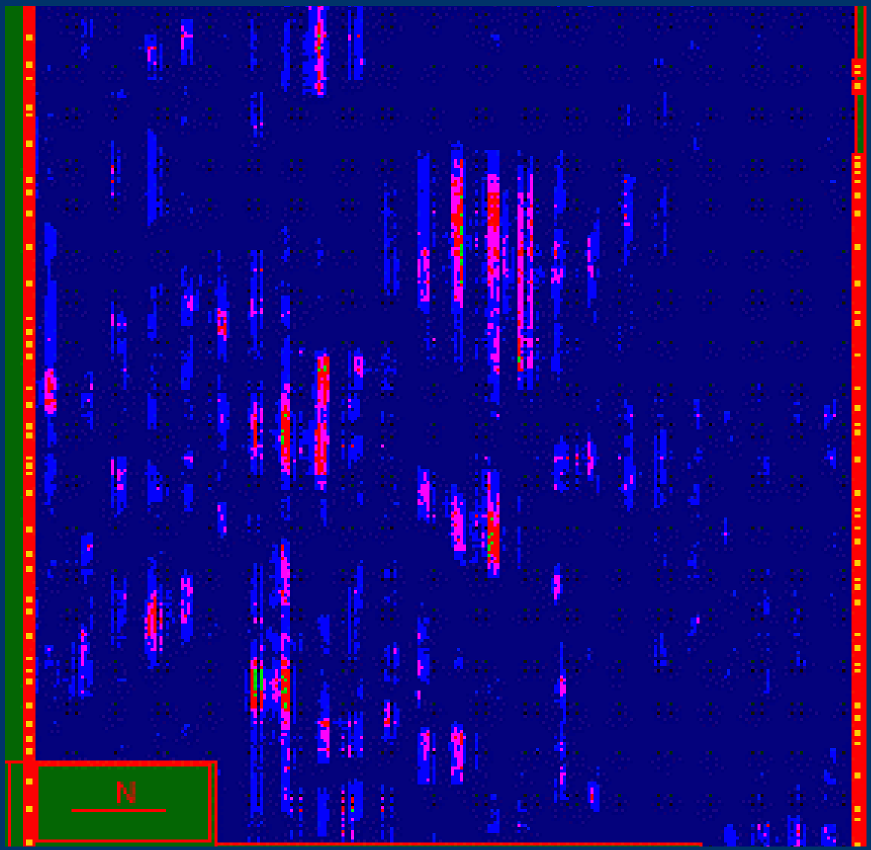
Congestion without optimization

Congestion with optimization

Testcase II: Congestion Removal



Congestion without optimization



Congestion with optimization

Conclusion

- Timing closure for complex designs requires fast and accurate congestion estimators
- Probabilistic congestion estimation is a key technology in physical synthesis
- Congestion optimization based on this algorithm demonstrates its effectiveness