Design Rule Generation for Interconnect Matching

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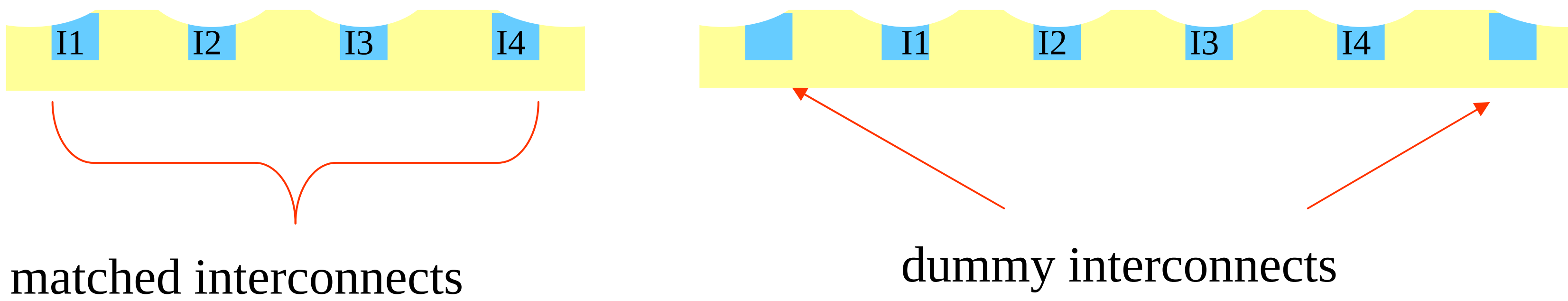
Outline

- Motivation
- Problem Definition
- Extraction for Mismatch
  - Correlation Model
  - Modification to Standard Extraction
  - Regression Model
  - Correlation Extraction
    - Optimization
    - Initialization Scheme
- Experimental Results
- Conclusions and Future Work

Motivation

- Interconnect delay has been dominating gate delay
- Process variations in interconnects will be increasingly important
- Certain interconnects (and clock trees, power grids) need to be matched in circuits
- <u>Matching guarantee rules have started to enter Design Rule Manuals (DRM)</u>
  - Example: "Two wires of length > X um spaced less than Y um apart will have < Z% RC mismatch."

Layout Optimizations Insufficient



- Dummy structures can be inserted to create uniformity so that systematic effects caused by manufacturing steps, e.g. dishing due to chemical-mechanical polishing, can be nullified
- Without dummies, mismatch between the pairs I1-I2 or I3-I4 would be different than mismatch between I2-I3
  - Longer-range pattern effects will also cause mismatch

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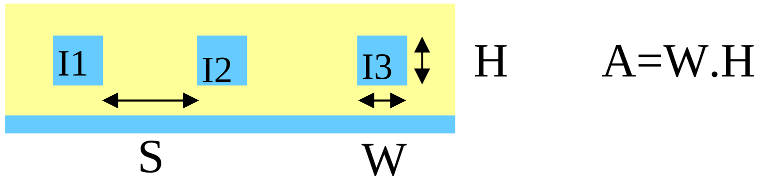
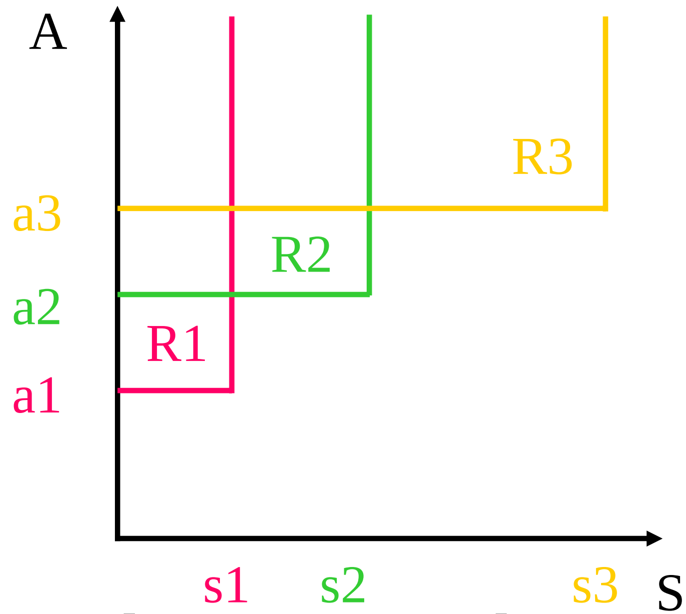
Problem Introduction



- The DRM contains a number, e.g. 1-4, of guarantee rules that give percent matching guarantees with respect to cross-section area (A) and spacing (S) combinations
- GOAL: Generate more rules to reduce design pessimism

Matching-Guarantee Space

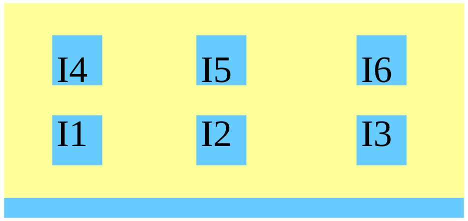


- *Rule i* states that when spacing between two matched interconnects < *si* and area of one of the interconnects > *ai*, matching is guaranteed by a given percent
- Question: What is the matching guarantee for an *ai*-*si* combination not given in DRM?

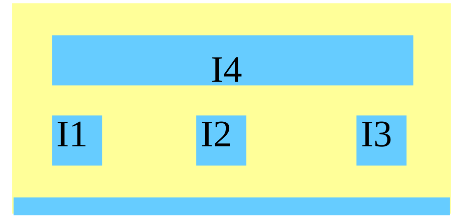
Obstacles

- Straightforward mathematical extrapolation not possible
- Process information should first be extracted
- A correlation function needs to be defined
- Modifications to traditional extraction scheme necessary to enable extraction of mismatch

Traditional (Cap) Extraction



Parallel and cross-over patterns



- A pattern is selected
- 3 parallel interconnects are placed in a simulation box
- Field simulation for various width, height, spacing combinations run; <u>data of middle line used</u>
- If 3D pattern, also length can be changed
- A regression function is used to fit data
- When a pattern is seen in design, function is used to calculate the coupling/total capacitances after application of signal integrity and model order reduction

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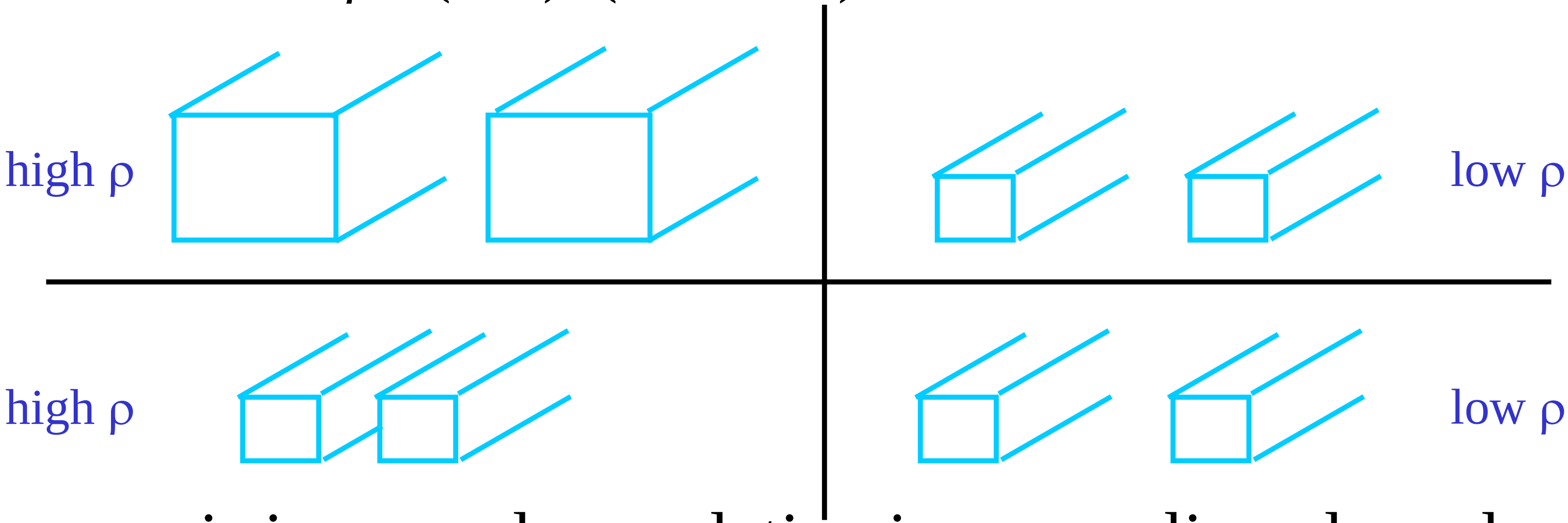
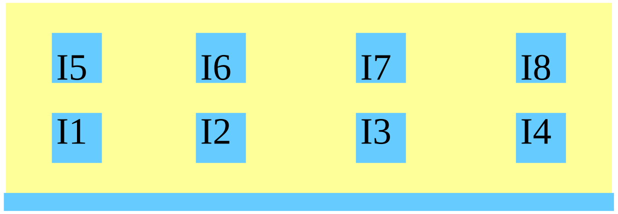
Correlation Model

- Assume an analytical interconnect-matching correlation model proposed similar to Pelgrom's:
  - correlation=ρ=f(A,S)=(a.A+b/S^2)

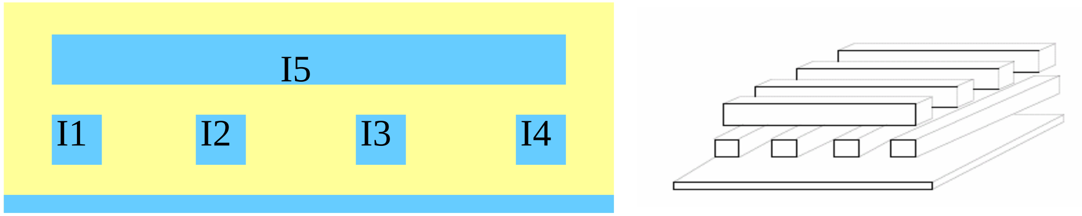


- As area is increased, correlation increases linearly and as spacing is increased, correlation decreases quadratically
- Note: Our proposed methodology <u>is</u> model-independent

Modification of Extraction Methodology for Mismatch



Parallel pattern



Cross-over pattern, 2D vs. 3D

- One more interconnect line is added into the simulation box for each pattern
- Correlation calculations used to assign dimensions to ***n*** interconnects:
  - $C=M.M^T$, where C is n**x**n positive-definite and symmetric correlation matrix, M found by Cholesky decomposition
  - Z=MG , where Gi = independent Gaussian R.N.'s N(0,1)
- Monte-Carlo simulations run for each pattern and spacing-dimension combinations
- **Two middle** interconnect lines used to extract mismatch

Regression Function

- After mismatch extraction, a regression function is fit on data
  - Correlation function: $\rho=f(A,S)=(a.A+b/S^2)$
  - Regression function for mismatch: $(e+f/A+gS^2)$
- When area increases or spacing decreases, mismatch decreases

Correlation Extraction

- Monte Carlo simulations yield a statistical information about mismatch, such as standard deviation of distribution for difference of capacitances of middle wires
- This deviation needs to be optimized with respect to the rules given in the design manual to extract *a*, *b* parameters of the correlation model
- Must ensure that modified extraction using Monte Carlo simulations using the correlation model yields same results as the provided design rules within prescribed error range
- But, different A and S combinations associated with different rules indicate different functions …….

Optimization Algorithm

- $\rho = f(A,S) = (a.A + b/S^2)$
- We propose a modified multi-variate Newton-Raphson for multiple functions to extract correlation parameters a and b from design rules
- ε is error rate

While $(((\rho\text{-}\rho^*)/\rho > \epsilon)$ **OR** $((\rho_n\text{-}\rho_n^*)/\rho_n > \epsilon))$ {
  If $((\rho\text{-}\rho^*)/\rho > \epsilon)$ {
    $a = a - (\rho^* - \rho)/\frac{\partial \rho}{\partial a}$
    $b = b - (\rho^* - \rho)/\frac{\partial \rho}{\partial b}$
    $\rho = a * A_n + b/S_n^2$ }
  If $((\rho_n\text{-}\rho_n^*)/\rho_n > \epsilon)$ {
    $a = a - (\rho_n^* - \rho_n)/\frac{\partial \rho_n}{\partial a}$
    $b = b - (\rho_n^* - \rho_n)/\frac{\partial \rho_n}{\partial b}$
    $\rho_n = a * A_n + b/S_n^2$ }}

ρ_n=n^th design rule

ρ^*=given in design manual

Optimization for Correlation Model

- Handle as many rules as necessary by replicating dotted blocks. Example above is for 2 rules, e.g. 2 A-S combinations
- Intuition to help avoid local optima: Choose the *If* block that is used the least at current step

While $(((\rho\text{-}\rho^*)/\rho > \epsilon)$ **OR** $((\rho_n\text{-}\rho_n^*)/\rho_n > \epsilon))$ {

  If $((\rho\text{-}\rho^*)/\rho > \epsilon)$ {

    $a = a - (\rho^* - \rho)/\frac{\partial \rho}{\partial a}$

    $b = b - (\rho^* - \rho)/\frac{\partial \rho}{\partial b}$

    $\rho = a * A_n + b/S_n^2$ }

  If $((\rho_n\text{-}\rho_n^*)/\rho_n > \epsilon)$ {

    $a = a - (\rho_n^* - \rho_n)/\frac{\partial \rho_n}{\partial a}$

    $b = b - (\rho_n^* - \rho_n)/\frac{\partial \rho_n}{\partial b}$

    $\rho_n = a * A_n + b/S_n^2$ }}

ρ_n=nth design rule

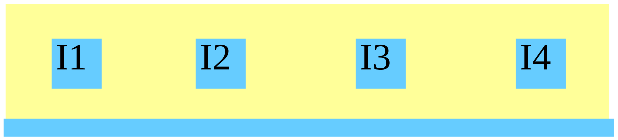
ρ^*=given in design manual

Initialization Scheme

- Newton-Raphson algorithms need close initial points for fast convergence
- We use a decomposition scheme for fast convergence
  - $\rho = f(A,S) = (a.A + b/S^2)$
  - If know $0.12 < A < 0.36\ (\mu m)^2$ and $0.12 < S < 0.36\ \mu m$
  - Re-write as $\rho = f(A,S) = (a' * A / 0.36 + b' * 0.12^2 / S^2)$
- Now a' and b' are weights for influence of area and spacing on correlation respectively. Restrict a'+b' to [0,1], i.e., to define a positive correlation

Special Case: Edge Matching

- Given a and b, more A-S combinations can be generated
- Monte Carlo run for field solutions on various A-S combinations and interconnect patterns
- Mismatch models extracted by regression on simulation data
- Edge matching, I1-I2 or I3-I4 can be different than matching of I2-I3, if dummy metal lines not used, ex. in a clock h-tree



- We suggest modeling these separately, using a different set of parameters for the regression function

Summary of Overall Flow

Input: correlation function,
matching rules,
proposed multi-function
Newton Raphson algorithm,
modified simulation patterns

Input: correlation function with
extracted parameters,
modified simulation patterns

(yellow)	process extraction step
(green)	generation step

Extract parameters of
correlation function
through Monte Carlo
field simulations

↓

Simulate new matching
guarantees through
Monte Carlo field
simulations on required
patterns and sizes

↓

Output: a regression function
for new matching rules

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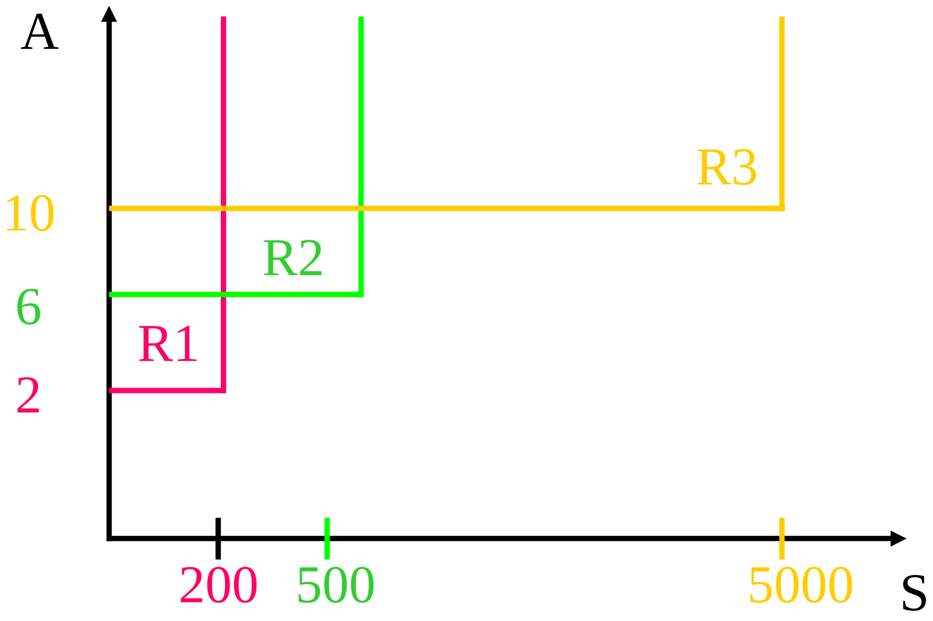
Experiment Targets

- Given an initial set of design rules, generate additional rules
- Raphael used for field solutions

Initial Rules



- Initially 3 Rules are Provided in the DRM:
  - Rule1: If W>2µm & S<200µm, mismatch<1.9987%
  - Rule2: If W>6µm & S<500µm, mismatch<1.9280%
  - Rule3: If W>10µm & S<5000µm, mismatch<2.0960%

Mismatch Results for Varying S

W=0.1µm, L=0.1µm

S (μm)	1	10	100
$\mu_{I2}(fF)$	3.2021e-2	3.2234e-2	3.1676e-2
$\sigma_{I2}(fF)$	9.8411e-3	1.0096e-3	1.6614e-3
$\sigma_{(I2-I3)}(fF)$	7.2388e-4	6.6459e-4	1.0804e-3
$\sigma_{(I2-I3)}/\sigma_{I2}$	1.3595	1.5191	1.5378
$\sigma_{(I2-I3)}/\mu_{I2}$			

- Keeping W and L fixed and increasing spacing increases mismatch

Mismatch Results for Varying L

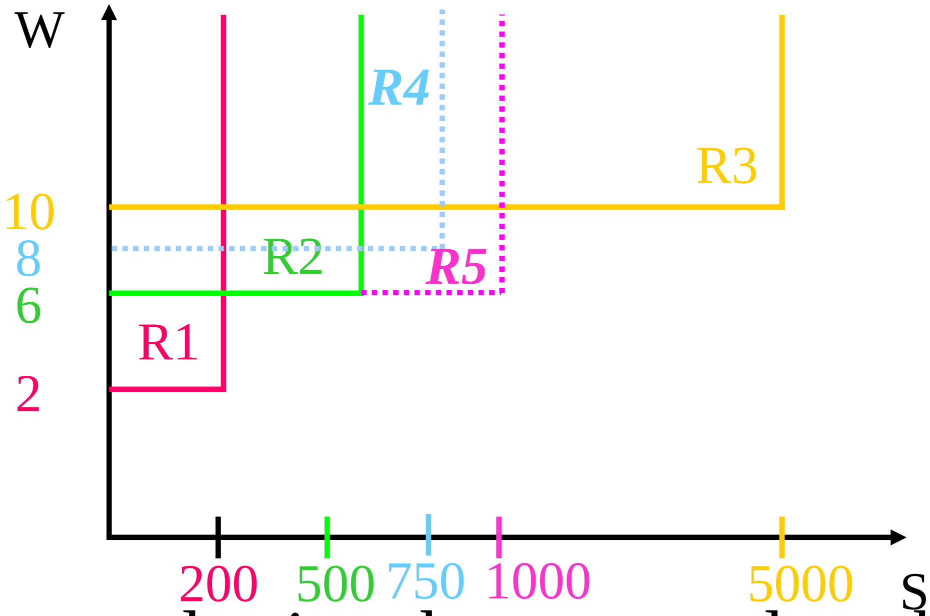
W=1, S=100

L (um)	1	10	100
$\mu_{I2}(fF)$	4.0674e-01	4.5773	5.4327e+1
$\sigma_{I2}(fF)$	1.8921e-2	1.8201e-1	1.8395
$\sigma_{(I2-I3)}(fF)$	1.3907e-2	1.4274e-1	1.5687
$\sigma_{(I2-I3)}/\sigma_{I2}$	1.3606	1.2752	1.1726
$\sigma_{(I2-I3)} / \mu_{I2}$			

- Keeping W and S fixed and increasing length decreases mismatch

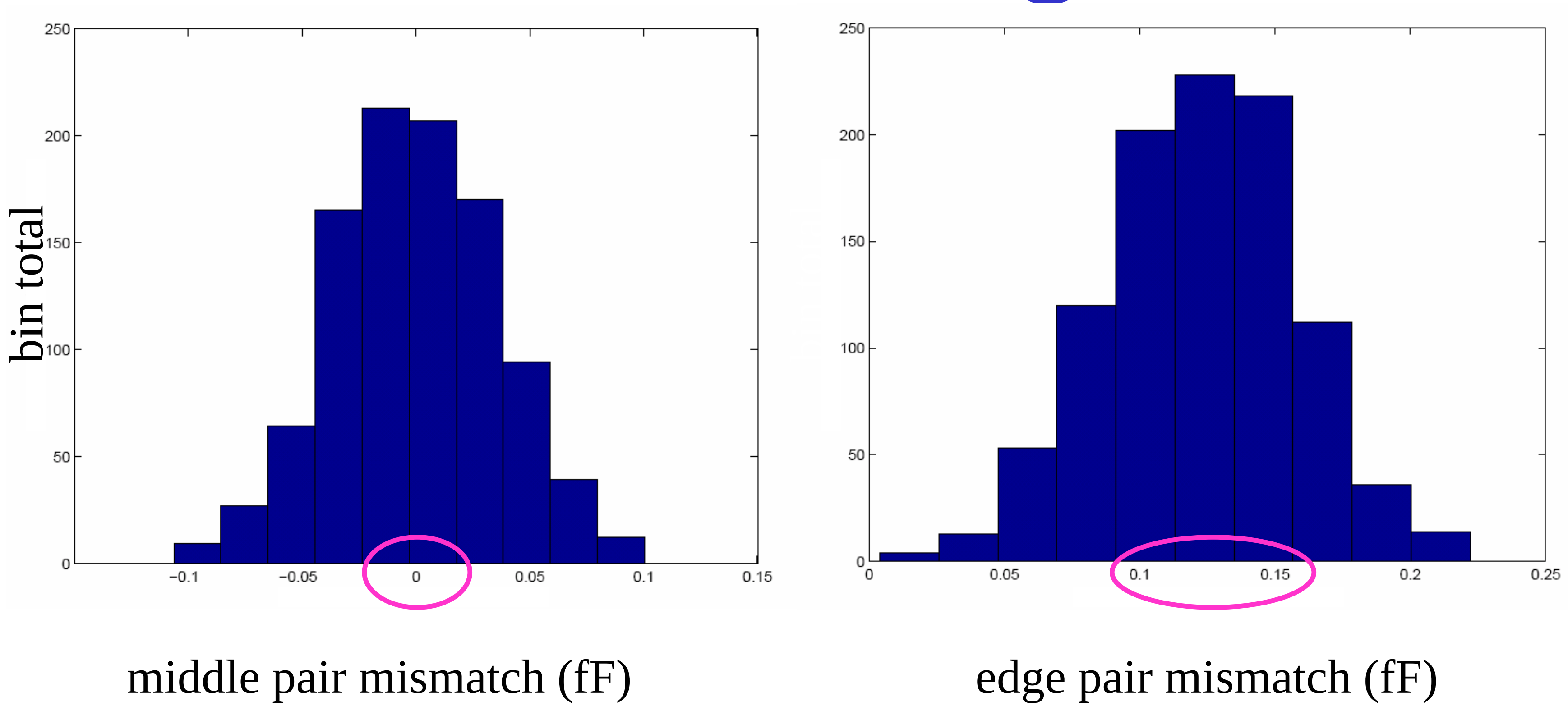
Guarantee Analysis

- Initially 3 Rules are Provided in the DRM:
  - Rule1: If W>2µm & S<200µm, mismatch<1.9987%
  - Rule2: If W>6µm & S<500µm, mismatch<1.9280%
  - Rule3: If W>10µm & S<5000µm, mismatch<2.0960%



- 2 rules are extracted using the proposed method:
  - Rule4: If W>8µm & S<750µm, mismatch<1.9017%
  - Rule5: If W>6µm & S<1000µm, mismatch<2.0388%

Mismatch Histograms



- Edge-pair mismatch shows a bias, hence better to be modeled separately

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Conclusions

- Interconnect correlation model introduced
- We have proposed a mismatch extraction method
  - Method is correlation-model independent
  - We have proposed a correlation extraction method consisting of initialization and optimization steps
- We introduced a design rule generation methodology

Future Work

- Interconnect optimization using design rule generation
  - To reduce design pessimism, critical interconnect such as in H-trees can be optimized for mismatch