Process-Induced Skew Reduction in Nominal Zero-Skew Clock Trees

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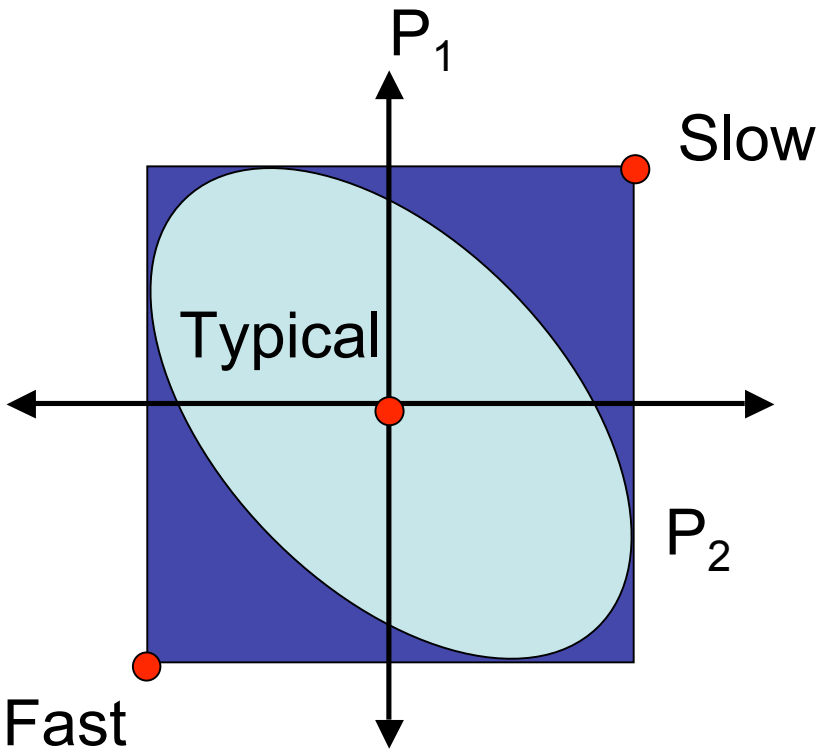
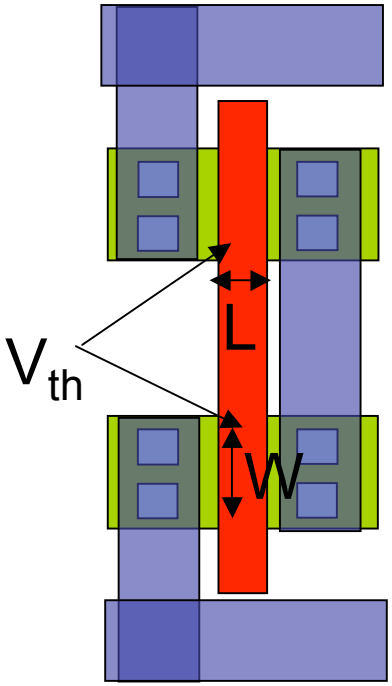
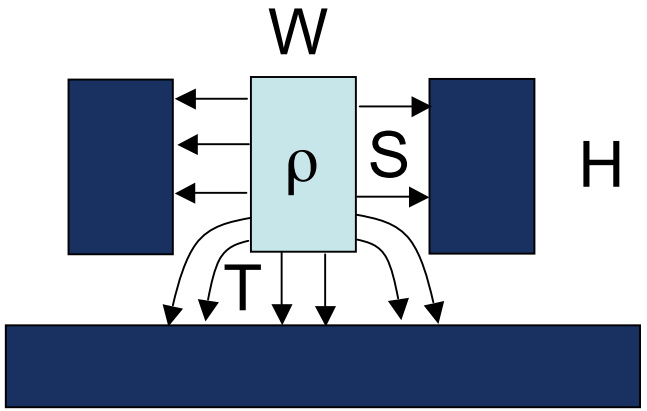
Motivation

- Variation is increasing
- Number of sources is increasing
  - Environmental (temperature, voltage, etc.)
  - Physical (lithography, materials, etc.)
  - Fatigue (NBTI, metal migration, etc.)
- Need statistical optimization
  - Process-Voltage-Temp (PVT) Optimization



Variation Sources





L_{eff}= 53nm±16.7%
$V_{thp=}$ 0.232±30%
V_{thn}= -0.273±30%

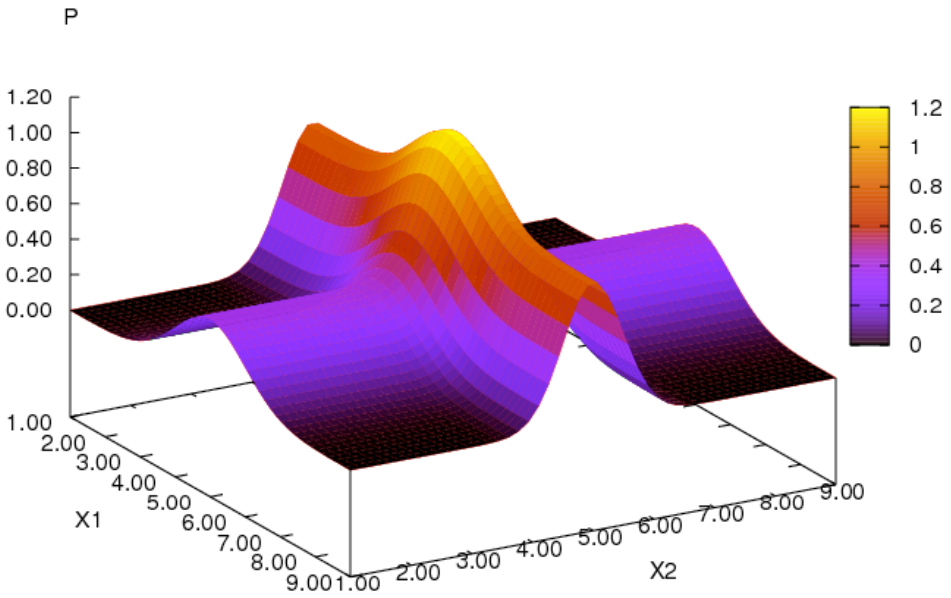
W =175nm±32nm
H = 280nm±15%
T = 280nm±10%
S = 175nm±20%
ρ = 2.2e-8±30%

Parameterized Model

Nominal Correlated Independent

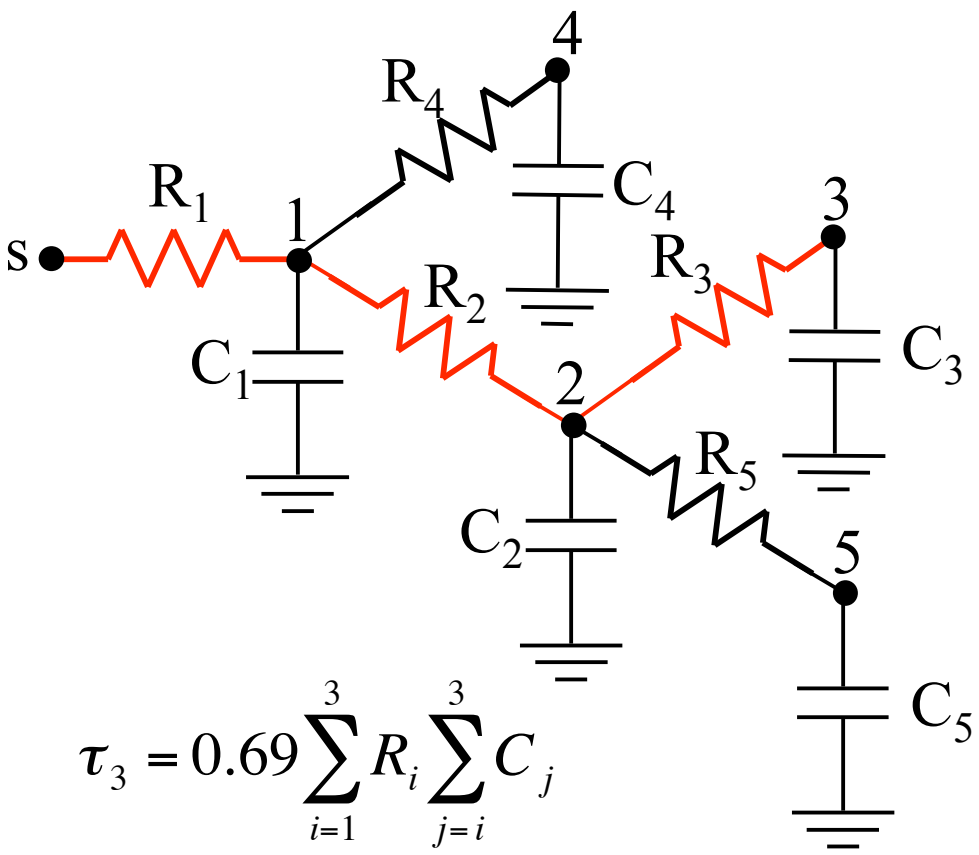
$$D = d_0 + \sum d_i X_i + d_r X_r$$

Random Variables



Elmore Delay

- Not accurate, but high fidelity.
- Results can be tuned later with better models.
- Fast for optimization.



$$\tau_3 = 0.69 \sum_{i=1}^{3} R_i \sum_{j=i}^{3} C_j$$

Parameterized Addition/Subtraction

$$A + B = (a_0 + b_0)$$
$$+(a_1 + b_1)X_1 + (a_2 + b_2)X_2 + \ldots$$
$$+\sqrt{a_r^2 + b_r^2}\,X_r$$

Parameterized Multiplication

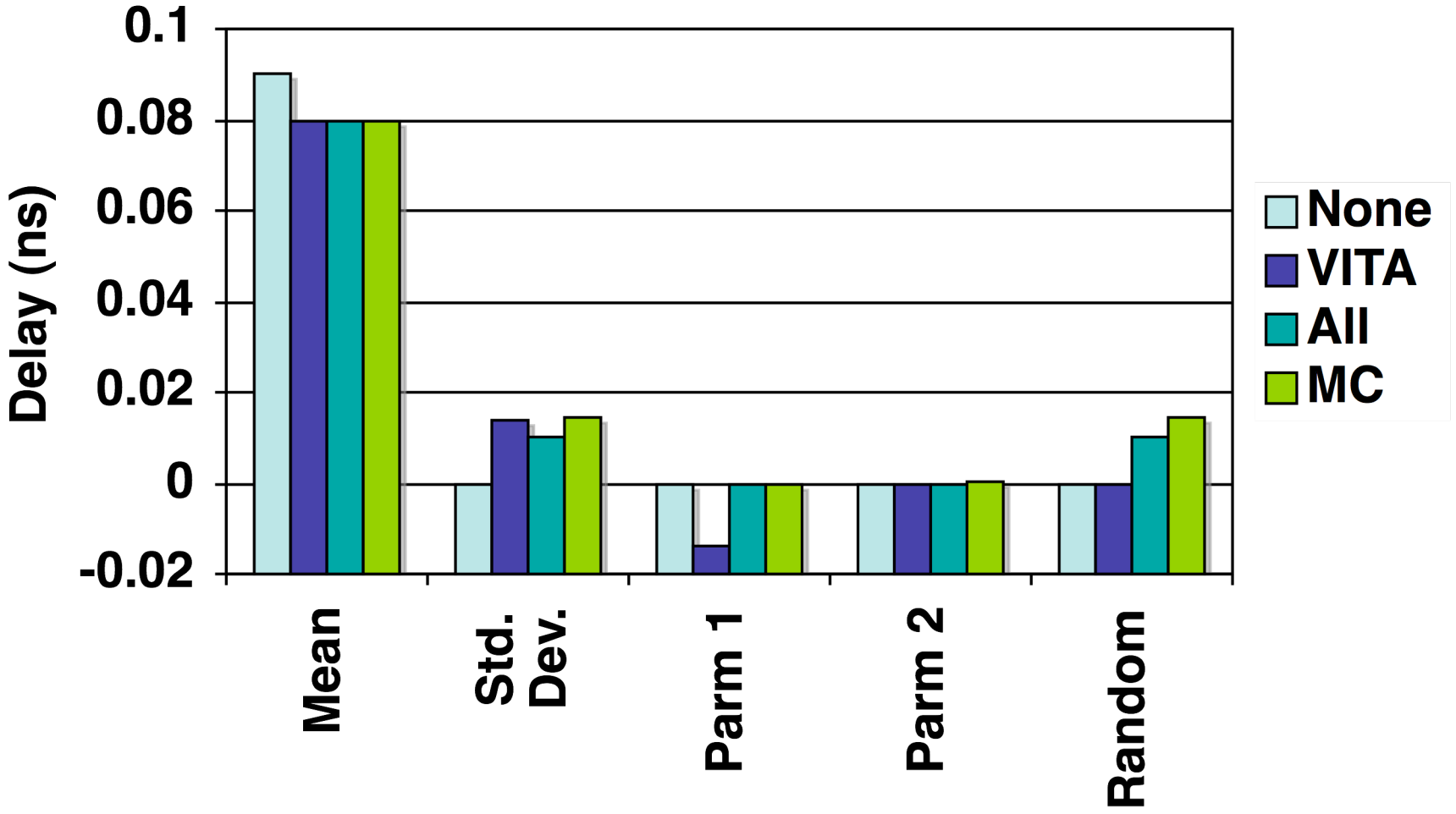
A x B	**a_0+**	**a_1X_1+**	**a_2X_2+**	**a_rX_r**
b_0 +	a_0b_0	$a_1b_0X_1$	$a_2b_0X_2$	$a_rb_0X_r$
b_1X_1+	$a_0b_1X_1$	$a_1b_1(X_1)^2$	$a_2b_1X_1X_2$	$a_rb_1X_1X_r$
b_2X_2+	$a_0b_2X_2$	$a_1b_2X_1X_2$	$a_2b_2(X_2)^2$	$a_rb_2X_2X_r$
b_rX_r	$a_0b_rX_r$	$a_1b_rX_1X_r$	$a_2b_rX_2X_r$	$a_rb_r(X_r)^2$

VITA $X_i^2 \approx \alpha + \beta X_i$

Ours $X_i^2 \approx \alpha + \beta X_r$

$X_i X_j \approx \alpha + \beta X_r$

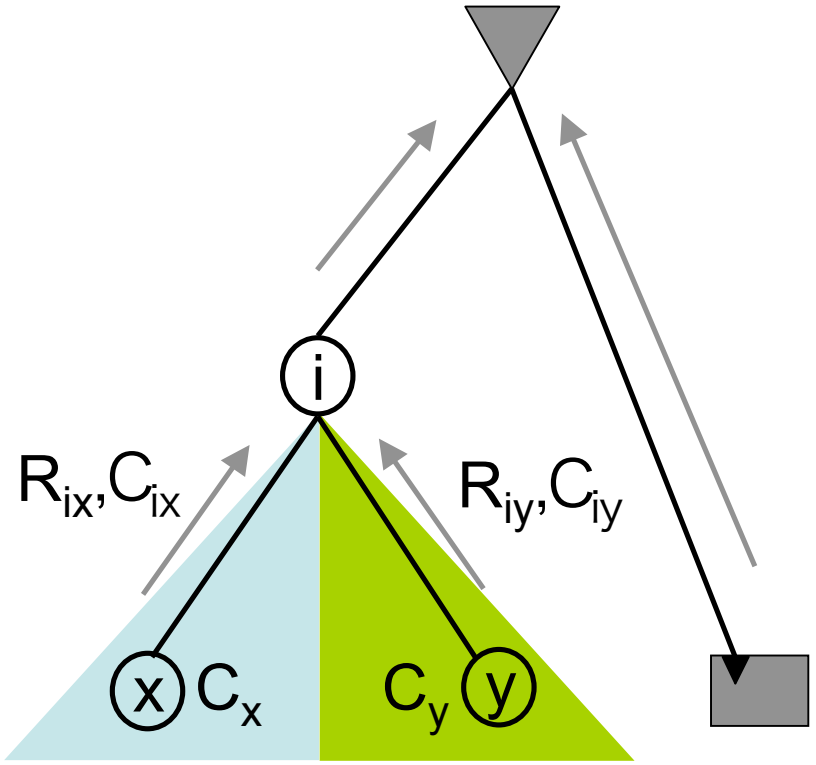
Multiplication Results - Anticorrelated



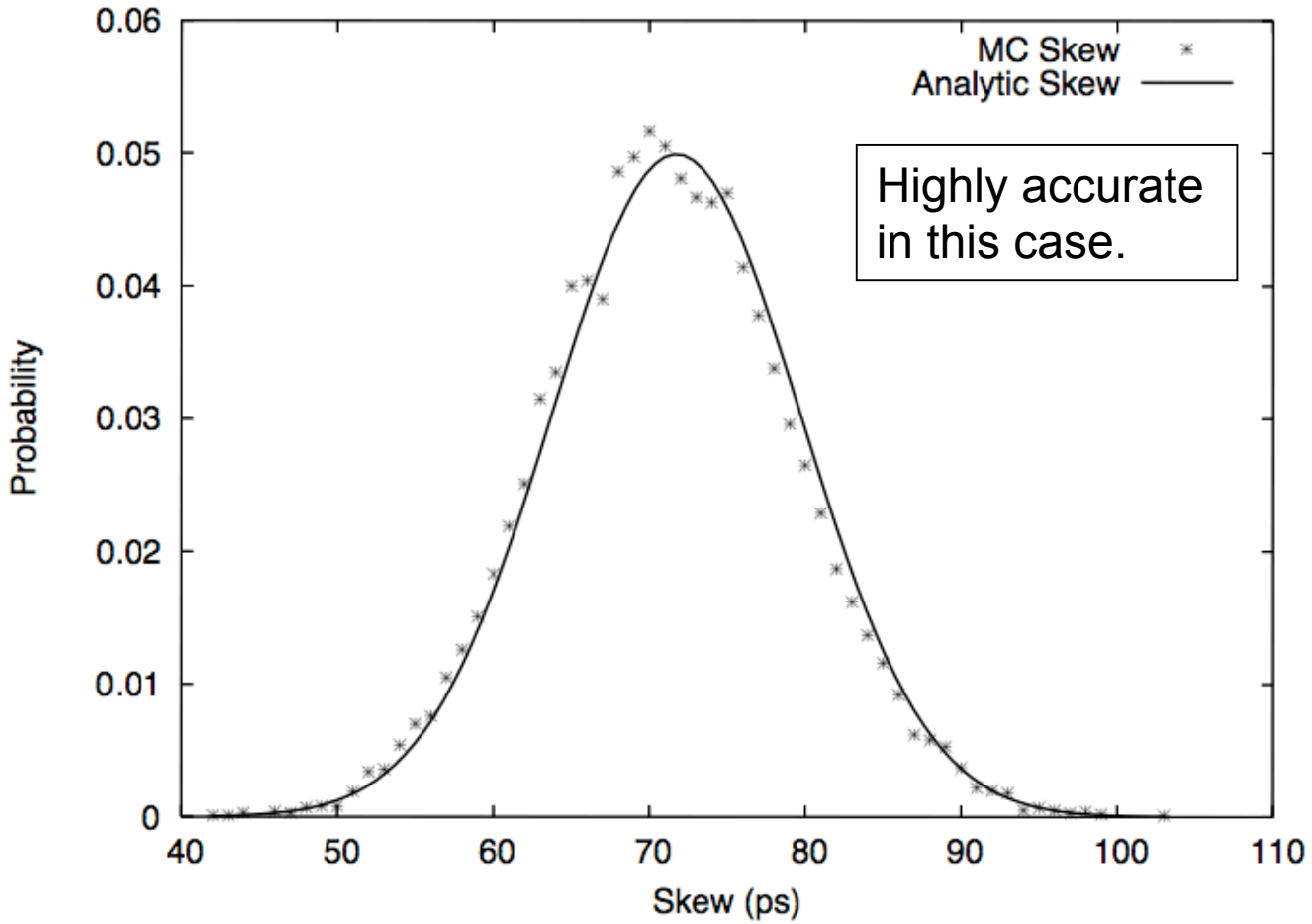
Statistical Analysis

$$D_{\max,i} = MAX(R_{ix}(\frac{C_{ix}}{2} + C_x) + D_{\max,x}, R_{iy}(\frac{C_{iy}}{2} + C_y) + D_{\max,y})$$

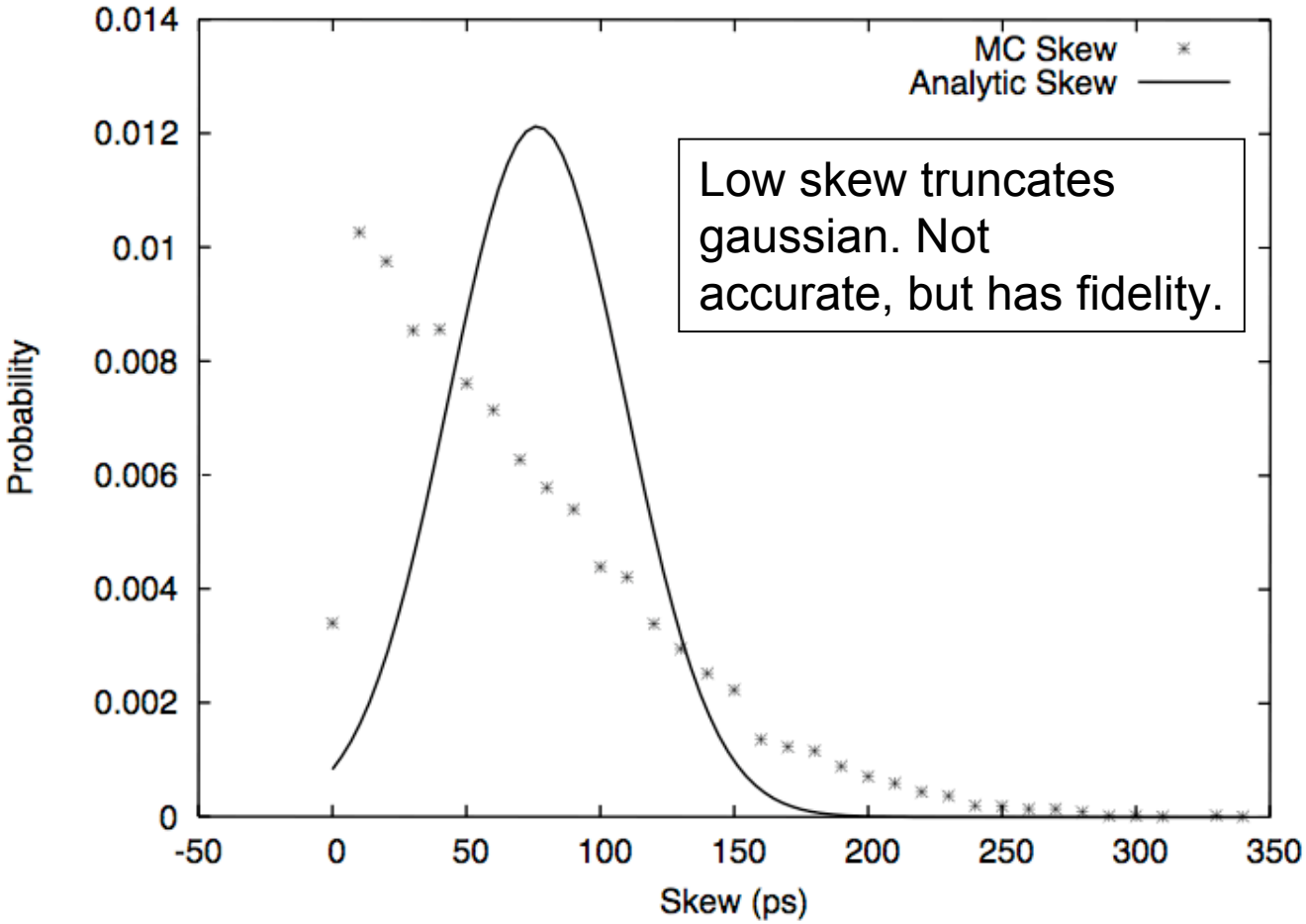
- Similar for $D_{min,i.}$
- These are parameterized R, C, and D values.
- $Skew_i$ is $D_{max,i}$ -$D_{min,i}$



S1423, Buffered: Analytic vs. Monte Carlo

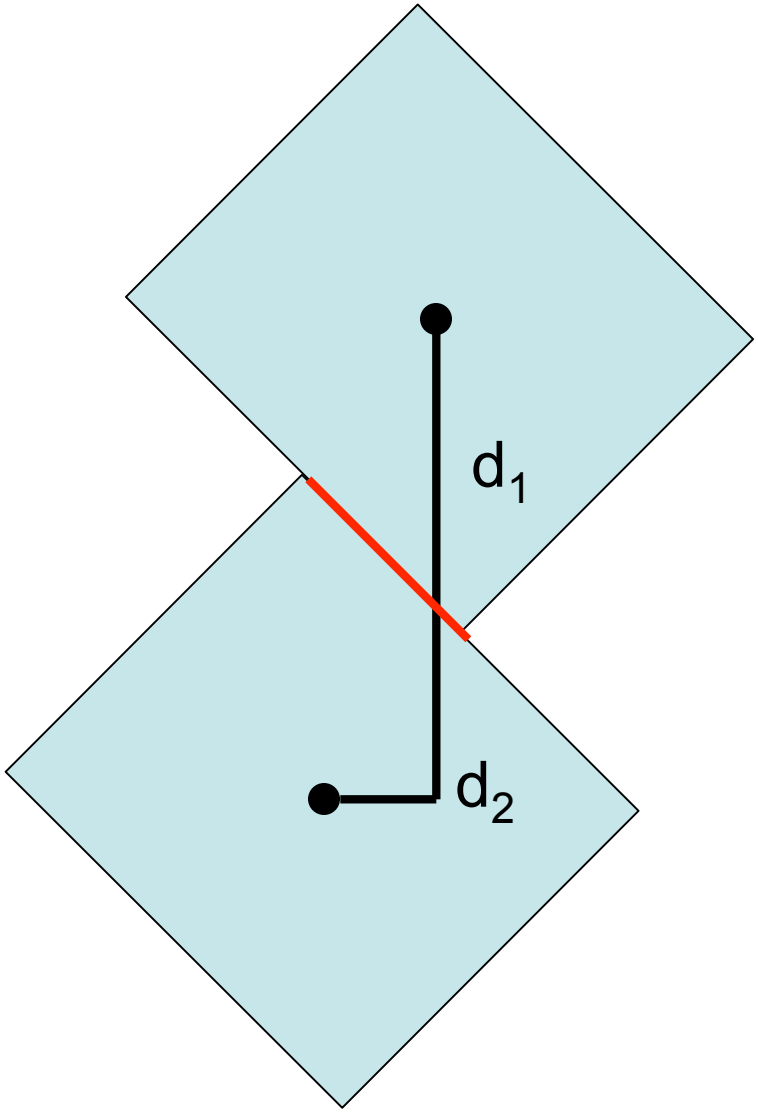


R1, No Buffers: Analytic vs. Monte Carlo

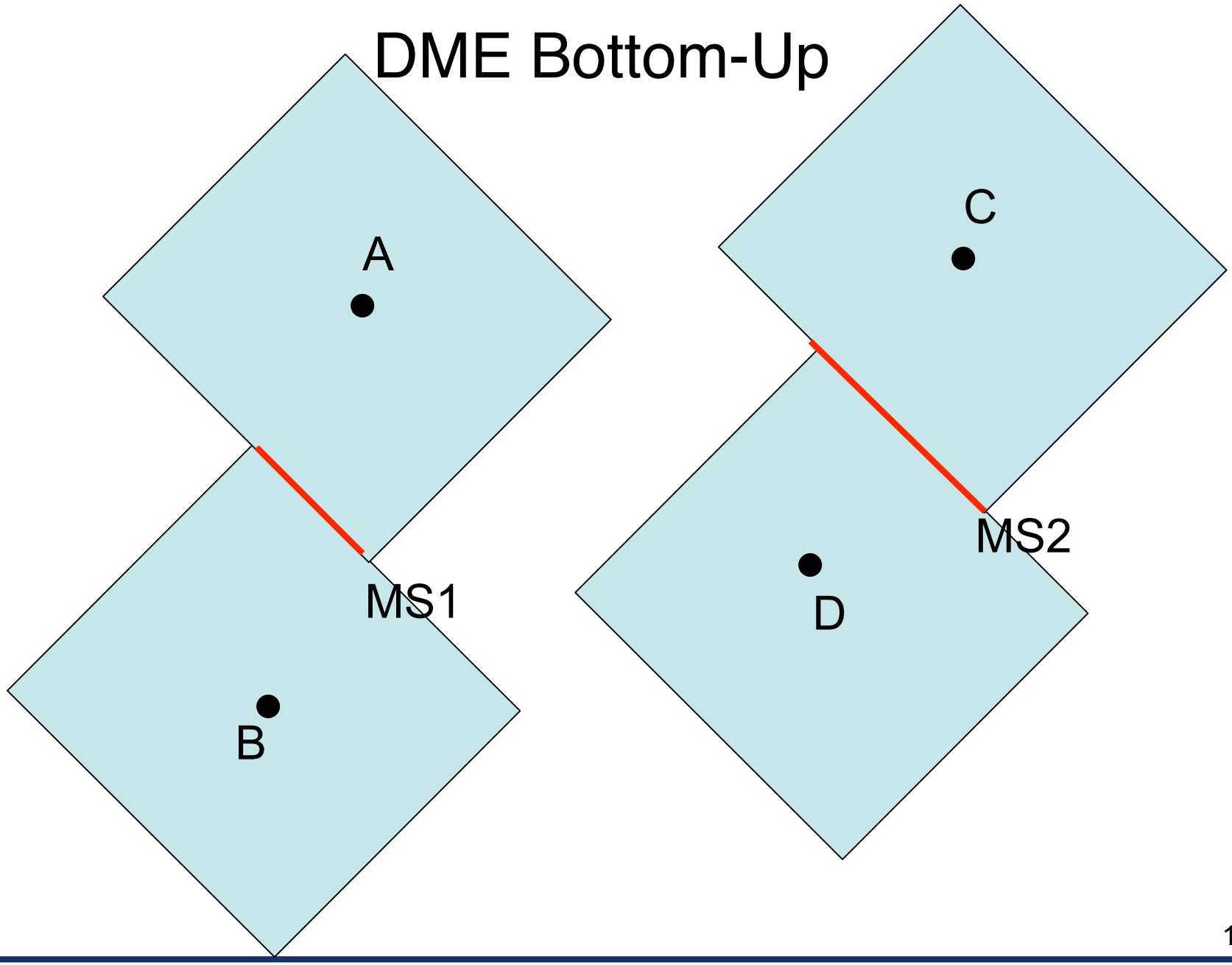


Deferred Merge Embedding

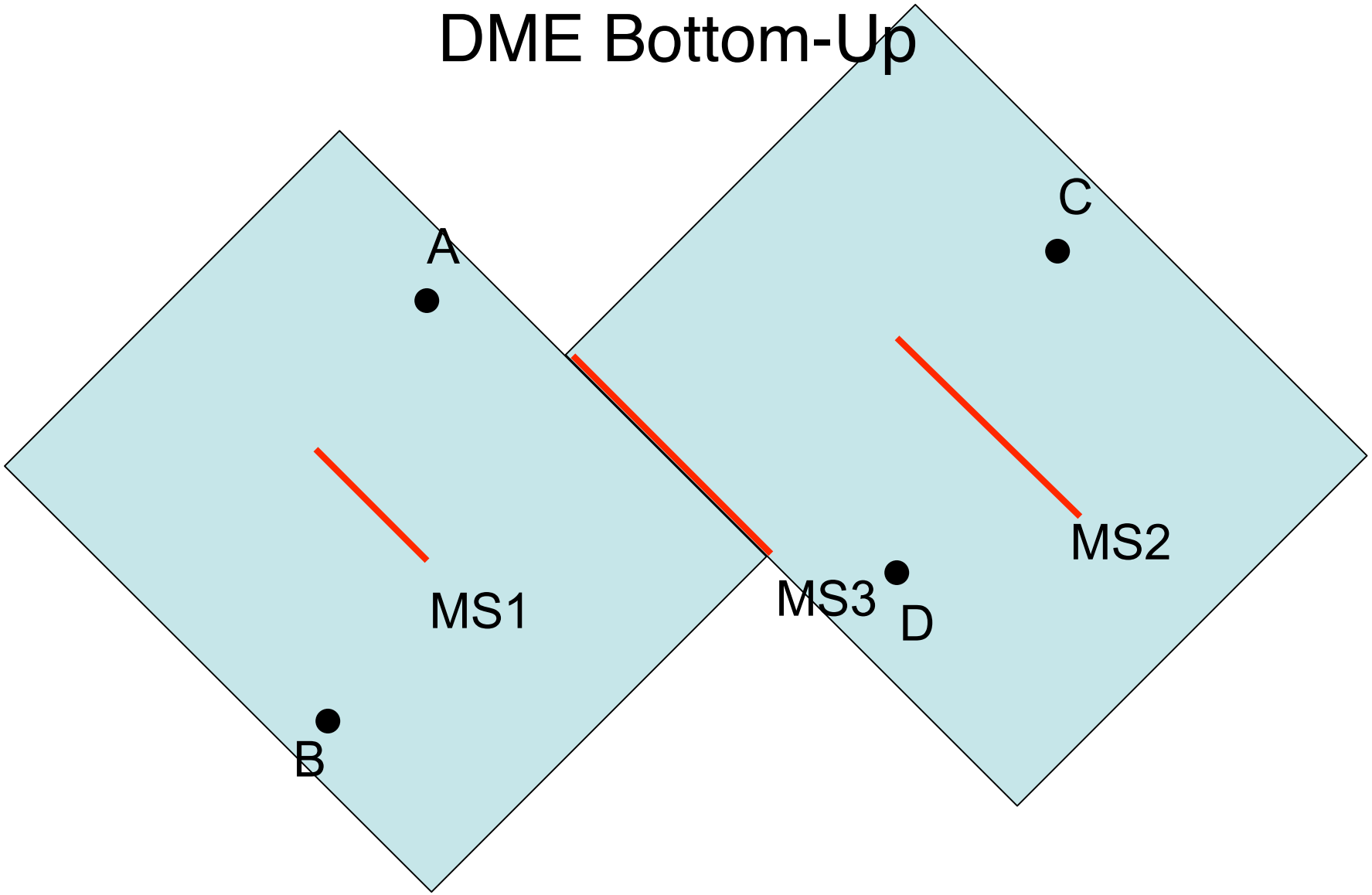
- d_1 and d_2 picked to equalize Elmore delay
- Extra wire jogs may be needed
- Topology is fixed



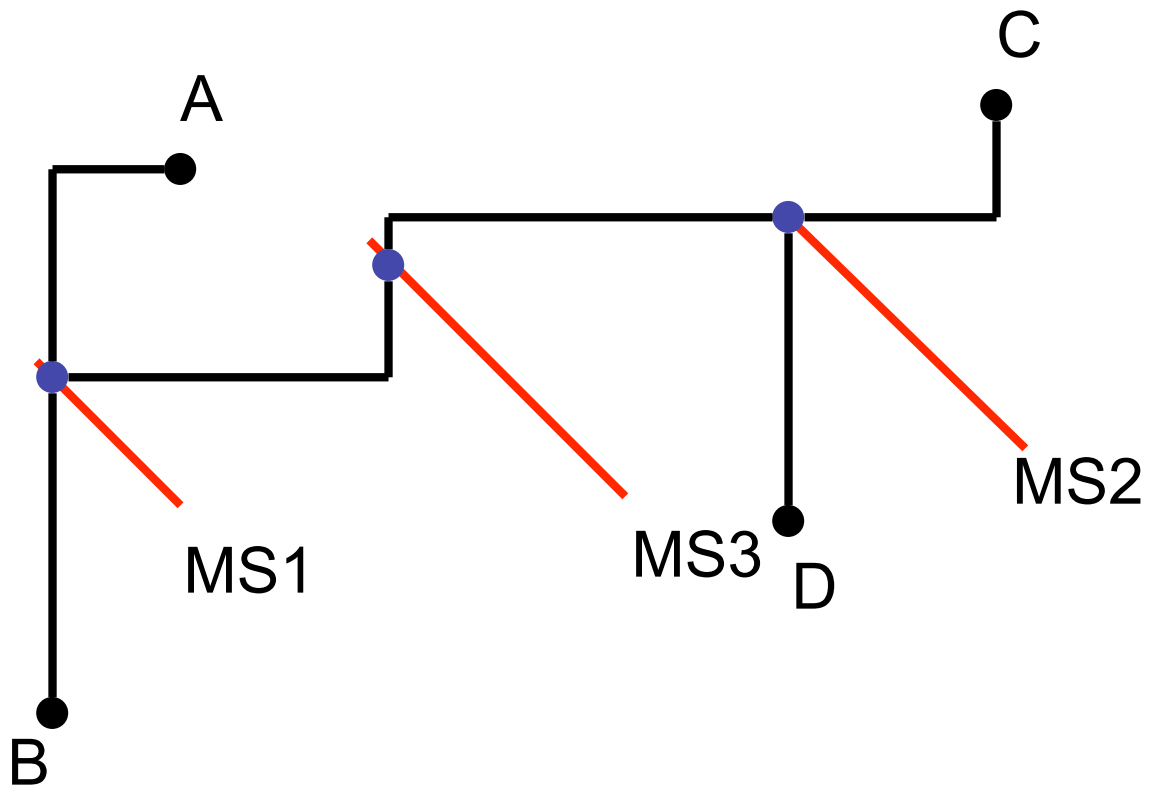
DME Bottom-Up



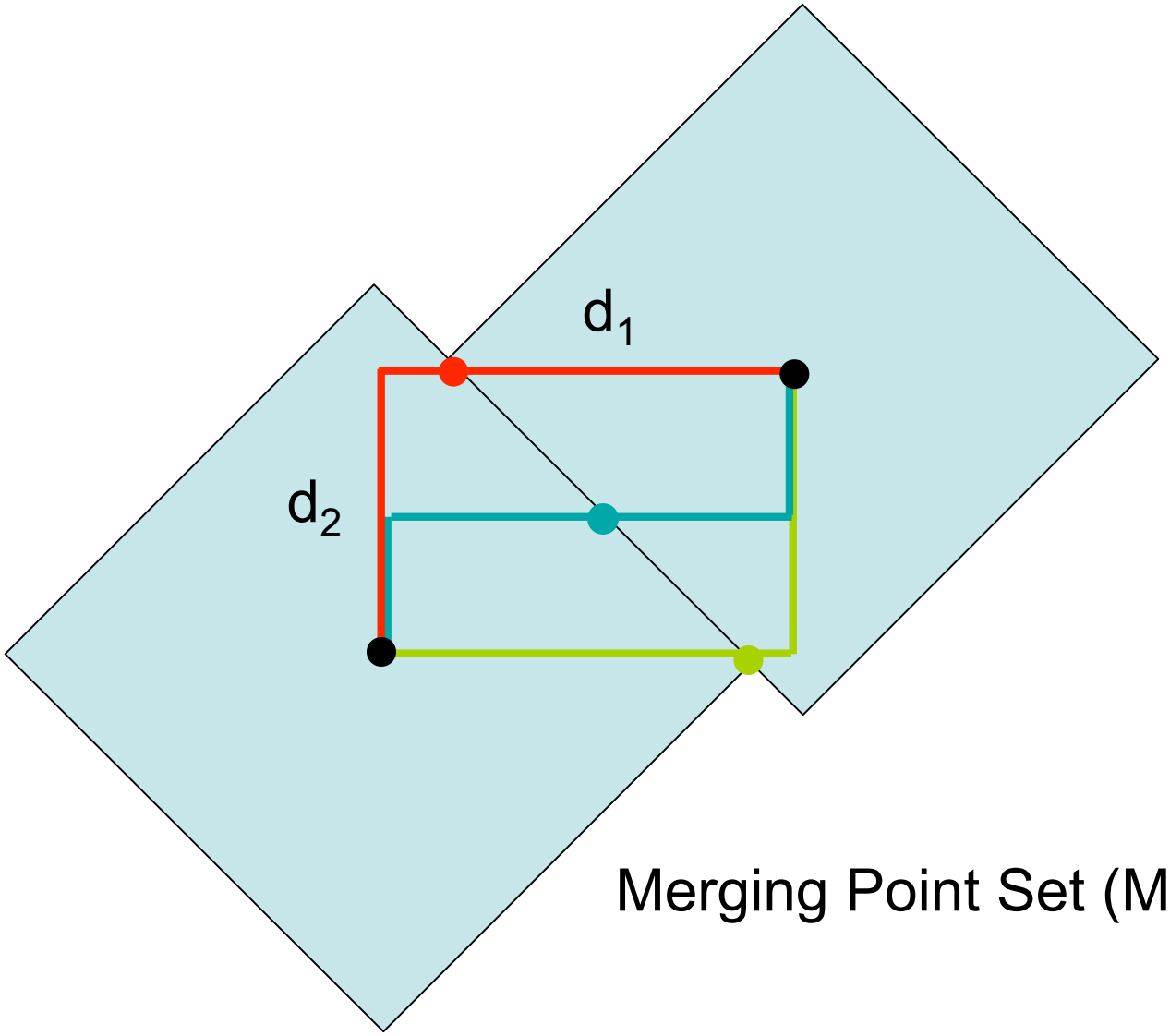
DME Bottom-Up



DME Top-Down

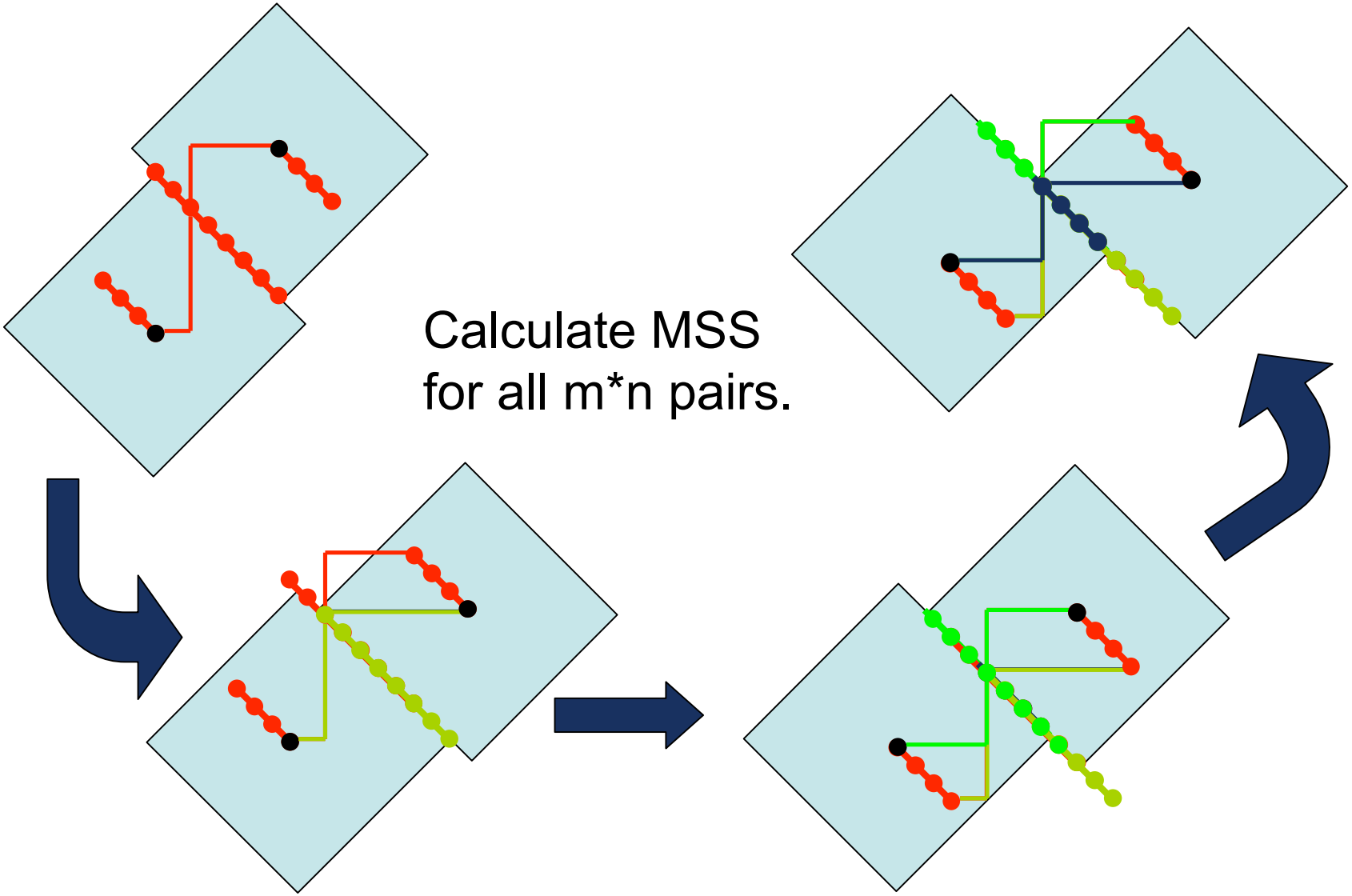


DME Sample Mode



Merging Point Set (MPS)

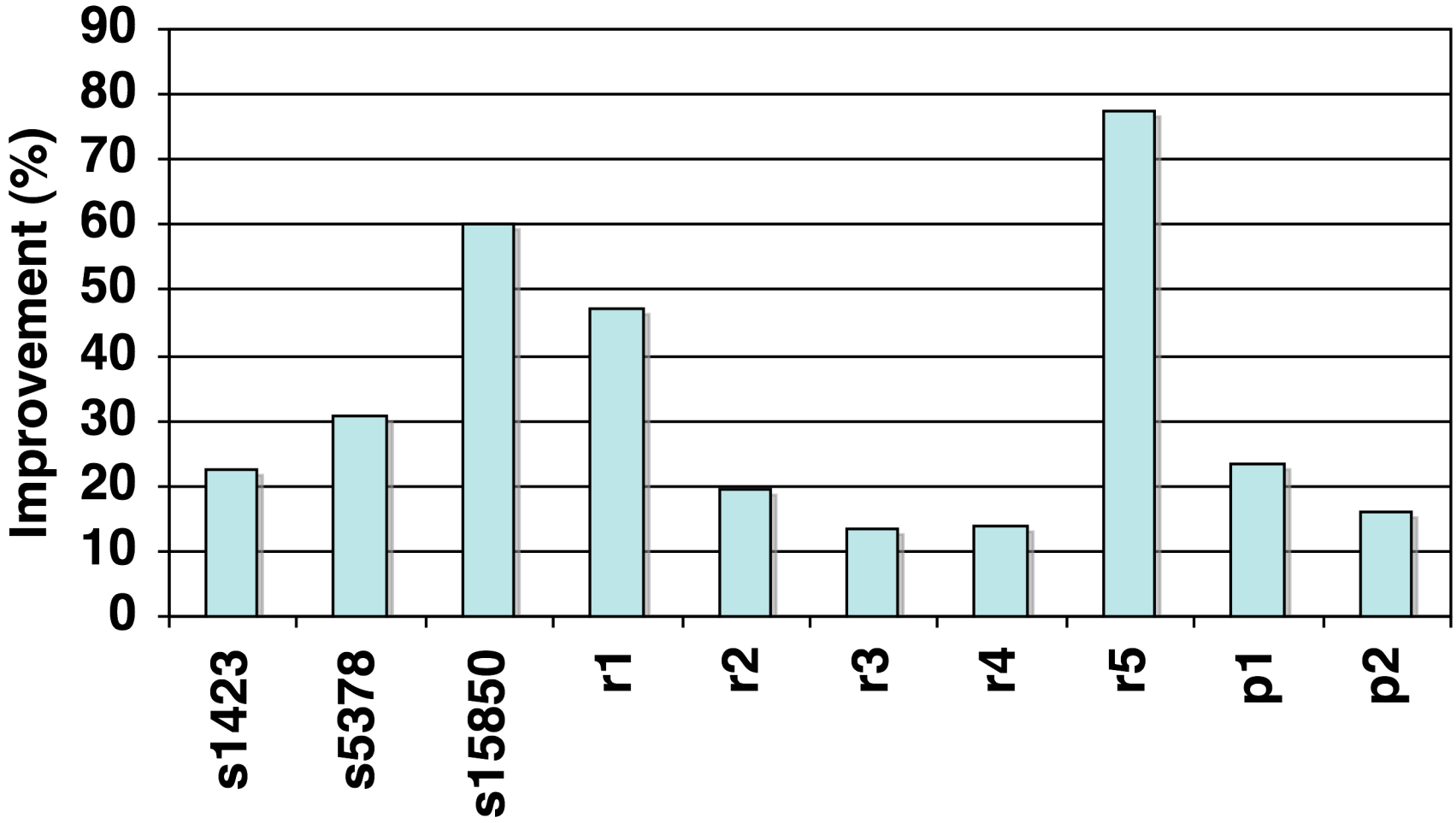
Multiple Embeddings



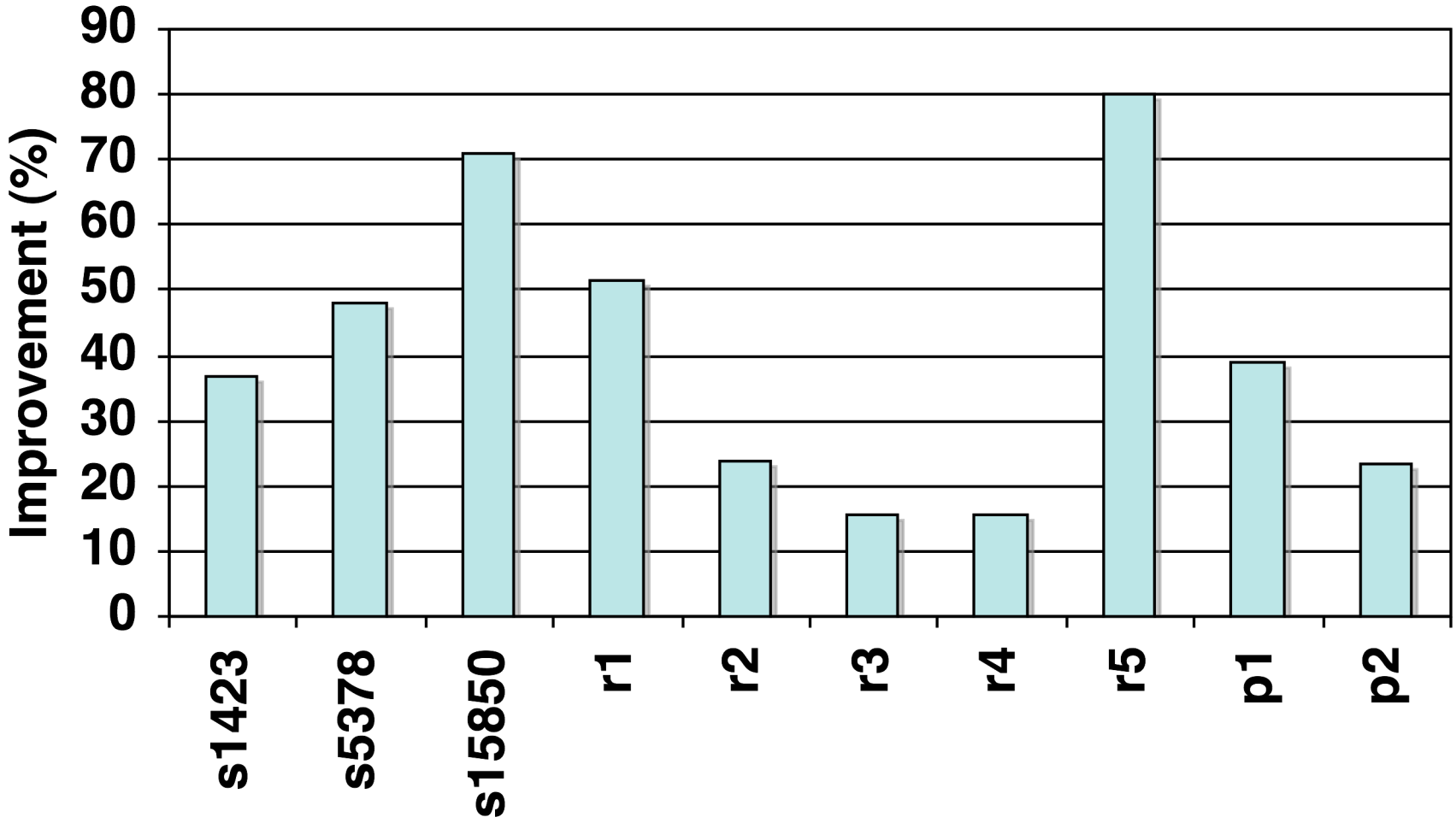
Pruning Strategies

- Parameterized Capacitance
  - Merging to same location with same sinks gives same cap.
  - Elmore does not have resistive shielding.
- Parameterized Delay
  - Delay difference is small, but present.
  - Whether to use D_{min} or D_{max} (or average) is unclear.
- Parameterized Local Skew
  - Keeping best mean skew candidate performs well.
  - Skew of any sub-tree limits the entire tree.

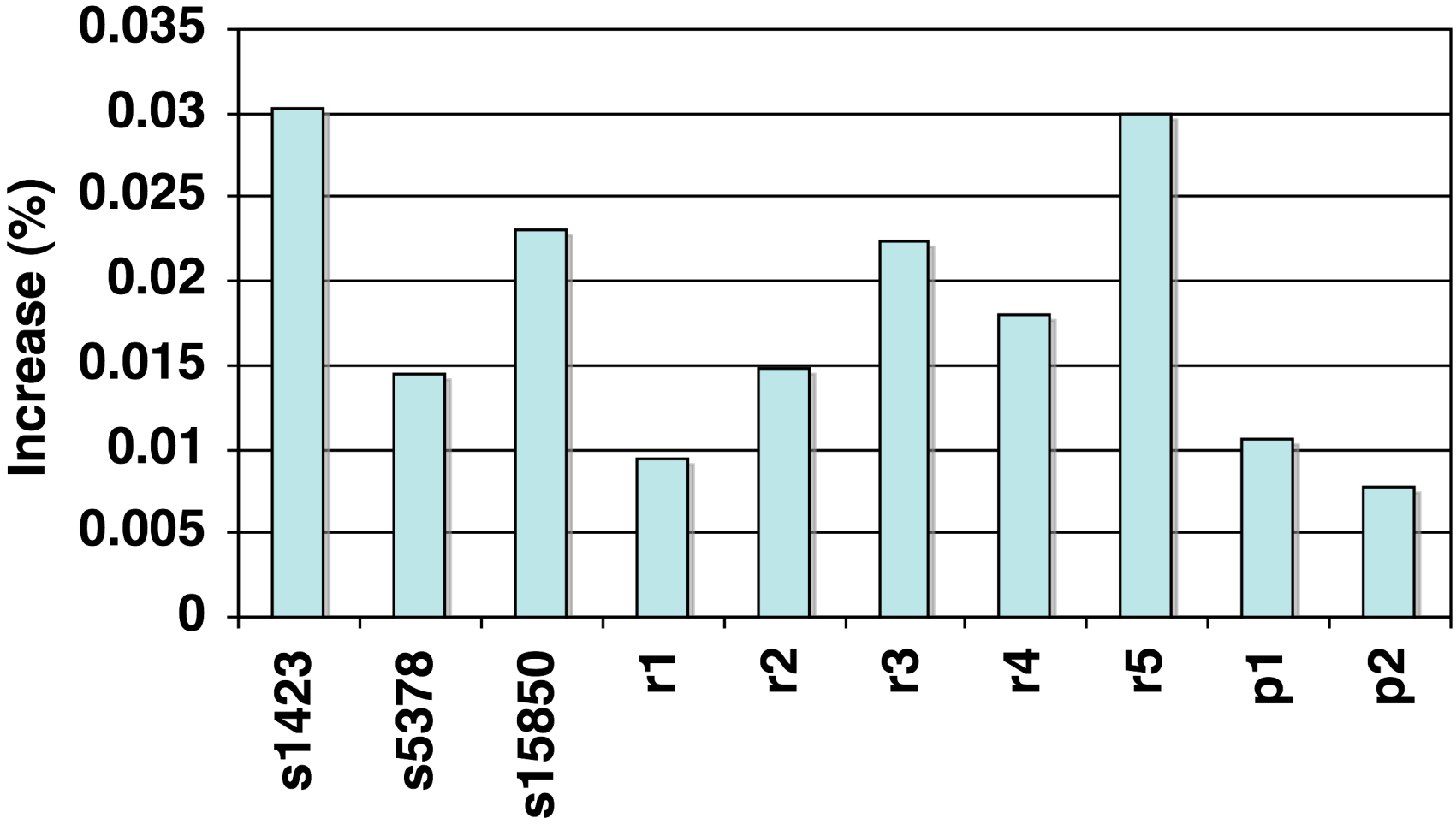
Mean Skew


Improvement (%)
90
80
70
60
50
40
30
20
10
0
s1423
s5378
s15850
r1
r2
r3
r4
r5
p1
p2

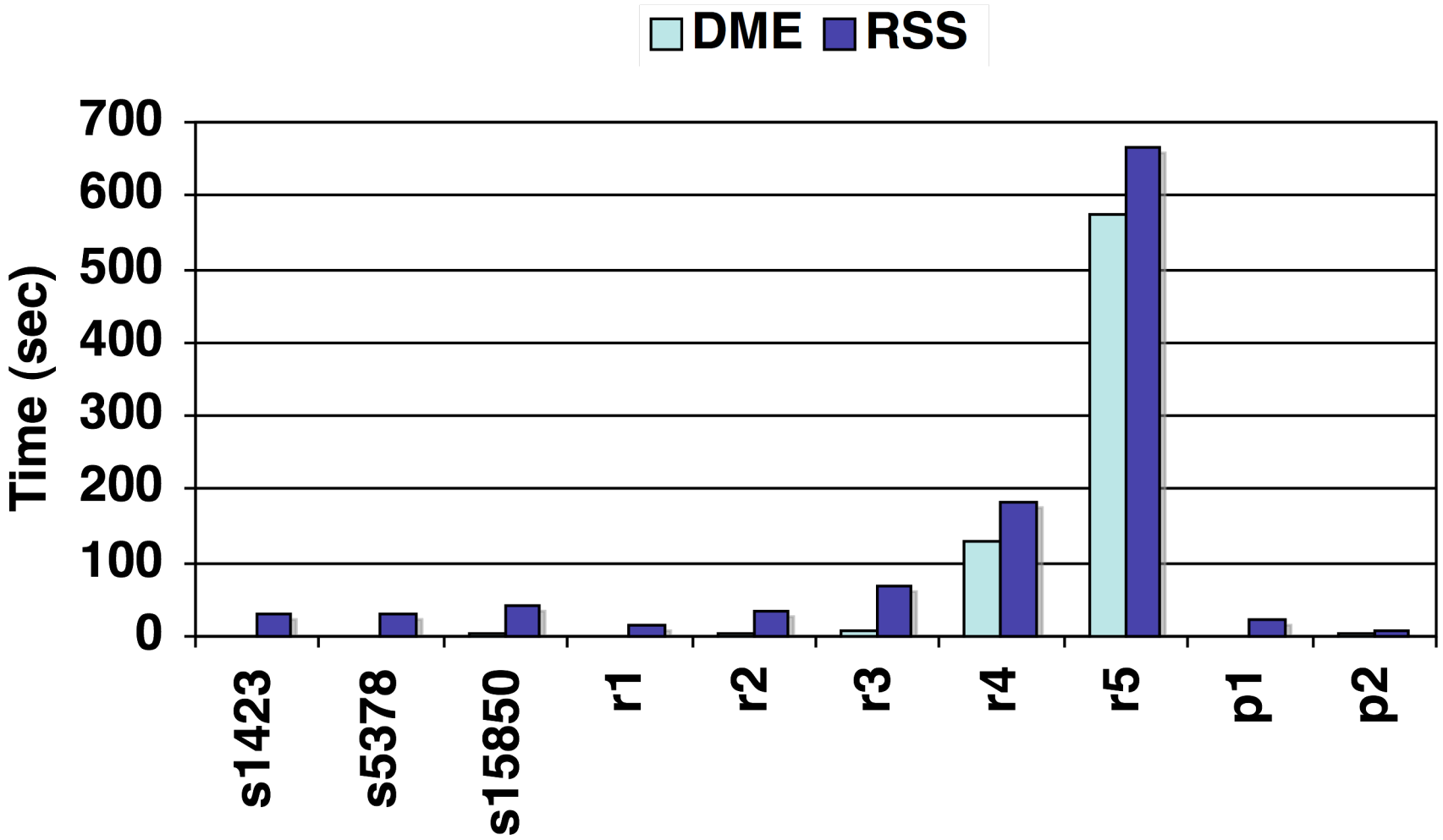
Std. Dev. Skew


Improvement (%)
90
80
70
60
50
40
30
20
10
0
s1423
s5378
s15850
r1
r2
r3
r4
r5
p1
p2

Power


Increase (%)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
s1423
s5378
s15850
r1
r2
r3
r4
r5
p1
p2

CPU Time


DME
RSS
Time (sec)
700
600
500
400
300
200
100
0
s1423
s5378
s15850
r1
r2
r3
r4
r5
p1
p2

Conclusions

- 12-75% mean skew reduction
- 15-80% std. dev. skew reduction
- Less than 0.03% power increase
- Run-time can be traded for power suboptimality
- Future Work
  - Topology Generation
  - Buffer Insertion
  - Wire Width Tuning