EARLY PROBABILISTIC NOISE ESTIMATION FOR CAPACITIVELY COUPLED INTERCONNECTS

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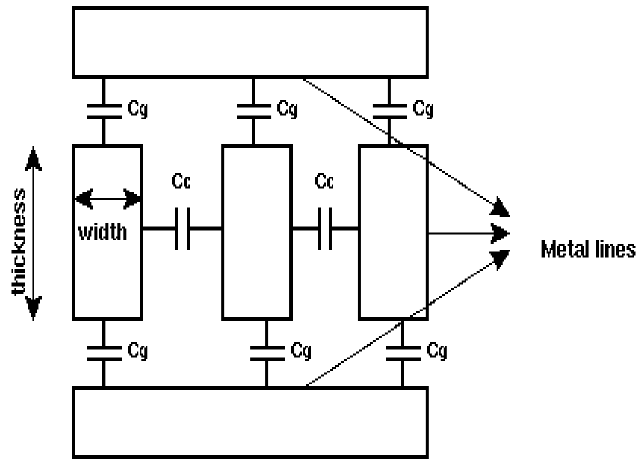
Introduction

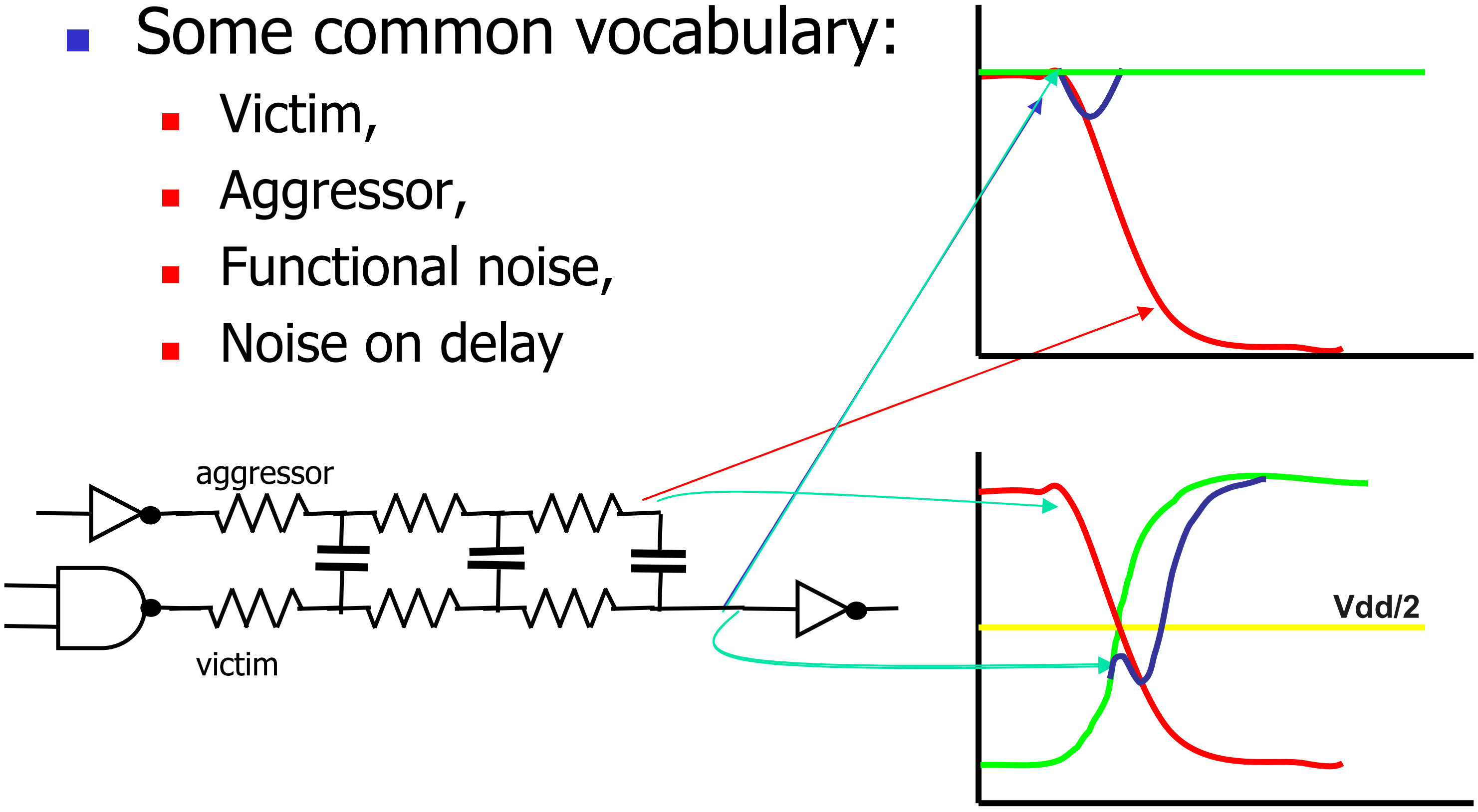
- Ratio of crosstalk capacitance to total capacitance is increasing.
- More performance aggressive circuit structures compromising noise immunity are being used.



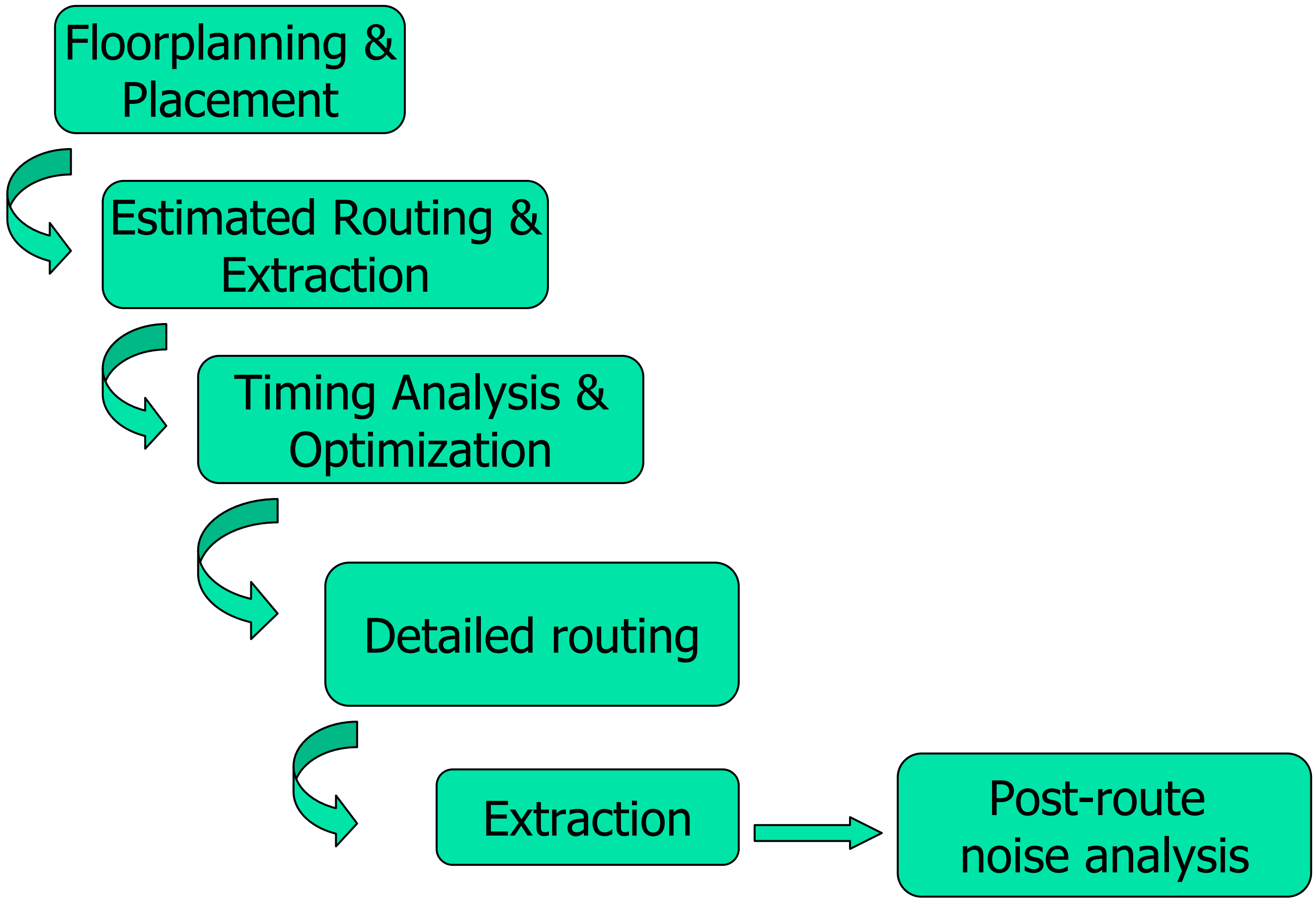
- Noise failures have become a significant design and verification issue for large and high performance designs.

Motivation

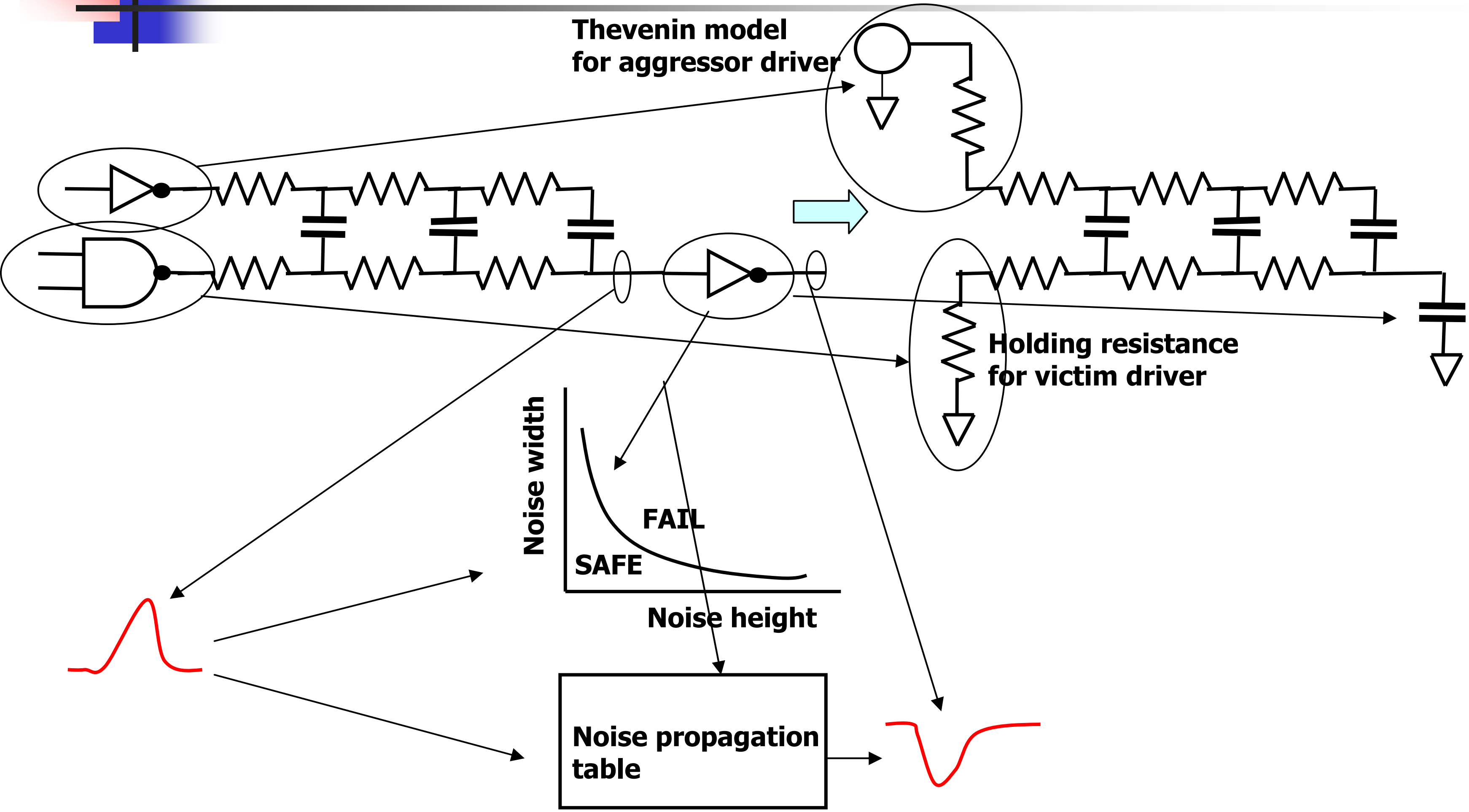
- Some common vocabulary:
  - Victim,
  - Aggressor,
  - Functional noise,
  - Noise on delay



Noise in Current Design Cycle



Post-route Noise Analysis



Post-route Noise Analysis: Too Late!!

- Number of failing nets reach several thousands!!
- Flexibility to change the design and fix these problems is greatly reduced.
- Driver sizing, wire spacing, buffer insertion etc. are difficult to apply at this stage and will require that the entire design be re-legalized and re-routed.
- This can give rise to new noise failures on previously stable nets.
- This can lead to convergence problems and lengthen the design cycle.

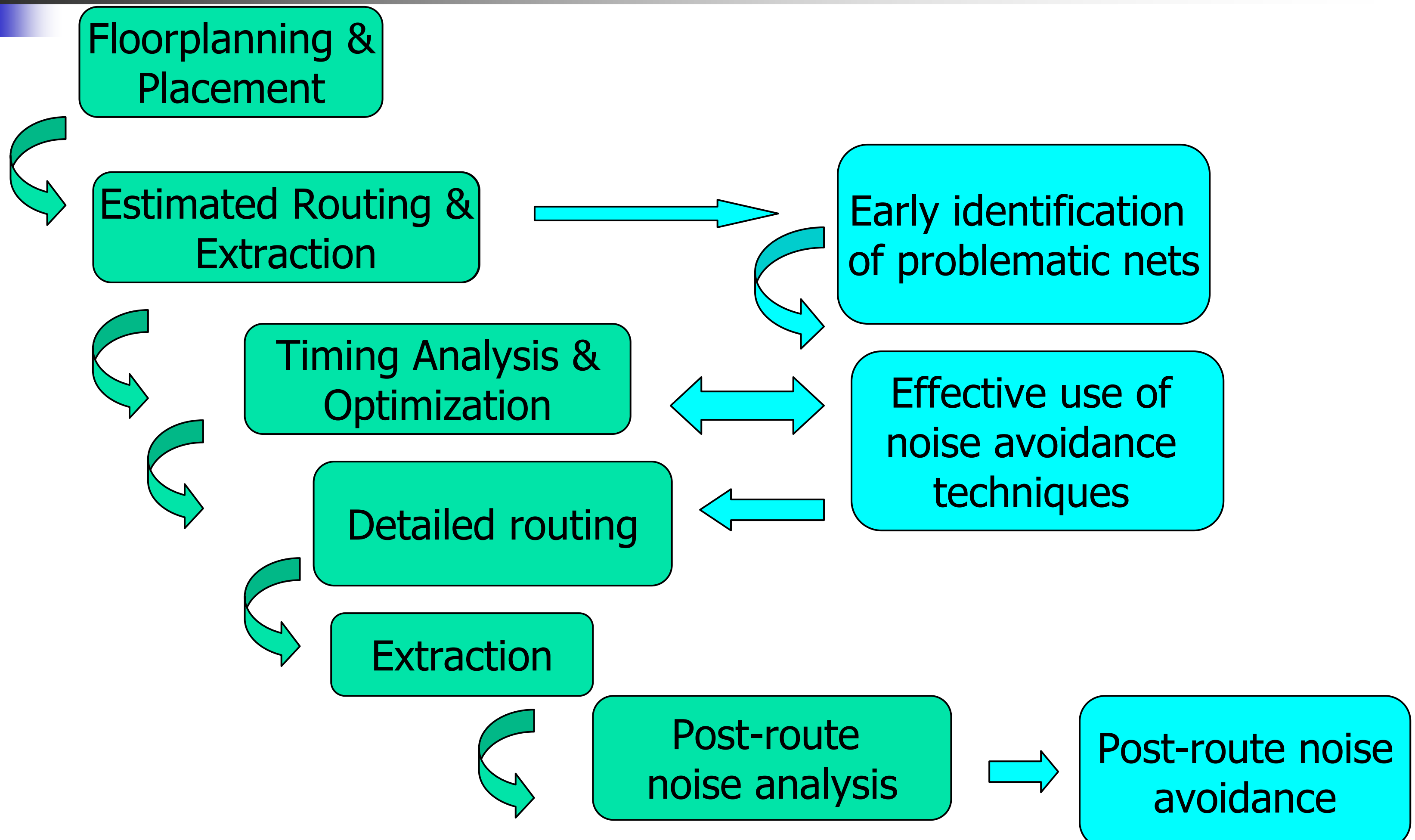
What needs to be done

- Noise awareness should be incorporated into the design cycle as early as possible.
- Methods have been proposed to solve noise problems during detailed routing.
- These methods utilize a limited set of noise avoidance methods: wire sizing and spacing.
- They use approximate noise models (e.g. only based on common parallel length of neighboring nets) for performance reasons.
- Detailed routing is already very complex. Such an approach will over-constrain an already hard problem.

What needs to be done

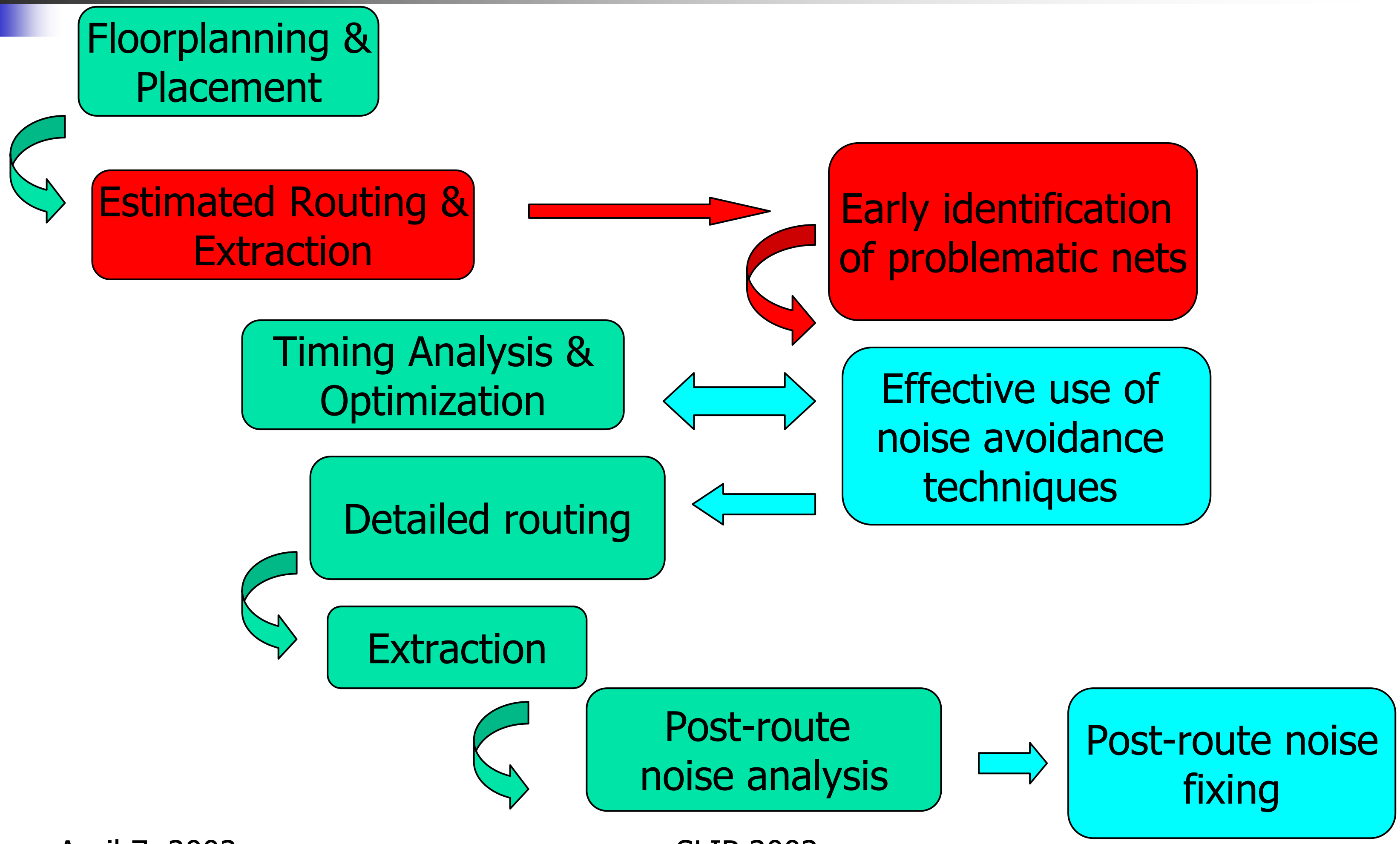
- Methods to identify problematic nets in an earlier design stage, before detailed routing, where flexibility is abundant.

Noise Aware Design Cycle



Blocks and connections addressed in this paper

Pre-route noise estimation



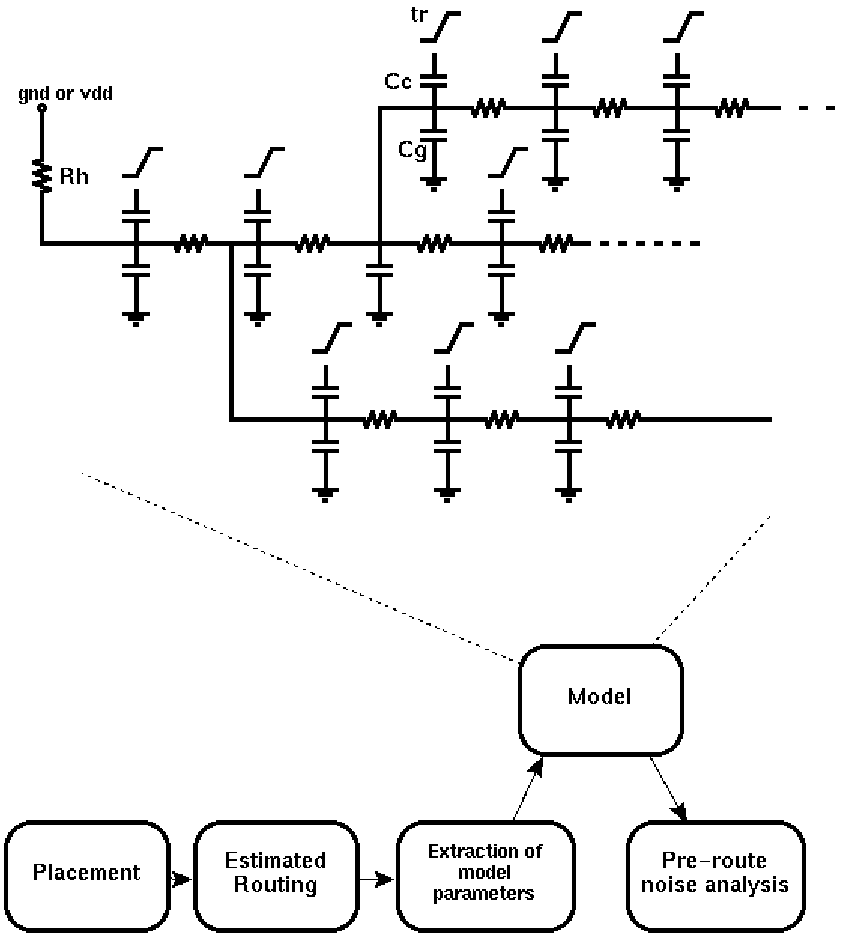
Pre-route noise estimation

- Goal: To identify problematic nets as early as possible

Pre-route Noise Estimation

- Although much flexibility exists to fix noise at this stage, little information is available on which nets are likely to fail.
- Exact wire length, wire topology, relative positioning of wires are not available.
- To be able to perform accurate pre-route noise estimation, need to estimate accurately:
  - distributed interconnect characteristics of a net,
  - its coupling capacitance to neighboring nets,
  - drive strength of its neighbors

Noise Estimation Methodology



Estimated routing

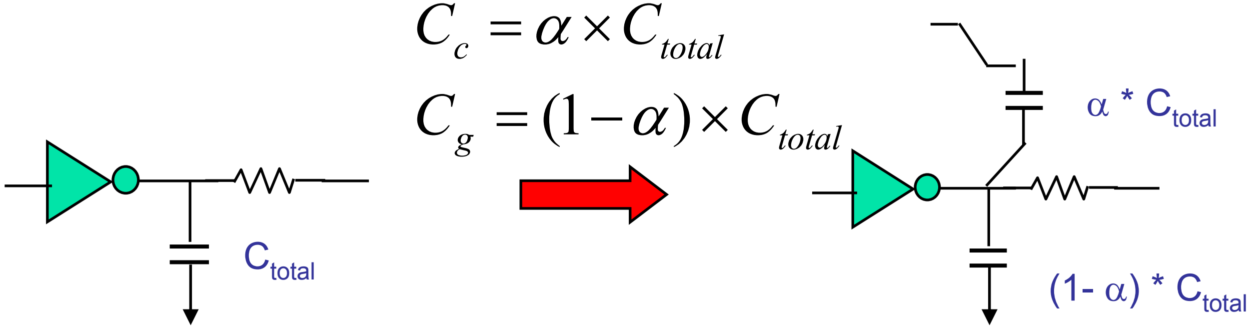
- An estimated routing is required to be able to extract the required parameters.
- Simplest form: Steiner tree routers.
  - Congestion is not taken into account,
  - Multiple nets can be assigned to a single track,
  - No information regarding proximity and identity of neighboring nets,
  - An estimate of length and topology of a net can be obtained.

Estimated Routing

- From this information, grounded RC tree representation of the net can be constructed.
- To estimate coupling capacitance:

$$C_c = \alpha \times C_{total}$$

$$C_g = (1-\alpha) \times C_{total}$$



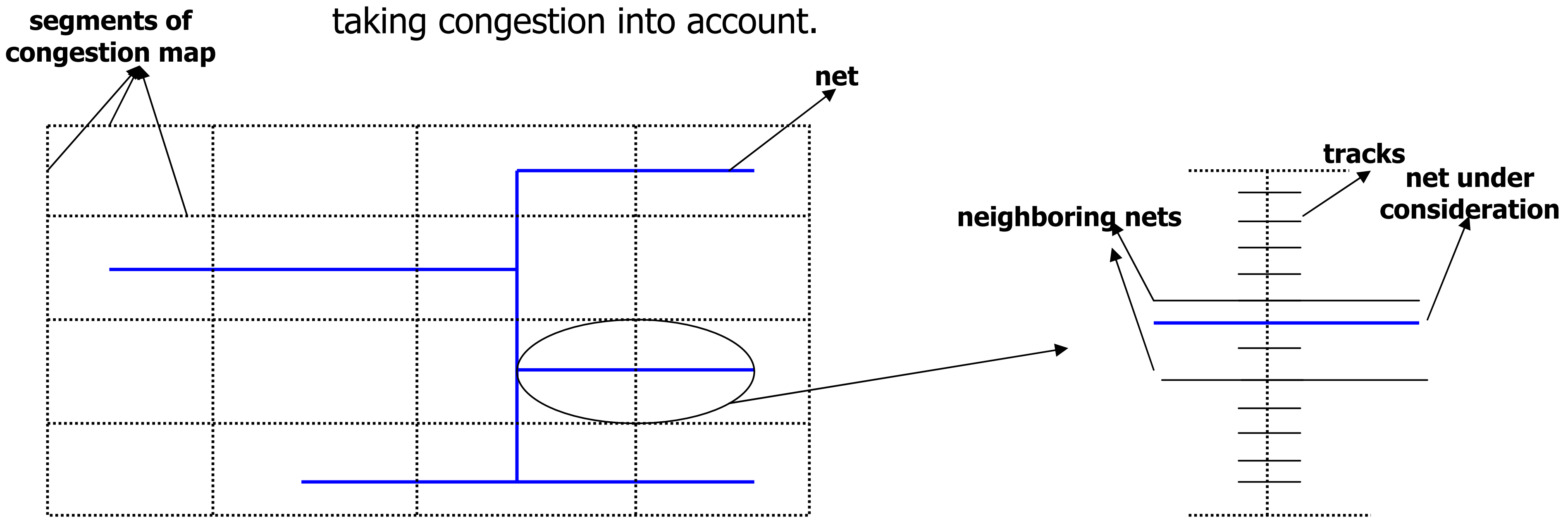
- Transition time t_r can be estimated conservatively based on the speed of the design.

Estimated Routing

- Due to the crude nature of these estimations, significant discrepancy between resulting estimated noise analysis and detailed noise analysis after routing:
  - False failures: Nets that are erroneously identified as failing in estimated noise analysis. They require unnecessary allocation of resources to fix them.
  - Missed failures: Nets that are erroneously identified as non-failing in estimated noise analysis. They will need to be in post-route stage.
- Goal: Minimize false failures and missed failures.

Estimated Global Routing

- Estimated global routers take congestion into account
  - Divides the design into cells,
  - Assigns the number of available tracks for each cell,
  - Connects the instance pins of a net utilizing available tracks of cells while taking congestion into account.

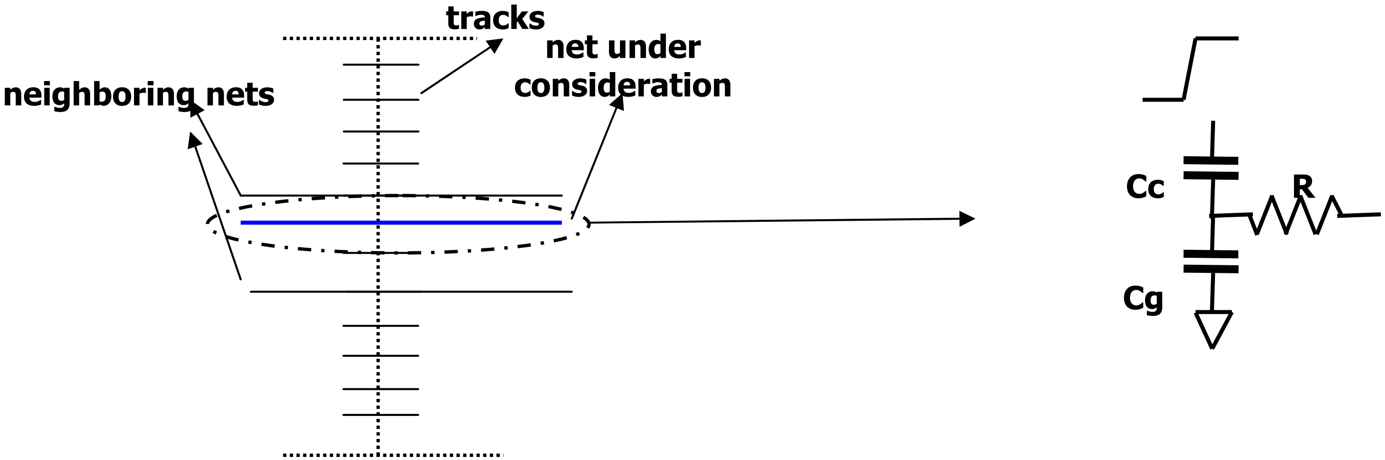


Estimated Global Routing

- Congestion information is given on a segment by segment basis. For each segment i:
  - total number of tracks: n_i
  - number of tracks used by global router: k_i
  - set of nets assigned to that segment are available.
- Note that there is no information on which particular track within the segment, a given net is using, i.e. nets are not ordered thus exact neighbors are still unknown.

Congestion Based Parameter Extraction

- We propose using the congestion map information to extract interconnect parameters such as resistance and ground capacitance as well as coupling capacitance and aggressor information for each net



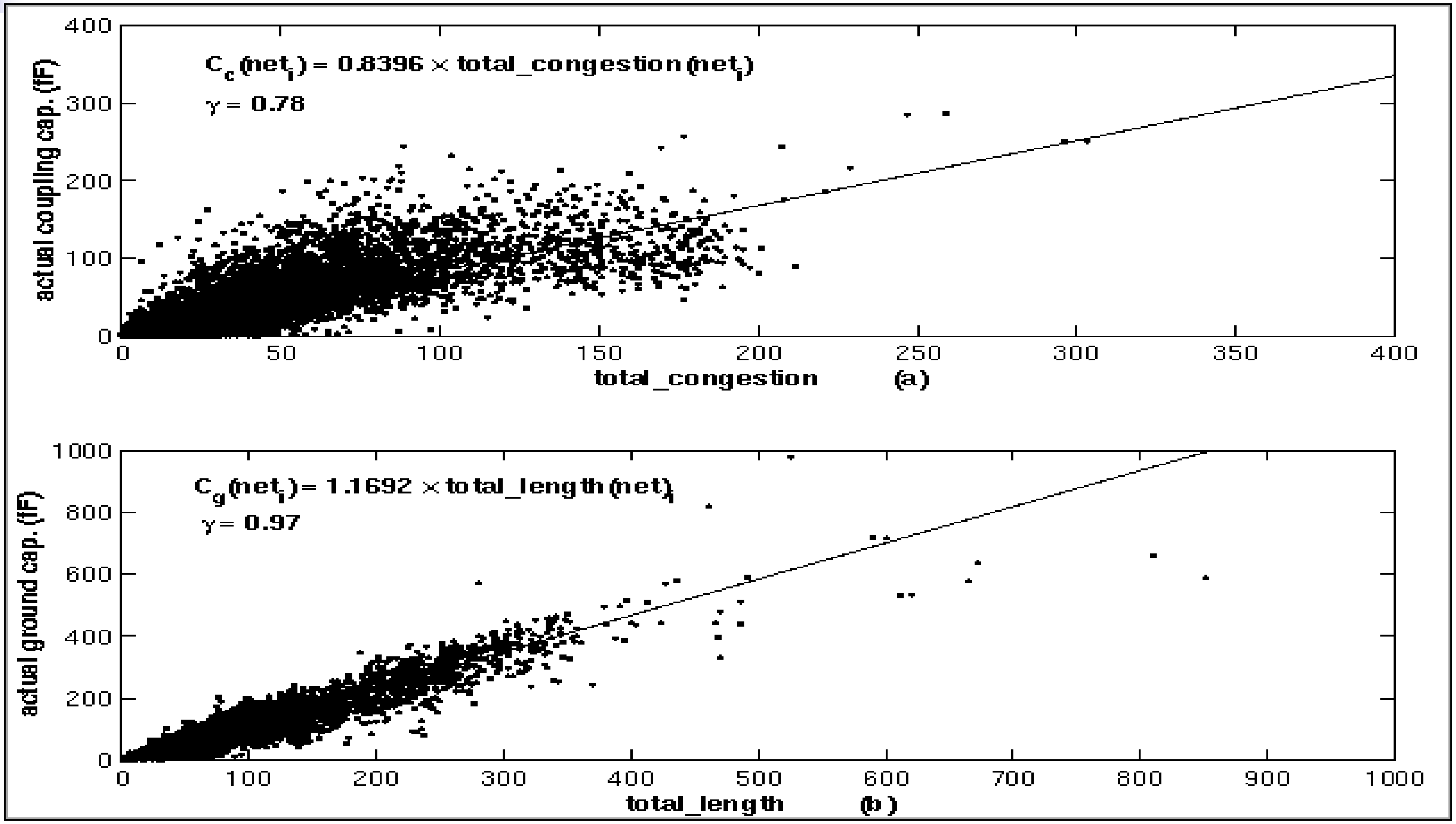
Correlations

- Length and congestion of nets resulting from estimated global routing are typically consistent with those after detailed routing.
- Look at some correlations to verify this on a 0.18μ high performance microprocessor (~58000 nets)
  - Estimated total congestion of a net vs. actual extracted coupling capacitance of a net,
  - Estimated total length of a net vs. actual extracted ground capacitance of a net

$$\text{total length} = \#\text{ of segments a net goes through}$$

$$\text{total congestion} = \sum_{i=1}^{\text{segments(net)}} \frac{k_i}{n_i}$$

Correlations



Calibration Method

- We propose to use correlation data for a previous completed design (possibly of an older technology) to estimate parameters of a new design.

Calculate coefficients for the older technology, t_{old}:

$$K_c(t_i) = C_c(t_{old}) / total\_congestion$$
$$K_g(t_i) = C_g(t_{old}) / total\_length$$

Map coefficients to the new technology, t_{new}:

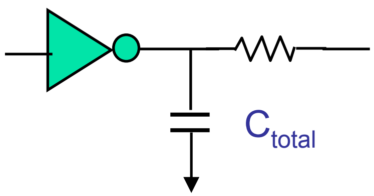
$$K_c(t_{new}) = \frac{C_{c\ unit}(t_{new})}{C_{c\ unit}(t_{old})} K_c(t_{old})$$
$$K_g(t_{new}) = \frac{C_{g\ unit}(t_{new})}{C_{g\ unit}(t_{old})} K_g(t_{old})$$

Estimate caps for each net:

$$C_c(t_{new}) = K_c(t_{new}) \times total\_congestion$$
$$C_g(t_{new}) = K_g(t_{new}) \times total\_length$$

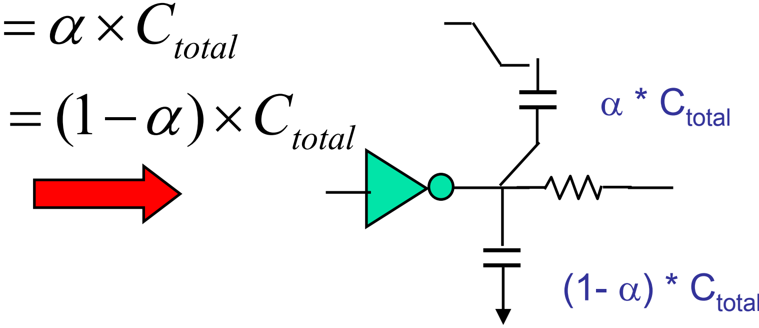
Calibration Method

- Can estimate total coupling and ground capacitance of a net using congestion map information.



$$C_c = \alpha \times C_{total}$$

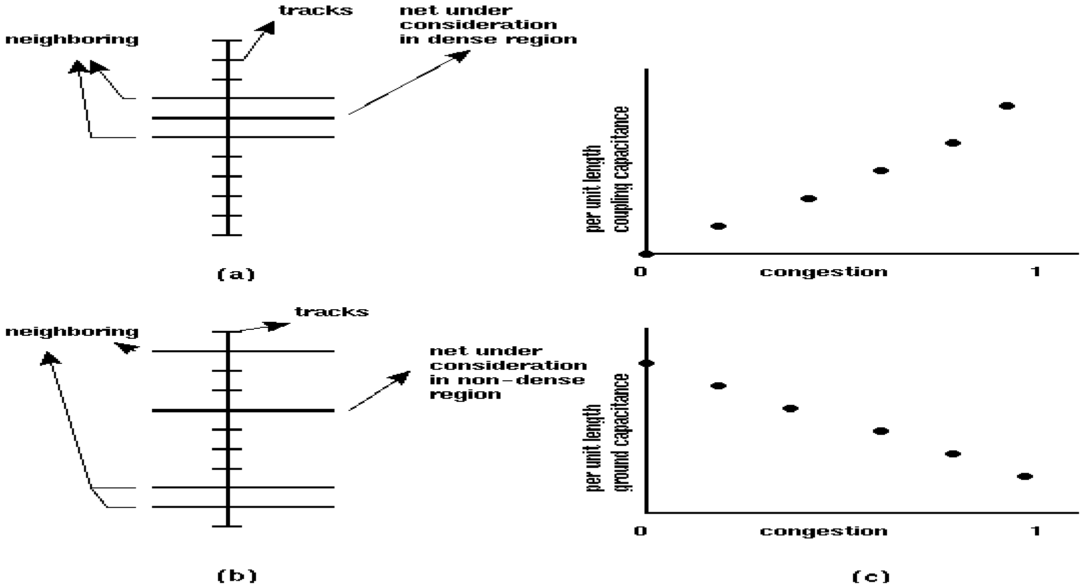
$$C_g = (1-\alpha) \times C_{total}$$



- A different α and total capacitance for <u>each net</u>.
- Total coupling and ground caps are distributed equally for each segment of the congestion map that the net traverses -> distributed RC netlist for each net.
- Drawback: Congestion is taken into account for a net as a whole. Resulting RC netlist will have same α ratio for all segments.

Probabilistic Extraction

- Probabilistic estimation of coupling and ground capacitances using congestion information for each segment that a net traverses.
- How?: Per unit coupling and ground caps for a particular interconnect technology are characterized for a number of density configurations:



Probabilistic Extraction

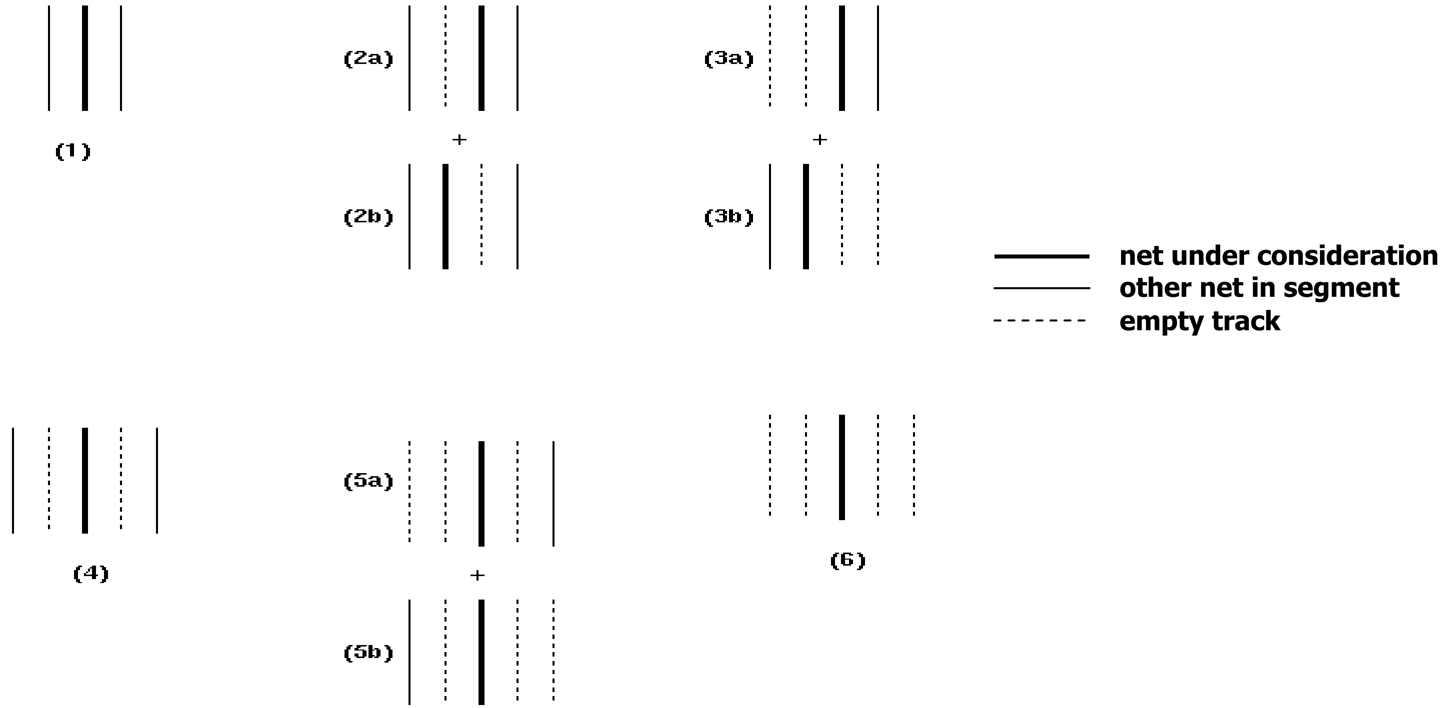
- Idea: Estimate per unit length capacitance for each segment by enumerating possible congestion configurations for that segment.
- Total number of possible configurations for a congestion map segment is

$$total\_configurations = \binom{n}{k} k!$$

- Infeasible to enumerate and characterize all possible congestion configurations
  - Capacitances of a net are effected only by the location of the nearest neighboring nets,
  - The effect of a neighboring net that is more than two tracks from the net is considered insignificant

Probabilistic Extraction

- Thus we consider 6 unique configurations:



- Capacitance to neighbors more than 2 tracks away is insignificant and ignored.

Probabilistic Extraction

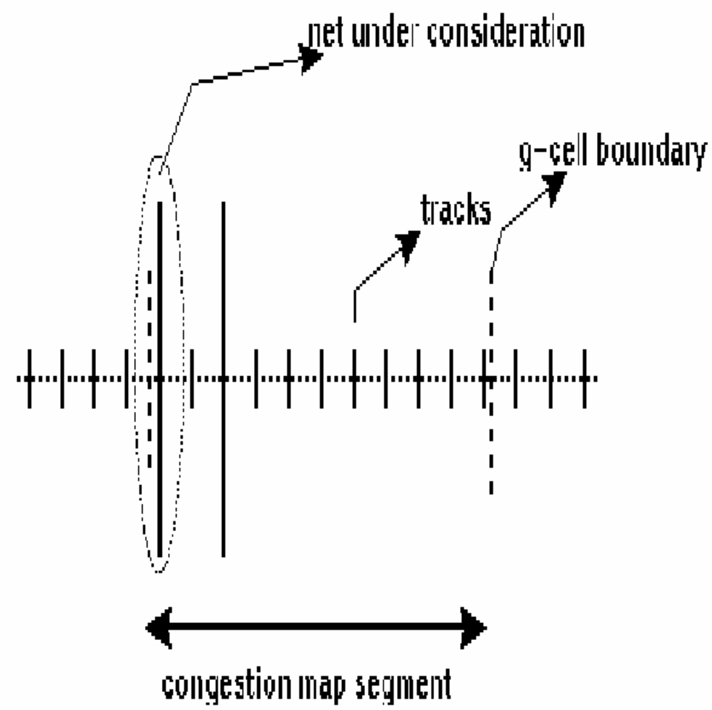
- After determining per unit length coupling and ground capacitance for each configuration, probability of each configuration is computed.

$$probability(i) = \frac{conf(i)}{total\_configurations} \qquad \text{for } i=1,\dots 6$$

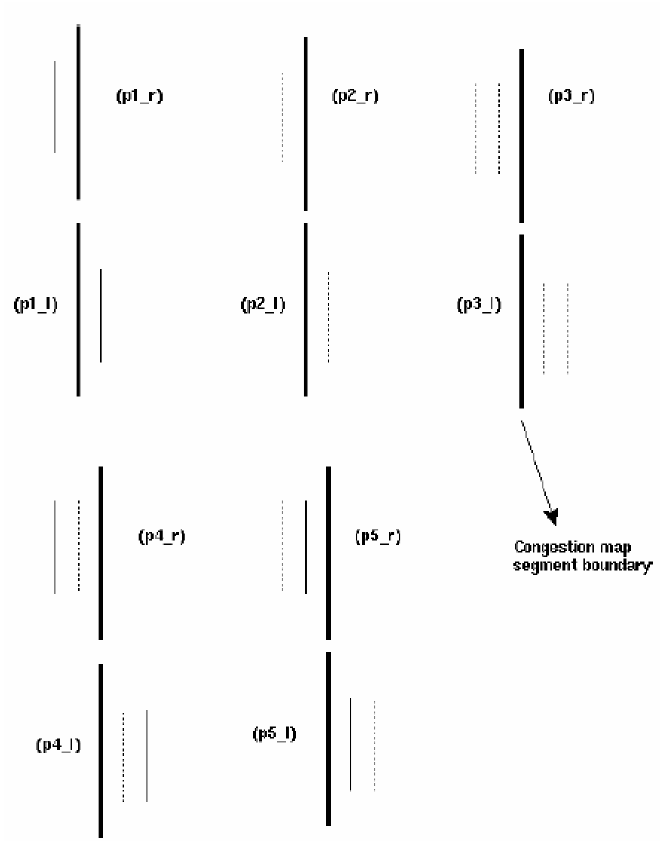
- The number of enumerations for each configuration depends on the number of tracks available (n) and number of tracks used (k) .
- For the cases where the net under consideration is close to the boundaries, the neighboring g-cells should also be taken into account

Neighboring g-cells

- How do we distribute these enumerations among the 6 defined density configurations ?
- Neighboring g-cell congestion should be taken into account



Neighboring g-cells



$$p1\_r = \frac{k\binom{n-1}{k-1}(k-1)!}{\binom{n}{k}k!}$$

Probability that the right most track of a g-cell is filled

Using these probabilities, we distribute the enumerations close to the boundaries among the defined configurations

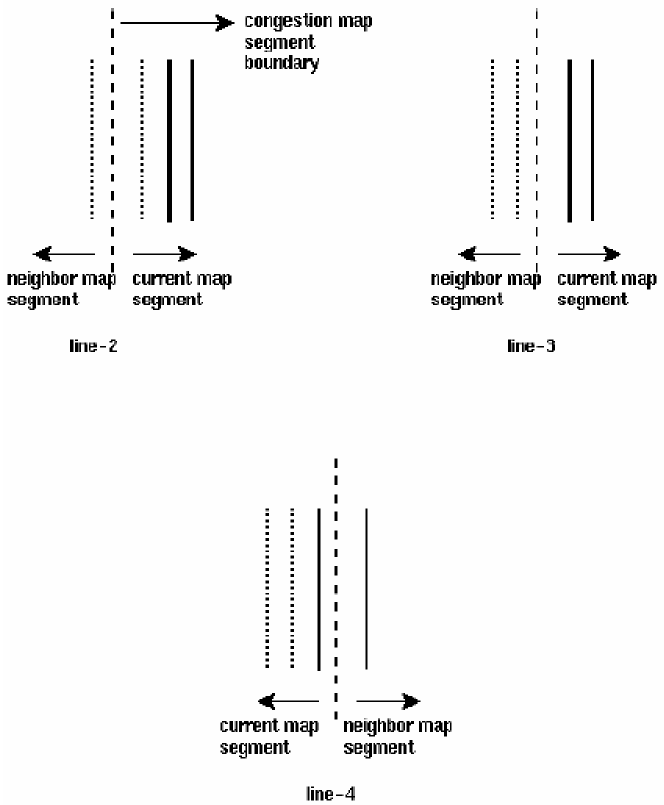
An Example

$$conf(3a) = (n-3)\times(k-1)\times\binom{n-4}{k-2}(k-2)!$$

$$+(k-1)\times\binom{n-3}{k-2}(k-2)!\times p2\_r$$

$$+(k-1)\times\binom{n-2}{k-2}(k-2)!\times p3\_r$$

$$+\binom{n-3}{k-1}(k-1)!\times p1\_l$$



Probabilistic Extraction

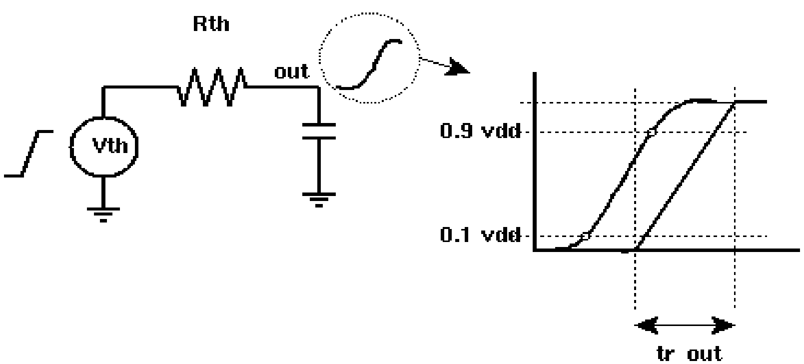
- For each segment that a net traverses, the pre-computed per-unit length coupling/ground capacitance $cc_{(i)} / cg_{(i)}$ of configuration i is weighted by the probability of configuration i, which is then scaled by the length of the segment. Estimated coupling/ground capacitance of a net segment is the summation of the weighted contributions for all configurations:

$$C_{c\,total(segment)} = \sum_{i=1}^{6} C_{c(i)} \times probability\left(conf_{(i)}\right) \times length(segment)$$

$$C_{g\,total(segment)} = \sum_{i=1}^{6} C_{g(i)} \times probability(config_{(i)}) \times length(segment)$$

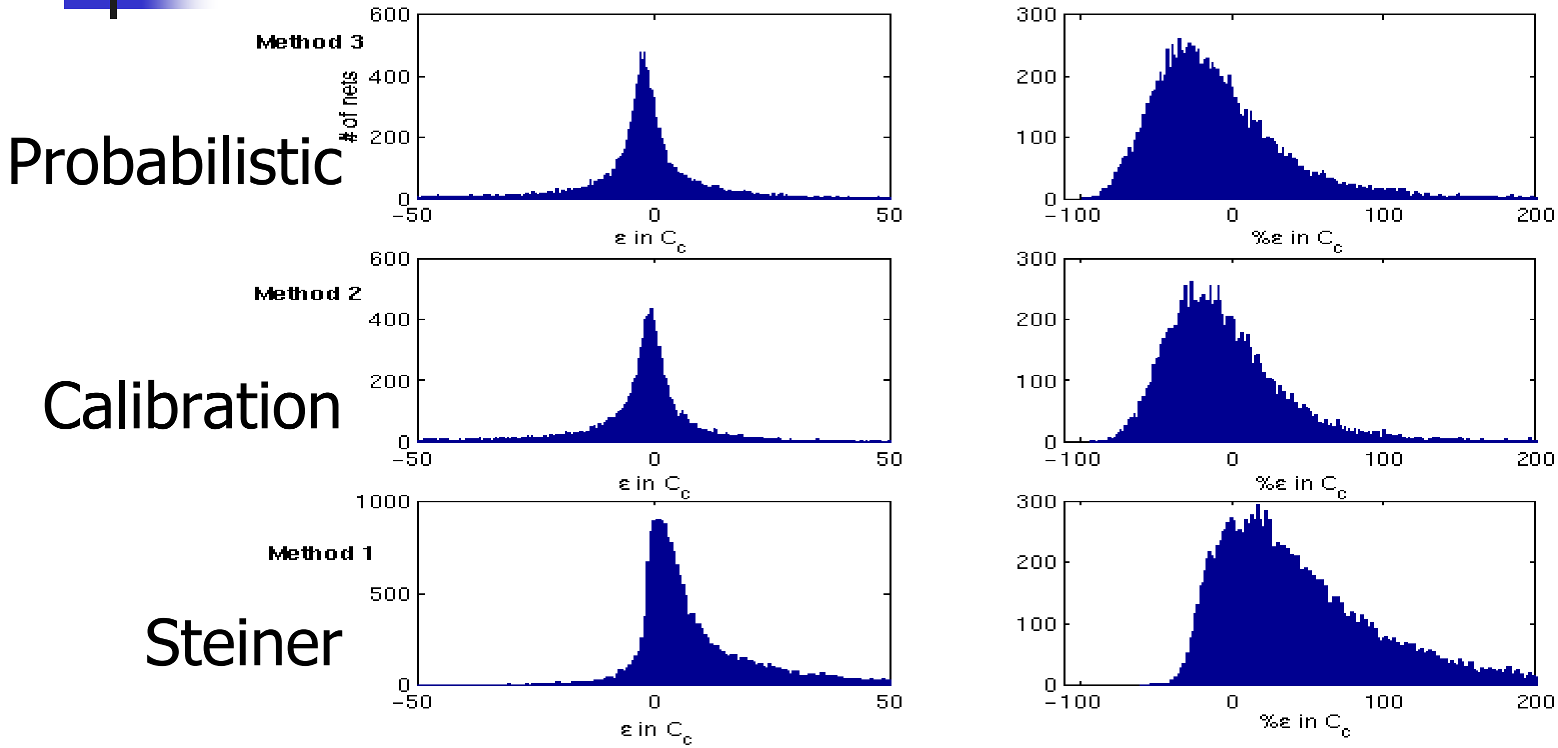
Aggressor Strength Estimation

- All nets that share a congestion map segment are possible neighbors.
- Likelihood of a net to be an aggressor to another net increases as the number of shared segments increases
- To estimate an average aggressor for a net:
  - Find, say,10 possible neighbors with the highest number of shared segments. For each of these aggressors,
    - Find total capacitance, as discussed before,
    - Obtain Thevenin model of the driver gate from cell library
    - Compute a weighted average transition time $t_{r_{out}}$ on the aggressor net



$$v_{out}(t)=\begin{cases}\dfrac{-RC+t+RCe^{-t/RC}}{t_r}, & 0<t\le t_r\\ \dfrac{-RC}{t_r}(e^{t_r/RC}-1)e^{-t/RC}+1, & t>t_r\end{cases}$$

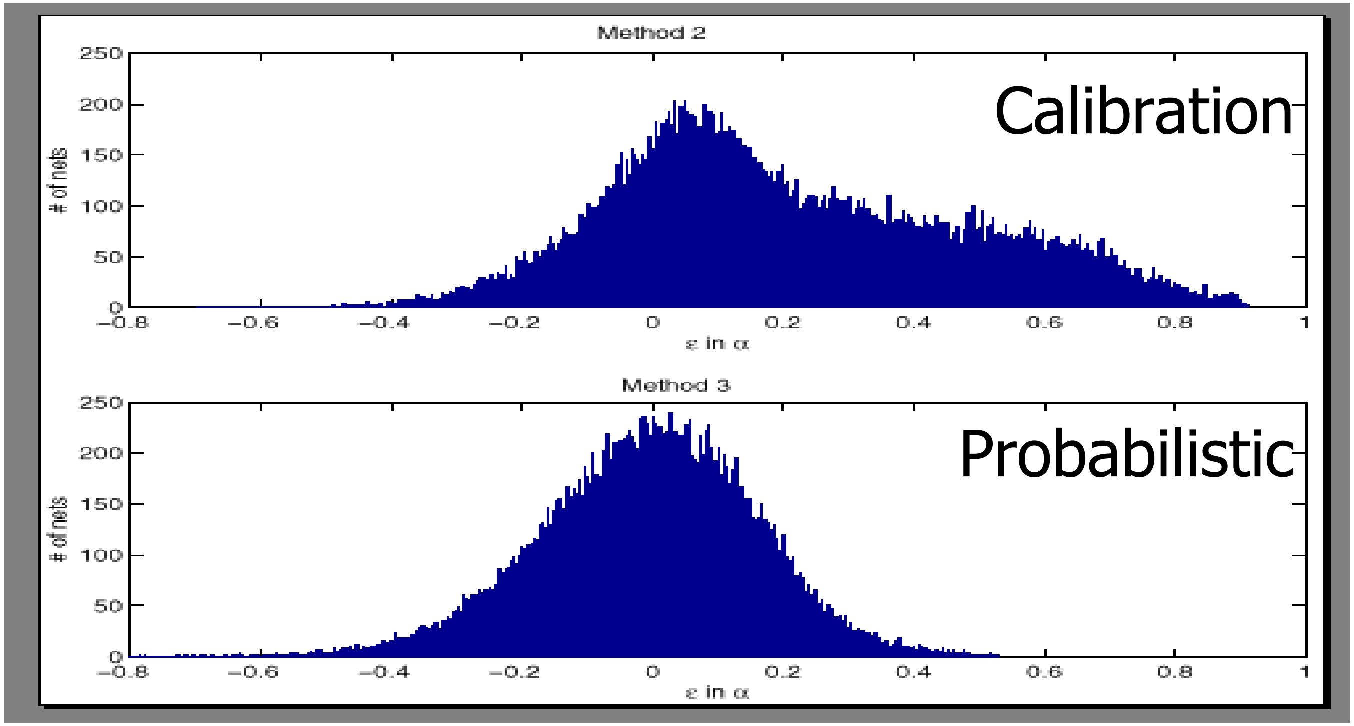
Estimation errors in 0.18μ processors (Two processors, 58K and 125K nets)



- Method 1: Steiner tree based approach: α=0.5 --> 52.74% and 85.14% error
- Method 2: Calibration method --> -2% and 16% error
- Method 3: Probabilistic extraction method --> -1.5% and 8% error

Calibration vs. Probabilistic

Absolute Error in α

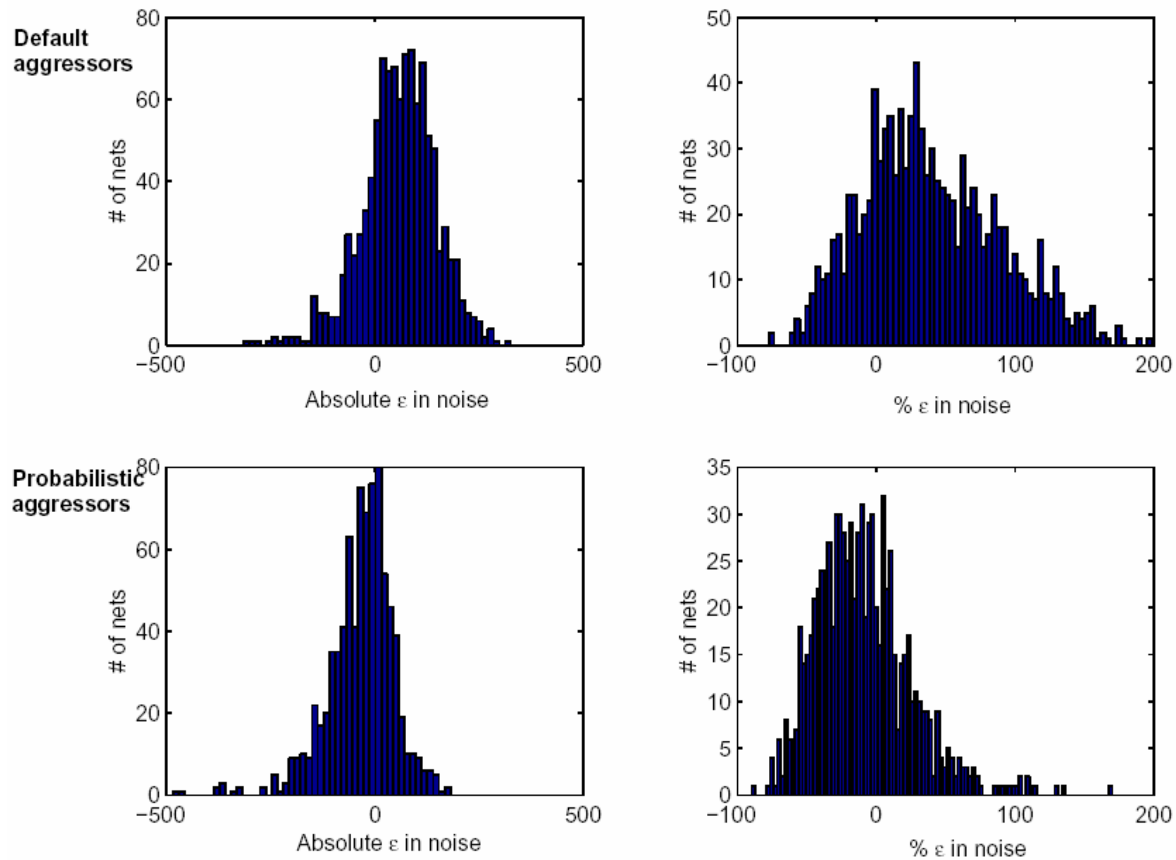


- Note, probabilistic method estimated localized α values, but calibration method used one α for all segments of the same net.

Probabilistic vs. Default Aggressors

Using probabilistic aggressors instead of strong default aggressors reduce average error in noise peak from 40% to 9%

A trade-off exists between estimated noise peak and early identified noisy nets



Failing nets in pre and post route noise analysis

Chip	Method	Missed	Common	False
chip-1	Steiner	148	694	531
	Calibration	207	635	241
	Probabilistic	161	681	205
chip-2	Steiner	134	487	3509
	Calibration	193	428	1591
	Probabilistic	90	531	1409

- Common: # of nets that fail in both pre- and post-route noise analysis
- Missed : # of nets not identified by pre-route noise analysis that subsequently failed in post-route noise analysis
- False : # of nets that failed in pre-route noise analysis but not in post-route noise analysis
- Probabilistic method reduced the number of false failures by as much as 60% while predicting about the same number of real failures as the Steiner based method

Conclusion

- Post-route stage is too late and too expensive for fixing noise violations
- Proposed 3 techniques for pre-route noise estimation based on Steiner/Global routing
- Congestion from global router combined with a probabilistic estimation of coupling and aggressor strength can predict noise violations quite reliably