



When Timing is Uncertain, Infer: Probabilistic Early FPGA Timing Analysis for Robust Critical Path Optimization

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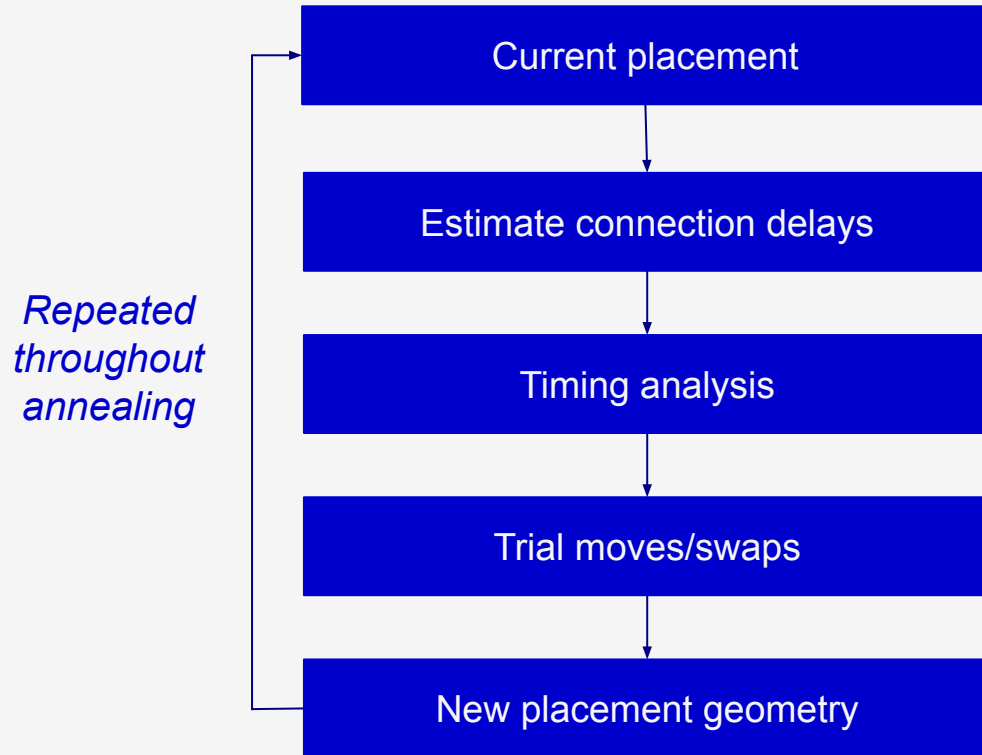
“Pre-routing placement decisions rely on provisional timing estimates”

We ask: *can explicitly modelling uncertainty
provide a better signal for timing-driven placement?*

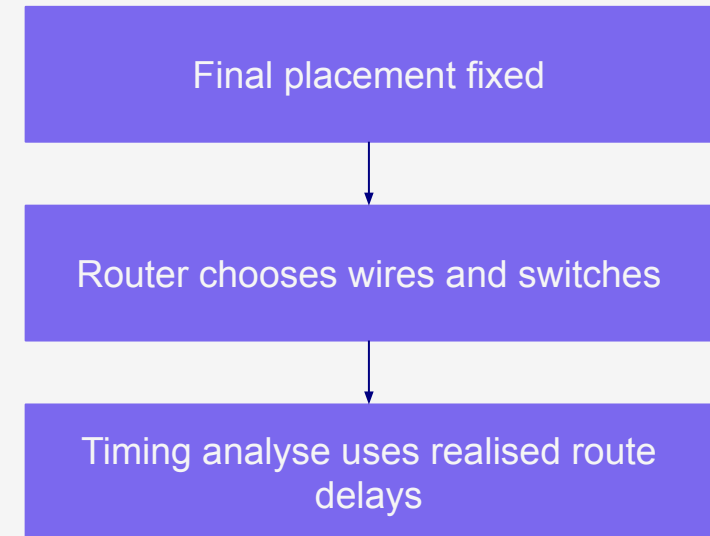
Timing estimates evolve throughout placement

Placement is aware of geometry, but not the final routed wires and switches

During placement



After detailed routing

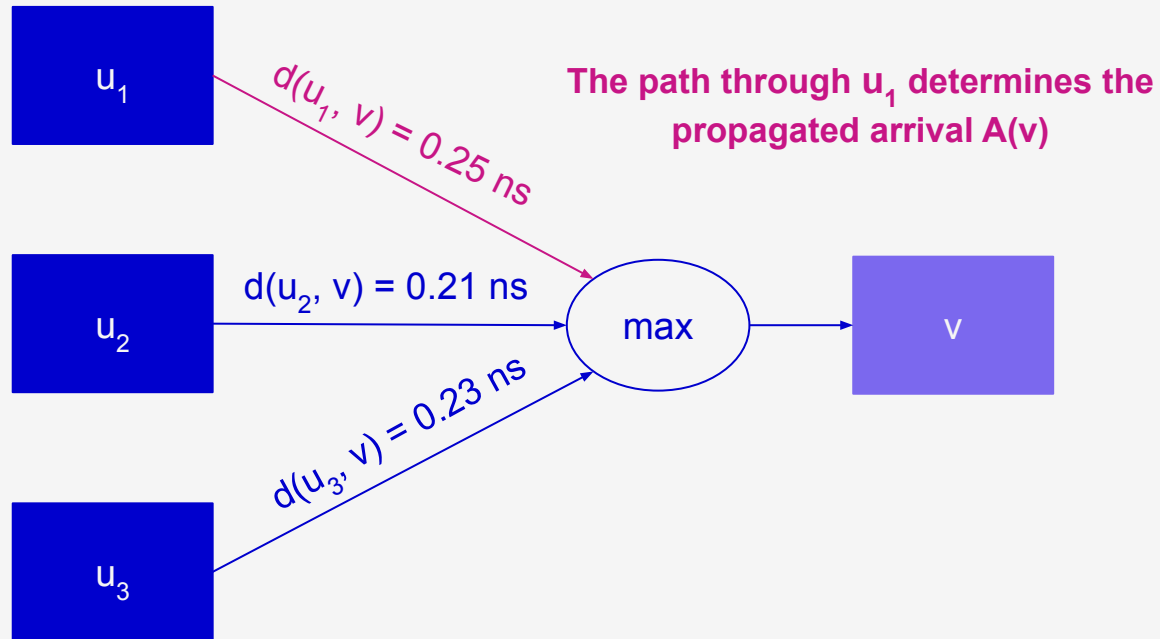


Only once the final placement geometry is selected does timing use realised route delays

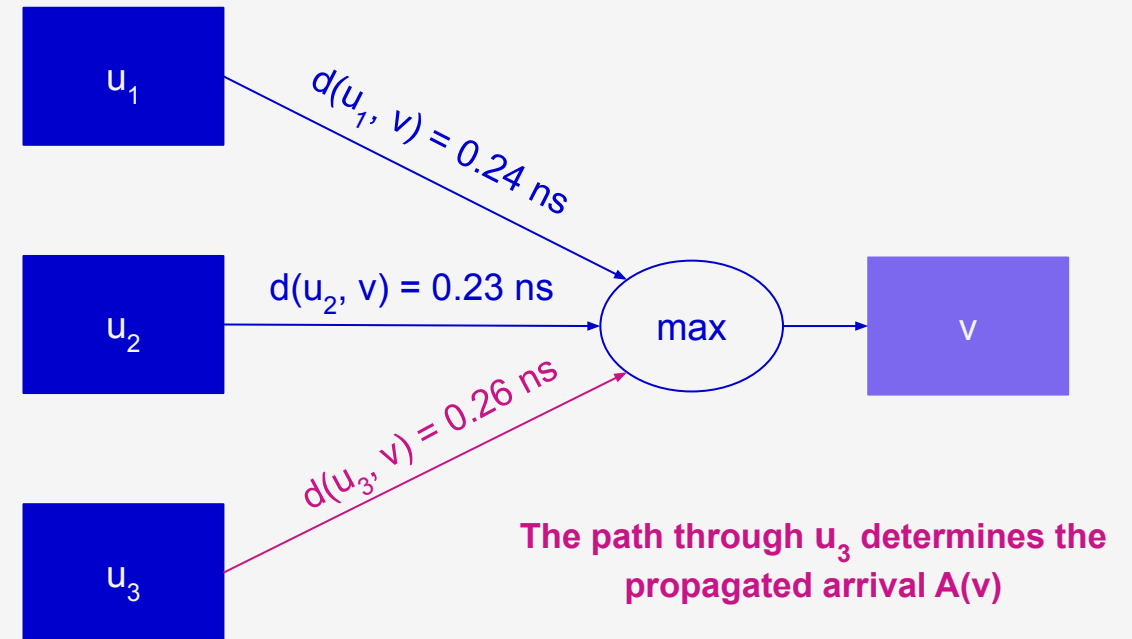
Conventional STA turns a close comparison into a hard decision

One incoming candidate determines the propagated arrival

During placement



After detailed routing (same placement)



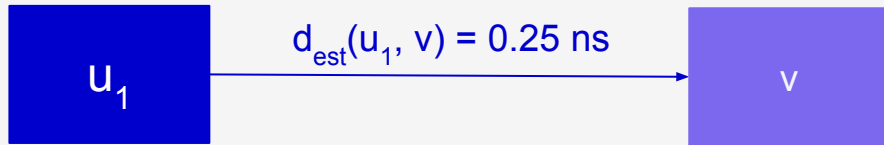
A close provisional comparison can change which predecessor drives downstream timing

Introducing uncertainty into placement timing

Candidate arrival times at a reconvergence become distributions

Incorporating uncertainty into arrival delays

Set the placement-time interconnect estimate as the mean of a delay distribution and assign an uncertainty model



Take placement-time delay estimates taken from pre-routing models

$$d_{\text{est}}(\mu_1, v) \sim N(\mu_{u1v}, \sigma_{u1v}^2)$$

Define pre-routing uncertainty model

$$\sigma_{u1v}^2 = (\alpha \mu_{u1v})[1 + \beta L(\mu_1, v)]$$

VPR delay estimate
set to mean:

$$d_{\text{est}}(\mu_1, v) = \mu_{u1v}$$

α : relative delay scale
Uncertainty scales with the
estimated delay magnitude

β : distance scale
Uncertainty increases with
placement distance

Form competing arrivals at a reconvergence

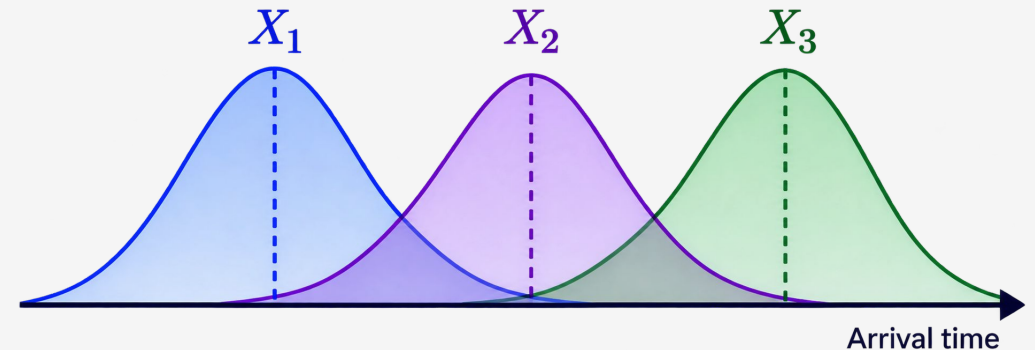
At a reconvergence v_i , each predecessor μ_i contributes a candidate arrival X_i : the time the signal would reach v if it propagated through μ_i .

$$X_i = A(\mu_i) + d(\mu_i, v)$$

$A(\mu_i)$: arrival accumulated up to u_i ,
including upstream uncertainty

$d(\mu_i, v)$: estimated connection delay
from u_i to v_i with pre-routing
uncertainty

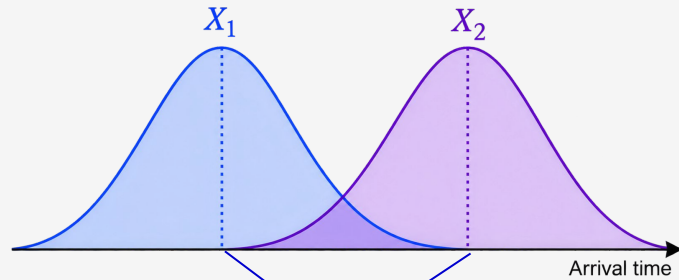
$$X_i \sim N(\mu_i, \sigma_i^2)$$



Transforming uncertain arrivals to placement timing pressure

Approximate uncertain maxima and amend VPR timing pressure

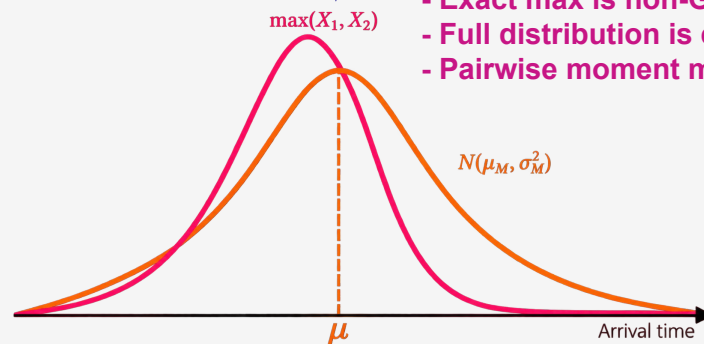
Keeping uncertain maxima tractable



At a reconvergence, compute $M = \max(X_1, X_2)$:

Why approximate?

- Exact max is non-Gaussian
- Full distribution is expensive to propagate
- Pairwise moment matching keeps only μ and σ^2



Moment-match the exact max's mean and variance,
then propagate only the compact Gaussian
summary: $M \approx N(\mu_M, \sigma_M^2)$

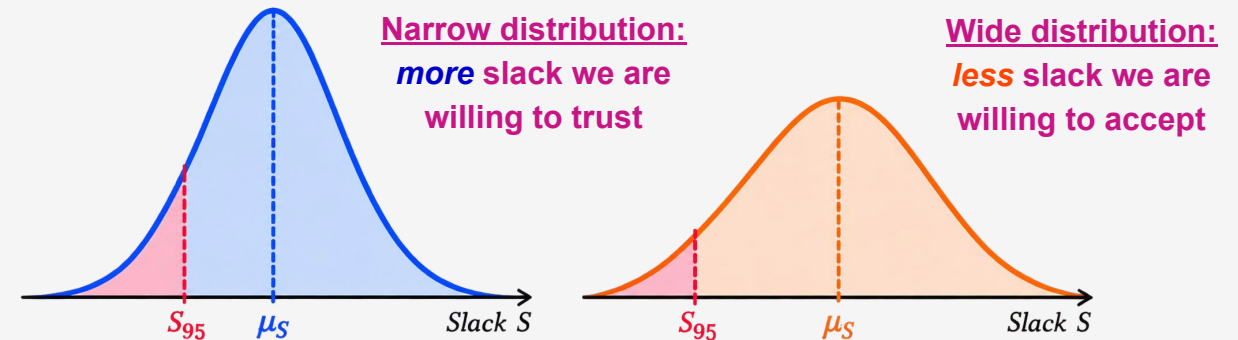
Converting uncertainty to placement pressure

Compute slack under uncertainty:

$$S = R - A$$

Compute a 95% conservative slack:

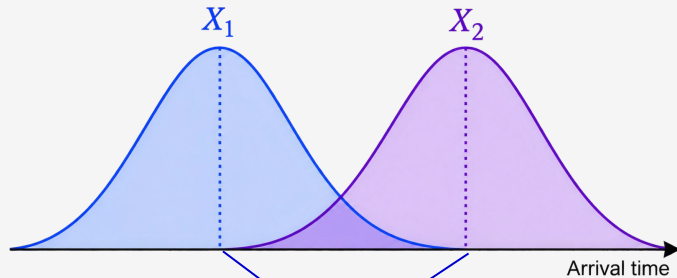
$$S_{95}(e) = \mu_S - 1.645 \sigma_S$$



Transforming uncertain arrivals to placement timing pressure

Approximate uncertain maxima and amend VPR timing pressure

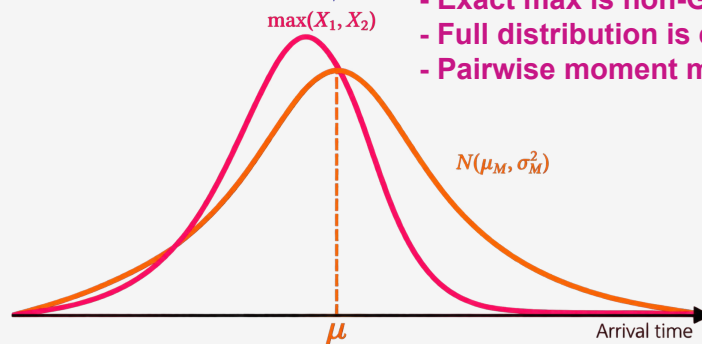
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Converting uncertainty to placement pressure

Compute slack under uncertainty:
 $S = R - A$

Compute a conservative slack:
 $S_{95}(e) = \mu_s - 1.645 \sigma_s$

Define a probabilistic criticality:
 $\text{Crit}_{\text{prob}}(e) = 1 - S_{95}(e)/T$

Compute timing risk:
 $\Delta(e) = \max(0, \text{Crit}_{\text{prob}}(e) - \text{Crit}_{\text{VPR}}(e))$

Amend VPR timing pressure:
 $P_{\text{timing}}^{\text{new}}(e) = P_{\text{timing}}^{\text{VTR}}(e) (1 + \lambda \Delta(e))$

λ : controls the
strength of the
additional timing
pressure

Evaluation

We evaluate four fixed uncertainty settings across VTR 7.0 benchmark suite (25 seeds per design configuration)

Define four fixed configurations

% reduction in geometric mean of final routed critical-path delay improvement vs. baseline VPR

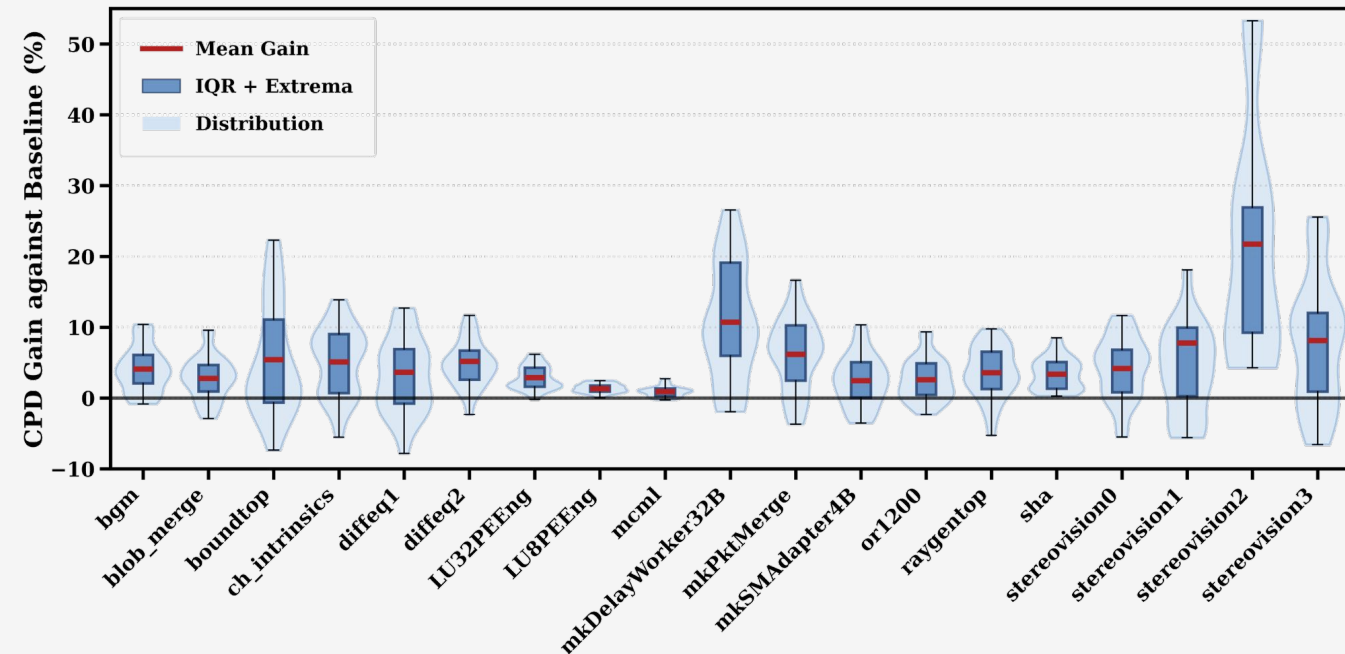
$(\lambda = 0.35)$	$\beta = 2$	$\beta = 4$
$\alpha = 0.01$	$\theta_1: 1.64\%$	$\theta_2: 1.26\%$
$\alpha = 0.03$	$\theta_3: 1.97\%$	$\theta_4: 1.34\%$

Select the best configuration per design

Portfolio Selector, $\max(\theta_1, \theta_2, \theta_3, \theta_4)$: 5.67%

+baseline fallback: $\max(\theta_{\text{baseline}}, \theta_1, \theta_2, \theta_3, \theta_4)$: 6.05%

Per-design routed CPD gain (%)



Large gains on routing-sensitive designs

- stereovision2: +21.76%
- mkDelayWorker32B: +10.95%

- ↓60.9% lower seed-dependent CPD variation
- ↓2.83% wirelength reduction
- ↑5.11% total-flow runtime overhead

In closing

Model uncertainty early and use it to guide placement

1. Near-tied placement-time timing decisions are the least stable once routing is resolved
2. Pre-routing uncertainty model that represents uncertainty in estimated delays and converts it into additional placement timing pressure
3. Tractable probabilistic timing propagation through the timing graph using compact Gaussian moment matching + VTR integration by augmenting the existing timing signal
4. Uncertainty design space exploration with a small portfolio of fixed configurations, demonstrating the potential upside: (6.05% routed CPD improvement)

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Limitations and future work

1. Move from portfolio selection to one adaptive run: use inferred timing uncertainty and placement state to adapt timing pressure α , β , λ online
2. Introduce a pre-routing uncertainty model that represents uncertainty in estimated delays and converts it into additional placement timing pressure