Kriging-Assisted Ultra-Fast Simulated-Annealing Optimization of a Clamped Bitline Sense Amplifier

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Outline of the talk

- Background and Motivation
- Related Prior Research
- Fundamentals of Kriging
- Proposed Design Optimization Flow Methodology
- CBSA and Figures of Merit
- Conclusions and Future Research Directions

Issues in NanoCMOS Design

- Expensive Computer Simulations
- Pronounced effects of process variations in deep nanometer regions
  - Increase in design parameters
  - Current modeling techniques unable to capture effects of process variation

Novel Contributions

- Design flow methodology incorporating Kriging metamodeling and simulated annealing based optimization.
- Two methods of Kriging metamodeling techniques that account for correlating effect of process parameters.

Prior Related Research

- Polynomial regression techniques
- Neural Networks
- Kriging Based Techniques
  - G.Yu --- re-iterative pareto fronts
  - H.You -- Metamodeling

Fundametals of Kriging

- Originally used in geostatistics fields for mining purposes.

$$y(\mathbf{x_0}) = \sum_{j=1}^{L} \lambda_j B_j(\mathbf{x}) + z(\mathbf{x}), \qquad (1)$$

- Each point is predicted based on a set of unique weights (λ_j).
- Two methods are considered
  - Ordinary Kriging
  - Simple Kriging

Fundametals of Kriging…

- Ordinary kriging weights are biased

$$\sum_{j=1}^{n} \lambda_j = 1. \qquad (3)$$

- Weighting

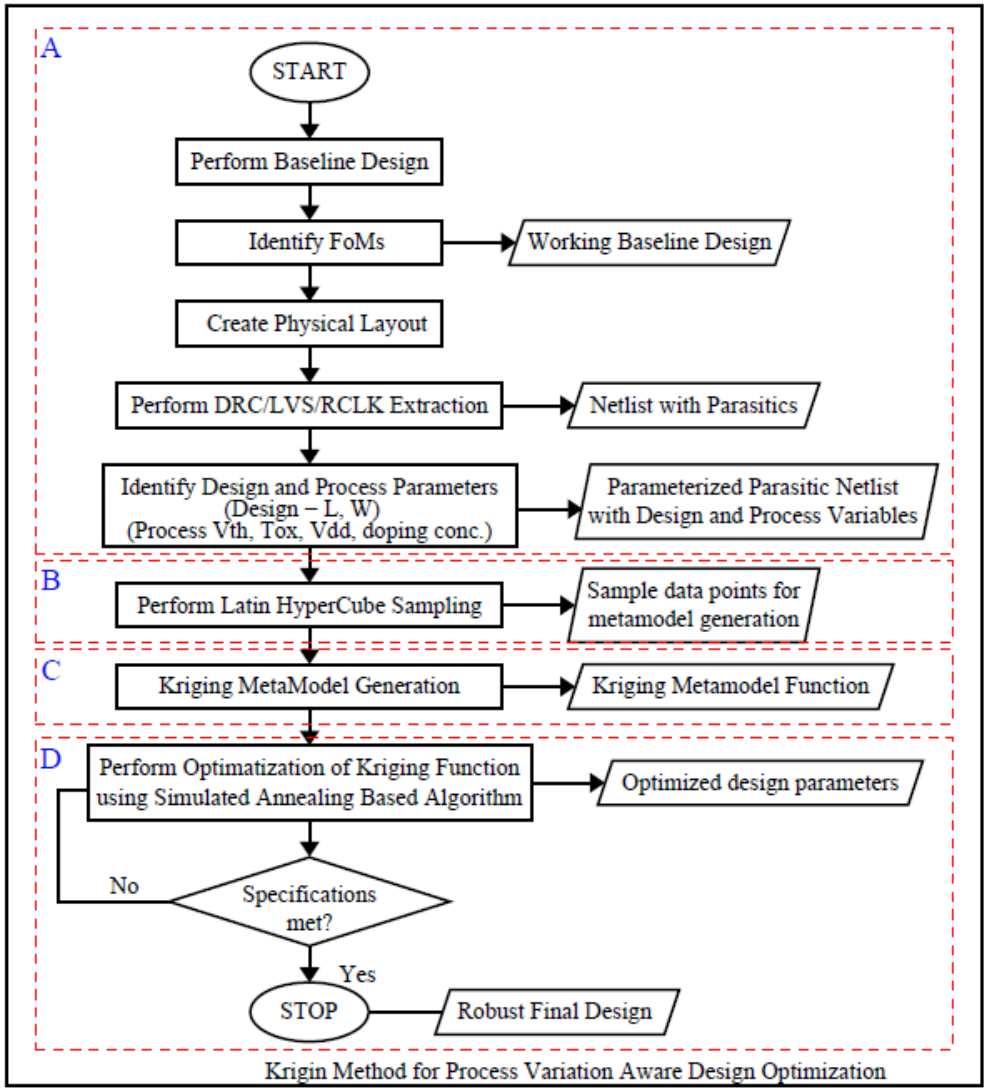
$$\begin{pmatrix} \lambda_1 \\ \vdots \\ \lambda_n \\ \mu \end{pmatrix} = \Gamma^{-1} \begin{pmatrix} \gamma(e_1, e_0) \\ \vdots \\ \gamma(e_n, e_0) \\ 1 \end{pmatrix}, \qquad (4)$$

$$\Gamma = \begin{pmatrix} \gamma(e_1, e_1) & \cdots & \gamma(e_1, e_n) & 1 \\ \vdots & \ddots & \vdots & 1 \\ \gamma(e_n, e_1) & \cdots & \gamma(e_n, e_n) & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix}, \qquad (5)$$

  - For simple kriging, eqn (5) does not have the last row and column

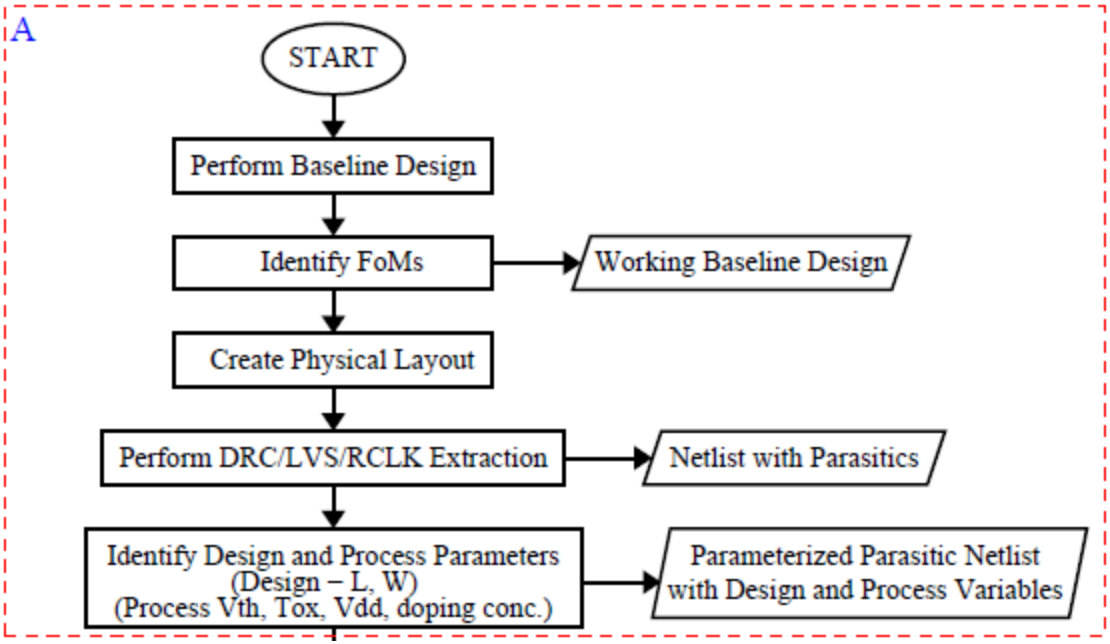
Proposed Design Optimization Flow

- Design netlist and parameterization
- Sampling Techniques
- Kriging Assisted Metamodel Generation
- Simulated Annealing Optimization Algorithm



Krigin Method for Process Variation Aware Design Optimization

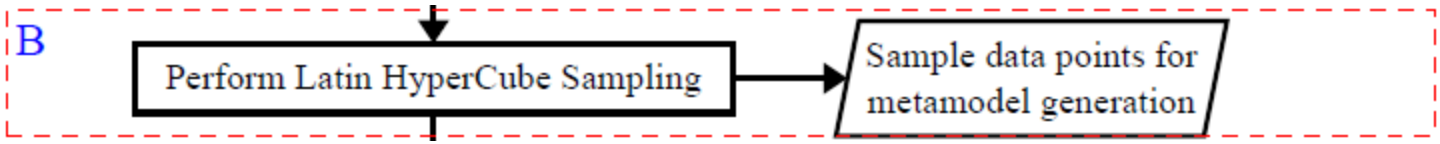
Design and Netlist Optimization



Baseline design flow

- Baseline design (schematic and layout)
- Parameterize extracted parasitic netlist
- Identify performance objectives to be optimized.

Sampling Techniques



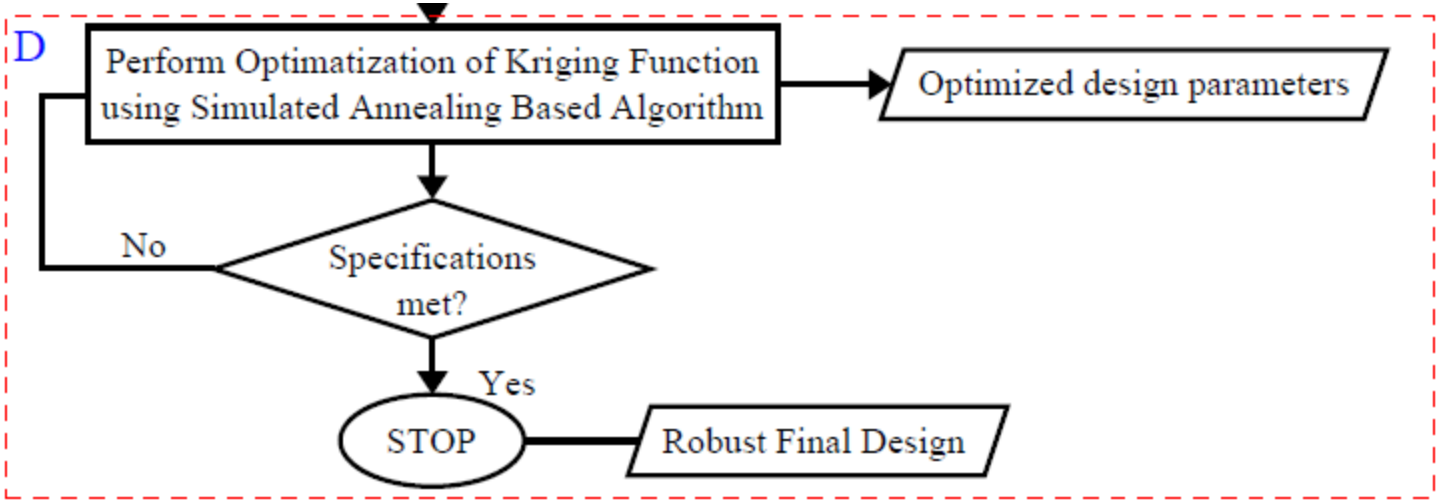
- Sampling with LHS
  - divides design space into equal number of n sample points.
  - L, W used as sampling corners and process parameters are varied
  - captures better representation of design space

Kriging assisted metamodels

- Metamodel for each design objective is generated
  - using mGstat (Matlab Kriging tool)
- Design objectives are functions of design parameters
  - eg.

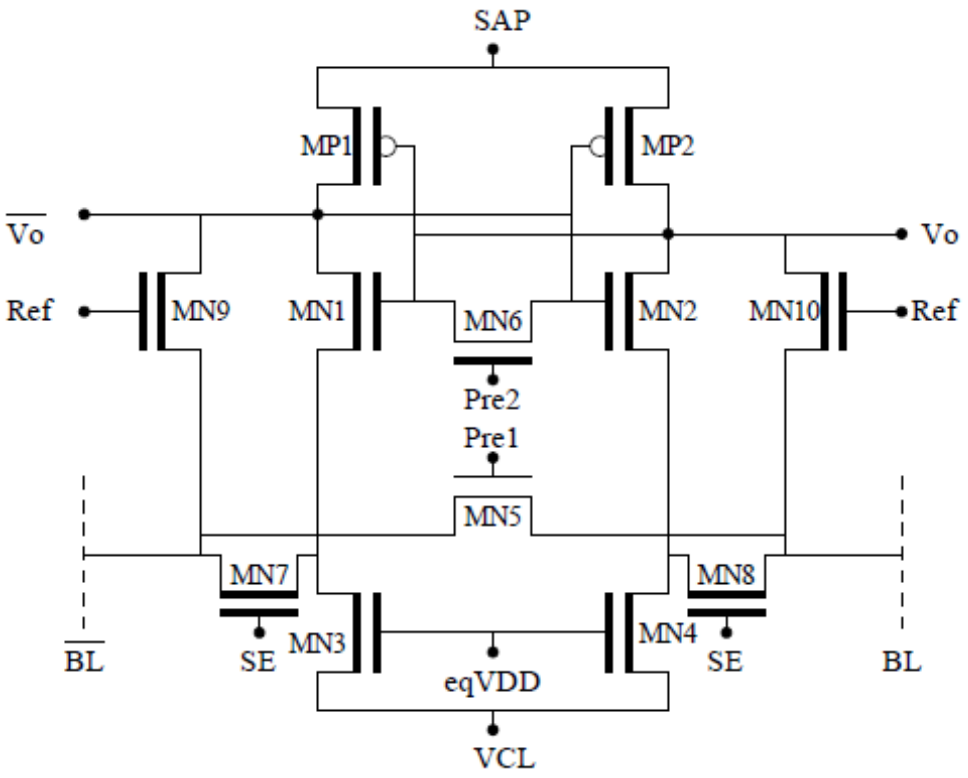
$$\widehat{Y}_{pr}\left(W_n^*\right) = \sum_{i=1}^{N} \lambda\left(W_n^*\right)_i Y_{pr}\left(W_{n_i}\right), \qquad (7)$$

Simulated Annealing based optimization algorithm



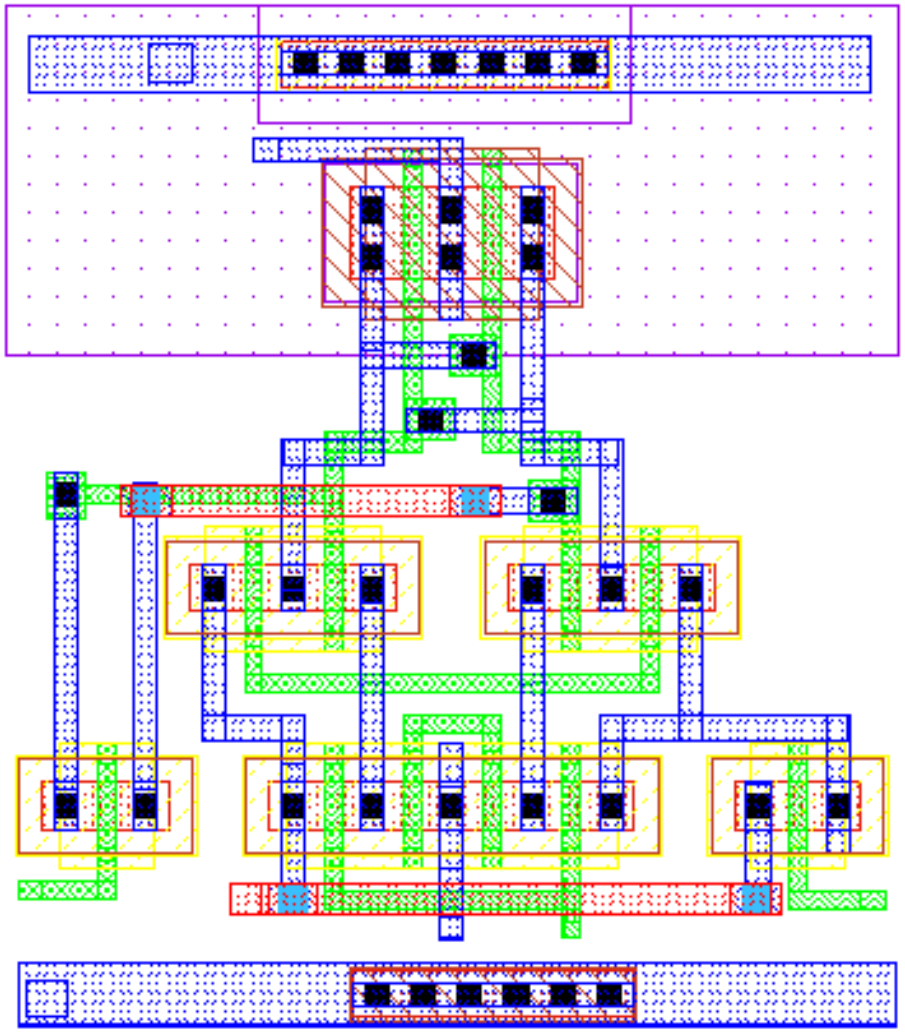
- Kriging based metamodels optimized with SA algorithm
- Conflicting design objectives used as optimization goal and constraint.

CBSA:Case Study Circuit



- MP_1, MP_2, MN_1 and MN_2 form cross-coupled inverters.
- VCL clamps bitlines to reduce capacitive effect.
- MN3 and MN4 provide low impedance.

CBSA:Case Study Circuit

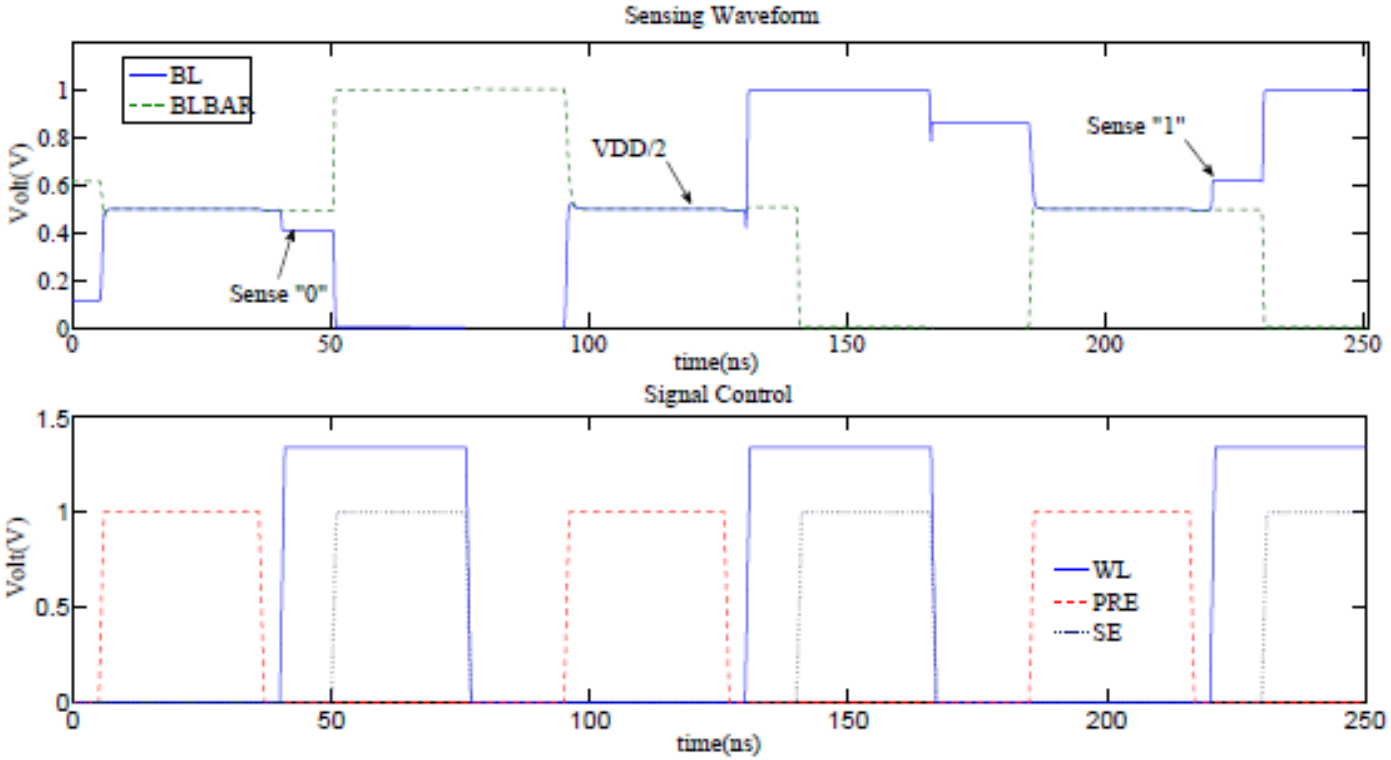


- L_n = 45nm, W_n = 120nm
- L_p = 45nm, W_p = 240nm

CBSA: Figure of Merits

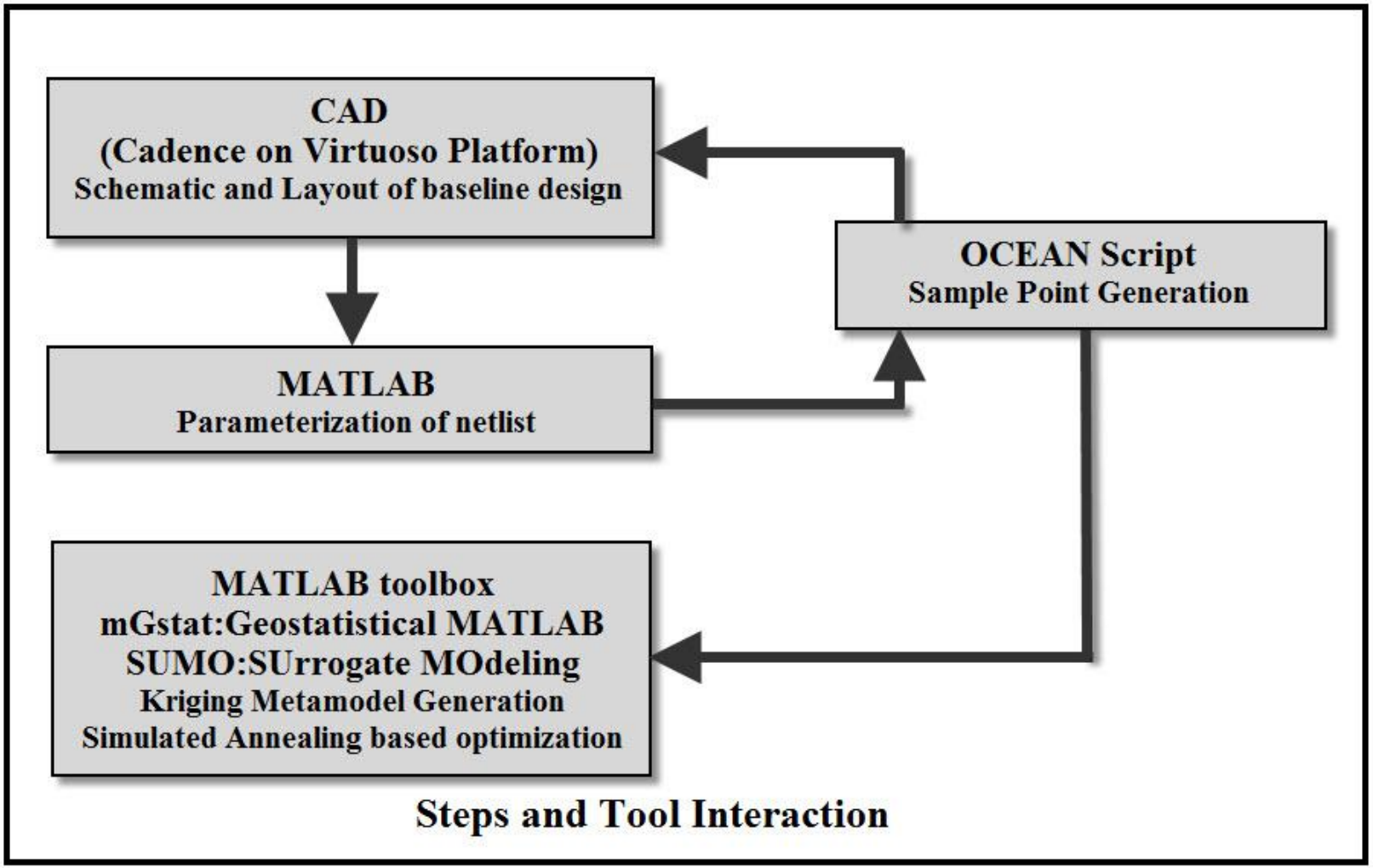
- Precharge time
  - Time required to setup bitlines
- Sense Delay
  - Time required for sufficient voltage to appear on bitlines
- Power Consumption
  - Average power consumption (including dynamic, subthreshold and leakage power)
- Sense Margin
  - Amount of sufficient voltage required for correct read or write

Functional simulation of CBSA



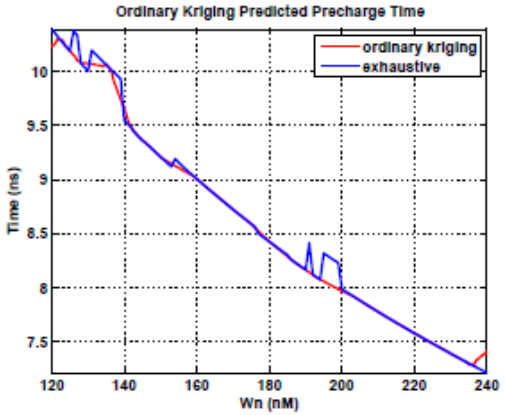
Design	Precharge time, T_{PC} (ns)	Sense delay, T_{SD} (ns)	Power, P_{SA} (μW)	Sense Margin, V_{SM} (mV)	Area (μm2)
Schematic	10.31	1.79	1.84	26.91	-
Layout	10.40	1.91	1.88	26.86	6.045

Setup and Tools Interaction

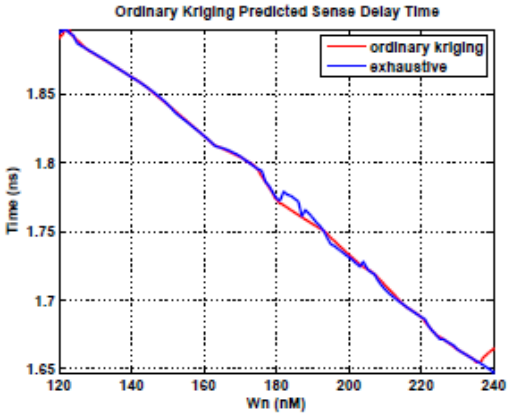


Steps and Tool Interaction

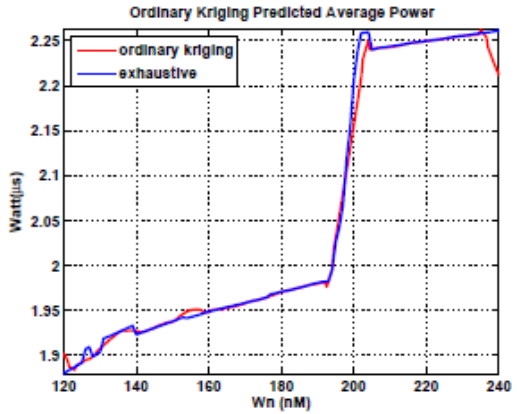
Kriging predicted metamodels (ordinary)



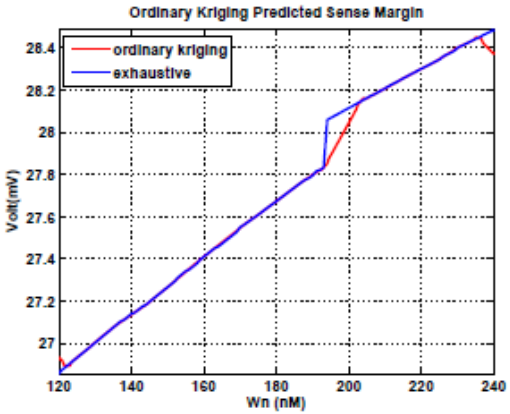
(a) Ordinary Kriging for precharge time



(b) Ordinary Kriging for sense delay

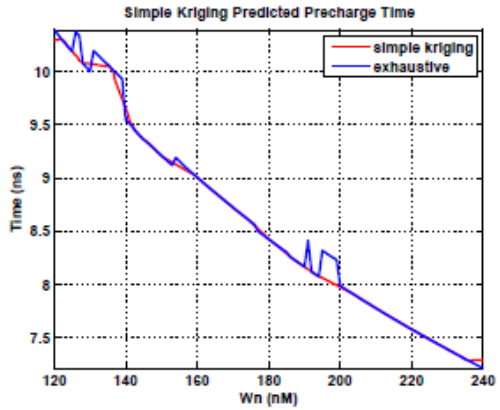


(c) Ordinary Kriging for average power

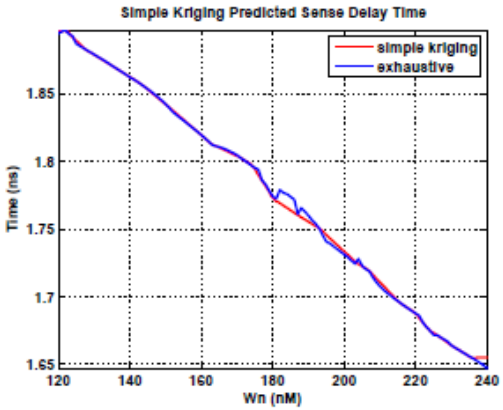


(d) Ordinary Kriging for sense margin

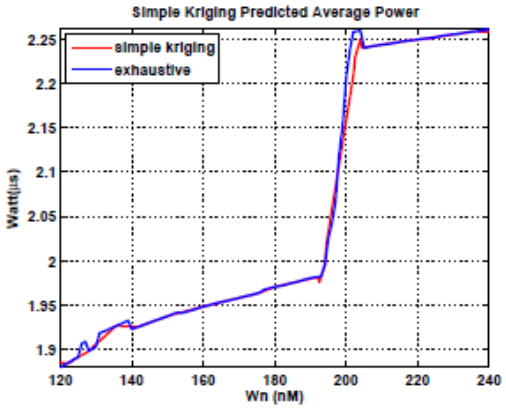
Kriging predicted metamodels (simple)



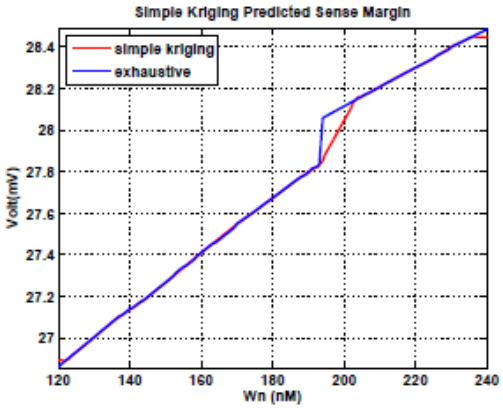
(a) Simple Kriging Predicted for Precharge time



(b) Simple Kriging Predicted for Sense Delay



(c) Simple Kriging Predicted for Average Power



(d) Simple Kriging Predicted for Sense Margin

Accuracy and Validation

STATISTICAL ANALYSIS OF THE KRIGING PREDICTED VALUES.

FoMs	Ordinary Kriging		Simple Kriging	
Samples	20	100	20	100
Precharge				
MSE	6.02×10^{-21}	3.85×10^{-19}	5.32×10^{-21}	3.63×10^{-19}
$RMSE$	7.76×10^{-11}	6.20×10^{-10}	7.29×10^{-11}	6.02×10^{-10}
R^2	0.9931	0.5560	0.9939	0.5810
STD	6.95×10^{-11}	6.09×10^{-10}	6.60×10^{-11}	5.91×10^{-10}
Sense Delay				
MSE	1.12×10^{-23}	8.27×10^{-24}	7.49×10^{-24}	4.02×10^{-24}
$RMSE$	1.02×10^{-10}	2.88×10^{-12}	2.73×10^{-12}	2.00×10^{-12}
R^2	0.9984	0.9985	0.9987	0.9993
STD	8.62×10^{-11}	2.64×10^{-12}	2.29×10^{-12}	1.79×10^{-12}
Power				
MSE	3.64×10^{-15}	4.35×10^{-15}	3.56×10^{-15}	4.69×10^{-15}
$RMSE$	6.24×10^{-11}	6.60×10^{-08}	5.96×10^{-08}	6.85×10^{-08}
R^2	0.9957	0.8145	0.8486	0.8003
STD	5.75×10^{-11}	6.40×10^{-08}	5.69×10^{-08}	6.66×10^{-08}
Sense Margin				
MSE	2.79×10^{-09}	6.31×10^{-09}	2.56×10^{-09}	4.32×10^{-09}
$RMSE$	5.28×10^{-05}	7.94×10^{-05}	5.06×10^{-05}	6.57×10^{-05}
R^2	0.9987	0.9753	0.9900	0.9831
STD	2.58×10^{-05}	7.73×10^{-05}	4.79×10^{-05}	6.41×10^{-05}

Design Optimization

Algorithm 1 Simulated-Annealing Based Optimization of the Clamped-Bitline Sense Amplifier.

Initialize iteration counter: $counter \leftarrow 0$.
Initialize temperature Θ.
Initialize $Cooling\_Rate$.
Start with an initial solution $\widehat{CBSA}_i$.
Calculate the FoMs for $\widehat{CBSA}_i$ using the Kriging models.
Consider the objective of interest T_{PC_i}.
$result \leftarrow \Delta_{T_{PC}} \leftarrow T_{PC_i}$.
while $(\Delta_{T_{PC}} != 0\ )$ **do**
  $counter \leftarrow max\_Iteration$.
  while $(counter > 0)$ **do**
    Generate random transition from solution $\widehat{CBSA}_i$ to $\widehat{CBSA}_j$.
    Calculate the FoMs for $\widehat{CBSA}_j$ using the Kriging models.
    if $(T_{PC_j} < result)$ **then**
      $result \leftarrow T_{PC_j}$.
      $\widehat{CBSA}_i \leftarrow \widehat{CBSA}_j$.
    else
      $\Delta_{T_{PC}} \leftarrow T_{PC_i} - T_{PC_j}$.
      if $(\ \Delta_{T_{PC}} < 0$, random(0,1) $< e^{\frac{\Delta_{T_{PC}}}{T}}\ )$ **then**
        $T_{PC_i} \leftarrow T_{PC_j}$.
        $\widehat{CBSA}_i \leftarrow \widehat{CBSA}_j$.
      end if
    end if
    $counter \leftarrow counter - 1$.
  end while
  $\Theta \leftarrow \Theta \times Cooling\_Rate$.
end while
return $result$ and $\widehat{CBSA}_i$.

Optimal Simulation Results

Design	Precharge time, T_{PC} (ns)	Sense delay, T_{SD} (ns)	Power, P_{SA} (µW)	Sense Margin, V_{SM} (mV)	Area (µm2)
Schematic	10.31	1.79	1.84	26.91	-
Layout	10.40	1.91	1.88	26.86	6.045
Optimized	8.16	1.68	1.98	28.03	6.356
Change	21.54%	12.04%	-5.32%	-4.36%	5.15%

Conclusions

- A novel design flow methodology incorporating Kriging metamodeling and simulated annealing based optimization algorithm was presented
- Two forms of Kriging prediction were explored.
- Optimized FoM (T_{PC}) by 21.54%
- Current techniques will be extended to high dimension parameters and multi objective optimization.


Thank you !!!