Supported by Cadence Design Systems, Inc.,
NSF, the Packard Foundation, and
State of Georgia's Yamacraw Initiative

Closing the Smoothness and Uniformity Gap in Area Fill Synthesis

Y. Chen, A. B. Kahng, G. Robins, A. Zelikovsky

(UCLA, UCSD, UVA and GSU)

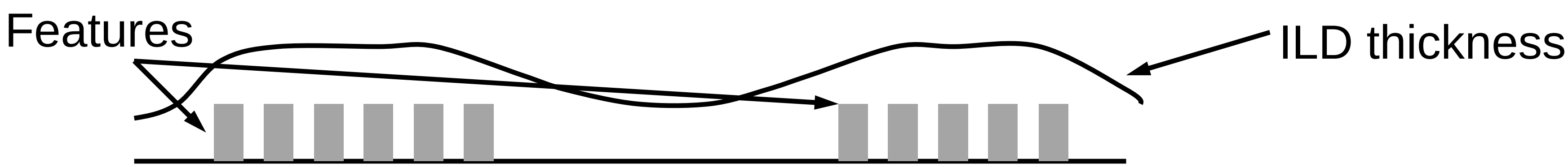
http://vlsicad.ucsd.edu

Outline

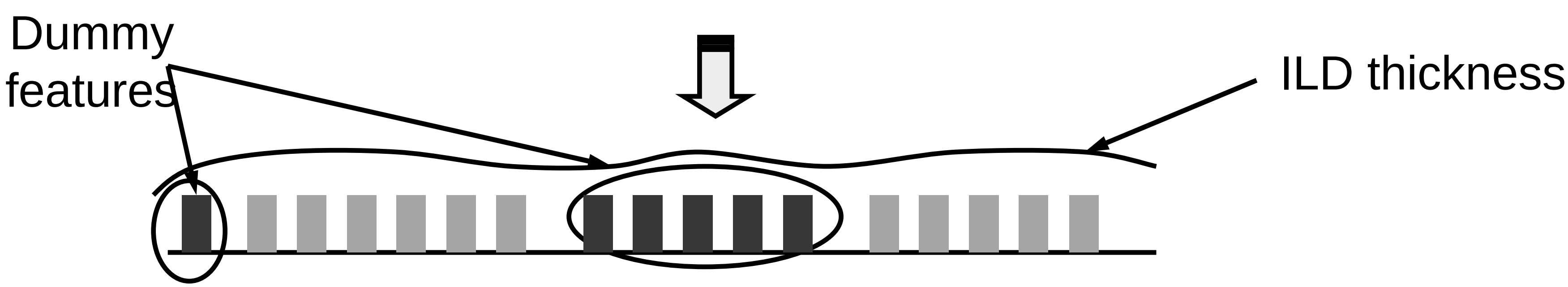
- ***Layout Density Control for CMP*** ⇦
- **Our Contributions**
- **Layout Density Analysis**
- **Local Density Variation**
- **Summary and Future Research**

CMP and Interlevel Dielectric Thickness

- **Chemical-Mechanical Planarization (CMP)**
  = wafer surface planarization
- **Uneven features cause polishing pad to deform**



- **Interlevel-dielectric (ILD) thickness ≈ feature density**
- **Insert dummy features to decrease variation**



Objectives of Density Control

- **Objective for Manufacture = Min-Var**

  minimize window density variation

  subject to upper bound on window density

- **Objective for Design = Min-Fill**

  minimize total amount of filling

  subject to fixed density variation

Filling Problem

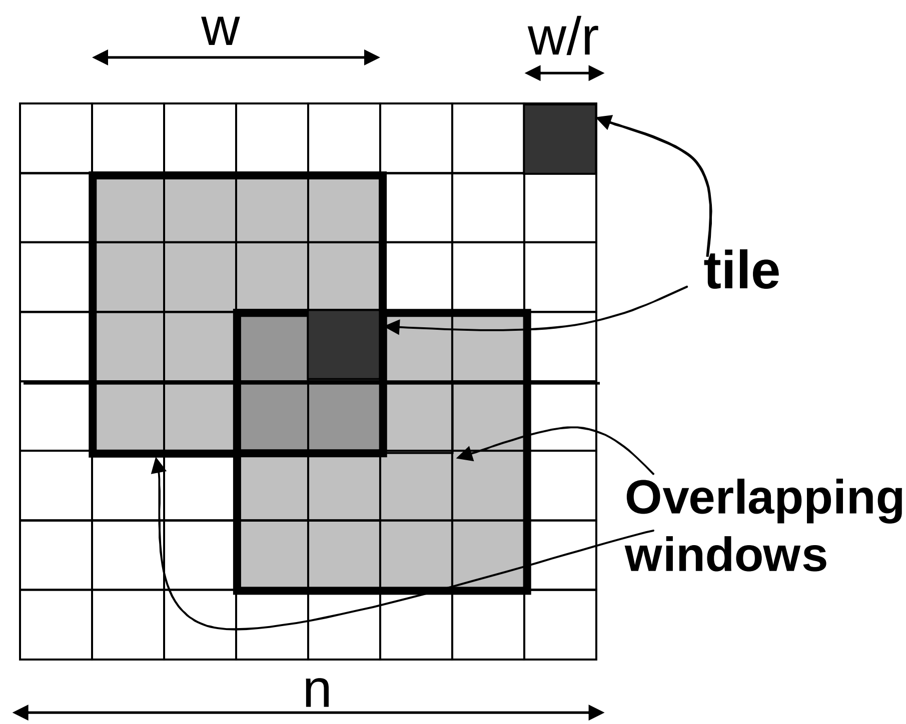
- **Given**
  - ⊙ **rule-correct layout in $n \times n$ region**
  - ⊙ **window size = $w \times w$**
  - ⊙ **window density upper bound U**

- **Fill layout with Min-Var or Min-Fill objective**

  such that *no* fill is added
  - ⊙ **within buffer distance B of any layout feature**
  - ⊙ **into any overfilled window that has density $\geq U$**

Fixed-Dissection Regime

- **Monitor only fixed set of $w \times w$ windows**
  - **"offset" = *w/r* (example shown: w = 4, r = 4)**
- **Partition n x n layout into $nr/w \times nr/w$ fixed dissections**
- **Each $w \times w$ window is partitioned into r^2 tiles**



Previous Works

- Kahng et al.
  - first formulation for fill problem
  - layout density analysis algorithms
  - first LP based approach for Min-Var objective
  - Monte-Carlo/Greedy
  - iterated Monte-Carlo/Greedy
  - hierarchical fill problem
- Wong et al.
  - Min-Fill objective
  - dual-material fill problem

Outline

- Layout Density Control for CMP
- *Our Contributions*
- Layout Density Analysis
- Local Density Variation
- Summary and Future Research

Our Contributions

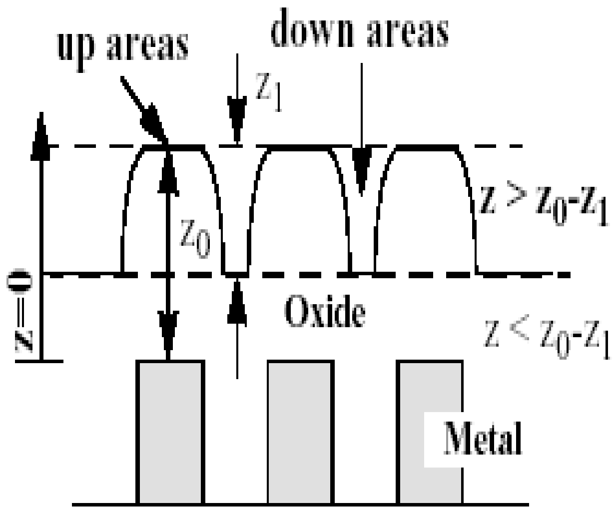
- **Smoothness gap in existing fill methods**
  - **large difference between fixed-dissection and floating window density analysis**
  - **fill result will not satisfy the given upper bounds**

- **New smoothness criteria: local uniformity**
  - **three new relevant Lipschitz-like definitions of local density variation are proposed**

Outline

- **Layout Density Control for CMP**
- **Our Contributions**
- ***Layout Density Analysis*** ⇦
- **Local Density Variation**
- **Summary and Future Research**

Oxide CMP Pattern Dependent Model



z = final oxide thickness over metal features
K_i = blanket oxide removal rate
t = polish time
ρ_0 = local pattern density

(Stine et al. 1997)

- **Removal rate inversely proportional to density**

$$\frac{dz}{dt} = -\frac{K}{\rho(x, y)}$$

- **Density assumed constant (equal to pattern) until local step has been removed:**

$$\rho(x,y,z) = \begin{cases} \rho_0(x,y) & z > z_0 - z_1 \\ 1 & z < z_0 - z_1 \end{cases}$$

- **Final Oxide thickness related to local pattern density**

$$z = \begin{cases} z_0 - \left(\dfrac{K_i t}{\rho(x,y)} \right) & t < (\rho_0 z_1)/K_i \\ z_0 - z_1 - K_i t + \rho_0(x,y) z_1 & t > (\rho_0 z_1)/K_i \end{cases}$$

pattern density $\rho_0(x,y)$ is crucial element of the model.

Layout Density Models

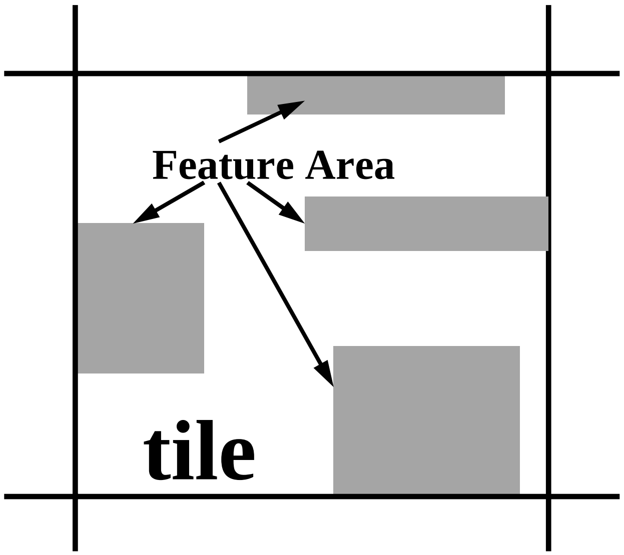
- **Spatial Density Model**

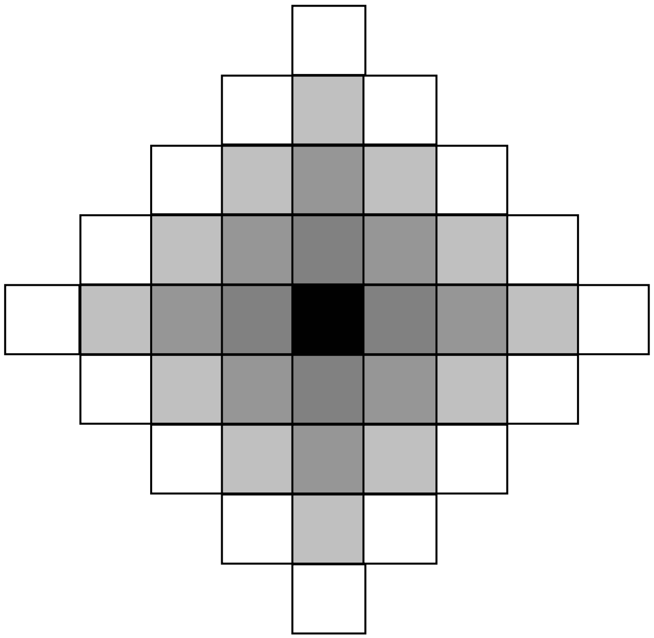
  window density ≈ sum of tiles feature area

- **Effective Density Model (more accurate)**

  window density ≈ weighted sum of tiles' feature area

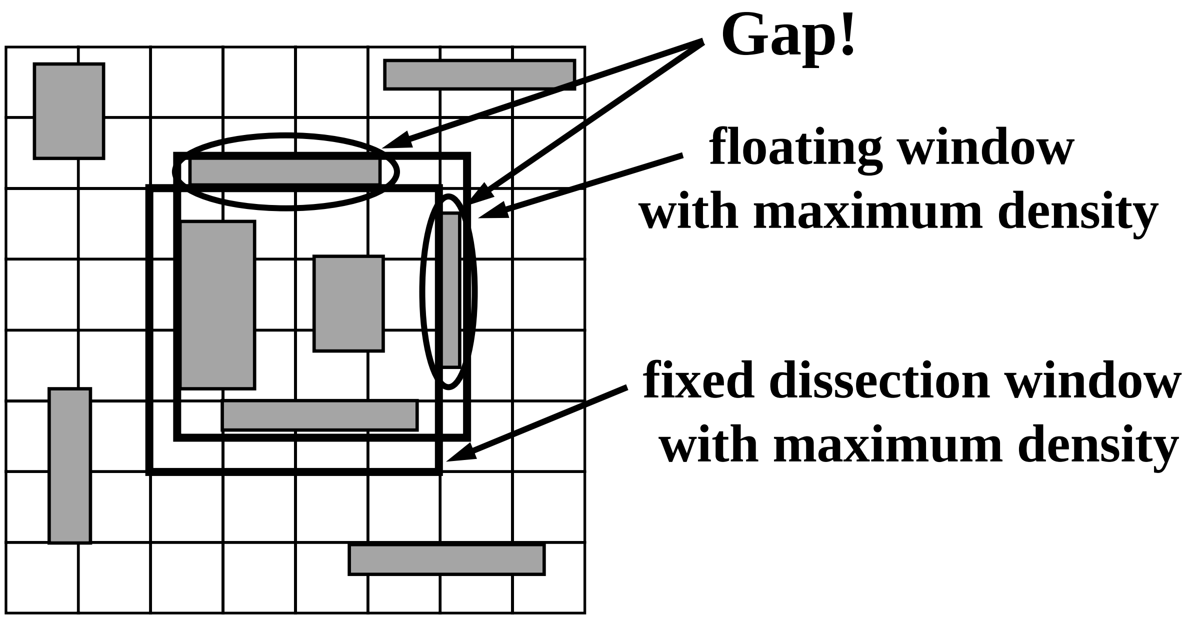
  - **weights decrease from window center to boundaries**





The Smoothness Gap

- Fixed-dissection analysis ≠ floating window analysis



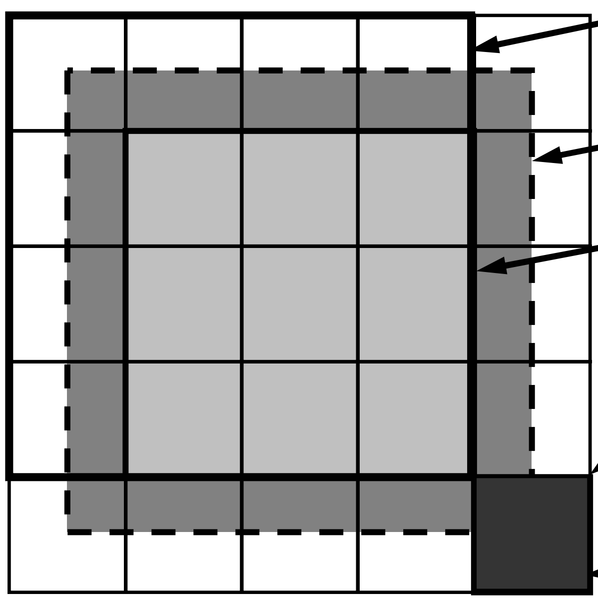
- Fill result will not satisfy the given bounds
- Despite this gap observed in 1998, all published filling methods fail to consider this smoothness gap

Accurate Layout Density Analysis

- **Optimal extremal-density analysis with complexity**

  ⇨ **inefficient**

- **Multi-level density analysis algorithm**
  - **An arbitrary floating window contains a shrunk window and is covered by a bloated window of fixed r-dissection**

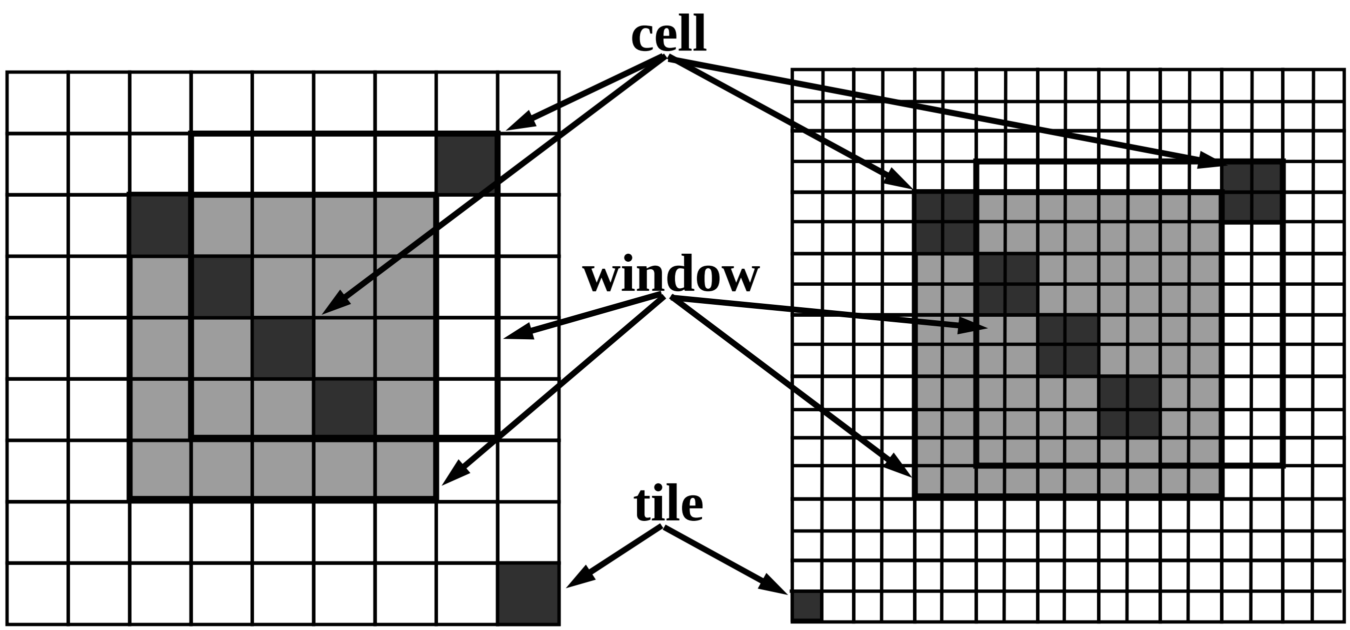


Multi-Level Density Analysis

- **Make a list *ActiveTiles* of all tiles**
- ***Accuracy* = ∞, *r* = 1**
- **WHILE *Accuracy* > 1 + 2ε DO**
  - **find all rectangles in tiles from *ActiveTiles***
  - **add windows consisting of *ActiveTiles* to *WINDOWS***
  - ***Max* = maximum area of window with tiles from *ActiveTiles***
  - ***BloatMax* = maximum area of bloated window with tiles from *ActiveTiles***
  - **FOR each tile *T* from *ActiveTiles* which do not belong to any bloated window of area > *Max* DO**
    - **remove T from ActiveTiles**
  - **replace in *ActiveTiles* each tile with four of its subtiles**
  - ***Accuracy* = *BloatMax/Max*, *r* = 2*r***
- **Output max window density = $(Max + BloatMax)/(2*w^2)$**

Multi-level Density Analysis on Effective Density Model

- Assume that the effective density is calculated with the value of r-dissection used in filling process
- The window phase-shift will be smaller
- Each cell on the left side has the same dimension as the one on right side



Accurate Analysis of Existing Methods

			LP			Greedy			MC			IGreedy			IMC		
Testcase	OrgDen		FD	Multi-Level		FD	Multi-Level		FD	Multi-Level		FD	Multi-Level		FD	Multi-Level	
T/W/r	MaxD	MinD	DenV	MaxD	Denv	DenV	MaxD	Denv	DenV	MaxD	Denv	DenV	MaxD	Denv	DenV	MaxD	Denv
Spatial Density Model																	
L1/16/4	.2572	.0516	.0639	.2653	.0855	.0621	.2706	.0783	.0621	.2679	.0756	.0621	.2653	.084	.0621	.2653	.0727
L1/16/16	.2643	.0417	.0896	.2653	.0915	.0705	.2696	.0773	.0705	.2676	.0758	.0705	.2653	.0755	.0705	.2653	.0753
L2/28/4	.1887	.05	.0326	.2288	.1012	.0529	.2244	.0986	.0482	.2236	.0973	.0326	.2202	.0908	.0328	.2181	.0898
L2/28/16	.1887	.0497	.0577	.1911	.0643	.0672	.1941	.0721	.0613	.1932	.0658	.0544	.1921	.0646	.0559	.1919	.0655
Effective Density Model																	
L1/16/4	.4161	.1073	.0512	.4244	.0703	.0788	.4251	.0904	.052	.4286	.0713	.0481	.4245	.0693	.0499	.4251	.0724
L1/16/16	.4816	0	.2156	.4818	.2283	.2488	.5091	.2787	.1811	.5169	.2215	.185	.4818	.2167	.1811	.4818	.2086
L2/28/4	.2977	.1008	.0291	.3419	.106	.063	.3385	.1097	.0481	.334	.0974	.048	.3186	.1013	.0397	.324	.0926
L2/28/16	.5577	0	.2417	.5753	.2987	.2417	.5845	.2946	.2617	.58	.3161	.2302	.5691	.2916	.2533	.5711	.3097

Multi-level density analysis on results from existing fixed-dissection filling methods

- **The window density variation and violation of the maximum window density in fixed-dissection filling are underestimated**

Outline

- **Layout Density Control for CMP**
- **Our Contributions**
- **Layout Density Analysis**
- ***Local Density Variation*** ⇦
- **Summary and Future Research**

Local Density Variation

- Global density variation does not take into account that CMP polishing pad can adjust the pressure and rotation speed according to pattern distribution
- The influence of density variation between far-apart regions can be reduced by pressure adjustment
- Only a significant density variation between neighboring windows will complicate polishing pad control and cause either dishing or underpolishing

⇩

Density variations between neighboring windows

Lipschitz-like Definitions

- **Local density variation definitions**
  - **Type I:**
    - **max density variation of every r neighboring windows in each row of the fixed-dissection**
    - **The polishing pad move along window rows and only overlapping windows in the same row are neighbored**
  - **Type II:**
    - **max density variation of every cluster of windows which cover one tile**
    - **The polishing pad touch all overlapping windows simultaneously**
  - **Type III:**
    - **max density variation of every cluster of windows which cover** $\frac{r}{2} \times \frac{r}{2}$ **tiles**
    - **The polishing pad is moving slowly and touching overlapping windows simultaneously**

Behaviors of Existing Methods on Smoothness Objectives

Testcase	LP			Greedy			MC			IGreedy			IMC		
T/W/r	LipI	LipII	LipIII	LipI	LipII	LipIII	LipI	LipII	LipIII	LipI	LipII	LipIII	LipI	LipII	LipIII
Spatila Density Model															
L1/16/4	.0832	.0837	.0713	.0712	.0738	.0627	.0678	.0709	.06	.0818	.0824	.063	.0673	.0698	.0597
L1/16/16	.0854	.0868	.0711	.073	.0742	.0644	.0708	.0742	.0643	.0724	.0725	.0617	.0707	.073	.061
L2/28/4	.0414	.0989	.0841	.0412	.096	.0893	.0289	.0947	.0852	.0333	.0883	.0755	.0286	.0873	.0766
L2/28/16	.033	.0642	.0632	.0388	.0713	.0707	.0248	.0658	.0658	.0272	.0619	.0604	.0265	.0631	.0606
Effective Density Model															
L1/16/4	4.048	4.333	3.864	5.332	5.619	5.19	3.631	4.166	3.448	3.994	4.254	3.132	4.245	4.481	3.315
L1/16/16	.843	.843	.835	.978	1.051	1.051	.814	.847	.847	.839	.847	.847	.763	.77	.77
L2/28/4	2.882	5.782	4.855	2.694	6.587	6.565	1.498	5.579	5.092	2.702	6.317	5.678	2.532	5.64	4.981
L2/28/16	1	1.159	1.159	1.061	1.147	1.147	1.115	1.235	1.23	.936	1.136	1.128	1.112	1.204	1.189

Comparison among the behaviors of existing methods w.r.t Lipschitz objectives

- **The solution with the best Min-Var objective value does not always have the best value in terms of "smoothness" objectives**

Linear Programming Formulations

- **Lipschitz Type I**

$$p_{ij} \geq 0 \qquad i, j = 0, \ldots, nr/w - 1$$

$$p_{ij} \leq slack(T_{ij}) \qquad i, j = 0, \ldots, nr/w - 1$$

$$\sum_{s=i}^{i+r-1} \sum_{t=j}^{j+r-1} p_{st} \leq \alpha_{ij}(U \bullet w^2 - area_{ij}) \qquad i, j = 0, \ldots, nr/w - 1$$

$$W_{ij} - W_{ik} \leq L \qquad i, j, k = 0, \ldots, nr/w - 1$$

here, $W_{ij} = \sum_{s=i}^{i+r-1} \sum_{t=j}^{j+r-1} area(T_{st}) + \sum_{s=j}^{i+r-1} \sum_{t=j}^{j+r-1} p_{st}$

- **Lipschitz Type II**

$$\min Den(i, j) \leq W_{lm} \leq \max Den(i, j) \qquad i, j, k = 0, \ldots, \frac{nr}{w} - 1$$

$$\max Den(i, j) - \min Den(i, j) \leq L \qquad l(m) = i(j) - r, \ldots, i(j) + r$$

Linear Programming Formulations

- **Lipschitz Type III**

$$\min Den(i,j) \le W_{lm} \le \max Den(i,j) \qquad i,j,k = 0,\ldots,\frac{nr}{w}-1$$

$$\max Den(i,j) - \min Den(i,j) \le L \qquad l(m) = i(j) - \frac{r}{2},\ldots,i(j)+\frac{r}{2}$$

- **Combined Objectives**
  - **linear summation of Min-Var, Lip-I and Lip-II objectives with specific coefficients**

$$Minimize \quad : \qquad C_0 * M + C_1 * L_I + C_2 * L_{II}$$

  - **add Lip-I and Lip-II constraints as well as**

$$M \le W_{ij} \qquad i,j = 0,\ldots,nr/w-1$$

Computational Experience

Testcase	Min-Var LP				Lipl LP			
T/W/r	Den V	Lip1	Lip2	Lip3	Den V	Lip1	Lip2	Lip3
Spatial Density Model								
L1/16/4	.0855	.0832	.0837	.0713	.1725	.0553	.167	.1268
L1/16/8	.0814	.0734	.0777	.067	.1972	.0938	.1932	.1428
L2/28/4	.1012	.0414	.0989	.0841	.0724	.0251	.072	.0693
L2/28/8	.0666	.034	.0658	.0654	.0871	.0264	.0825	.0744
Effective Density Model								
L1/16/4	.0703	.0045	.0043	.0039	.2662	.004	.0154	.01
L1/16/8	.1709	.0025	.0025	.0023	.3939	.002	.006	.0052
L2/28/4	.106	.0029	.0058	.0049	.1051	.0013	.0061	.0061
L2/28/8	.1483	.0015	.0023	.0022	.1527	.0007	.0024	.0024

Comparison among LP methods on Min-Var and Lipschitz condition objectives (1)

Computational Experience

Testcase	LipII LP				LipIII LP				Comb LP			
T/W/r	DenV	Lip1	Lip2	Lip3	DenV	Lip1	Lip2	Lip3	DenV	Lip1	Lip2	Lip3
Spatial Density Model												
L1/16/4	.1265	.0649	.0663	.0434	.1273	.0733	.0734	.0433	.1143	.0574	.0619	.0409
L1/16/8	.1702	.1016	.1027	.0756	.1835	.1158	.1224	.0664	.1707	.0937	.1005	.0766
L2/28/4	.0888	.0467	.0871	.0836	.0943	.0462	.0928	.0895	.0825	.0242	.0809	.0758
L2/28/8	.07	.0331	.0697	.0661	.1188	.0594	.1033	.0714	.0747	.0255	.0708	.0656
Effective Density Model												
L1/16/4	.1594	.0039	.0047	.0033	.1792	.0043	.0051	.003	.1753	.004	.0045	.0034
L1/16/8	.2902	.0025	.0025	.0018	.2906	.0028	.0029	.0018	.268	.0021	.0022	.0019
L2/28/4	.1022	.0029	.0064	.0054	.1039	.0026	.0064	.0052	.0953	.0015	.0057	.0049
L2/28/8	.1559	.0015	.0023	.0022	.2063	.0018	.0032	.0022	.1382	.0007	.0021	.0021

Comparison among LP methods on Min-Var and Lipschitz condition objectives (2)

- **LP with combined objective achieves the best comprehensive solutions**

Outline

- **Layout Density Control for CMP**
- **Our Contributions**
- **Layout Density Analysis**
- **Local Density Variation**
- ***Summary and Future Research*** ⇦

Summary and Future Research

- **Smoothness gap in existing fill methods**
  - **for the first time, we show the viability of gridless window analysis for both spatial density model and effective density model**
- **New smoothness criteria: local uniformity**
  - **three new relevant Lipschitz-like definitions of local density variation are proposed**
- **Ongoing research**
  - **extension of multi-level density analysis to measuring local uniformity w.r.t. other CMP models**
  - **improved methods for optimizing fill synthesis w.r.t. new local uniformity objectives**