# Block-wise Lensless Compressive Camera

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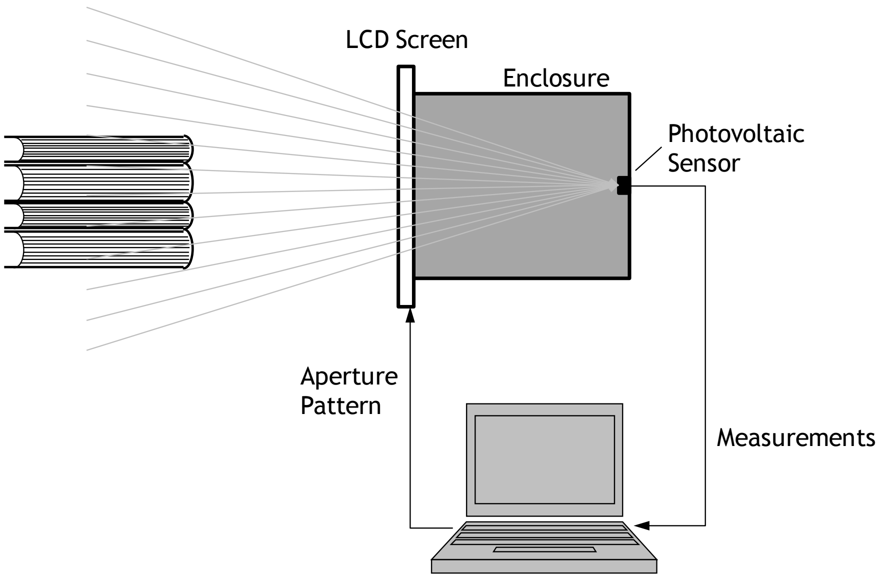
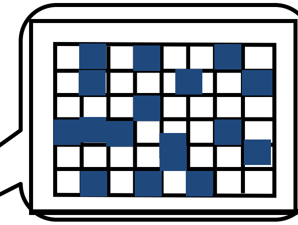
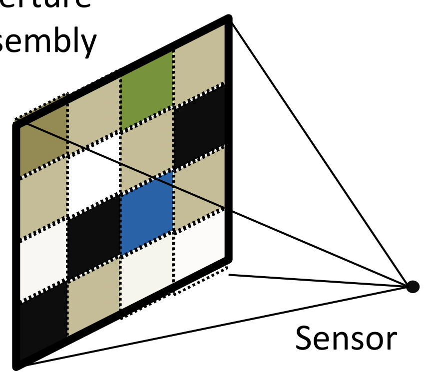
# Compressive Sensing via Lensless Imaging



$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_M \end{bmatrix} = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1N-1} & w_N \\ w_{21} & w_{11} & \cdots & w_{2N-1} & w_{2N} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ w_{M1} & w_{M2} & \cdots & w_{MN-1} & w_{MN} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{N-1} \\ x_N \end{bmatrix}$$

Scene



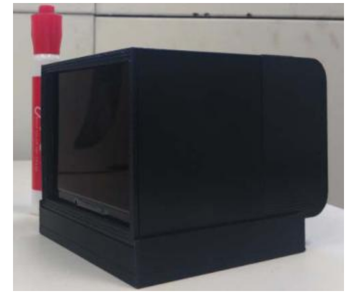

Number of required measurements:

$$m = \frac{n}{r}$$

$n -$ Resolution (total number of "pixels")

$r -$ ratio of compression

# First Lensless Camera → Current Lensless Camera



Size: ~12 inches
Capture time: hours

Size: 3~5 inches
Capture time: minutes

*Huang et al. ICIP 2013*

*Yuan et al. IEEE Sensors Journal, 2016*

# Problems in Existing Lensless Camera

- **Low capture rate**

  Take a long time to get a high resolution image

  Provide a low resolution image in a short time

- **Slow Reconstruction**

  Iterative algorithms usually take a long time to reconstruct the target image

# Proposed Solutions

- **Low capture rate -> Block-wise Lensless Camera**

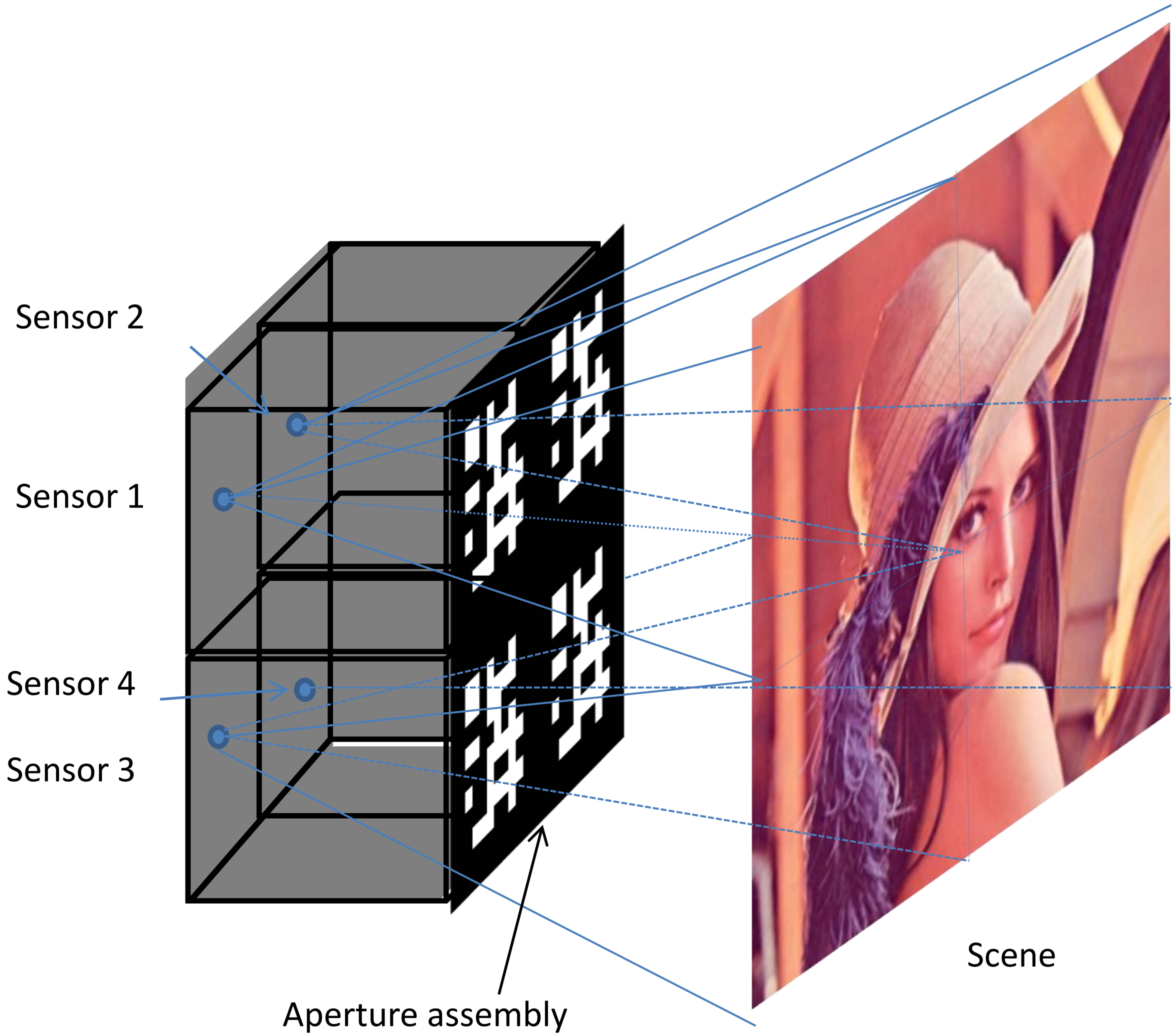
  Multiple sensors capture the image *in parallel*

  Each sensor capture *a fraction* of the image

- **Slow Reconstruction -> Closed-form Reconstruction**

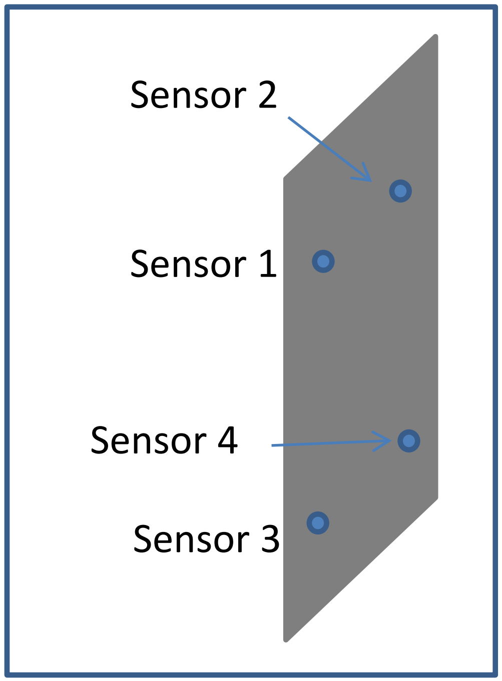
  For each block, *real time* reconstruction can be achieved via *closed-form* recovery

# The Block-wise Lensless Camera

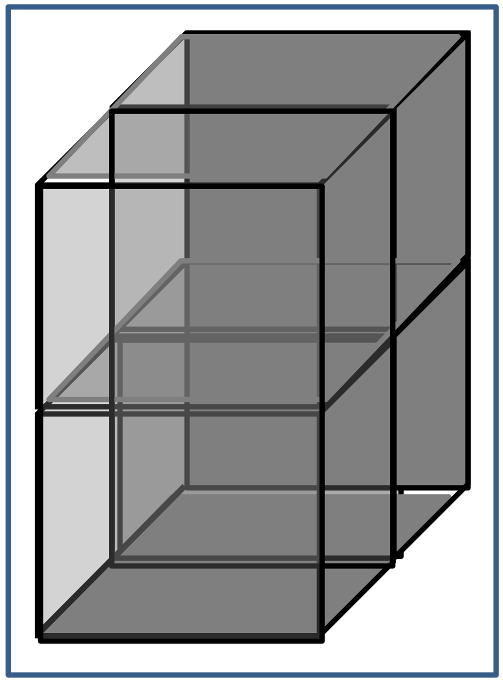


# Hardware Components

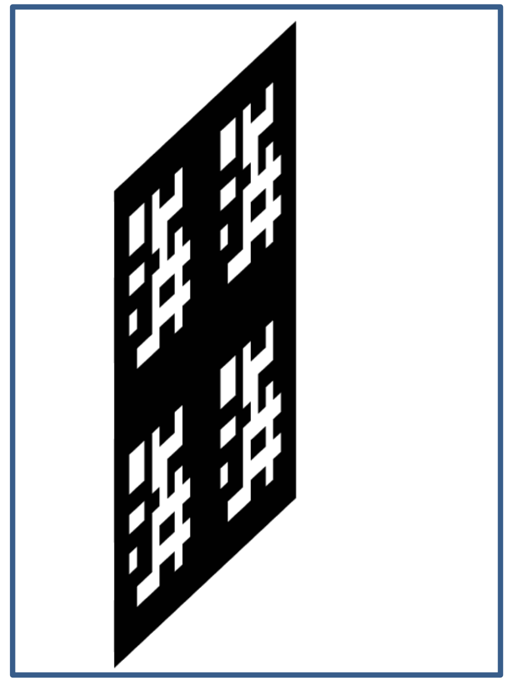
Sensor board



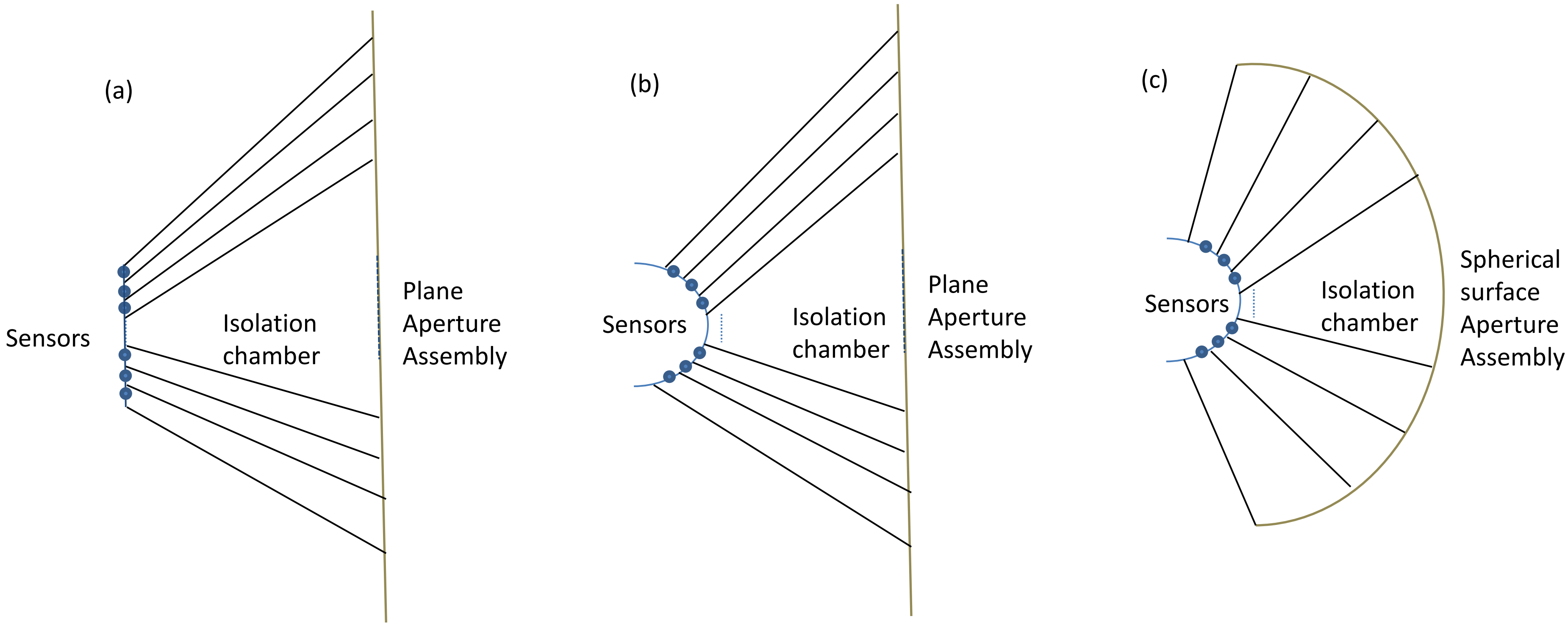

Isolation chambers



Aperture assembly



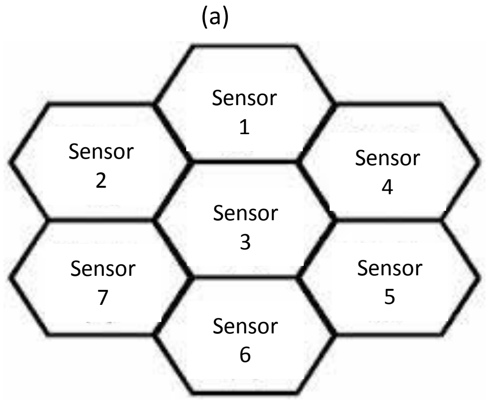
# Concentration-Sensor Configuration

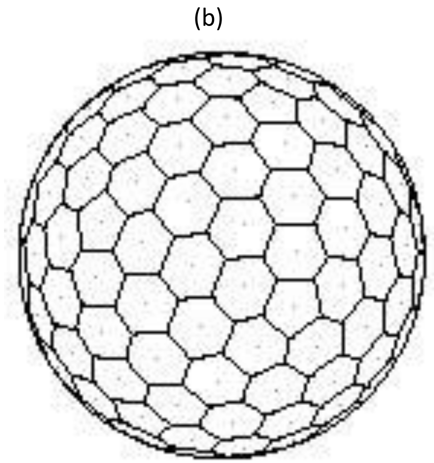



Sensors, isolation chamber and aperture assembly can be put in different geometries.

# Concentration-Sensor Configuration

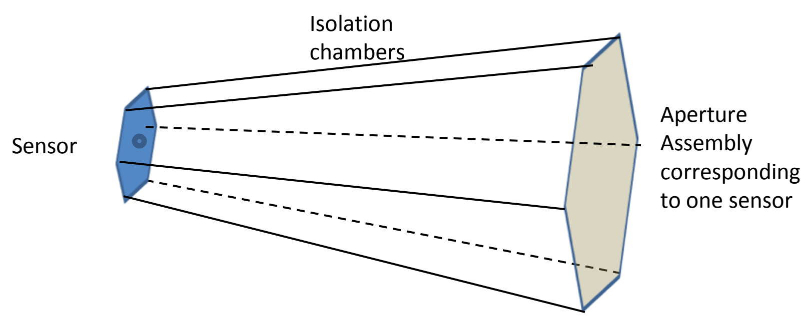
3D geometry:




For a wide-angle camera, the sensor can be put together to form a "cellular" shape and each sensor corresponds to a approximate "hexagon" area.

A "curved lcd" can be used as the aperture assembly.



# Advantages

This new block-wise lensless camera enjoys the following advantages in addition to the embedding benefits of the existing lensless camera.

1) Since each block can be very small, i.e. 8x8, we only need to capture ~10 measurements to achieve decent reconstruction, therefore **the capture time can be very short.**
2) The coding patterns used in each block can be the same, therefore the sensing matrix is only of the block size; this saves the **memory requirement** of sensing matrix as well as **speeds up the reconstruction**.
3) Patch based image reconstruction can be very fast (and implemented in parallel on GPU) and since real time stitching algorithms exists, we can get **real time reconstruction** (high resolution image).
4) These blocks can be added as much as possible, therefore, leading to extra **high resolution images** while keeping the capture rate and reconstruction fast .
5) Each block can use different patterns, thus leading to **adaptive sensing**.

# Reconstruction: Model

Consider same patterns for each block

$$Y = AX + N$$

Signal $X \in R^{P \times N_P}$

*P:* dimension of the vectorized block

*$N_P$:* number of blocks

Sensing matrix $A \in R^{M \times P}, \quad M << P$

Measurement $Y \in R^{M \times N_P}$

# Iterative Algorithms

Introduce a basis *D*

$$Y = ADS + N$$

Solve

$$\min \|\mathbf{S}\|_1, \quad \text{subject to} \quad \mathbf{Y} = \mathbf{ADS}$$

or similar $L_1$ minimization problem.

Usually slow!!

# Closed-form Inversion via GMM

Gaussian Mixture Model (GMM)

$$\boldsymbol{x}_i \sim \sum_{k=1}^{K} \pi_k \mathcal{N}(\boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k) \qquad \sum_k \pi_k = 1$$

$$y = \mathbf{A}x + \epsilon,\ \epsilon \in \mathcal{N}(0, \mathrm{R})$$

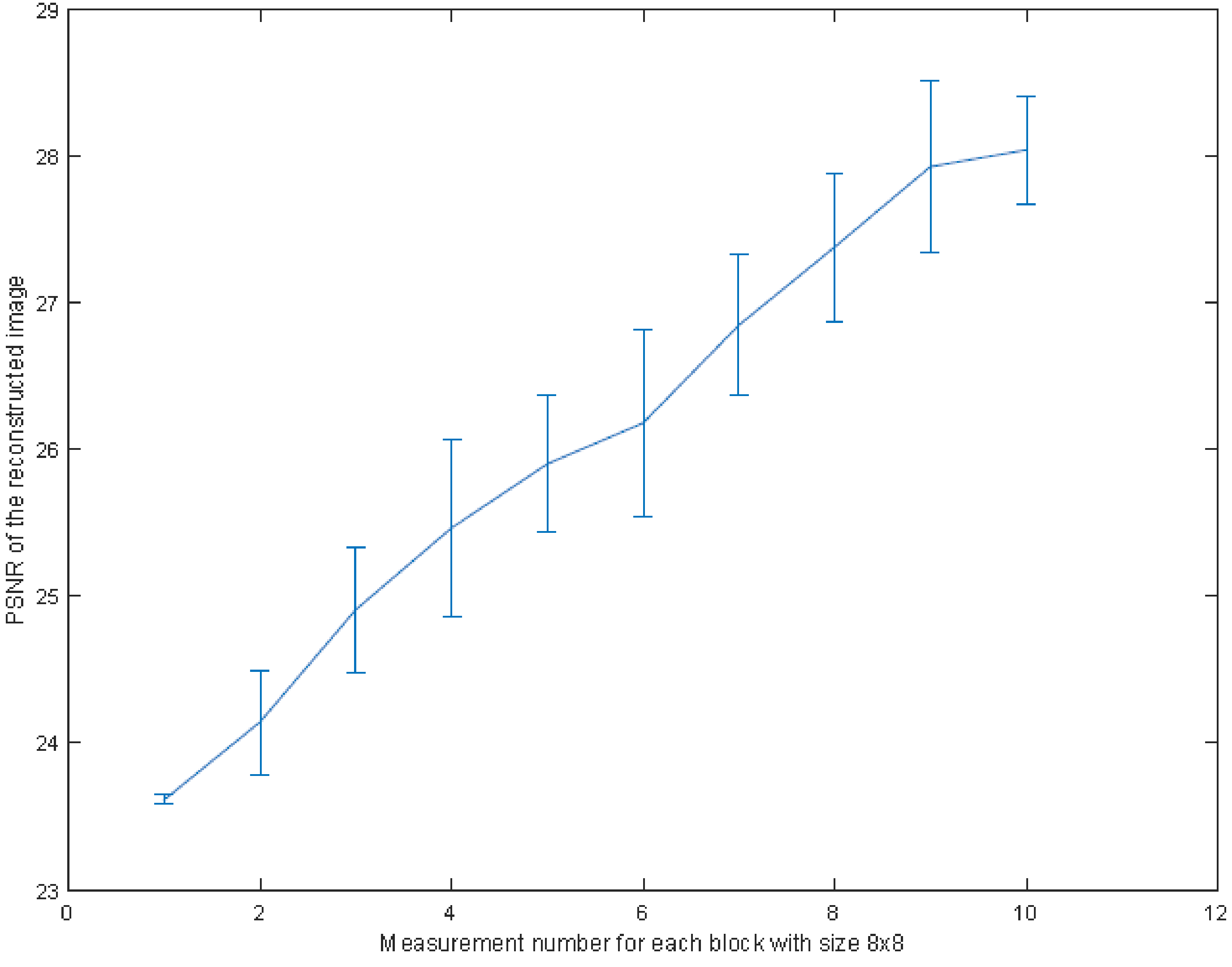
$$p(\boldsymbol{x}|\boldsymbol{y}) = \sum_{k=1}^{K} \tilde{\pi}_k \mathcal{N}(\boldsymbol{x}|\tilde{\boldsymbol{\mu}}_k, \tilde{\boldsymbol{\Sigma}}_k)$$

$$\tilde{\pi}_k = \frac{\pi_k \mathcal{N}(\mathbf{y}|\mathbf{A}\boldsymbol{x}_k, \mathbf{R}^{-1} + \mathbf{A}\boldsymbol{\Sigma}_k\mathbf{A}^T)}{\sum_{l=1}^{K} \pi_l \mathcal{N}(\mathbf{y}|\mathbf{A}\mathbf{x}_l, \mathbf{R}^{-1} + \mathbf{A}\boldsymbol{\Sigma}_l\mathbf{A}^T)} \quad \mathbb{E}[\hat{\boldsymbol{x}}] \quad = \quad \sum_{k=1}^{K} \tilde{\pi}_k \tilde{\boldsymbol{\mu}}_k.$$

$$\tilde{\boldsymbol{\Sigma}}_k = (\mathbf{A}^T\mathbf{R}\mathbf{A} + \boldsymbol{\Sigma}_k^{-1})^{-1},$$

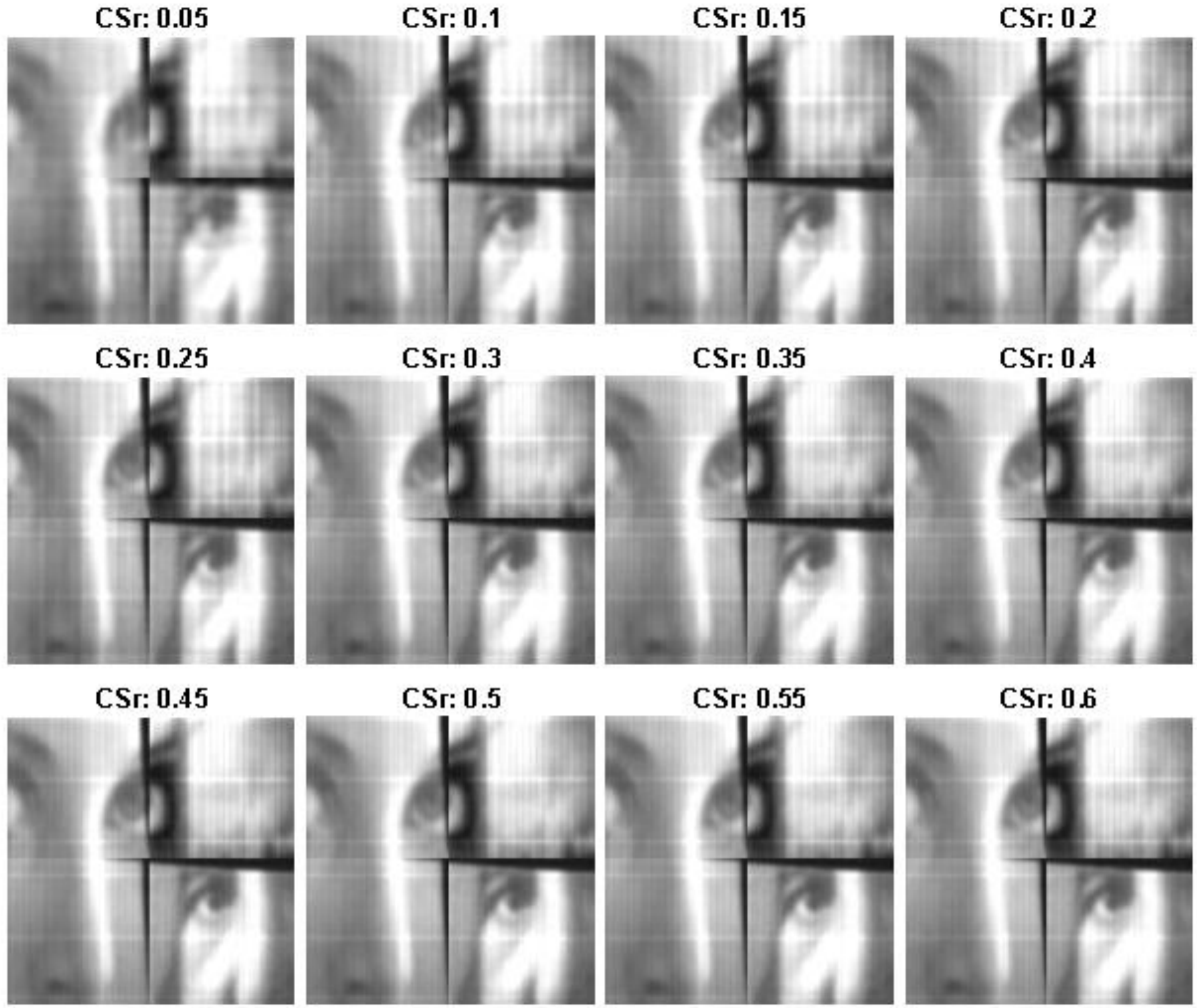
$$\tilde{\boldsymbol{\mu}}_k = \tilde{\boldsymbol{\Sigma}}_k(\mathbf{A}^T\mathbf{R}\mathbf{y} + \boldsymbol{\Sigma}_k^{-1}\boldsymbol{\mu}_k).$$

# Results: Simulation



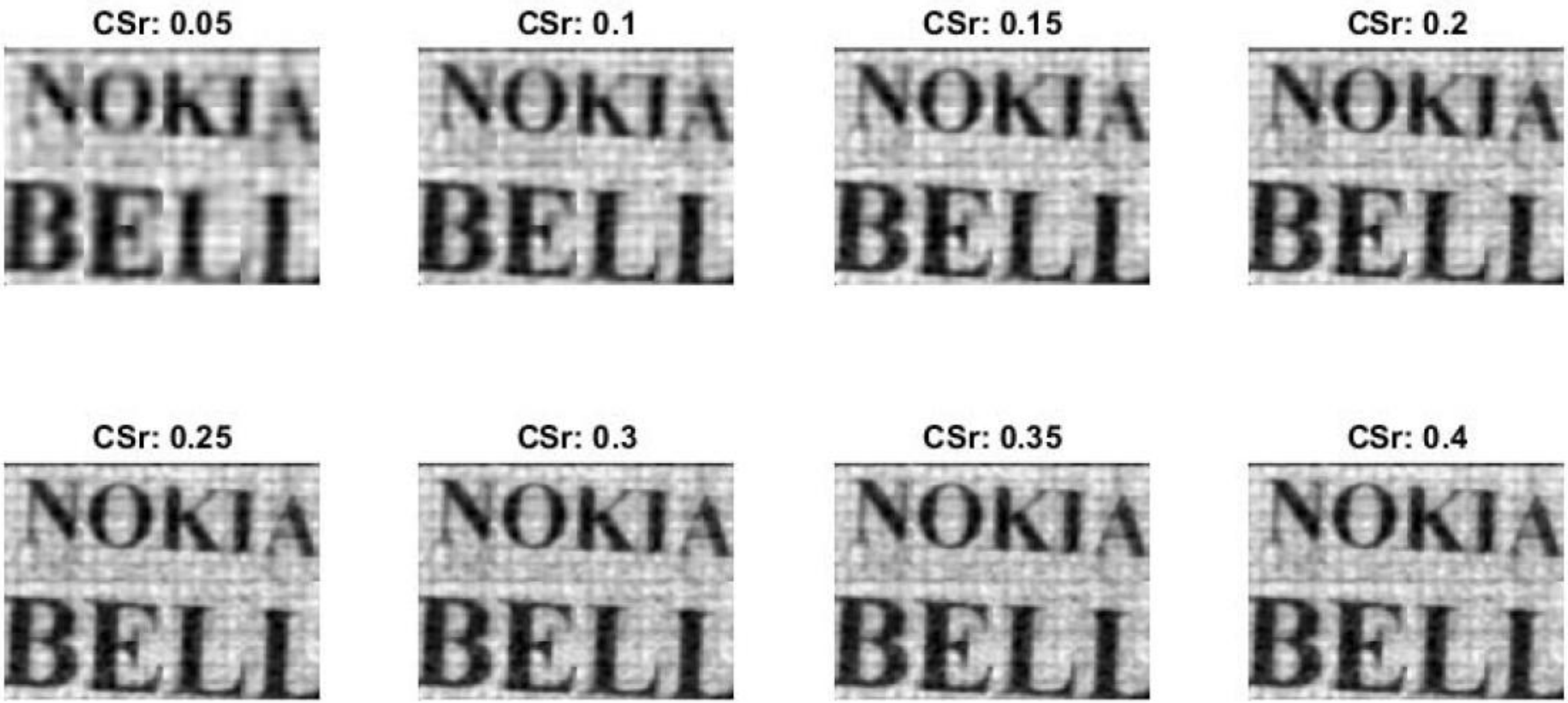
# Results: Simulation

# Real Data Results: 2x2 sensors




Each block has 32x32 pixels

# Real Data: 4x4 sensors




Each block has 16x16 pixels

# Summary

- Proposed the block-wise lensless compressive camera
  Different configurations have been discussed

- Developed closed-form inversion via GMM
  Reconstruction takes less than 5ms for 16x16 blocks

- Built several prototypes to verify the configuration

Thanks!

Q & A

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