New Color Filter Arrays of High Light Sensitivity and High Demosaicking Performance

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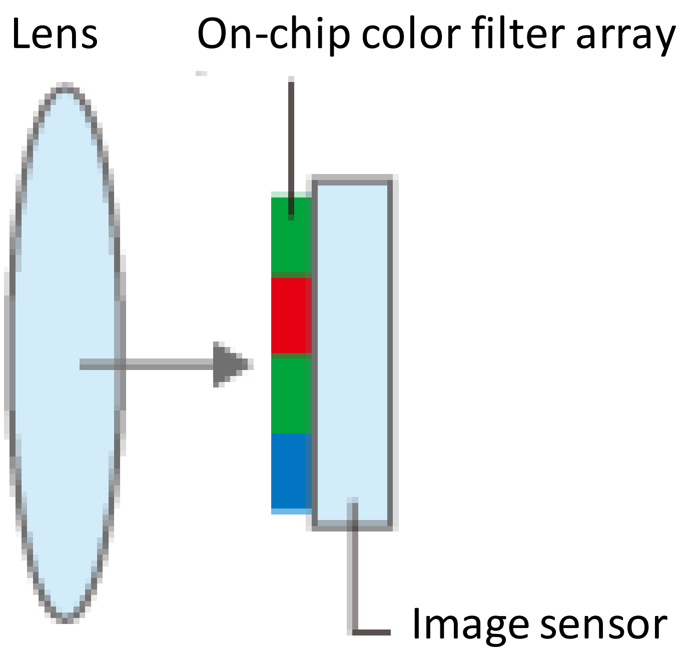
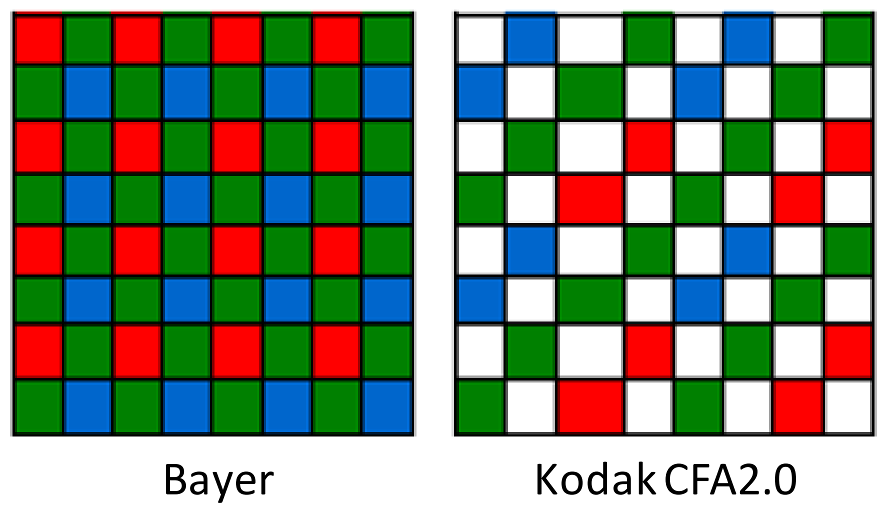
Outline

- Introduction: What is CFA
- How CFA works: demosaicking
- CFA representation: frequency structure
- CFA design: what should be optimized
- CFA design: what constraints
- New CFA designs & Evaluation
- Conclusions

Single-chip Color Cameras

- Single-Chip Camera is based on a color filter mosaic fabricated on top of the light sensors, and the mosaic is generally an array (Color Filter Array, CFA).

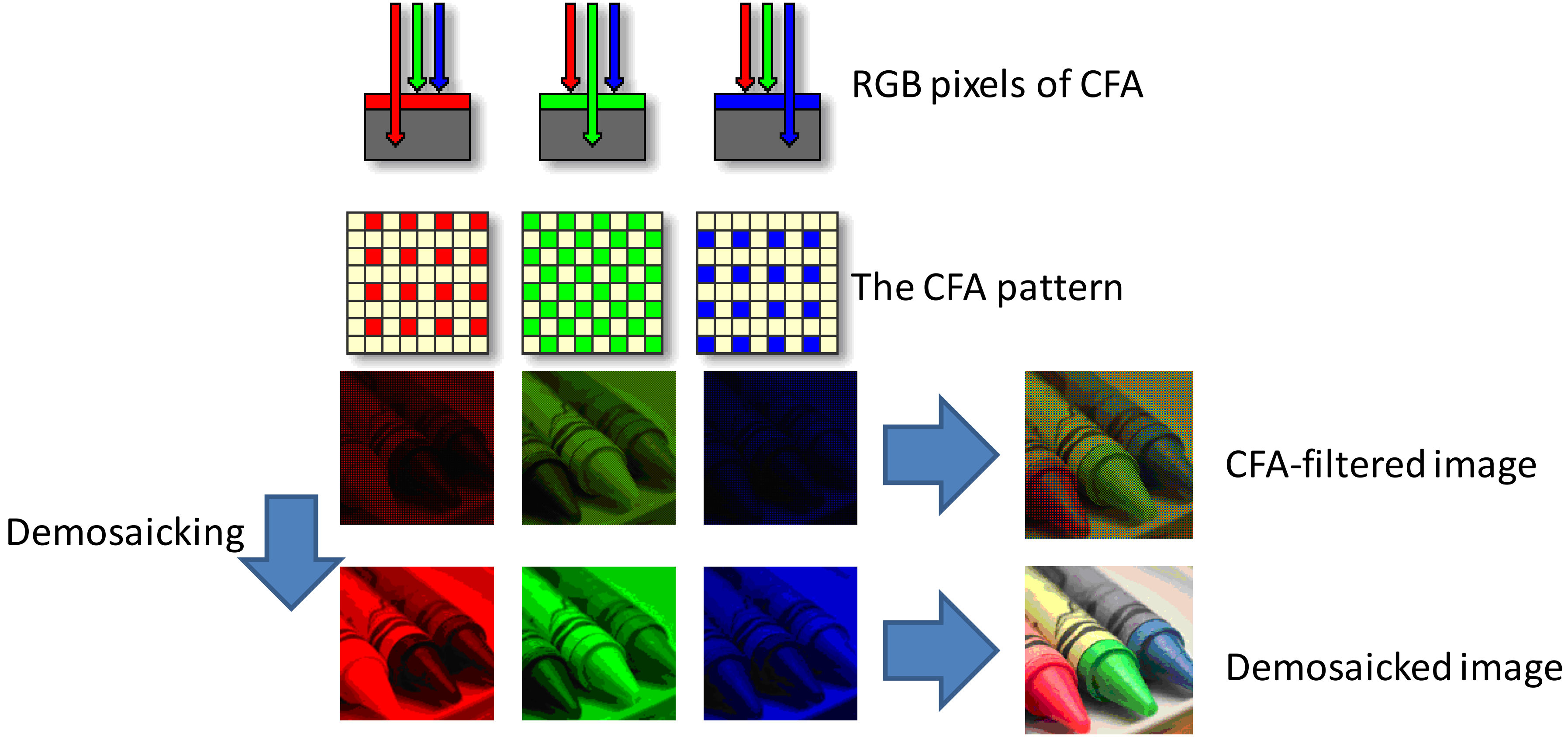




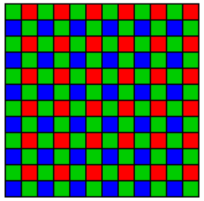
Color filter arrays

Demosaicking

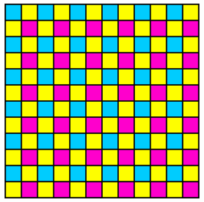
- As each individual sensor only records one color, at each pixel all the three primary colors, red, green and blue, of a color image must be reconstructed using a computational interpolation method – **demosaicking**.



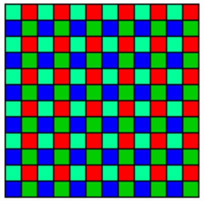
A few Commercialized CFAs



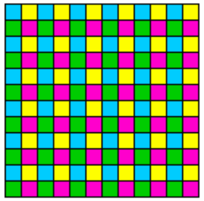
Bayer CFA pattern (Kodak, red, green, blue)



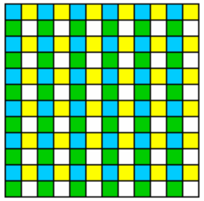
CMY CFA (Kodak, cyan, yellow, magenta)



RGBE CFA (Sony, red, green, blue, emerald)

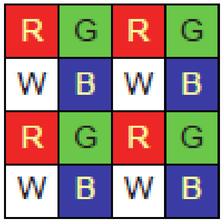


CYGM CFA (a few, cyan, yellow, green, magenta)

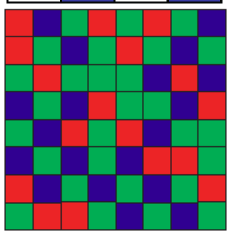


CYGW CFA (JVC, yellow, cyan, green, unfiltered)

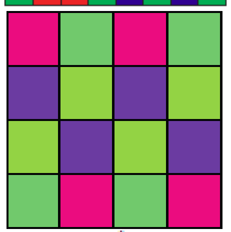
CFAs proposed by researchers



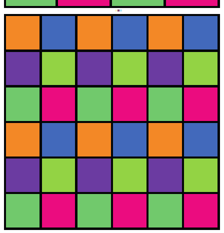
Gindele & Gallagher (with white, 2002)



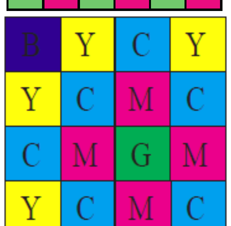
Parmar & Reeves (random, 2004)



Hirakawa & Wolfe (better recovery, 2008)



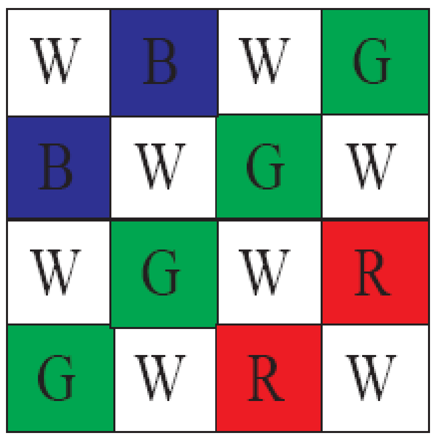
Condat (robust to noise, 2009)

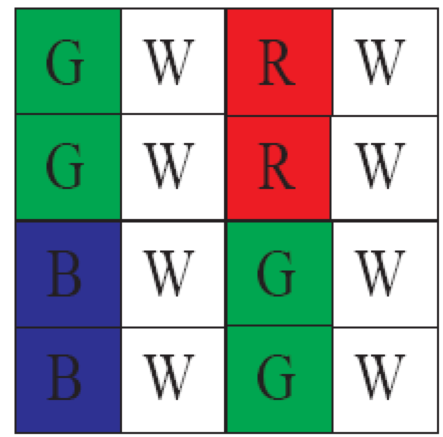


Hao, Li, Lin & Dubois (better demosaicking, 2011)

Kodak's CFA2.0

- Second generation CFA for high-light sensitivity

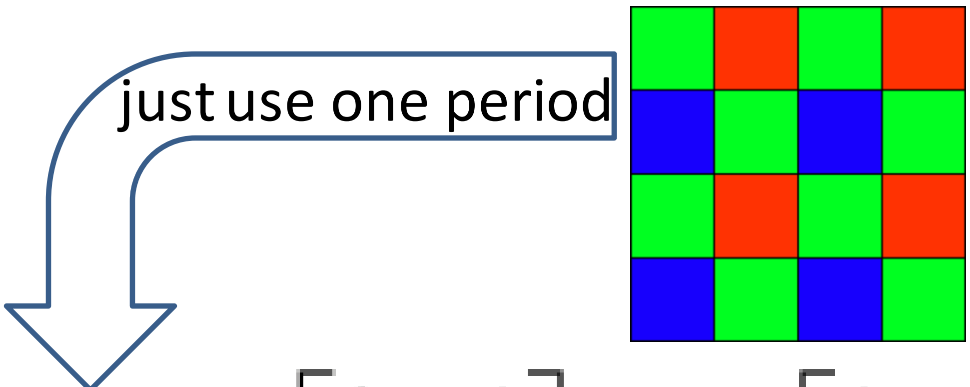




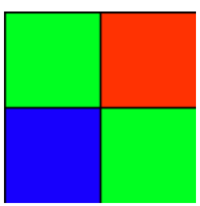
with 50% unfiltered pixels (2007)
(aka panchromatic or white pixels)

Periodical CFAs: Representation

- Matrix representation in the spatial domain



Bayer CFA



$$= \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \cdot \mathrm{r} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \cdot \mathrm{g} + \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \cdot \mathrm{b}$$

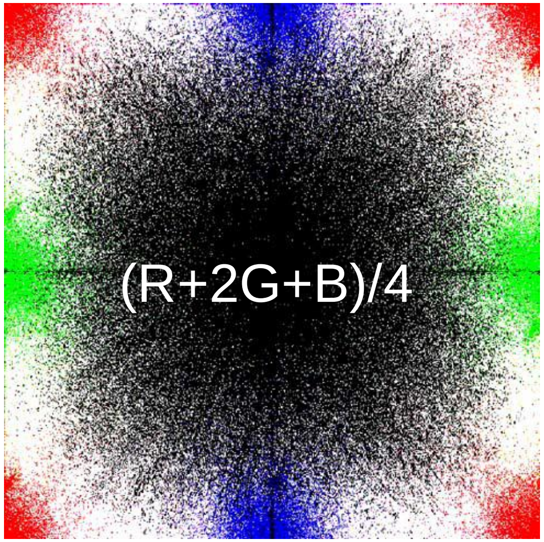
$$= \begin{bmatrix} G & R \\ B & G \end{bmatrix}$$

The Frequency Structure

- Apply symbolic DFT to the one period matrix representation in the spatial domain

$$DFT\begin{bmatrix} G & R \\ B & G \end{bmatrix} = \frac{1}{4}\begin{bmatrix} R+2G+B & B-R \\ R-B & 2G-R-B \end{bmatrix} = \begin{bmatrix} F_L & F_{C2} \\ -F_{C2} & F_{C1} \end{bmatrix}$$

The spectrum with Bayer CFA



The Frequency Structure

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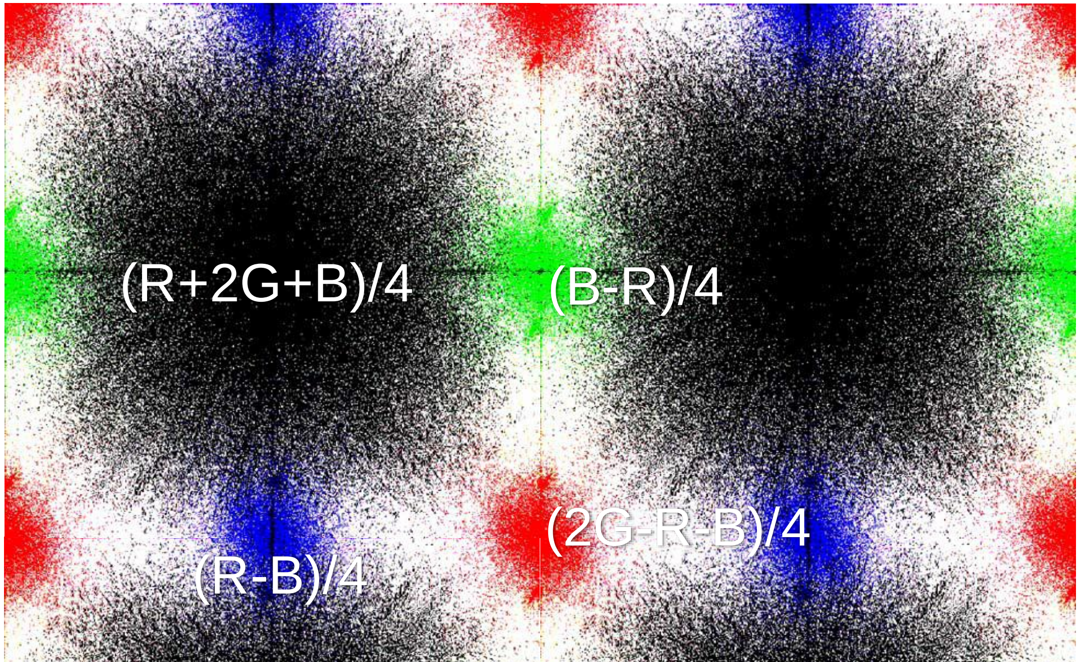
The spectrum with Bayer CFA (periodical)



Relations: luma&chromas and RGB

- It is a linear transform:

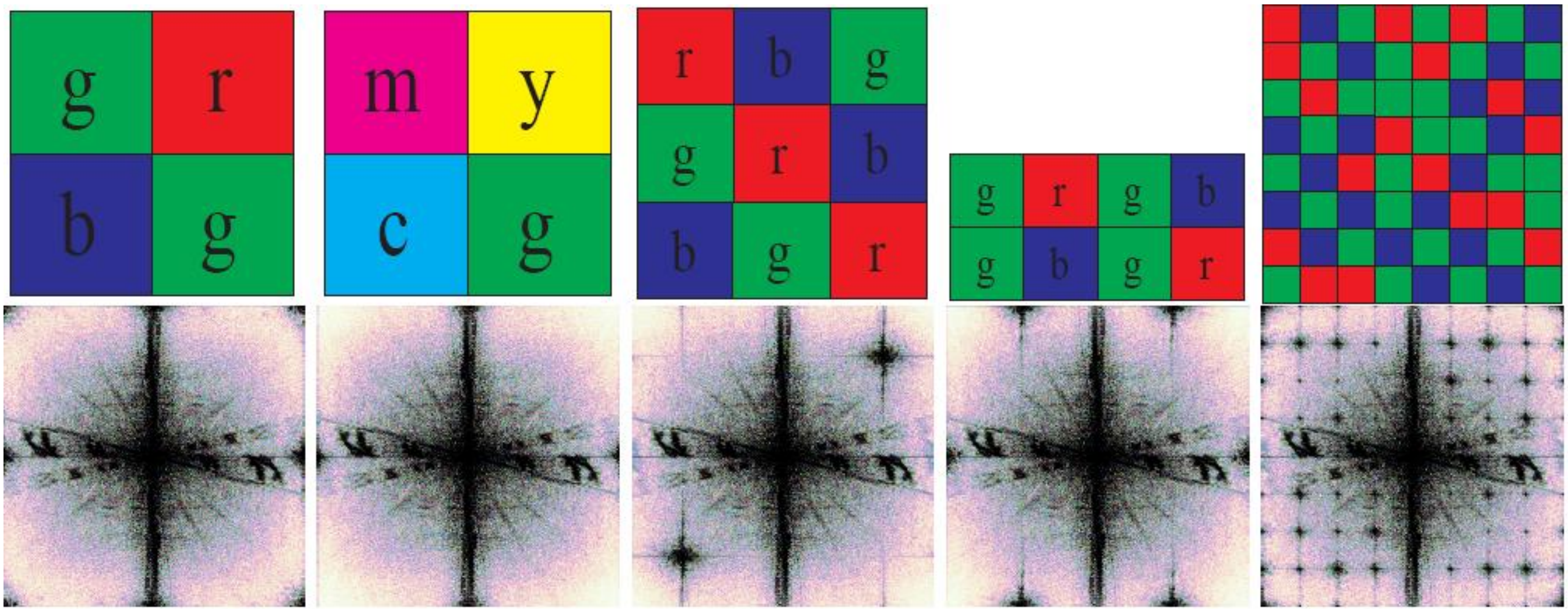
$$DFT\begin{bmatrix} G & R \\ B & G \end{bmatrix} = \frac{1}{4}\begin{bmatrix} R+2G+B & B-R \\ R-B & 2G-R-B \end{bmatrix} = \begin{bmatrix} F_L & F_{C2} \\ -F_{C2} & F_{C1} \end{bmatrix}$$

$$\begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \end{bmatrix} = \frac{1}{4}\begin{bmatrix} 1 & 2 & 1 \\ -1 & 2 & -1 \\ -1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} = T \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

where *T* is a multiplexing matrix

Spectra and Frequency Structures

- DFT of the CFA-filtered image and CFA patterns



$$\begin{bmatrix} F_L & F_{C2} \\ -F_{C2} & F_{C1} \end{bmatrix} \quad \begin{bmatrix} F_L & F_{C1} \\ F_{C2} & 0 \end{bmatrix} \quad \begin{bmatrix} F_L & 0 & 0 \\ 0 & 0 & F_{C1} \\ 0 & F_{C2} & 0 \end{bmatrix} \quad \begin{bmatrix} F_L & 0 & F_{C1} & 0 \\ 0 & F_{C2} & 0 & -F_{C2} \end{bmatrix} \quad \begin{bmatrix} F_L & \cdots & F_{C?} \\ \vdots & \ddots & \vdots \\ F_{C?} & \cdots & F_{C?} \end{bmatrix}$$

$$T = \frac{1}{4}\begin{bmatrix} 1 & 2 & 1 \\ -1 & 2 & -1 \\ -1 & 0 & 1 \end{bmatrix} \quad \frac{1}{4}\begin{bmatrix} 1 & 2 & 1 \\ 0 & -1 & 1 \\ 1 & -1 & 0 \end{bmatrix} \quad \frac{1}{6}\begin{bmatrix} 2 & 2 & 2 \\ 2 & -1-i\sqrt{3} & -1+i\sqrt{3} \\ 2 & -1+i\sqrt{3} & -1-i\sqrt{3} \end{bmatrix} \quad \frac{1}{4}\begin{bmatrix} 1 & 2 & 1 \\ -1 & 2 & -1 \\ -1 & 0 & 1 \end{bmatrix} \quad \begin{bmatrix} \cdots & \cdots & \cdots \\ \vdots & \vdots & \vdots \\ \cdots & \cdots & \cdots \end{bmatrix}$$

Demosaicking

- First: to find the luma and the chromas by filtering/interpolation: F_L, F_{C1} and F_{C2} .
- Second: to find the RGB values by the inverse :

$$\begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \end{bmatrix} = T \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \Rightarrow \begin{bmatrix} R \\ G \\ B \end{bmatrix} = T^{-1} \cdot \begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \end{bmatrix} = D \cdot \begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \end{bmatrix}$$

or

$$\begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \\ \vdots \end{bmatrix} = T \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \Rightarrow \begin{bmatrix} R \\ G \\ B \end{bmatrix} = T^{+} \cdot \begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \\ \vdots \end{bmatrix} = D \cdot \begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \\ \vdots \end{bmatrix}$$

where *D* is a demosaicking matrix

Demosaicking Optimization

- First: to find more accurate luma and chromas: F_L, F_{C1} and F_{C2} $\rightarrow$ further distance (less cross-talk) $\rightarrow$ to choose a good frequency structure.
- Second: to find accurate RGB values from the inverse :

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = D \cdot \begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \\ \vdots \end{bmatrix} \quad \Rightarrow \quad \min \|D\|$$

$\| D \|$ is an objective function to be minimized.

Constraints for High Light Sensitivity

- Some pixels are prescribed as unfiltered pixels, aka panchromatic or white pixels (W).
- Pixels are only of primary colors, red, green and blue, and white: $\forall(i, j), CFA(i, j) \in \{R, G, B, W\}$
- Then to optimize for high demosaicking performance.

- Not all frequency structures satisfy all the constraints – this makes the problem hard.

A Frequency Structure and Optimization

- The frequency structure:

$$\begin{bmatrix} F_L & 0 & 0 & 0 & 0 \\ 0 & 0 & F_{C2} & 0 & 0 \\ 0 & 0 & 0 & 0 & F_{C1}^* \\ 0 & F_{C1} & 0 & 0 & 0 \\ 0 & 0 & 0 & F_{C2}^* & 0 \end{bmatrix}$$

- By optimization : min ‖ *D* ‖

$$\begin{aligned} F_L &= (R+G+B)/3, \\ F_{C1} &= ((\sqrt{5} - i\sqrt{25-2\sqrt{5}})R + \sqrt{5}(1 + i\sqrt{5+2\sqrt{5}})G \\ &\quad -(2\sqrt{5} + i\sqrt{10-2\sqrt{5}})B)/30, \\ F_{C2} &= (-(\sqrt{5} + i\sqrt{25+2\sqrt{5}})R + i\sqrt{5}(i + \sqrt{5-2\sqrt{5}})G \\ &\quad +(2\sqrt{5} + i\sqrt{2(5+\sqrt{5})})B)/30. \end{aligned}$$

New High Light Sensitivity CFA

- The corresponding CFA pattern (40% white, 5x5):

$$\begin{bmatrix} F_L & 0 & 0 & 0 & 0 \\ 0 & 0 & F_{C2} & 0 & 0 \\ 0 & 0 & 0 & 0 & F_{C1}^* \\ 0 & F_{C1} & 0 & 0 & 0 \\ 0 & 0 & 0 & F_{C2}^* & 0 \end{bmatrix} \xrightarrow{Symbolic\ \ IDFT} \begin{bmatrix} W & R & B & W & G \\ W & G & W & R & B \\ R & B & W & G & W \\ G & W & R & B & W \\ B & W & G & W & R \end{bmatrix}$$

- The multiplexing matrix T =

$$\begin{bmatrix} 1/3 & 1/3 & 1/3 \\ (\sqrt{5} - i\sqrt{25-2\sqrt{5}})/30 & \sqrt{5}(1+i\sqrt{5+2\sqrt{5}})/30 & -(2\sqrt{5}+i\sqrt{10-2\sqrt{5}})/30 \\ -(\sqrt{5}+i\sqrt{25+2\sqrt{5}})/30 & i\sqrt{5}(i+\sqrt{5-2\sqrt{5}})/30 & (2\sqrt{5}+i\sqrt{2(5+\sqrt{5})})/30 \end{bmatrix}$$

Demosaicking Performance

	Dubois's method [15]		Condat's method [16]	
Image	Kodak	Proposed	Kodak	Proposed
1	23.18	**35.23**	34.21	**35.35**
2	30.94	**37.49**	36.80	**38.11**
3	32.68	**37.46**	38.23	**38.40**
4	32.75	**37.32**	36.95	**38.32**
5	25.89	**32.96**	32.41	**33.62**
6	25.34	**36.56**	35.52	**36.74**
7	31.71	**38.22**	37.47	**38.83**
8	22.21	**33.28**	31.69	**33.37**
9	29.50	**38.78**	38.13	**39.33**
10	32.00	**36.63**	**38.87**	38.12
11	27.56	**36.13**	35.62	**36.77**
12	31.62	**40.18**	39.68	**40.61**
13	23.52	**30.91**	31.37	**31.75**
14	27.21	**32.24**	32.01	**33.30**
15	32.86	**36.29**	36.83	**37.60**
16	28.81	**39.58**	39.20	**39.89**
17	32.25	**37.90**	38.09	**39.11**
18	27.17	**33.87**	33.91	**34.83**
19	24.37	**37.53**	35.72	**37.63**
20	30.57	**36.71**	37.33	**38.02**
21	26.13	**36.14**	35.14	**36.69**
22	29.25	**35.59**	35.33	**36.55**
23	32.59	**38.86**	37.29	**39.20**
24	26.60	**31.90**	33.01	**33.23**
Avg.	27.30	**35.42**	35.17	**36.19**

Demosaicking Performance

Original image

(a) Kodak CFA with [15]

(b) Proposed CFA with [15]

Dubois's demosaicing method

(c) Kodak CFA with [16]

(d) Proposed CFA with [16]

Condat's demosaicing method

More Challenges

- High light sensitivity
- High noise tolerance
- High dynamic range
- Good color matching
- Low manufacture costs
- Easy and fast demosaicking
- ……

Thank you