Synthesis of Color Filter Array Pattern in Digital Images

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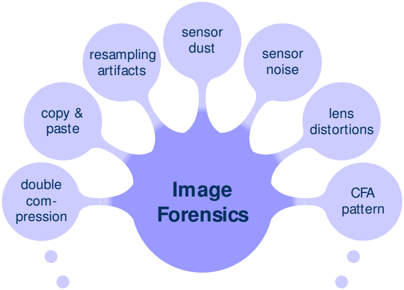
Digital image forensics and tamper hiding

- variety of different forensic tools can be found in the literature
- existing schemes work well under laboratory conditions



How reliable are forensic results if the presumed **counterfeiter is aware of the forensic tools?**

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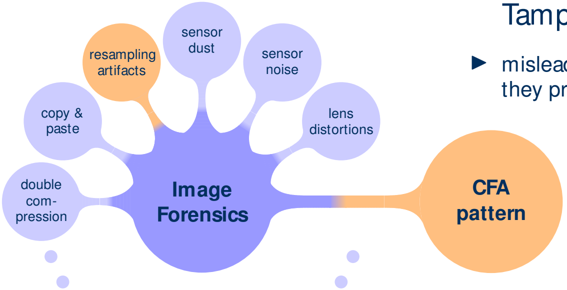

How reliable are forensic results if the presumed **counterfeiter is aware of the forensic tools?**

Tamper hiding

- mislead forensic tools such that they produce false negatives

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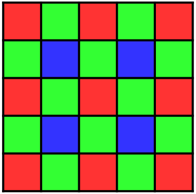
CFA Synthesis

Problem statement

- typical digital cameras use a **color filter array** (CFA) to capture full color images



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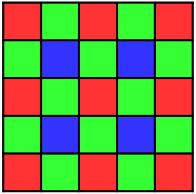

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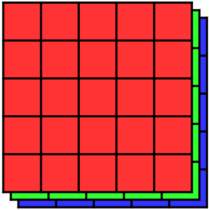

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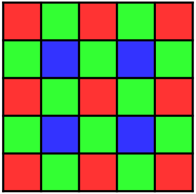
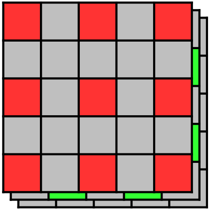


- color filter interpolation introduces **periodic correlation pattern** between neighboring pixels

- CFA pattern has to be restored to conceal traces of manipulation
- straight-forward: **re-interpolation**



- overwrites two thirds of all pixels with new (interpolated) values

A minimal distortion approach

Linear model

- CFA interpolation follows a linear equation $\hat{\mathbf{y}} = \mathbf{H}\mathbf{x}$
- image with incomplete/missing CFA pattern is corrupted by an additive residual $\boldsymbol{\epsilon}$ $\mathbf{y} = \mathbf{H}\mathbf{x} + \boldsymbol{\epsilon}$

CFA synthesis

- find a possible sensor signal $\mathbf{x}$ such that
- least squares solution

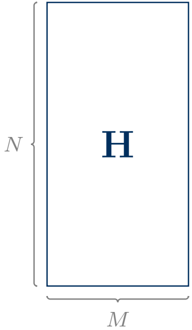
$$\|\boldsymbol{\epsilon}\| = \|\mathbf{y} - \hat{\mathbf{y}}\| \rightarrow \min$$

$$\mathbf{x} = (\mathbf{H}'\mathbf{H})^{-1}\mathbf{H}'\mathbf{y}$$

CFA re-interpolation not from the signal itself, but from a pre-filtered version

Structure of $\mathbf{H}$

- for $\boldsymbol{N}$ **pixels per channel** and $M \leq N/2$ genuine sensor samples, a direct implementation of the LS solution is impossible for typical image sizes



- matrix $\mathbf{H}$ has dimension $N \times M$
- cubic complexity: $\mathbf{x} = (\mathbf{H}'\mathbf{H})^{-1}\mathbf{H}'\mathbf{y}$

inversion $\mathcal{O}(M^3)$ multiplication $\mathcal{O}(M^2 N)$

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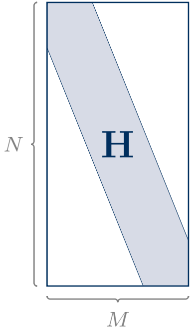

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Efficiency improvements

- matrix $\mathbf{H}$ is typically **sparse** (interpolation kernels have finite support) and has a **regular structure** (Bayer pattern)

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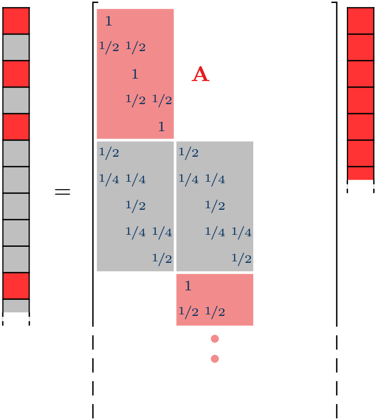
Red Channel

Partitioning $\mathbf{H}$



- columns partition $\mathbf{H}$ into repeating blocks $\mathbf{A}$, $\mathbf{B}$ with $\mathbf{B} = {}^1\!/_2\mathbf{A}$
- $\mathbf{H} = \mathbf{A} \otimes \mathbf{A}$
- $\mathbf{A}$ has only dimension $\sqrt{N} \times \sqrt{N}/2 + 1$

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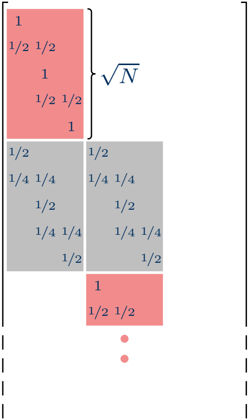

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Kronecker tweaks

$$\mathbf{x} = (\mathbf{H}'\mathbf{H})^{-1}\mathbf{H}'\,\mathbf{y}$$

with $\mathbf{H}^{\times} = \mathbf{H}'\mathbf{H}$:

- $(\mathbf{H}^{\times})^{-1} = (\mathbf{A}^{\times})^{-1} \otimes (\mathbf{A}^{\times})^{-1}$

with $\mathbf{H}^{+} = (\mathbf{H}^{\times})^{-1}\mathbf{H}'$:

- $\mathbf{H}^{+} = \mathbf{A}^{+} \otimes \mathbf{A}^{+}$ (pseudo-inverse)

Analytical inversion $\Phi = (\mathbf{A}^{\times})^{-1}$

$$\mathbf{A}^{\times} = \begin{bmatrix} 5/4 & 1/4 & & & & & & \\ 1/4 & 3/2 & 1/4 & & & & 0 & \\ & 1/4 & 3/2 & 1/4 & & & & \\ & & 1/4 & 3/2 & 1/4 & & & \\ & & & \ddots & \ddots & \ddots & & \\ & & & & 1/4 & 3/2 & 1/4 & \\ & 0 & & & & 1/4 & 3/2 & 1/4 \\ & & & & & & 1/4 & 5/4 \end{bmatrix}$$

$\mathbf{A}^{\times}$ is tridiagonal symmetric

- method by Huang & McColl (1997)

  second order linear recurrences:

  $$\zeta_i = 3/2\, \zeta_{i-1} - (1/4)^2\, \zeta_{i-2}$$
  $$\upsilon_j = 3/2\, \upsilon_{j+1} - (1/4)^2\, \upsilon_{j+2}$$

  and ratios:

  $$\xi_i = \frac{\zeta_i}{\zeta_{i-1}} \quad \text{and} \quad \gamma_i = \frac{\upsilon_i}{\upsilon_{i+1}}$$

Analytical inversion $\mathbf{\Phi} = (\mathbf{A}^{\times})^{-1}$

$\mathbf{\Phi} =$ (matrix with:)

- above the diagonal: $\Phi_{i,j} = \frac{-1/4}{\gamma_i}\,\Phi_{i+1,j}$
- on the diagonal: $\Phi_{j,j} = \left(A^{+}_{j,j} - 1/16\,(\xi^{-1}_{j-1} + \gamma^{-1}_{j+1})\right)^{-1}$
- below the diagonal: $\Phi_{i,j} = \frac{-1/4}{\xi_i}\,\Phi_{i-1,j}$

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  and ratios:

  $$\xi_i = \frac{\zeta_i}{\zeta_{i-1}} \quad \text{and} \quad \gamma_i = \frac{\upsilon_i}{\upsilon_{i+1}}$$

- inversion has complexity $\mathcal{O}(N/4)$

Red channel approximate solution

Infinite image

- $\mathbf{\Phi}$ is asymptotically **symmetric Toeplitz**

$$\Phi_{j,j} \to \Phi_D$$

$$\Phi_{i,j} \to \left(\frac{-1/4}{q}\right)^{|i-j|} \Phi_D$$

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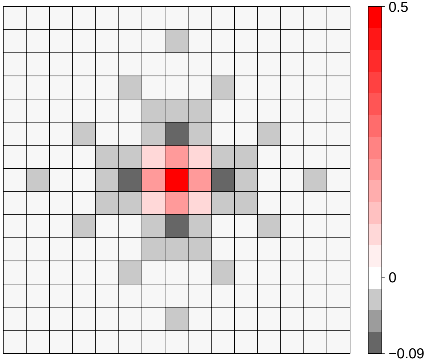
< 1

- off-diagonal elements decay exponentially

Asymptotic kernel



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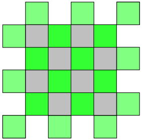
Green Channel

Green channel in a nutshell

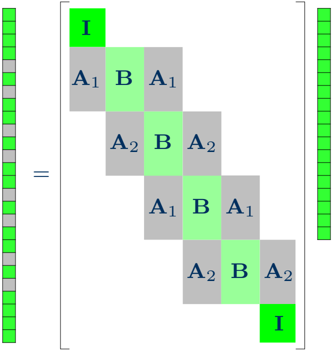
Additional border pixels

- avoid special interpolation kernel for margin pixels



Block structure

- columns partion $\mathbf{H}$ into repeating blocks $\mathbf{A}_1$, $\mathbf{A}_2$, and $\mathbf{B}$
- **but: no trivial decomposition**



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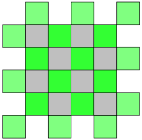

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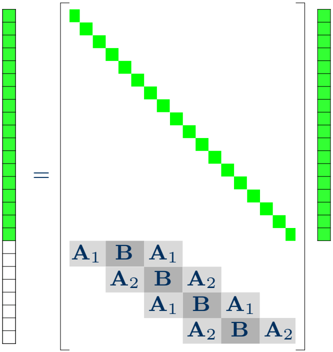
Re-ordering: $\tilde{\mathbf{H}} = \begin{bmatrix}\mathbf{I}\\ \mathbf{A}\end{bmatrix}$



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Experimental Results

Tamper hiding performance measures

Evaluation of attacks against digital image forensics should always be benchmarked against (at least) two criteria (Kirchner & Böhme, 2008):

(Un)detectability

- state-of-the-art detector can not distinguish between original and synthesized CFA images

Visual quality

- higher image quality than naive re-interpolation

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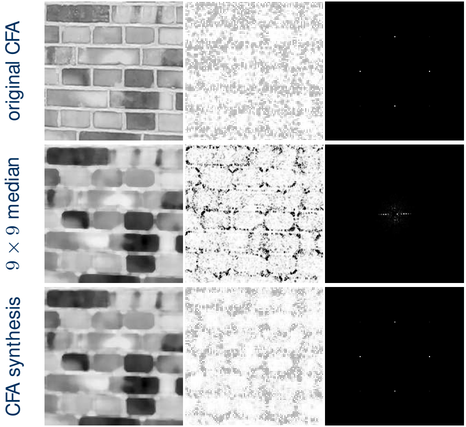
(Un)detectability

- state-of-the-art detector can not distinguish between original and synthesized CFA images
- fast version of Popescu and Farid's detector (Popescu & Farid, 2005; Kirchner, 2008)

Visual quality

- higher image quality than naive re-interpolation
- $\Delta\,\mathrm{PSNR}(\mathbf{y}_1, \mathbf{y}_2; \mathbf{y}_0) = \mathrm{PSNR}(\mathbf{y}_1, \mathbf{y}_0) - \mathrm{PSNR}(\mathbf{y}_2, \mathbf{y}_0)$

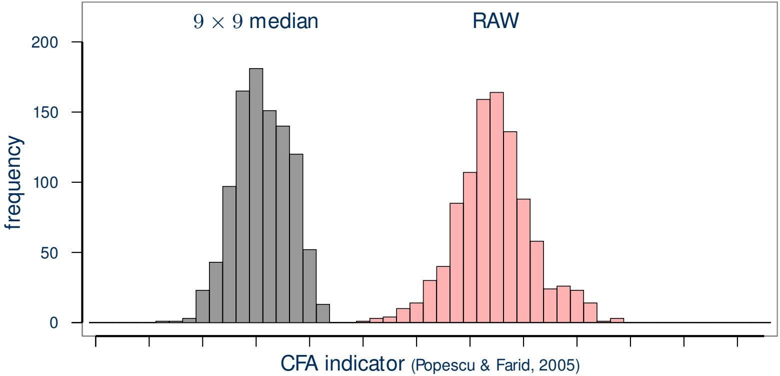
Detectability



- periodic p-map and strong high-frequency interpolation peaks
- post-processing destroys CFA pattern
- CFA pattern synthesis re-introduces typical artifacts

Detectability, quantitive results

Histograms from 1000 images



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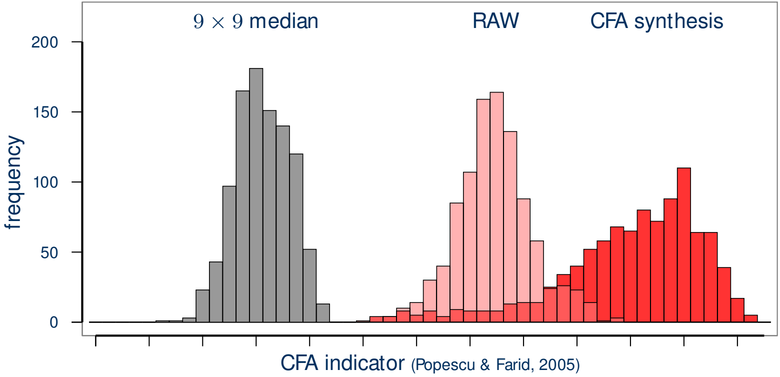

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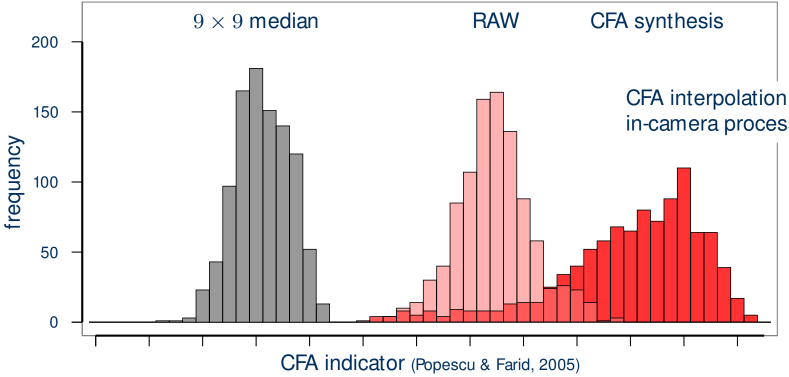

CFA interpolation not the last in-camera processing step!

Image quality

Quartiles from 1000 images

synthesis gain [dB]	Q_{25}	Q_{50}	Q_{75}	IQR	Q_{25}	Q_{50}	Q_{75}	IQR
	1.07	1.18	1.28	0.21	0.89	0.94	0.99	0.10

LS approach yields better visual quality after re-interpolation.

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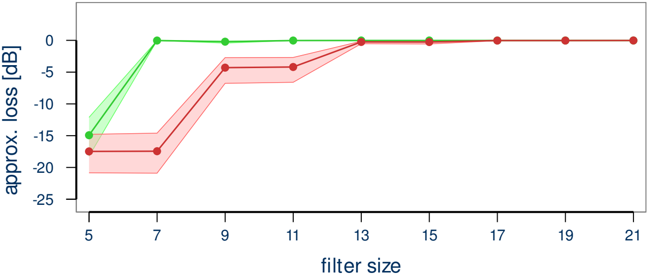

Linear filter approximation equivalent to exact solution for reasonable filter dimensions.

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Conclusion

Concluding Remarks

Results in a nutshell

- CFA synthesis is important **building block** for **tamper hiding** techniques.
- Minimal distortion CFA synthesis can be formulated as **least squares problem**.
- Special structure allows efficient implementation; near-optimal approximate solution is only of **linear complexity**.

Further research and limitations

- More sophisticated (and signal-adaptive) interpolation algorithms?
- Discrete optimum?
- CFA interpolation not the last step in the in-camera processing chain!

Thanks for your attention

Questions?

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Red channel explicit solution

$$\mathbf{x} = \mathbf{H}^{+}\mathbf{y} = \left(\mathbf{A}^{+} \otimes \mathbf{A}^{+}\right)\, \mathbf{y}$$

$$x_i = \sum_{j=1}^{N} \left(A^{+}_{r,s} \cdot A^{+}_{u,v}\right)\, y_j$$

- Elements $A^{+}_{i,j}$ can be derived efficiently from $\mathbf{\Phi} = (\mathbf{A}^{\times})^{-1}$.

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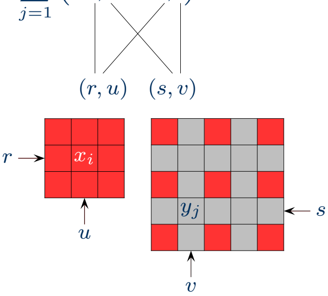

- Elements $A^{+}_{i,j}$ can be derived efficiently from $\mathbf{\Phi} = (\mathbf{A}^{\times})^{-1}$.
- Indices (r,u) and (s,v) are the 2D coordinates of pixels x_i and y_j in the subsampled genuine image and input image, respectively.

Green channel in a nutshell (cont'd)

Explicit solution

with $\mathbf{\Phi} = (\tilde{\mathbf{H}}^{\times})^{-1}$

- $\mathbf{x} = \mathbf{\Phi}\tilde{\mathbf{y}}_{\mathsf{G}} + \mathbf{\Phi}\mathbf{A}'\tilde{\mathbf{y}}_{\mathsf{CFA}}$

Analytical inversion of $\tilde{\mathbf{H}}^{\times}$

- $\mathbf{\Phi} = \mathbf{I} - \mathbf{A}'(\mathbf{I} + \mathbf{A}\mathbf{A}')^{-1}\mathbf{A}$
- $\mathbf{I} + \mathbf{A}\mathbf{A}'$ is block tridiagonal Toeplitz
- Huang & McColl (1997): second order matrix recurrences

Approximate filter kernel

		−0.001	0.001	0.001	0.001	−0.001		
	−0.001	0.003	0.005	−0.004	0.005	0.003	−0.001	
−0.001	0.003	0.009	−0.022	−0.029	−0.022	0.009	0.003	−0.001
0.001	0.005	−0.022	−0.072	0.165	−0.072	−0.022	0.005	0.001
0.001	−0.004	−0.029	0.165	0.835	0.165	−0.029	−0.004	0.001
0.001	0.005	−0.022	−0.072	0.165	−0.072	−0.022	0.005	0.001
−0.001	0.003	0.009	−0.022	−0.029	−0.022	0.009	0.003	−0.001
	−0.001	0.003	0.005	−0.004	0.005	0.003	−0.001	
		−0.001	0.001	0.001	0.001	−0.001		