TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Computer Science Institute of Systems Architecture, Privacy and Data Security Research Group

Efficient Estimation of CFA Pattern Configuration in Digital Camera Images

Electronic Imaging 2010
Media Forensics and Security II

Matthias Kirchner
Technische Universität Dresden

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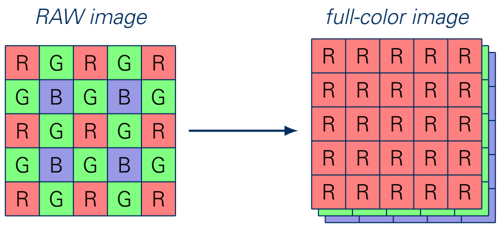
CFA Interpolation

- typical digital cameras use only one CCD / CMOS sensor and a **color filter array** (CFA) to capture full-color images
- missing color information is estimated from surrounding genuine elements in the raw image



CFA interpolation / demosaicing

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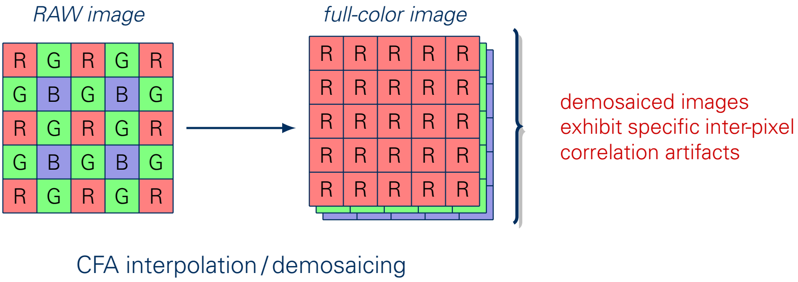
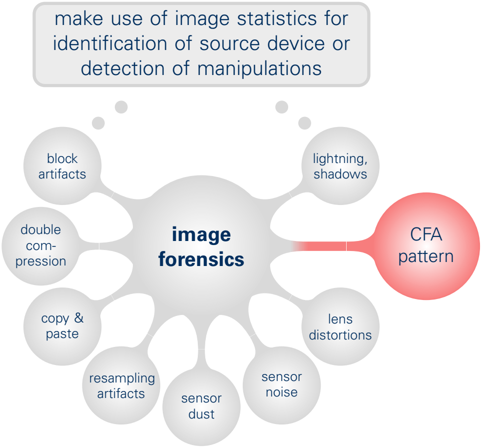


CFA Artifacts in Digital Image Forensics



- color filter array (CFA) interpolation artifacts form an important class of device characteristics

source identification

- ▷ different camera models use different interpolation procedures

manipulation detection

- ▷ post-processing damages characteristic inter-pixel correlation pattern

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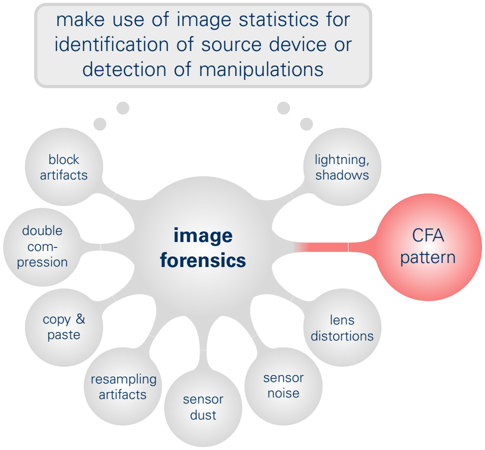

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- applications in steganalysis or digital watermarking

Example Application [Popescu & Farid, 2005]

- periodic artifacts in the linear predictor residue (p-map)

Dresden Palace, image is part of the ‘Dresden Image Database’
[Gloe & Böhme, 2010]

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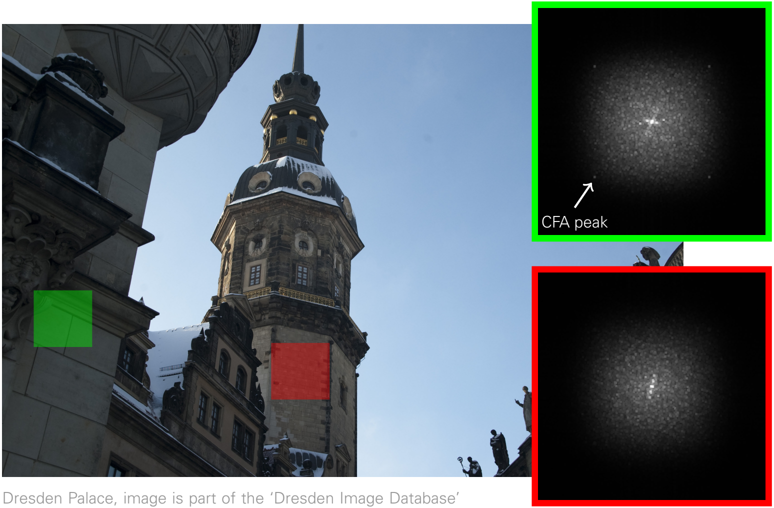
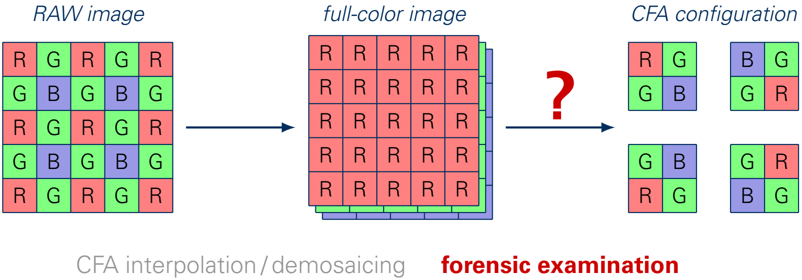
DFT(p-map)



Dresden Palace, image is part of the 'Dresden Image Database'
[Gloe & Böhme, 2010]

CFA Pattern Configuration

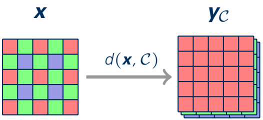
- early methods did not explicitly incorporate knowledge about the actual configuration of the CFA pattern [Popescu & Farid, 2005; Bayram et al, 2005]
  - problem of periodic, but locally inconsistent inter-pixel correlation
- CFA configuration valuable both for source identification [Swaminathan et al., 2007] and manipulation detection [Dirik et al., 2009]
  - generally a means to **decrease the degrees of freedom** in image forensics



CFA Configuration Estimation in the Literature

- **minimum re-interpolation error assumption**

for CFA configuration $\mathcal{C}$ and the demosaicing function d



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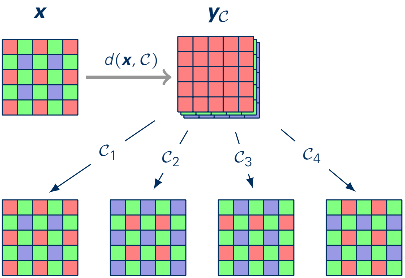

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$$\mathrm{d}^{-1}(\boldsymbol{y}_{\mathcal{C}}, \mathcal{C}_i)$$

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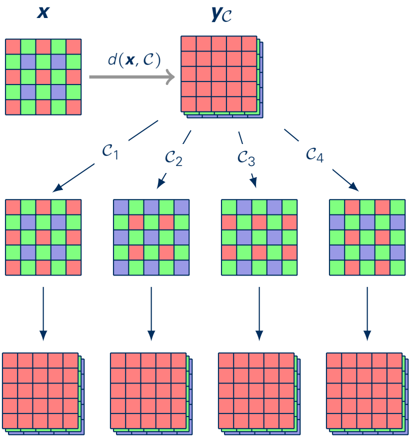

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$$\mathrm{d}\left(\mathrm{d}^{-1}(\boldsymbol{y}_{\mathcal{C}}, \mathcal{C}_i), \mathcal{C}_i\right)$$

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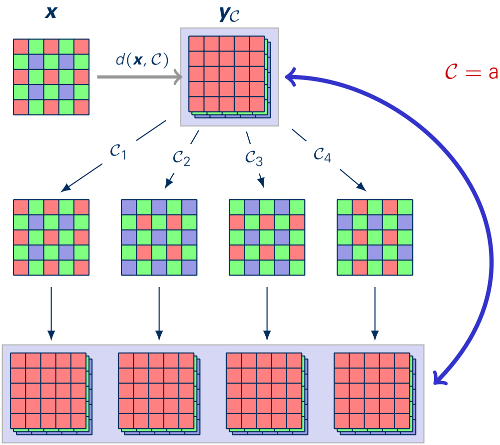

for CFA configuration $\mathcal{C}$ and the demosaicing function d

$$\mathcal{C} = \arg\min_{\mathcal{C}_i} \underbrace{\left\| \boldsymbol{y}_{\mathcal{C}} - \mathrm{d}\left(\mathrm{d}^{-1}(\boldsymbol{y}_{\mathcal{C}}, \mathcal{C}_i), \mathcal{C}_i\right) \right\|}_{\|\boldsymbol{e}_{\mathcal{C}_i}\|}$$

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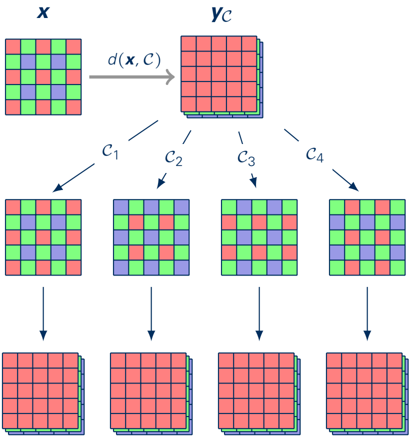

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- ▷ subsampling matrix $\mathbf{S}_{\mathcal{C}_i}$ as simple approximation of inverse demosaicing

  $$\mathrm{d}^{-1}(\boldsymbol{y}, \mathcal{C}_i) = \mathbf{S}_{\mathcal{C}_i}\boldsymbol{y}$$

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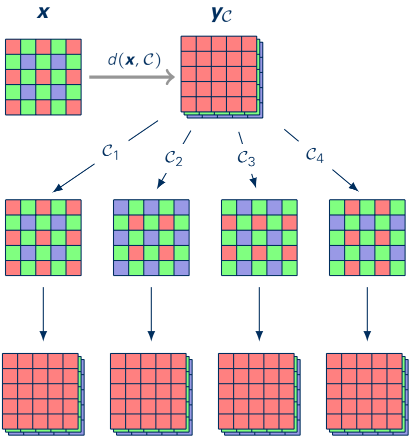

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- subsampling matrix $\mathbf{S}_{\mathcal{C}_i}$ as simple approximation of inverse demosaicing

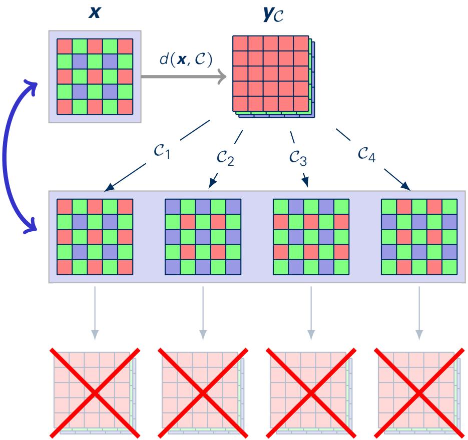
  $$\mathrm{d}^{-1}(\boldsymbol{y}, \mathcal{C}_i) = \mathbf{S}_{\mathcal{C}_i}\boldsymbol{y}$$

- assume linear relationship between raw and interpolated pixels

  $$\mathrm{d}(\boldsymbol{x}, \mathcal{C}_i) = \mathbf{H}_{\mathcal{C}_i}\boldsymbol{x}$$

An Alternative Approach

- **assume that we actually know the genuine raw sensor output**



$$\mathcal{C} = \arg\min_{\mathcal{C}_i} \underbrace{\left\| \boldsymbol{x} - \mathrm{d}^{-1}(\boldsymbol{y}_{\mathcal{C}}, \mathcal{C}_i) \right\|}_{\left\| \boldsymbol{e}_{\mathcal{C}_i}^{\mathrm{d}^{-1}} \right\|}$$

- ▹ subsampling matrix $\mathbf{S}_{\mathcal{C}_i}$ as simple approximation of inverse demosaicing

  $\mathrm{d}^{-1}(\boldsymbol{y}, \mathcal{C}_i) = \mathbf{S}_{\mathcal{C}_i} \boldsymbol{y}$

- ▹ re-interpolation for each possible configuration $\mathcal{C}_i$ not necessary

CFA Pattern Synthesis [Kirchner & Böhme, 2009]

basic idea

- find a possible sensor signal $\tilde{\boldsymbol{x}}$ such that $\|\boldsymbol{y}_{\mathcal{C}} - \mathrm{d}(\tilde{\boldsymbol{x}}, \mathcal{C})\|_2 \rightarrow \min$
- following the linearity assumption

  this is an ordinary least squares (OLS) problem

$$\boldsymbol{y}_{\mathcal{C}} = \mathbf{H}_{\mathcal{C}}\boldsymbol{x} + \boldsymbol{\epsilon}$$

$$\tilde{\boldsymbol{x}}_{\mathcal{C}} = (\mathbf{H}_{\mathcal{C}}^{\top}\mathbf{H}_{\mathcal{C}})^{-1}\mathbf{H}_{\mathcal{C}}^{\top}\boldsymbol{y}$$

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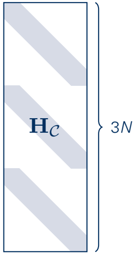
caveat

- for a N-pixel image, $\mathbf{H}_{\mathcal{C}}$ is of dimension $3N \times N$
- direct implementation of the OLS solution not tractable

efficiency improvements

- $\mathbf{H}_{\mathcal{C}}$ is typically sparse (finite filter support) and of regular structure (periodic CFA)



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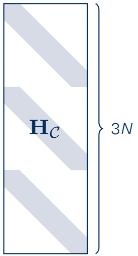
- $\mathbf{H}_\mathcal{C}$ is typically sparse (finite filter support) and of regular structure (periodic CFA)
- analytical solution for the **bilinear interpolation kernel**



Approximate Solution

- by considering an infinite image without border conditions, approximate solutions in terms of a channel-dependent fixed linear filter can be found [Kirchner & Böhme, 2009]

$$\tilde{\boldsymbol{x}}_{\mathcal{C}_i} \approx \mathbf{S}_{\mathcal{C}_i} (\mathbf{F}\boldsymbol{y}) = \mathbf{S}_{\mathcal{C}_i} \begin{bmatrix} \mathbf{F}^{(R)}\boldsymbol{y}^{(R)} \\ \mathbf{F}^{(G)}\boldsymbol{y}^{(G)} \\ \mathbf{F}^{(B)}\boldsymbol{y}^{(B)} \end{bmatrix}$$

equivalent to the analytical solution for large enough filter kernels

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application to the CFA configuration estimation problem

$$\mathcal{C} = \arg\min_{\mathcal{C}_i} \left\| \tilde{\boldsymbol{x}}_{\mathcal{C}_i} - \mathbf{S}_{\mathcal{C}_i}\boldsymbol{y} \right\|_2$$

- process image with linear CFA synthesis filters
- sub-sample image and filtered image to CFA pattern $\mathcal{C}_i$
- calculate difference between both
- only one linear filtering operation

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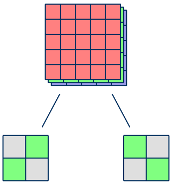
our assumptions:

- Bayer CFA pattern
- bilinear interpolation
- continuous solution

Refinements to the Estimation Procedure

- CFA configuration can be best determined for the green channel elements (twice as much genuine sensor pixels)



$\mathcal{C}^{(G)}$

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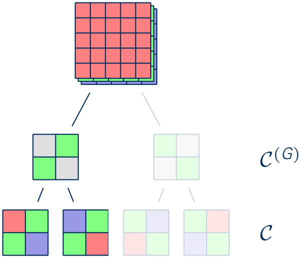
two-stage approach:

- decision for the complete configuration conditional to the estimated green channel configuration



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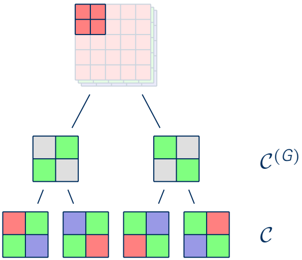

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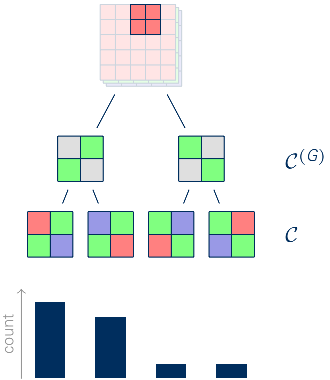
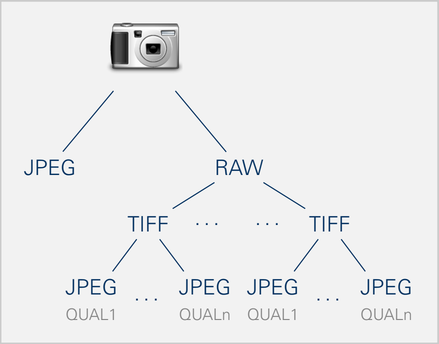
  block-based approach:

  - majority voting over all non-overlapping 2×2 blocks



Experimental Setup

- test database derived from ≈ 1000 full-resolution digital camera images from the **'Dresden Image Database'** [Gloe & Böhme, 2010]



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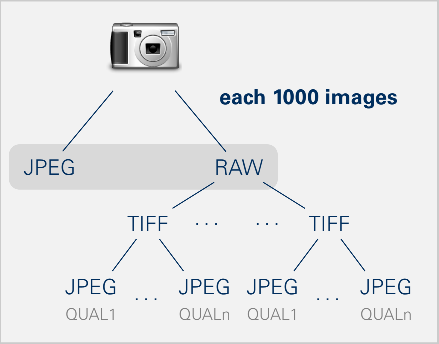

- 5 different camera models with combined JPEG / RAW output
  - ▷ Nikon D200 (1)
  - ▷ Nikon D70/s (each 1)
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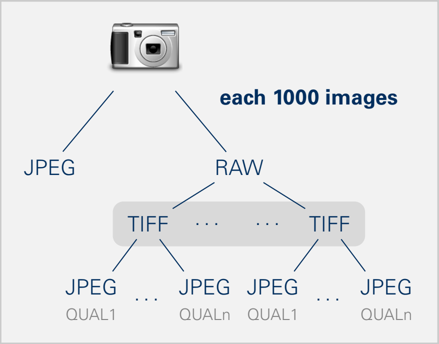

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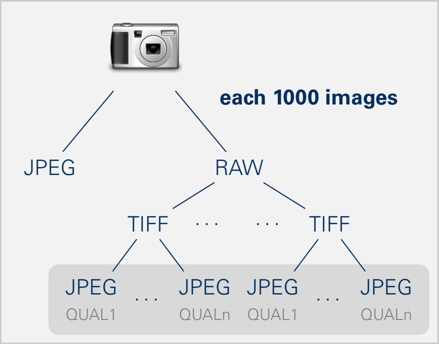

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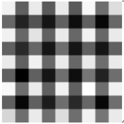
  - 4 interpolation procedures: bilinear, VNG, AHD, LR
- JPEG compression with varying quality factors after demosacing

Ground Truth in our Experiments

- experimental evaluation requires ground truth CFA configurations
- not explicitly known for the cameras in use
  - EXIF data not necessarily contains this information
  - sensor datasheets are unreliable (active vs. effective pixels)

- CFA pattern becomes visible in the raw data of almost blue / red scences



raw data

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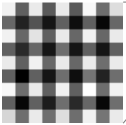

raw data

- Lightroom images (and genuine camera images) are smaller than `dcraw` images
  - synchronization by maximum cross-correlation over all possible crops of the larger image

Baseline Results

Percentage of correctly determined configurations

	D200		D70		D70s		FZ750		GX100		overall	
	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$
bilinear interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (block)	100	100	100	100	100	100	99.2	99.2	100	100	**99.8**	**99.8**
VNG interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	88.8	88.8	97.4	97.4	95.1	95.1	97.7	97.7	99.0	99.0	96.3	96.3
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (total)	64.8	64.8	80.8	80.8	83.4	83.4	94.2	94.2	96.4	96.4	87.6	87.6
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (block)	97.7	97.7	100	100	98.2	98.2	99.2	99.2	99.8	99.8	**99.1**	**99.1**
AHD interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	95.0	91.1	96.2	71.8	96.9	59.5	98.8	98.4	99.3	97.8	97.9	89.3
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (total)	86.0	81.6	88.5	66.7	93.3	66.9	98.4	98.1	98.6	97.1	95.0	88.1
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (block)	100	98.9	100	94.9	100	96.9	99.2	99.2	100	99.8	**99.8**	**98.7**
Adobe Lightroom												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	87.7	39.1	100	57.7	100	67.5	98.8	65.0	97.8	80.4	96.9	66.5
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (total)	98.9	46.4	100	71.8	100	78.5	100	66.9	99.3	83.1	99.5	71.8
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (block)	97.2	82.7	100	97.4	100	94.5	100	77.0	97.6	94.0	**98.6**	**88.5**

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Percentage of correctly determined configurations

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	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$
bilinear interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	100	100	100	100	100	100	99.2	99.2	100	100	**99.8**	**99.8**
VNG interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	88.8	88.8	97.4	97.4	[illegible]	[illegible]	[illegible]	97.7	99.0	99.0	96.3	96.3
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	64.8	[illegible]	[illegible]	80.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	87.6	87.6
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	97.7	[illegible]	[illegible]	100	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**99.1**	**99.1**
AHD interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	95.0	91.1	96.2	71.8	96.9	59.5	98.8	98.4	99.3	97.8	97.9	89.3
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	86.0	81.6	88.5	66.7	93.3	66.9	98.4	98.1	98.6	97.1	95.0	88.1
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	100	98.9	100	94.9	100	96.9	99.2	99.2	100	99.8	**99.8**	**98.7**
Adobe Lightroom												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	87.7	39.1	100	57.7	100	67.5	98.8	65.0	97.8	80.4	96.9	66.5
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	98.9	46.4	100	71.8	100	78.5	100	66.9	99.3	83.1	99.5	71.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	97.2	82.7	100	97.4	100	94.5	100	77.0	97.6	94.0	**98.6**	**88.5**

$\mathbf{e}_{\mathcal{C}_i}$ (total) ▷ re-interpolation with bilinear kernel [Dirik et al., 2009]

$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total) ▷ CFA synthesis, global decision

$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block) ▷ CFA synthesis, block decision

Baseline Results

Percentage of correctly determined configurations

	D200		D70		D70s		FZ750		GX100		overall	
	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$
bilinear interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{d-1}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{d-1}_{\mathcal{C}_i}$ (block)	100	100	100	100	100	100	99.2	99.2	100	100	**99.8**	**99.8**
VNG interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	88.8	88.8	97.4	97.4	95.1	95.1	97.7	97.7	99.0	99.0	96.3	96.3
$\mathbf{e}^{d-1}_{\mathcal{C}_i}$ (total)	64.8	64.8	80.8	80.8	83.4	83.4	94.2	94.2	96.4	96.4	87.6	87.6
$\mathbf{e}^{d-1}_{\mathcal{C}_i}$ (block)	97.7	97.7	100	100	98.2	98.2	99.2	99.2	99.8	99.8	**99.1**	**99.1**
AHD interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	95.0	91.1	96.2	71.8	96.9	59.5	98.8	98.4	99.3	97.8	97.9	89.3
$\mathbf{e}^{d-1}_{\mathcal{C}_i}$ (total)	86.0	81.6	88.5	66.7	93.3	66.9	98.4	98.1	98.6	97.1	95.0	88.1
$\mathbf{e}^{d-1}_{\mathcal{C}_i}$ (block)	100	98.9	100	94.9	100	96.9	99.2	99.2	100	99.8	**99.8**	**98.7**
Adobe Lightroom												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	87.7	39.1	100	57.7	100	67.5	98.8	65.0	97.8	80.4	96.9	66.5
$\mathbf{e}^{d-1}_{\mathcal{C}_i}$ (total)	98.9	46.4	100	71.8	100	78.5	100	66.9	99.3	83.1	99.5	71.8
$\mathbf{e}^{d-1}_{\mathcal{C}_i}$ (block)	97.2	82.7	100	97.4	100	94.5	100	77.0	97.6	94.0	**98.6**	**88.5**

Baseline Results

Percentage of correctly determined configurations

	D200 $\mathcal{C}^{(\mathrm{G})}$	D200 $\mathcal{C}$	D70 $\mathcal{C}^{(\mathrm{G})}$	D70 $\mathcal{C}$	D70s $\mathcal{C}^{(\mathrm{G})}$	D70s $\mathcal{C}$	FZ750 $\mathcal{C}^{(\mathrm{G})}$	FZ750 $\mathcal{C}$	GX100 $\mathcal{C}^{(\mathrm{G})}$	GX100 $\mathcal{C}$	overall $\mathcal{C}^{(\mathrm{G})}$	overall $\mathcal{C}$
bilinear interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	100	100	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**99.8**	**99.8**
VNG interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	88.8	88.8	97.4	97.4	95.1	95.1	97.7	97.7	99.0	99.0	96.3	96.3
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	64.8	64.8	80.8	80.8	83.4	83.4	94.2	94.2	96.4	96.4	87.6	87.6
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	97.7	97.7	100	100	98.2	98.2	99.2	99.2	99.8	99.8	**99.1**	**99.1**
AHD interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	95.0	91.1	96.2	71.8	96.9	59.5	98.8	98.4	99.3	97.8	97.9	89.3
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	86.0	81.6	88.5	66.7	93.3	66.9	98.4	98.1	98.6	97.1	95.0	88.1
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	100	98.9	100	94.9	100	96.9	99.2	99.2	100	99.8	**99.8**	**98.7**
Adobe Lightroom												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	87.7	39.1	100	57.7	100	67.5	98.8	65.0	97.8	80.4	96.9	66.5
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	98.9	46.4	100	71.8	100	78.5	100	66.9	99.3	83.1	99.5	71.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	97.2	82.7	100	97.4	100	94.5	100	77.0	97.6	94.0	**98.6**	**88.5**

- green channel configuration can be determined most reliably

Baseline Results

Percentage of correctly determined configurations

	D200		D70		D70s		FZ750		GX100		overall	
	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$	$\mathcal{C}^{(\mathrm{G})}$	$\mathcal{C}$
bilinear interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (block)	100	100	100	100	100	100	99.2	99.2	100	100	**99.8**	**99.8**
VNG interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	88.8	88.8	97.4	97.4	95.1	95.1	97.7	97.7	99.0	99.0	96.3	96.3
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (total)	64.8	64.8	80.8	80.8	83.4	83.4	94.2	94.2	96.4	96.4	87.6	87.6
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (block)	97.7	97.7	100	100	98.2	98.2	99.2	99.2	99.8	99.8	**99.1**	**99.1**
AHD interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	95.0	91.1	96.2	71.8	96.9	59.5	98.8	98.4	99.3	97.8	97.9	89.3
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (total)	86.0	81.6	88.5	66.7	93.3	66.9	98.4	98.1	98.6	97.1	95.0	88.1
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (block)	100	98.9	100	94.9	100	96.9	99.2	99.2	100	99.8	**99.8**	**98.7**
Adobe Lightroom												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	87.7	39.1	100	57.7	100	67.5	98.8	65.0	97.8	80.4	96.9	66.5
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (total)	98.9	46.4	100	71.8	100	78.5	100	66.9	99.3	83.1	99.5	71.8
$\mathbf{e}^{\mathrm{d}-1}_{\mathcal{C}_i}$ (block)	97.2	82.7	100	97.4	100	94.5	100	77.0	97.6	94.0	**98.6**	**88.5**

Baseline Results

Percentage of correctly determined configurations

	D200		D70		D70s		FZ750		GX100		overall	
	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$
bilinear interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	100	100	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**99.8**	**99.8**
VNG interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	88.8	88.8	97.4	97.4	95.1	95.1	97.7	97.7	99.0	99.0	96.3	96.3
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	64.8	64.8	[illegible]	[illegible]	[illegible]	83.4	94.2	94.2	96.4	96.4	87.6	87.6
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	97.7	97.7	100	100	98.2	98.2	99.2	99.2	99.8	99.8	**99.1**	**99.1**
AHD interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	95.0	91.1	96.2	71.8	96.9	59.5	98.8	98.4	99.3	97.8	97.9	89.3
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	86.0	81.6	88.5	66.7	93.3	66.9	98.4	98.1	98.6	97.1	95.0	88.1
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	100	98.9	100	94.9	100	96.9	99.2	99.2	100	99.8	**99.8**	**98.7**
Adobe Lightroom												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	87.7	39.1	100	57.7	100	67.5	98.8	65.0	97.8	80.4	96.9	66.5
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	98.9	46.4	100	71.8	100	78.5	100	66.9	99.3	83.1	99.5	71.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	97.2	82.7	100	97.4	100	94.5	100	77.0	97.6	94.0	**98.6**	**88.5**

- ► green channel configuration can be determined most reliably
- ► block-based CFA synthesis approach superior in virtually all cases

Baseline Results

Percentage of correctly determined configurations

	D200 $\mathcal{C}^{(G)}$	D200 $\mathcal{C}$	D70 $\mathcal{C}^{(G)}$	D70 $\mathcal{C}$	D70s $\mathcal{C}^{(G)}$	D70s $\mathcal{C}$	FZ750 $\mathcal{C}^{(G)}$	FZ750 $\mathcal{C}$	GX100 $\mathcal{C}^{(G)}$	GX100 $\mathcal{C}$	overall $\mathcal{C}^{(G)}$	overall $\mathcal{C}$
bilinear interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	100	100	100	100	100	100	99.2	99.2	100	100	**99.8**	**99.8**
VNG interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	88.8	88.8	97.4	97.4	95.1	95.1	97.7	97.7	99.0	99.0	96.3	96.3
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	64.8	64.8	80.8	80.8	83.4	83.4	94.2	94.2	96.4	96.4	87.6	87.6
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	97.7	97.7	100	100	98.2	98.2	99.2	99.2	99.8	99.8	**99.1**	**99.1**
AHD interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	95.0	91.1	96.2	71.8	96.9	59.5	98.8	98.4	99.3	97.8	97.9	89.3
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	86.0	81.6	88.5	66.7	93.3	66.9	98.4	98.1	98.6	97.1	95.0	88.1
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	100	98.9	100	94.9	100	96.9	99.2	99.2	100	99.8	**99.8**	**98.7**
Adobe Lightroom												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	87.7	39.1	100	57.7	100	67.5	98.8	65.0	97.8	80.4	96.9	66.5
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	98.9	46.4	100	71.8	100	78.5	100	66.9	99.3	83.1	99.5	71.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	97.2	82.7	100	97.4	100	94.5	100	77.0	97.6	94.0	**98.6**	**88.5**

Baseline Results

Percentage of correctly determined configurations

	D200		D70		D70s		FZ750		GX100		overall	
	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$
bilinear interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	100	100	100	100	100	100	99.2	99.2	100	100	99.8	99.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	100	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**99.8**	**99.8**
VNG interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	88.8	88.8	97.4	97.4	95.1	95.1	97.7	97.7	99.0	99.0	96.3	96.3
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	64.8	64.8	[illegible]	[illegible]	[illegible]	83.4	94.2	94.2	96.4	96.4	87.6	87.6
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	97.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**99.1**	**99.1**
AHD interpolation												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	95.0	91.1	96.2	71.8	96.9	59.5	98.8	98.4	99.3	97.8	97.9	89.3
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	86.0	81.6	88.5	66.7	93.3	66.9	98.4	98.1	98.6	97.1	95.0	88.1
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	100	98.9	100	94.9	100	96.9	99.2	99.2	100	99.8	**99.8**	**98.7**
Adobe Lightroom												
$\mathbf{e}_{\mathcal{C}_i}$ (total)	87.7	39.1	100	57.7	100	67.5	98.8	65.0	97.8	80.4	96.9	66.5
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (total)	98.9	46.4	100	71.8	100	78.5	100	66.9	99.3	83.1	99.5	71.8
$\mathbf{e}^{\mathrm{d}^{-1}}_{\mathcal{C}_i}$ (block)	97.2	82.7	100	97.4	100	94.5	100	77.0	97.6	94.0	**98.6**	**88.5**

- green channel configuration can be determined most reliably
- block-based CFA synthesis approach superior in virtually all cases
- reliability depends to some extent on the source of the image

Influence of Image Size

- analysis of smaller image blocks of particular interest for the manipulation detection

percentage of correctly determined configurations for all blocks of all images
(CFA synthesis, block based)

	D200		D70		D70s		FZ750		GX100		overall	
	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$
AHD interpolation												
256×256	98.7	95.7	99.2	92.1	98.6	91.2	98.1	97.2	99.0	97.4	**98.7**	**96.2**
512×512	99.1	96.5	99.4	93.7	99.0	93.4	98.7	98.1	99.4	98.1	**99.1**	**97.3**
1024×1024	99.7	97.1	98.7	94.2	99.1	95.1	98.8	98.4	99.8	99.2	**99.4**	**98.2**
Adobe Lightroom												
256×256	92.7	65.3	99.4	83.9	99.3	81.9	99.1	52.0	96.7	79.8	**96.9**	**70.2**
512×512	94.4	72.6	99.9	90.0	100	88.7	99.3	56.6	96.7	88.2	**97.3**	**76.8**
1024×1024	95.4	79.0	100	96.8	100	92.9	99.7	66.0	96.3	91.1	**97.4**	**82.1**

Influence of Image Size

- analysis of smaller image blocks of particular interest for the manipulation detection

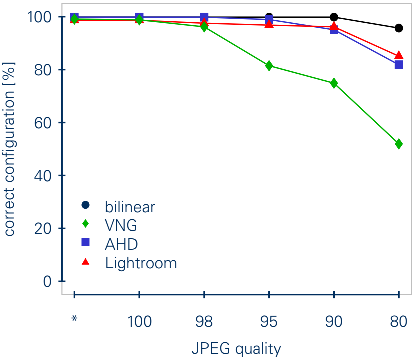
percentage of correctly determined configurations for all blocks of all images
(CFA synthesis, block based)

	D200		D70		D70s		FZ750		GX100		overall	
	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$	$\mathcal{C}^{(G)}$	$\mathcal{C}$
AHD interpolation												
256 × 256	98.7	95.7	99.2	92.1	98.6	91.2	98.1	97.2	99.0	97.4	**98.7**	**96.2**
512 × 512	99.1	96.5	99.4	93.7	99.0	93.4	98.7	98.1	99.4	98.1	**99.1**	**97.3**
1024 × 1024	99.7	97.1	98.7	94.2	99.1	95.1	98.8	98.4	99.8	99.2	**99.4**	**98.2**
Adobe Lightroom												
256 × 256	92.7	65.3	99.4	83.9	99.3	81.9	99.1	52.0	96.7	79.8	**96.9**	**70.2**
512 × 512	94.4	72.6	99.9	90.0	100	88.7	99.3	56.6	96.7	88.2	**97.3**	**76.8**
1024 × 1024	95.4	79.0	100	96.8	100	92.9	99.7	66.0	96.3	91.1	**97.4**	**82.1**

- configuration of Adobe Lightroom images is particularly harder to determine for smaller block sizes
  - local, signal-adaptive post-processing?

JPEG Post-compression

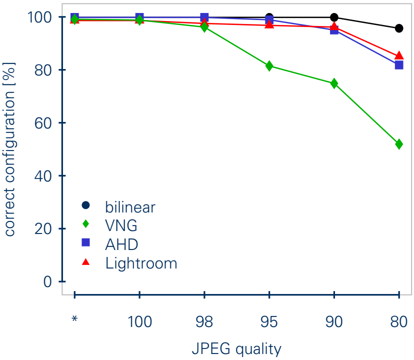
green channel configuration $\mathcal{C}^{(\mathbf{G})}$



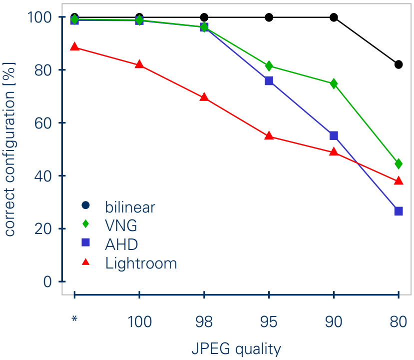
- green channel configuration can be determined relatively reliable for JPEG qualities as low as 90

JPEG Post-compression

green channel configuration $\mathcal{C}^{(\mathbf{G})}$



complete configuration $\mathcal{C}$



- green channel configuration can be determined relatively reliable for JPEG qualities as low as 90
- complete configuration estimation is more vulnerable to JPEG

Concluding Remarks

- CFA pattern configuration is valuable additional knowledge in the forensic examination of digital camera images
- in this study: efficient method to determine the CFA pattern
  - approximate solution to the CFA synthesis problem
  - two-stage, block-based approach
  - requires only 1 linear filtering step per image
- promising results despite the overly simplistic assumptions

Limitations

- strong post-processing and JPEG compression hamper a reliable identifictation

Future work

- extend the CFA synthesis method to more sophisticated demosaicing procedures
  - separate filter coefficients for horizontal / vertical edges
- allow for ‘neutral’ decision (CFA pattern not known)

Thanks for your attention

Questions?

Matthias Kirchner
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