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Camera identification based on PRNU[1] analysis

Introduction

In accordance to the 2017 report prepared by the Public Opinion Research Centre 'Mobile phone usage'[2] 92% of adult Polish citizens used mobile phones and 57% of them used smart phones. The number of smart phone users is still on the rise. Only between 2015 and 2017 it increased by 7 percentage points. Telephones (this group includes not only traditional mobile phones, but also technically more advanced smart phones), apart from their basic function, i.e. conducting conversations (100% respondents), were used for sending and receiving messages (78%),taking photos (62%), and recording movies (36%). Comparing these data with the report of POLSKA.JEST.MOBI entitled '*Smartphonisation* in Poland in 2018' it should be pointed out that the number of smart phone owners has increased from 62% (2016) to 64% (2018). According to the data mentioned in the report, smart phone users in Poland spend 2 hours per day exploiting its various functions, which places our country above the average rate in the Southern and Western Europe (around 2 hours), but below the average rate estimated for the overall population of the planet (over 2.5 hours).[3] Taking into consideration the comparison and the undeniable fact that most people have access to photo cameras – starting from compact cameras through mirrorless cameras and finally reflex cameras – and take photos or record movies with them, it should be kept in mind that some of these files may be used as evidence in criminal cases e.g. offences against the sexual liberty and morality, committed to the detriment of the minors. Therefore, it is necessary to answer a question whether those files could be made with a device seized in the course of an investigation. This report shows the results of research, which are to answer the foregoing question. The analysis was carried out on the basis of graphic files produced by five camera devices in mobile phones. Identification process of the recording device was conducted on

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1 The article was written in the framework of the Project No. PL/2017/PR/0005 entitled „The terminal for device identification and verification of authenticity of video records" co-financed by the European Union from the State Program of Internal Security Fund.

2 *Korzystanie z telefonów komórkowych*, Komunikat z badań nr 99/2017, CBOS, Warszawa 2017, pp. 1–2.

3 M. Mikowska, A. Skalna, K. Siwiński, *POLSKA.JEST.MOBI 2018*, part: *Smartfonizacja w Polsce w 2018 roku*, prepared with Kantar TNS, 4 edition, pp. 5, 10. Also: POLSKA_JEST_MOBI_2018.pdf.

the basis of the analysis of a model of the PRNU[4] image noise that is unique for each sensor model.[5]

In order to perform such a task, several evidence photos and more than 2.500 natural and flat field reference photos were taken with the use of available devices. Flat field photos can be taken using natural or artificial lightening. Not only can a homogenous and evenly lit artificial screens be photographed but also celestial sphere in the sunlight (without disruptive objects such as clouds, aircrafts). The next stage was to calculate the noise patterns of the PRNU sensor pattern noise for the previously taken photos. The patterns were determined based on the FSTV method.[6] Next, they were compared with respect to each of the camera models that were under analysis. The result of the comparison was the PCE correlation coefficient.[7]

Image acquisition

The source camera identification requires the understanding of the acquisition process of the observed object into a digital file. Image 1 shows a pattern of the typical track of capturing the observed reality and recording it into a graphic file. Such a track includes the observed physical object, optical system of the recorder, CCD/CMOS sensor with CFA, DSP (processing the image in accordance with the chosen parameters and the recording in the chosen graphic format). The last element is a graphic file saved in the device's memory or external storage device, such as a memory card.

4 M. Goljan, J. Fridrich, T. Filler, *Large scale test of sensor fingerprint camera identification*, Conference Paper in Proceedings of SPIE – The International Society for Optical Engineering, 2009, p. 3.

5 E. Kalaimannan, P. Sengupta, V. Sameer, R. Naskar, *Source anonymization of digital images: a counter-forensic attack on prnu based source identification techniques*, ADFSL Conference on Digital Forensics, Security and Law, 2017, p. 97; E. Alles, Z. Geradts, C. Veenman, *Source Camera Identification for Low Resolution Heavily Compressed Images*, International Conference on Computational Sciences and its Applications ICCSA, 2008, p. 559.

6 B. Werkhoven, P. Hijma, C. Jacobs, J. Maassen, Z. Geradts, H Bal., *A jungle computing approach to common image source identification in large collections of images*, Digital Investigation 2018, nr 27, p. 3.

7 M. Brouwers, R. Mousa, *Automatic comparison of photo response non uniformity (PRNU) on Youtube*, "System and Network Engineering", January 2017, p. 3.

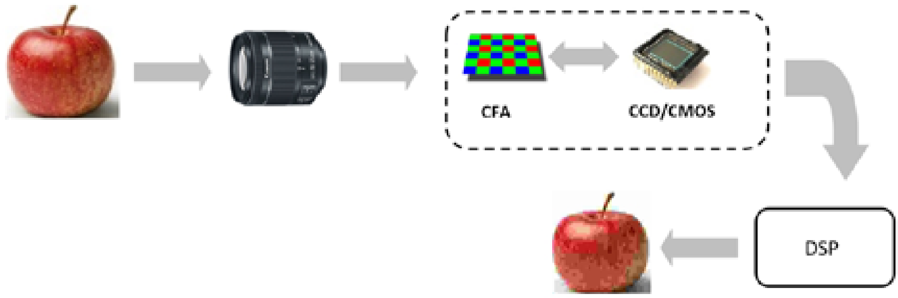
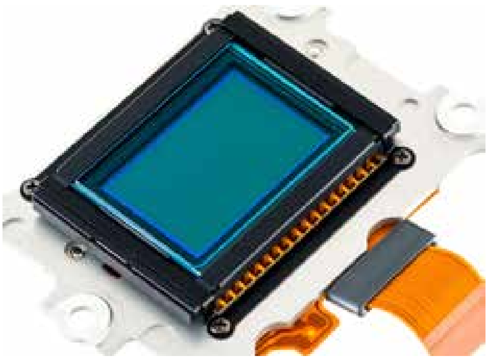


Image 1. Typical image acquisition pattern.

Source: Own study based on Vikas K., Shobhit K., Shukla N., Image Acquisition and Techniques to Perform Image Acquisition, https://www.researchgate.net/publication/318500799_Image_Acquisition_and_Techniques_to_Perform_Image_Acquisition/download [access: 5 I 2019].



Pic. 1. Example of a CCD sensor.

Source: https://www.fixyourcamera.org/nikon-d50/nikon-d50-review-teardown-276-ccd-sensor/ [access: 10 I 2019].

The element of the pattern shown above that special attention should be paid to - due to its role in the process of creating a link between the photo and the camera or in determination whether specific graphic files were taken using a single or a few devices, is the sensor, or more precisely, the noise pattern. Two types of sensors that should be distinguished among those used in photo cameras or popular smart phones are CMOS (along with its other versions like Exmor, LiveMos) and CCD.

Pic. 2. Sensor CMOS SONY IMX 586.

Source: https://www.digit.in/mobile-phones/sony-announces-imx586-companys-first-48-megapixel-smartphone-camera-sensor-42377.html [access: 10 I 2019].

CCD sensors (charge coupled device) produced since 1969 are built of a silicon wafer that contains photosensitive elements that capture light and save it as photons. The sensor is divided into pixels, the number of which is specified by the producer. Picture 1 shows an example of such a sensor.

Analogically to the CCD sensor, CMOS sensor (complementary metal oxide semiconductor) is characterized by a certain number of pixels located on its surface. The system is also built of photosensitive elements. However, its distinguishing feature is the construction. In the CMOS type of sensors each pixel is connected with the converter of the electric charge into electric voltage. On the other hand, in the case of the CCD sensor one the converter of the electric charge into electric voltage and one AD converter.[8] Therefore, the added value of the CMOS sensor in comparison with the CCD sensor is the possibility of reading any number of pixels. The first sensor of such type was produced in 1970. Picture 2 shows 48 megapixel sensor CMOS SONY IMX 586.

Theoretical description of the study method

It is typical of any graphic file, as well as a video to record not only a specific object but also the noise. The noise types can be divided into two categories:[9] **random noise** that differs in subsequent photos or frames in the case of video recordings, as well as the so-called **PRNU**, i.e. **pattern noise** that does not change dramatically in each subsequent file. Whereas the random noise reduction is possible through e.g. non-linear filtration[10], it is extremely difficult to reduce pattern noise with such techniques. PRNU pattern noise is a physical parameter determined based on irregularities that are made in its production process.[11] It is assumed that each pixel should have the same physical size, and consequently record the same amount of light in the form of photons. If homogenous light falls on the camera's sensor, each pixel should 'emit' exactly the same value as it receives. Little differences in the size of pixels lead to slightly different exit values. The difference between the theoretical response of the sensor and a uniform comprehensive response is described as "photo response non-uniformity" – PRNU.[12] The PRNU value depends on the physical features of the sensor. Therefore, this particular parameter is considered to be the typical characteristics of a particular sensor. It may also be seen as an indicator of its errors. For this reason the PRNU value is regarded as a unique 'sensor fingerprint'.[13]

[8] J. Parzych, A. Hulewicz, Z. Krawiecki, *Matryce* światłoczułe *– właściwości, parametry, zastosowania*, "Electrical Engineering" 2017, no. 92, p. 190.

[9] R. Hornsey, *Noise in Image Sensors*, https://ece.uwaterloo.ca/~ece434/Winter2008/Noise.pdf, pp. 116–118 [access: 17 I 2019].

[10] P. Trusz, *Wybrane metody poprawy jakości obrazów i sekwencji wideo*, "Problemy Kryminalistyki" 2016, no. 294, p. 20.

[11] Ch. Meij, Z. Geradts, *Source camera identification using Photo Response Non-Uniformity on WhatsApp*, "Digital Investigation" 2018, no. 24, p. 144.

[12] M. Goljan, M. Chen, P. Comesaña, J. Fridrich, *Effect of Compression on Sensor-Fingerprint Based Camera Identification*, "Society for Imaging Science and Technology", 2016, p. 2.

[13] M. Goljan, J. Fridrich, T. Filler, *Large scale test of sensor…*, p. 2.

The image below shows the difference between the theoretical ideal characteristics of the value of a single pixel and the real value affected by the production process, recorded noise artifacts or exact reflection of colour intensity.

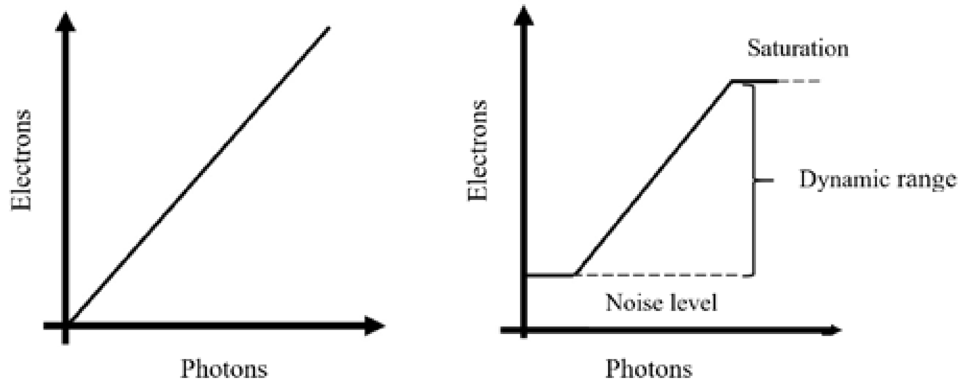


Image 2. Characteristics of ideal (left hand side) or real (right hand side) response of a pixel to lighting.

Source: Own study based on Hornsey R., Noise in Image Sensors, https://ece.uwaterloo.ca/~ece434/Winter2008/Noise.pdf [access: 17 I 2019].

As the PRNU value is a unique parameter of the sensor, it is possible to use it for tests aimed at the identification of a specific model of a camera. In order to do that it is necessary to specify the PRNU parameters for evidence photos, as well as natural and flat field reference photos, which were subsequently compared.[14] Based on the study results so far, the PRNU value for a photo may be described as:[15]

$$PRNU = I - F(I)$$

where:
I – analyzed graphic file,
F(I) – graphic file after removing the noise.

However, the algorithm that is characterized by the best results of noise extraction is FSTV (First Step Total Variation):[16]

[14] M. Brouwers, R. Mousa, *Automatic…*, p. 5.

[15] E. Alles, Z. Geradts, C. Veenman, *Source Camera…*, pp. 558–560.

[16] A. Khapare, D. Phalke, *Source Camera Based Image Retrieval From Internet Using Simplified Total Variation*, “International Journal of Advance Engineering and Research Development” 2017, no. 4, p. 423.

$$\mathrm{FSTV} = -\nabla\left(\frac{\nabla \mathrm{I}}{|\nabla \mathrm{I}|\varepsilon}\right)$$

where:
I – pixel intensity in a graphic file,
∇ – gradient operator,
ε – positive parameter implemented in order to avoid peculiarity.

The image below shows a comparison of a sample photo with a pre-determined noise pattern of the sensor and visible contours. PRNU was determined using the FSTV method.

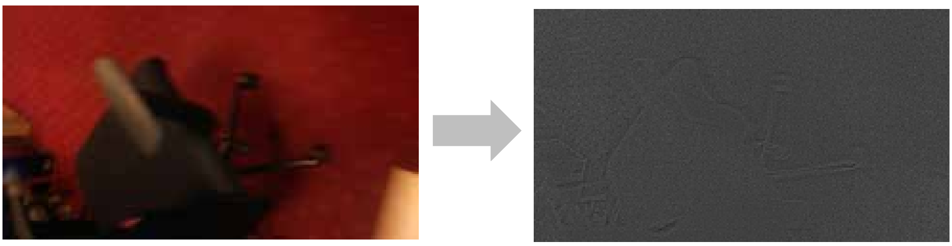


Image 3. Example of noise pattern extraction PRNU sensor.

Source: Own study based on https://foter.com/photo2/row-of-ancient-books/ [access: 12 I 2019].

Next, the resulting noise patterns for questioned (evidence) files and natural reference files, as well as questioned and Flat field reference files undergo comparative analysis using the PCE correlation method,[17] which is more effective than the Pearson coefficient:[18]

$$\mathrm{PCE} = \frac{p_{peak}^2}{\frac{1}{|s| - |\varepsilon|}\sum s \notin \varepsilon p_s^2}$$

where:

p – normalized cross corelation between the total noise pattern of the file and the noise pattern of the PRNU sensor,
s – map of subsequent p iterations,
p_{peak} – maximum value of p coefficient,
ε – region around the p_{peak} value,
|s| – |ε| – number of total iterations outsider.

[17] M. Goljan, M. Chen, P. Comesaña, J. Fridrich, *Effect of Compression…*

[18] M. Brouwers, R. Mousa, *Automatic…*, p. 3.

According to the results of the studies carried out so far[19] with regard to the PCE correlation coefficient there was no false positive result between the comparison of the patterns determined based on the analysis of evidence materials and natural reference, as well as evidence and flat field reference materials higher than 50.

Results of the examinations

Source camera identification based on photo-response non-uniformity (PRNU) noise sensor analysis was performed in accordance with the following methodology.[20]

1) analysis of the device's functionality and technical documentation,
2) taking questioned photos – 1 up to 3 graphic files,
3) taking reference photos (natural and flat field). Natural photos should be taken in conditions possibly closest to the production conditioned of the questioned photos,
4) analysis of the photos – i.a. analysis of formats consistency, vertical and horizontal resolution,
5) identification of sensor pattern noise for questioned photos,
6) identification of sensor pattern noise for reference photos – natural and flat field,
7) comparing PRNU pattern of the questioned photos with sensor pattern noise of the natural and flat field photos,
8) conclusions (individual).

One of the main assumptions of the methodology used for this study included using the same resolution for reference and questioned photos and using camera provided for examination together with other camera devices of the same model.[21] Therefore, at least a few devices of the same model must be used for the examination which makes a wider evaluation possible and enables performing a statistical study of the extracted data. It would not be possible with only one device. However, the analysis of photos with the same resolution is justified due to the PRNU noise distribution which can be characterized by repeatability between the subsequent graphic files (of the same dimension and analyzed with the same sensor type). Although it is possible to analyze images of different resolutions,[22] resulting from – for example, using a digital zoom

[19] M. Goljan, J. Fridrich, T. Filler, *Large scale test of sensor*…, p. 10.

[20] T. Baar, W. Houten, Z. Geradts, *Camera identification by grouping images from database, based on shared noise patterns*, ArXiv, 2012, pp. 2–4; M. Brouwers, R. Mousa, *Automatic*…, pp. 3–5.

[21] T. Baar, W. Houten, Z. Geradts, *Camera*…, p. 1; S. Georgievska, R., Bakhshi A. Gavai, A. Sclocco, B. Verkhoven, *Clustering Image Noise Patterns by Embedding and Visualization for Common Source Camera Detection*, "Digital Investigation" 2017, no. 23, p. 10.

[22] M. Goljan, J. Fridrich, *Camera Identification from Cropped and Scaled Images*, Proceedings of SPIE – The International Society for Optical Engineering, 2008, p. 8.

in graphics software or other editing – saving only a fragment of a digital file. This type of examination is not the subject of this study.

Identification tests were performed with 33 mobile devices of the following producers: LG Electronics Inc., Samsung Group and Apple Inc. List of devices used for examinations is presented in Table 1.

Table 1. List of used devices.

No.	Phone model	Camera model	Number of devices
1.	LG K4 2017	M160	12
2.	LG K4 LTE	K120E	6
3.	Samsung S5611	GT – S5611	6
4.	Apple iPhone 4s	iPhone 4s	4
5.	Samsung SM-B550H	B550H	5

Source: Own study.

First, 33 devices were used to take 69 questioned graphic files. One to three images were taken with each of the devices. Next, digital cameras were used to take 2667 reference graphic files, including 1299 natural images – of physical objects or nature. Other images (1368) were flat field. Table 2 presents numbers of taken reference images (natural and flat field) and questioned files including a specification of different camera models.

Table 2. List of devices used with a number of digital images.

<table>
<tr><th rowspan="2">No.</th><th rowspan="2">Phone model</th><th rowspan="2">Camera model</th><th rowspan="2">Designation</th><th colspan="2">Reference files</th><th rowspan="2">Number of taken questioned images</th></tr>
<tr><th>natural images</th><th>flat field images</th></tr>
<tr><td>1.</td><td>LG K4 2017</td><td rowspan="12">M160</td><td>LG K4 2017 1</td><td>46</td><td>44</td><td>3</td></tr>
<tr><td>2.</td><td>LG K4 2017</td><td>LG K4 2017 2</td><td>45</td><td>37</td><td>3</td></tr>
<tr><td>3.</td><td>LG K4 2017</td><td>LG K4 2017 3</td><td>39</td><td>43</td><td>1</td></tr>
<tr><td>4.</td><td>LG K4 2017</td><td>LG K4 2017 4</td><td>45</td><td>55</td><td>2</td></tr>
<tr><td>5.</td><td>LG K4 2017</td><td>LG K4 2017 5</td><td>43</td><td>46</td><td>2</td></tr>
<tr><td>6.</td><td>LG K4 2017</td><td>LG K4 2017 6</td><td>41</td><td>38</td><td>1</td></tr>
<tr><td>7.</td><td>LG K4 2017</td><td>LG K4 2017 7</td><td>47</td><td>53</td><td>3</td></tr>
<tr><td>8.</td><td>LG K4 2017</td><td>LG K4 2017 8</td><td>37</td><td>41</td><td>2</td></tr>
<tr><td>9.</td><td>LG K4 2017</td><td>LG K4 2017 9</td><td>43</td><td>44</td><td>2</td></tr>
<tr><td>10.</td><td>LG K4 2017</td><td>LG K4 2017 10</td><td>38</td><td>40</td><td>3</td></tr>
<tr><td>11.</td><td>LG K4 2017</td><td>LG K4 2017 11</td><td>44</td><td>62</td><td>2</td></tr>
<tr><td>12.</td><td>LG K4 2017</td><td>LG K4 2017 12</td><td>42</td><td>52</td><td>3</td></tr>
</table>

13.	LG K4 LTE		LG K4 LTE 1	42	44	2
14.	LG K4 LTE		LG K4 LTE 2	48	46	3
15.	LG K4 LTE	K120E	LG K4 LTE 3	48	53	1
16.	LG K4 LTE		LG K4 LTE 4	33	17	2
17.	LG K4 LTE		LG K4 LTE 5	48	52	3
18.	LG K4 LTE		LG K4 LTE 6	45	42	2
19.	Samsung S5611		Samsung S5611 1	44	50	3
20.	Samsung S5611		Samsung S5611 2	44	84	1
21.	Samsung S5611	GT–S5611	Samsung S5611 3	42	45	3
22.	Samsung S5611		Samsung S5611 4	43	43	2
23.	Samsung S5611		Samsung S5611 5	42	43	1
24.	Samsung S5611		Samsung S5611 6	43	46	3
25.	Apple iPhone 4s		Apple iPhone 4s 1	15	19	1
26.	Apple iPhone 4s	Iphone 4s	Apple iPhone 4s 2	14	21	3
27.	Apple iPhone 4s		Apple iPhone 4s 3	16	14	1
28.	Apple iPhone 4s		Apple iPhone 4s 4	19	18	3
29.	Samsung SM-B550H		Samsung SM -B550H 1	47	45	1
30.	Samsung SM-B550H		Samsung SM -B550H 2	38	42	3
31.	Samsung SM-B550H	B550H	Samsung SM -B550H 3	59	36	1
32.	Samsung SM-B550H		Samsung SM -B550H 4	55	36	2
33.	Samsung SM-B550H		Samsung SM -B550H 5	44	46	3

Source: Own study.

Photos were taken with standard camera settings – without using flash, without changing resolution of the graphic file, without any color correction or any other changes. Photos after being taken, the same as after being uploaded to the analyzing computer's drive, were not edited. Examples of a reference, flat field and questioned image are presented in Image no 4.

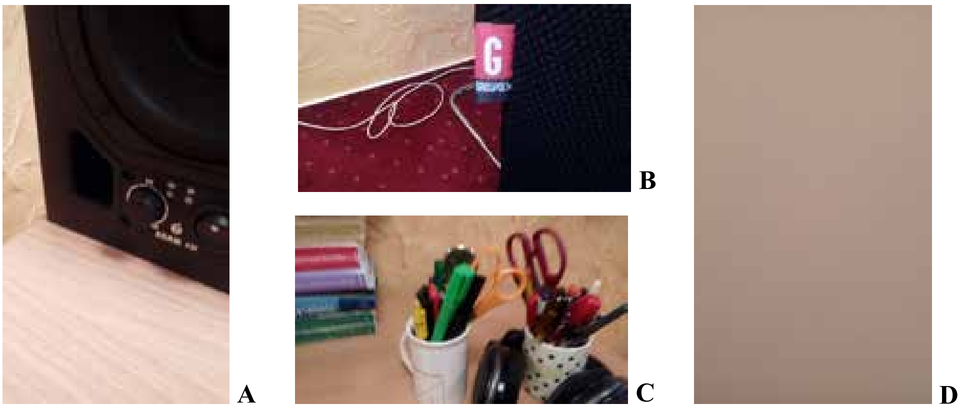


Image 4. Examples of photos – camera used M160 (LG K4 2017) A) questioned image, B) natural referene image, C) natural reference image, D) flat field.

Source: Own study.

The next task was to extract sensor pattern noise for the questioned, natural and flat field images. Each unit of the tested camera was given three sensor noise patterns. For example, in order to calculate PRNU parameters for K120E (LG K4 LTE 4) camera (no. 16 in Table 2) sensor pattern noise for natural images was calculated based on an analysis of 33 files, flat field – 17 photos and for questioned photos two files were taken into consideration. Consequently, 99 sensor noise patterns were identified for all of the analyzed devices. Subsequently, PRNU patterns identified for the questioned files were compared with patterns identified for reference images. Correlation method was used in this comparative analysis in order to identify a PCE correlation coefficient. In accordance with the assumptions made for this methodology, comparisons were made in respect of the same device model. Therefore five comparative tests were performed for this examination.

Test 1 – 288 comparative analyses (for all LG K4 2017 devices) between the PRNU pattern of the questioned material and patterns identified in the analysis of the reference files.

Test 2 – 72 comparative analysis (for all LG K4 LTE devices) between the PRNU pattern of the questioned material and patterns identified in the analysis of the reference files.

Test 3 – 72 comparative analyses (for all Samsung S5611 devices) between the PRNU pattern of the questioned material and patterns identified in the analysis of the reference files.

Test 4 – 32 comparative analysis (for all iPhone 4s devices) between the PRNU pattern of the questioned material and patterns identified from in analysis of the reference files.

Test 5 – 50 comparative analyses (for all Samsung SM-B550H devices) between the PRNU pattern of the questioned material and patterns identified in the analysis of the reference files.

As a result, PCE correlation coefficient between individual comparisons was identified, decisive parameter was defined at the level PCE>50. The tests were aimed at analyzing the obtained results and examining the potential false positive indications for any of the examples.

The results of the performed examination are presented in Table 3–7. Grey color indicates correct indications, meaning those for which PRNU patterns of the reference and questioned images were identified in the result of performed noise analyses of the same sensor.

Table 3. Results of comparative analyses for LG K4 2017 telephone equipped with M160 camera.

PCE coefficent values / Device		LG K4 2017 1	LG K4 2017 2	LG K4 2017 3	LG K4 2017 4	LG K4 2017 5	LG K4 2017 6	LG K4 2017 7	LG K4 2017 8	LG K4 2017 9	LG K4 2017 10	LG K4 2017 11	LG K4 2017 12	Standard deviation (without correct indication)
Comparison 1	*flat field images*	1354,261	10,028	1,143	0,0002	1,579	3,222	6,192	6,676	0,081	1,585	0,404	0,00003	3,37
Comparison 2		0,025	17125,521	0,596	3,7495	0,004	1,879	0,036	1,482	1,466	0,215	2,877	0,06299	1,29
Comparison 3		0,022	0,636	13375,152	2,7014	0,168	1,478	0,142	2,052	0,042	0,065	2,829	2,46807	1,17
Comparison 4		1,007	0,902	1,108	2376,8987	0,502	0,367	0,091	2,325	4,820	2,556	1,856	1,69841	1,34
Comparison 5		0,811	1,595	1,434	0,0090	1543,855	0,202	5,971	1,536	2,273	0,263	2,157	0,20228	1,69
Comparison 6		0,716	1,038	7,395	0,2367	1,229	19312,066	0,808	3,069	1,829	1,769	5,568	0,49722	2,29
Comparison 7		0,001	0,008	1,823	1,7285	0,366	0,445	20451,871	1,508	0,094	2,921	0,531	0,15879	0,97
Comparison 8		0,017	4,711	0,355	-0,0160	0,273	0,158	-0,521	17719,270	2,364	0,268	15,046	0,68345	4,54
Comparison 9		9,399	0,165	0,143	0,0216	0,781	5,718	0,119	6,818	13956,747	9,629	0,602	0,03608	4,00
Comparison 10		0,000	10,597	-0,069	6,2096	0,171	1,718	1,327	0,842	1,805	5705,416	0,322	3,30557	3,29
Comparison 11		2,511	0,166	0,218	2,3809	0,980	10,642	0,052	-0,003	0,072	11,573	10173,549	0,14637	4,30
Comparison 12		1,357	-0,233	0,747	0,4905	0,424	4,126	0,433	1,480	0,177	2,611	1,351	7672,94800	1,25
Comparison 1	natural images	1772,177	0,097	4,262	1,3813	0,226	0,001	1,209	5,862	0,254	0,000	-0,393	0,17939	2,02
Comparison 2		1,523	12059,578	0,285	6,9235	0,677	0,384	0,639	7,340	4,991	0,132	1,864	0,10612	2,78
Comparison 3		0,658	1,712	7225,095	0,7920	0,211	2,134	0,204	0,755	0,045	1,359	0,604	1,31464	0,67
Comparison 4		0,130	3,090	0,625	2291,2754	0,446	2,023	1,386	0,721	0,375	0,154	1,064	1,20034	0,89
Comparison 5		0,605	0,939	2,801	0,0014	2305,993	0,500	1,517	0,888	0,519	2,494	1,485	0,00096	0,93
Comparison 6		0,082	1,931	0,731	0,0222	0,338	18664,574	1,879	8,465	3,078	5,441	0,772	-0,00017	2,69

PCE coefficent values / Device		LG K4 2017 1	LG K4 2017 2	LG K4 2017 3	LG K4 2017 4	LG K4 2017 5	LG K4 2017 6	LG K4 2017 7	LG K4 2017 8	LG K4 2017 9	LG K4 2017 10	LG K4 2017 11	LG K4 2017 12	Standard deviation (without correct indication)
Comparison 7		0,600	3,945	0,749	2,5839	0,025	3,159	9465,447	0,412	1,328	2,147	4,323	0,47503	1,52
Comparison 8		0,299	0,131	4,648	-0,0118	0,074	2,983	0,097	10223,801	0,818	0,004	5,494	2,39438	2,03
Comparison 9		3,981	0,089	4,254	1,9249	0,236	1,231	1,524	0,122	11738,666	4,337	-0,083	0,92259	1,73
Comparison 10		0,067	3,088	0,414	6,9475	2,826	0,452	1,251	0,011	6,592	6372,965	0,586	0,55665	2,54
Comparison 11		2,202	2,090	0,097	1,9570	0,395	0,783	0,001	0,349	5,807	1,776	6006,981	7,23412	2,37
Comparison 12		0,205	0,036	0,853	0,0007	0,713	0,643	0,048	1,285	0,325	3,618	0,133	3873,79170	1,05

Source: Own study.

Table 4. Results of comparative analyses for LG K4 LTE telephone equipped with K120E camera.

PCE coefficent values / Device		LG K4 LTE 1	LG K4 LTE 2	LG K4 LTE 3	LG K4 LTE 4	LG K4 LTE 5	LG K4 LTE 6	Standard deviation (without correct indication)
Comparison 1	images *flat field*	6748,33	8,91	8,35	7,68	13,54	11,82	2,51
Comparison 2		10,28	1370,06	2,90	5,09	4,25	9,50	3,29
Comparison 3		7,76	0,86	32123,02	2,66	1,24	2,85	2,76
Comparison 4		0,30	5,06	8,84	2487,70	1,91	11,26	4,59
Comparison 5		0,95	2,17	8,55	4,50	18505,29	7,65	3,32
Comparison 6		6,01	2,67	15,60	4,00	7,40	10366,64	5,07

PCE coefficent values \ Device		LG K4 LTE 1	LG K4 LTE 2	LG K4 LTE 3	LG K4 LTE 4	LG K4 LTE 5	LG K4 LTE 6	Standard deviation (without correct indication)
Comparison 7	natural images	1596,58	1,13	7,63	1,74	10,89	15,10	5,98
Comparison 8		3,28	683,51	0,44	7,29	1,63	5,66	2,82
Comparison 9		3,52	3,75	13693,58	5,91	1,21	0,02	2,31
Comparison 10		1,97	8,95	10,57	1594,43	3,56	0,56	4,40
Comparison 11		0,63	1,18	6,92	2,45	10215,60	2,94	2,47
Comparison 12		0,69	3,18	4,48	0,04	12,75	10042,90	5,09

Source: Own study.

Table 5. Results of comparative analyses for Samsung S5611 telephone equipped with GT–S5611 camera.

PCE coefficent values \ Device		Samsung S5611 1	Samsung S5611 2	Samsung S5611 3	Samsung S5611 4	Samsung S5611 5	Samsung S5611 6	Standard deviation (without correct indication)
Comparison 1	images *flat field*	11428,041	0,743	6,562	4,870	3,608	-0,015	2,77
Comparison 2		4,547	9243,641	2,233	0,745	16,065	2,006	6,27
Comparison 3		0,808	7,206	8818,944	3,980	1,006	0,003	2,98
Comparison 4		10,028	3,189	0,042	12826,950	9,095	6,493	4,16
Comparison 5		1,390	9,714	9,850	15,717	11464,295	4,765	5,47
Comparison 6		5,409	2,040	1,890	10,644	10,356	10334,404	4,28

PCE coefficent values \ Device		Samsung S5611 1	Samsung S5611 2	Samsung S5611 3	Samsung S5611 4	Samsung S5611 5	Samsung S5611 6	Standard deviation (without correct indication)
Comparison 1	natural images	10540,928	1,515	3,002	3,202	0,673	1,413	1,09
Comparison 2		13,777	9112,986	0,863	1,617	7,227	5,740	5,19
Comparison 3		4,687	1,103	12389,146	0,087	2,206	-0,164	1,97
Comparison 4		3,975	0,064	0,567	9740,520	10,196	4,073	4,04
Comparison 5		4,008	0,247	1,700	6,241	9534,318	0,014	2,65
Comparison 6		0,107	0,969	1,700	6,849	1,134	8524,820	2,69

Source: Own study.

Table 6. Results of comparative analyses for iPhone 4s telephone equipped with a camera.

PCE coefficent values \ Device		iPhone 4s 1	iPhone 4s 2	iPhone 4s 3	iPhone 4s 4	Standard deviation (without correct indication)
Comparison 1	images *flat field*	797,75	1,28	0,10	5,23	2,69
Comparison 2		5,08	1515,25	0,51	8,24	3,89
Comparison 3		2,92	0,47	1964,23	2,12	1,25
Comparison 4		2,25	1,98	0,25	3559,47	0,19

PCE coefficent values \ Device		iPhone 4s 1	iPhone 4s 2	iPhone 4s 3	iPhone 4s 4	Standard deviation (without correct indication)
Comparison 1	natural images	3836,86	0,26	0,77	1,00	0,38
Comparison 2		3,25	4587,56	2,65	4,23	0,80
Comparison 3		4,24	0,58	2658,12	0,58	2,11
Comparison 4		1,36	2,23	0,01	8654,98	0,62

Source: Own study.

Table 7. Comparative test results for the Samsung SM-B550H phone equipped with B550H camera.

PCE coefficent values \ Device		Samsung SM-B550H 1	Samsung SM-B550H 2	Samsung SM-B550H 3	Samsung SM-B550H 4	Samsung SM-B550H 5	Standard deviation (without correct indication)
Comparison 1	images *flat field*	7210,396	3,262	2,055	0,099	1,125	1,35
Comparison 2		0,044	12141,655	0,003	0,539	0,829	0,40
Comparison 3		0,001	0,600	4065,450	6,942	0,233	3,34
Comparison 4		0,043	0,237	0,211	14658,395	0,002	0,12
Comparison 5		0,070	1,175	0,496	1,494	7983,906	0,64
Comparison 1	natural images	4986,918	0,259	0,831	8,479	4,713	3,82
Comparison 2		1,960	5758,262	0,509	1,884	0,189	0,92
Comparison 3		0,240	-0,084	3294,110	0,112	0,014	0,14
Comparison 4		0,456	1,049	12,430	6445,446	3,269	6,75
Comparison 5		0,485	0,289	0,487	1,097	8548,546	0,35

Source: Own study.

When analyzing the results it should be noted that – according to the adopted identification criterion (coefficient PCE > 50 false positive results were not obtained. Over half of the negative results (> 55%) are within the PCE correlation coefficient from 0 to 3. Standard deviations for each comparison group (excluding positive results) show similarity, not exceeding the PCE value of 7. These images are lower by several orders of magnitude compared to the positive ones. The highest negative result for all tests performed was PCE 15,717, a result of comparing the sensor pattern noise of the questioned material and the PRNU pattern determined on the basis of flat field photographs (GT-S5611 camera, comparison 5). On the other hand, the positive result for this analysis was PCE 11464.295. Thus, the positive result was by three orders of magnitude higher than the highest negative result.

Chart 1–7 present examples of comparative results between PRNU patterns of questioned and reference files.

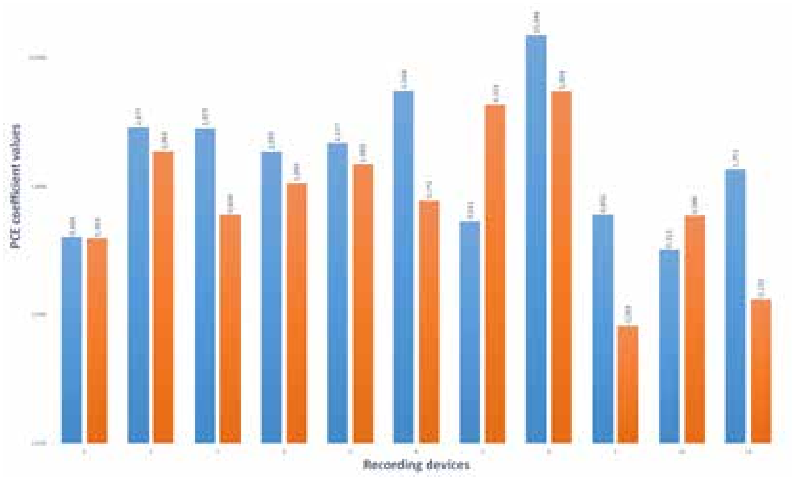


Chart 1. The results of the comparison of the questioned material pattern produced with the LG K4 2017 no. 12 camera with two patterns of reference images (natural photos orange colour and flat field blue colour) taken with 11 different LG K4 2017 phones. Among the reference pictures there were no files taken with the camera no. 12.

Source: Own study.

Chart 1 shows the results of the comparison of the questioned material – PRNU pattern was determined on the basis of the analysis of three photographs – taken with the M160 LG K4 2017 camera with 22 samples of sensor pattern noise calculated based on the reference photographs taken with 11 LG K4 2017 devices. Among the analyzed reference patterns there was no sensor pattern noise in the camera that took the questioned files. When analyzing the obtained results attention should be given to the very small spread of the received data. The standard deviation determined for comparisons of the PRNU patterns of questioned files and natural photographs is 1.775, while for flat field – 4.269. The analysis of the results obtained in this way does not provide any basis for indicating any of the analyzed devices as the one that was in all likelihood used to take the questioned photographs.

Charts 2–3 show examples of comparative results between sensor pattern noise determined for questioned and natural photographs (blue colour) and questioned and flat field (orange colour). The presented comparative analyses include, among the group of reference materials, a PRNU device pattern which was used to take the questioned photos.

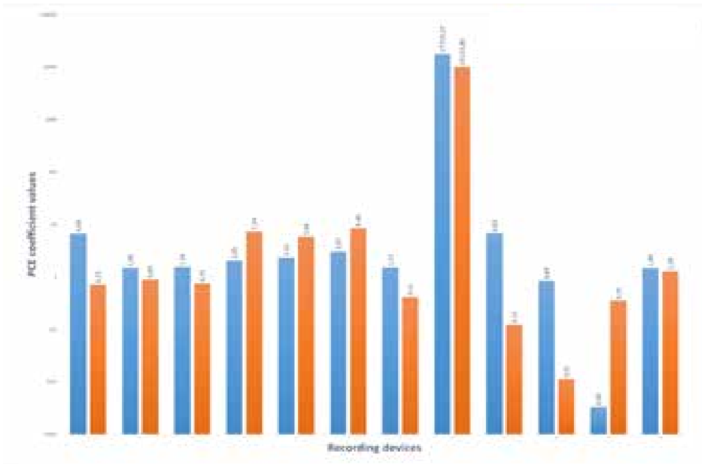


Chart 2. The results of the comparison of the questioned material pattern produced with one of the M160 cameras (item 8, table 2) with two patterns of reference images (natural photos orange colour and flat field blue colour) taken with 12 LG K4 2017 phones.

Source: Own study.

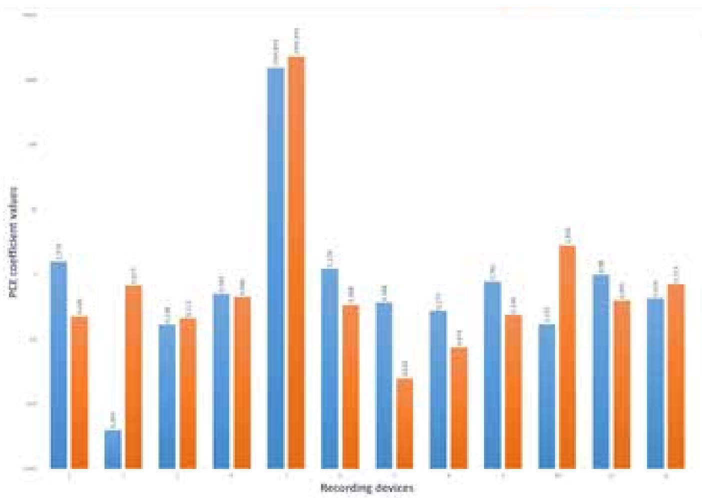


Chart 3. The results of the comparison of the questioned material pattern produced with one of the M160 cameras (item 5, table 2) with two patterns of reference images (natural photos orange colour and flat field blue colour) taken with 12 LG K4 2017 phones.

Source: Own study.

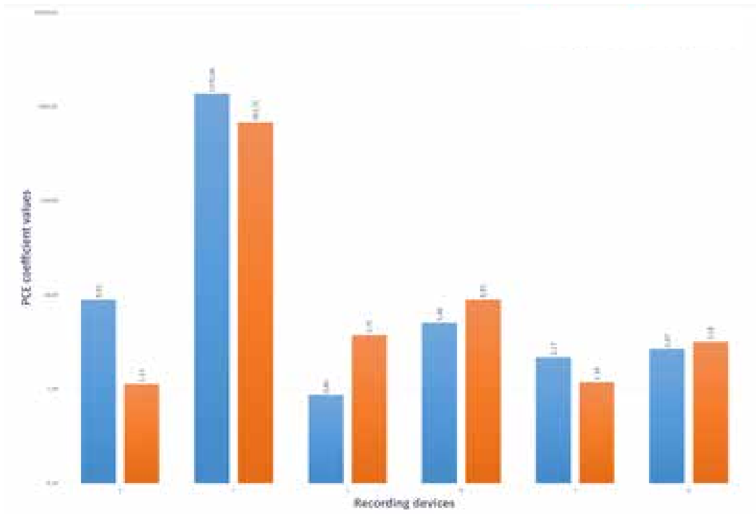


Chart 4. The results of the comparison of the questioned material pattern produced with one of the K120E cameras (item 15, table 2) with two patterns of reference images (natural photos orange colour and flat field blue colour) taken with 6 LG K4 LTE phones.

Source: Own study.

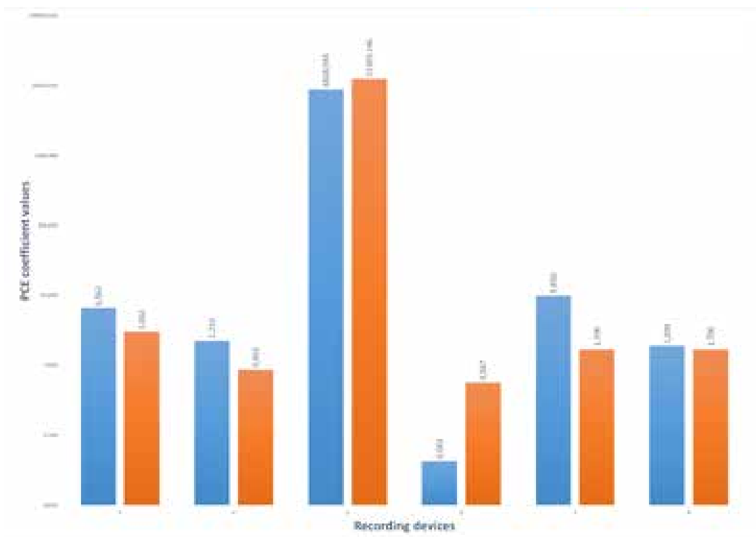


Chart 5. The results of the comparison of the questioned material pattern produced with one of the GT-S5611 cameras (item 22, table 2) with two patterns of reference images (natural photos orange colour and flat field blue colour) taken with 6 Samsung S5611 Utopia phones.

Source: Own study.

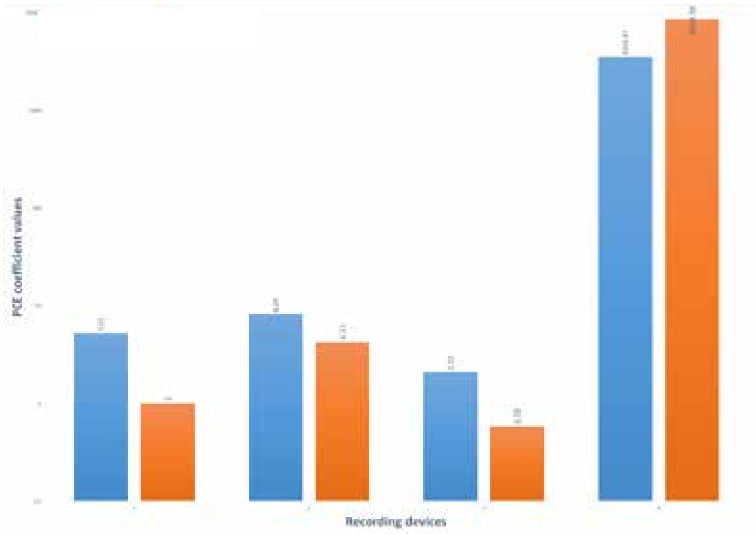


Chart 6. The results of the comparison of the questioned material pattern produced with one of the iPhone 4s cameras (item 26, table 2) with two patterns of reference images (natural photos orange colour and flat field blue colour) taken with 4 iPhone 4s phones.

Source: Own study.

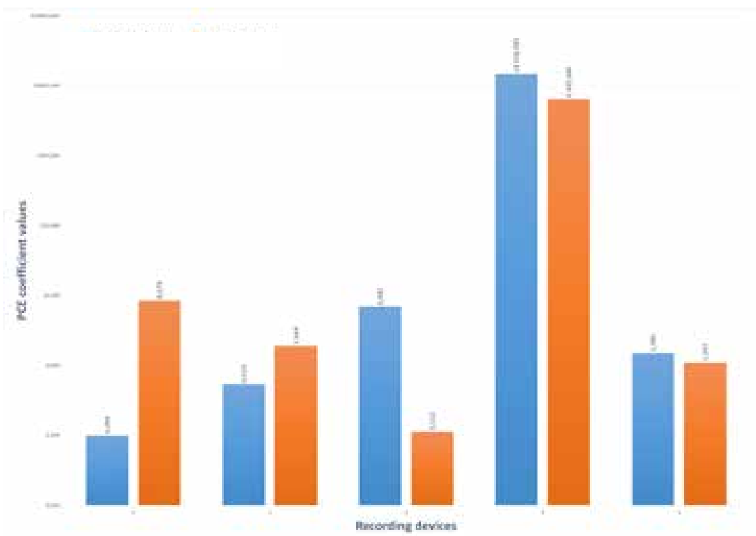


Chart 7. The results of the comparison of the questioned material pattern produced with one of the B550H cameras (item 31, table 2) with two patterns of reference images (natural photos orange colour and flat field blue colour) taken with 5 Samsung SM-B550H phones.

Source: Own study.

Charts 2–7 show examples of comparative analysis results for each of the tested models of digital cameras. It should be noted that the PCE coefficient values for negative results were at a similar level. On the other hand, positive results (correct assignment of the questioned material pattern to the reference pattern) were characterized by values greater by at least three orders of magnitude compared to the false results.

Conclusions

The results of the experiments show that the individual identification of the camera is possible thanks to the PRNU method. However, in order to achieve this, it is necessary to fulfil several criteria. First of all, the analysis has to be carried out on the device used to take a questioned photograph, as well as other cameras of the same model. Secondly, it is necessary to take several dozen natural reference pictures with the content similar to the evidence picture and flat field images with all available models of cameras. What is more, the analyzed photographs have to be of converging technical parameters, it is permissible, among others, to take reference photos using optical zoom, whereas using digital zooming is not allowed in comparative studies.

While performing tests, the sensor pattern noise was determined for over 2.5 thousand graphic files. The questioned and reference photographs were taken with 33 mobile phones. The obtained sensor pattern noise data was compared in the next stage with each other to observe the PCE correlation coefficient. No false positives were obtained in any of the 514 comparisons carried out. PCE higher than 50 was marked as a valid identification criterion (the highest negative result was PCE 15.717). The analyzed photographs were taken at the default resolution and were not edited. What is more, the comparative studies were carried out including only a given model of camera taking the utmost account of the analysis of the individual features of the photographic sensor, which include the PRNU noise pattern.

During the analysis of the results no regularity in the form of an increased PCE correlation coefficient between the evidence material and a specific type of reference photographs was observed. There were cases in which these values were characterized by higher correlation coefficients between PRNU patterns for questioned and natural photographs, e.g. the analysis of files from the LG K4 2017 equipped with M160 camera (comparison 1) and *vice versa* (camera GT-S5611, comparison 4). In view of the above, it can be assumed that the analysis of files in the questioned-natural set and questioned-flat field are justified, and the obtained results are closely related to a specific sensor implemented in the camera.

Despite the satisfactory results, the issue of interference on the basis of the received data remains open. Considering the fact that this type of research represents qualitative analysis, the evaluation of the results is individual for each case. According to the present state of knowledge, it is not possible to unequivocally indicate, with 100% certainty, a specific sensor model, even though according to the previously performed tests the PRNU pattern represents a unique value. This stems especially from the fact that there are thousands of phone and camera models available on the market, which in combination with thousands and often even millions of devices of one type gives the amount of data that is impossible to analyze.