Single-Sensor Camera Image Compression

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**Abstract — ***This paper presents digital camera image compression solutions suitable for the use in single-sensor consumer electronic devices equipped with the Bayer color filter array (CFA). The proposed solutions code camera images available either in the CFA format or as the full-color demosaicked data, thus offering different design characteristics, performance and computational efficiency. Extensive experimentation reported in this paper indicates that pipelines which employ a JPEG 2000 coding scheme achieve significant performance improvements compared to similar processing pipelines equipped with a JPEG coder. Other improvements, both objective and subjective, are observed in terms of color appearance, image sharpness and the presence of visual artifacts in the captured images.*[1]

Index Terms — Image-enabled consumer electronics, single-sensor imaging, Bayer pattern, camera image compression, color filter array interpolation, demosaicking.

I. INTRODUCTION

Single-sensor imaging constitutes a cost-effective tool to capture the visual scene. This approach is widely used in consumer electronic devices [1]-[5], such as digital still and video cameras, image-enabled mobile phones, and wireless personal digital assistants (PDAs). To overcome the monochromatic nature of the single image sensor, usually a charge-coupled device (CCD) [6] or complementary metal oxide semiconductor (CMOS) [7] sensor, a color filter array (CFA) [8] is placed on top of the sensor. Since each sensor cell has its own spectrally selective filter, the acquired CFA values constitute a mosaic-like gray-scale image [8],[9], thus requiring the so-called demosaicking process to restore the full-color information (Fig. 1) [8]-[13].

Typical consumer cameras use the demosaicking process as part of the processing pipeline implemented in the camera hardware/software. The demosaicked images are usually stored in a compressed format using the Joint Photographic Experts Group (JPEG) standard. In addition to the image data, the metadata information about the camera and the environment is added to the compressed file using the Exchangeable Image File (EXIF) format [14]. The image file-recording format is strictly based on existing formats used by commercial applications to utilize available functions for viewing and manipulating the images. Uncompressed RGB data is recorded in conformance with baseline TIFF 6.0 for RGB full-color images. The EXIF standard can also record uncompressed YCbCr data by following TIFF 6.0 extensions for YCbCr images. In this mode, the image data is stored along with additional information about the RGB to YCbCr color transformation matrix coefficients, chrominance sub-sampling, and matching/non-matching of chrominance and luminance samples. Finally, in the most popular EXIF mode the images are compressed using the JPEG adaptive discrete cosine transformation (ADCT) format [14],[15].

Apart from the EXIF driven devices, there also exist digital cameras which store the acquired CFA image using the Tagged Image File Format for Electronic Photography (TIFF-EP) [16] along with metadata information about camera setting, spectral sensitivities and used illuminant. The uncompressed image data is recorded in conformance with the TIFF 6.0 specification, whereas essential compression is usually obtained using the JPEG DCT scheme. Although TIFF-EP supports the recording of the image data in the (lossy or lossless) JPEG-DCT compression format, or using other JPEG versions, or even in a vendor unique compression format; the current standard mainly supports baseline (lossy DCT) based compression to allow the reading of the camera image by commercial applications [16]. In the JPEG-DCT format, the use of lossy compression may require to store the information about JPEG quantization and Huffman coding tables. For lossless JPEG compression, the standard recommends the use of lossless sequential Differential Pulse Code Modulation (DPCM) along with Huffman coding. The demosaicking process is performed off-camera using a companion personal computer (PC) which interfaces with the TIFF-EP-driven camera [9].

Both EXIF and TIFF-EP are made to be as compatible as possible by unifying the tags' definitions. For example, the tags are used to indicate image data format, color space information, camera and lens setting, CFA type, and camera characterization. The tag-fields are readable by dedicated PC software. The annotation of the captured image by storing the metadata information about the date/time, location, semantic information, authorship and copyright is also supported. This so-called picture information can support the digital rights management (DRM) operations and it can be also used to organize and retrieve the digital photographs in personal and public image databases [17]. Note that the EXIF specification allows also the inclusion of an audio file format enabling the recording of audio as a supplementary function and indicating the relation between image and audio files [14].

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Contributed Paper
Manuscript received December 19, 2005

0098 3063/06/$20.00 © 2006 IEEE

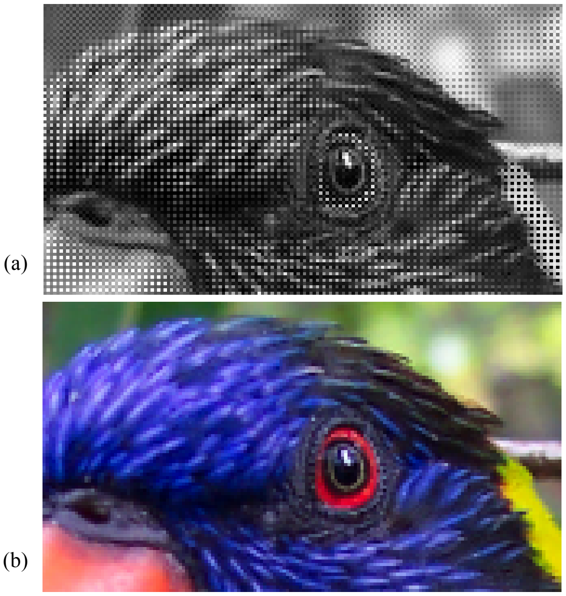


Fig. 1. Bayer CFA-based single-sensor imaging: (a) mosaic-like gray-scale CFA image, (b) demosaicked full-color image.

This paper deals with compression of the captured images using JPEG and JPEG 2000. Although various lossless and near-lossless image compression solutions have been recently proposed in [2],[18]-[21], the above EXIF/TIFF-EP overview revealed that camera manufacturers mainly rely on lossy JPEG-type compression applied either to the full-color demosaicked image or to the grayscale CFA data. Since compression of the CFA image allows the transmission of significantly less information compared to the full-color image compression, it is expected that CFA-oriented compression methods [18]-[25] may be of great interest in wireless image-enabled devices. Furthermore, JPEG 2000 has been established as a new standard for still image compression [26] and used as the replacement of the previous JPEG coder in a wide range of image processing applications [27]. It is therefore expected that overcoming the difficulties with the computational complexity and memory requirements, JPEG 2000 will be employed in the next generation of digital cameras. Moreover, since JPEG 2000 supports different metadata information, its inclusion in both EXIF and TIFF-EP formats should offer new possibilities for various computer vision and multimedia applications based on single-sensor consumer electronic devices.

Some initial research effort has been devoted to the utilization of JPEG 2000 in single-sensor imaging and evaluation of the image compression efficiency [18],[19],[25],[28]. However, there is no known study addressing the performance issues with respect to the quality of the decoded demosaicked image. Since the demosaicked images are used for displaying, printing, and storage at the final stage of the single-sensor processing pipeline (Fig. 2), the analysis of the visual quality of the decoded and demosaicked image from the end-user perspective is even more emergent. To this end, this paper presents three camera image processing pipelines suitable for coding of the CFA images or demosaicked full-color images. Furthermore, four state-of-the-art demosaicking solutions and two (JPEG, JPEG 2000) coding schemes are used to demonstrate the influence of both demosaicking and image compression at various compression ratios on the sharpness, color appearance and the presence of visual artifacts in the captured images.

The rest of this paper is organized as follows. Section II introduces single-sensor image compression solutions. Motivation and design characteristics are discussed in detail. In Section III, the proposed camera image processing solutions are tested using a number of color images, and various demosaicking and coding schemes. Evaluations of performance, both objective and subjective, are provided. Finally, conclusions are drawn in Section IV.

II. SINGLE-SENSOR CAMERA IMAGE COMPRESSION

In a single-sensor digital camera, the captured image can be stored either in the CFA format (Fig. 1a) or as the demosaicked full color image (Fig. 1b). As shown in Fig. 2, the storage format denotes the order of the demosaicking and image compression steps. Thus, it essentially determines both the design and performance characteristics of the single-sensor imaging pipeline.

A. Demosaicked Image Compression

Compression of a demosaicked image represents a typical approach implemented in the consumer-grade camera. Built on the advances of color image processing, the camera manufacturers use conventional color image compression methods [14],[26]-[28] to reduce redundancy in the full-color image data (Fig. 1b) obtained using the demosaicking process. Note that in-camera processing is usually performed using sub-optimal methods because of the real-time constraints imposed on the processing solution.

Although comfortable to use, compression of demosaicked images directly in the digital camera can be counterproductive [2],[23]. Demosaicking triples the amount of the data to be compressed by populating the two missing color components at each spatial location of the acquired gray-scale CFA image. Since color image compression aims to de-correlate the image data, the solution shown in Fig. 2a may reduce compression ratios to be possibly achieved and increase the computational complexity.

B. CFA Image Compression

High-end single-sensor cameras store the captured image directly in the CFA image format. Compressing the CFA data before demosaicking can achieve the acceptable visual quality at high compression ratios [18]-[25]. By decompressing the CFA image in its original quality or with a small compression error, the end-user can obtain a high-quality demosaicked image by running computationally expensive, sophisticated demosaicking algorithms using a companion PC. Therefore, the solution shown in Fig. 2b is suitable for both

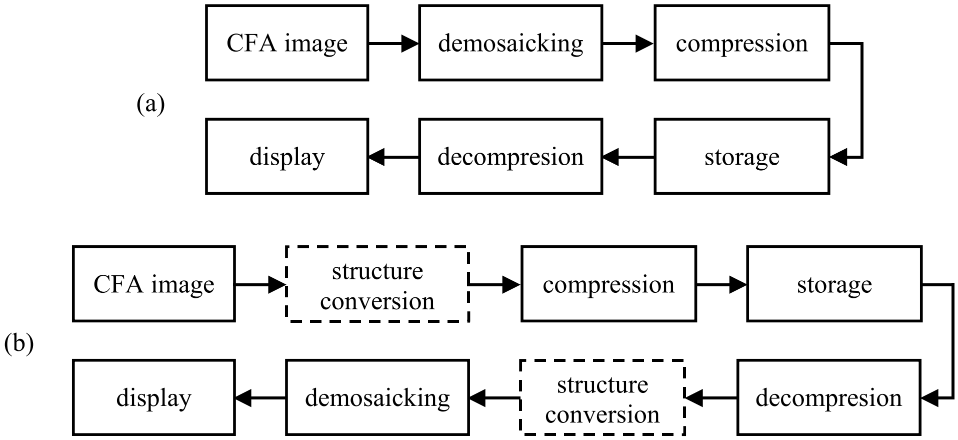
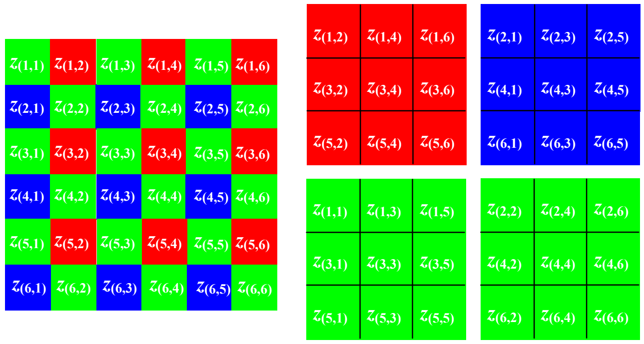


Fig. 2. Single-sensor camera image compression solutions: (a) demosaicked image compression, (b) CFA image compression. Note that the coding scheme in (b) can be either applied directly to the CFA image or it may optionally request the structure conversion prior to image compression.



$z_{(1,1)}$	$z_{(1,2)}$	$z_{(1,3)}$	$z_{(1,4)}$	$z_{(1,5)}$	$z_{(1,6)}$
$z_{(2,1)}$	$z_{(2,2)}$	$z_{(2,3)}$	$z_{(2,4)}$	$z_{(2,5)}$	$z_{(2,6)}$
$z_{(3,1)}$	$z_{(3,2)}$	$z_{(3,3)}$	$z_{(3,4)}$	$z_{(3,5)}$	$z_{(3,6)}$
$z_{(4,1)}$	$z_{(4,2)}$	$z_{(4,3)}$	$z_{(4,4)}$	$z_{(4,5)}$	$z_{(4,6)}$
$z_{(5,1)}$	$z_{(5,2)}$	$z_{(5,3)}$	$z_{(5,4)}$	$z_{(5,5)}$	$z_{(5,6)}$
$z_{(6,1)}$	$z_{(6,2)}$	$z_{(6,3)}$	$z_{(6,4)}$	$z_{(6,5)}$	$z_{(6,6)}$

(a)

$z_{(1,2)}$	$z_{(1,4)}$	$z_{(1,6)}$	$z_{(2,1)}$	$z_{(2,3)}$	$z_{(2,5)}$
$z_{(3,2)}$	$z_{(3,4)}$	$z_{(3,6)}$	$z_{(4,1)}$	$z_{(4,3)}$	$z_{(4,5)}$
$z_{(5,2)}$	$z_{(5,4)}$	$z_{(5,6)}$	$z_{(6,1)}$	$z_{(6,3)}$	$z_{(6,5)}$
$z_{(1,1)}$	$z_{(1,3)}$	$z_{(1,5)}$	$z_{(2,2)}$	$z_{(2,4)}$	$z_{(2,6)}$
$z_{(3,1)}$	$z_{(3,3)}$	$z_{(3,5)}$	$z_{(4,2)}$	$z_{(4,4)}$	$z_{(4,6)}$
$z_{(5,1)}$	$z_{(5,3)}$	$z_{(5,5)}$	$z_{(6,2)}$	$z_{(6,4)}$	$z_{(6,6)}$

(b)

Fig. 3. CFA pixel arrangement in the Bayer CFA: (a) before structure conversion, (b) after structure conversion.

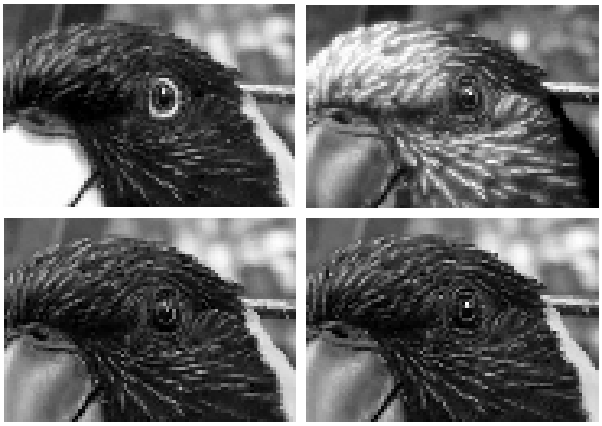


Fig. 4. Structure conversion applied to the CFA image shown in Fig. 1a. The sub-images' order follows the arrangement in Fig. 3b.

consumer and professional digital photography, as well as emerging applications such as digital cinema, astronomy and medical imaging.

Apart from high-end cameras, CFA image compression is of paramount importance to image-enabled consumer electronic devices, such as wireless PDAs, mobile phones, and surveillance systems. Since bandwidth reduction is crucial for transmission of captured images in wireless networks, compression of the CFA data rather than the demosaicked data basically allows a three-fold reduction of the information to be transmitted. On the other hand, operating on the CFA pixels arranged in the original mosaic layout may limit the compression efficiency due to the artificial high frequencies in the CFA image (Fig. 1a).

C. CFA Image Compression Using Structure Conversion

To overcome the mosaic-like structure of the acquired CFA data and further increase the CFA image coding efficiency, a CFA data structure conversion should be used prior to image compression (Fig. 2b). The structure conversion step transforms the CFA pixels corresponding to the same color filters into a structure more appropriate for image coding [23]. Fig. 3 shows one of several possible re-arrangements of the pixels captured using the Bayer CFA [21]. As shown in Fig. 4, the process creates the sub-images which contain natural edges and transitions between the flat regions. Therefore, the structure conversion can help to achieve higher compression ratios compared to the direct coding of the acquired CFA image. As shown in Fig. 2b, an inverse structure conversion should be used after the image decompression to restore the CFA mosaic layout.

III. EXPERIMENTAL RESULTS

In this section, various single-sensor image processing solutions are used to produce the decoded full-color camera image. Following the scenario shown in Fig. 2, the generated image is displayed to the end-user for visual inspection and used for comparative evaluations of the visual quality. The objective of this experimentation is to demonstrate strong dependencies of the final image quality on: i) the order of demosaicking and compression operations, ii) the selection of the demosaicking solution and/or the coding scheme, iii) various compression ratios, and iv) the utilization of the structure conversion step in support of CFA image compression.


(a) (b) (c) (d)

(e) (f) (g) (h)

Fig. 5. Test color images: (a) Lighthouse, (b) Bikes, (c) Girls, (d) Parrots, (e) Train, (f) Rafting, (g) Flower, (h) Face.

A. *Processing Solutions Under Consideration*

Three single-sensor image processing pipelines (IPP) are considered. Namely, IPP_1 first demosaicks the CFA image and then compresses the generated full-color image. The compressed image is decoded and displayed. IPP_2 first compresses the CFA data in a straight-forward manner (without structure conversion) and then demosaicks the decoded CFA image. Finally, IPP_3 uses the structure conversion step prior to compression of the CFA image data An inverse structure conversion is used after decoding the compressed CFA image. The full-color image is obtained by demosaicking the data in the restored CFA layout.

The proposed pipelines can employ various compression and demosaicking solutions. In this work, we used JPEG and JPEG 2000 to compress the image data. Demosaicking solutions under consideration include the bilinear interpolation (BI) scheme, the Kimmel algorithm (KA) [29], the enhancement/demosaicking (ED) scheme [30], and the color-correlation adaptive (CCA) demosaicking scheme [31]. The combination of these four demosaicking solutions and two coding schemes in three processing pipelines allows for the testing of total 24 processing solutions. Thus, this work extensively covers a wide range of design and performance issues which are essential in single-sensor imaging.

B. *Evaluation Procedure*

The performance of the proposed solutions was tested using the 512×512 color images shown in Fig. 5. Following the procedure reported in [9], the $K_1\times K_2$ test images $\mathbf{o}: Z^2\rightarrow Z^3$ were sampled by the Bayer CFA (Fig. 3a) to produce the CFA images z. The full-color image $\mathbf{x}$ to be displayed to the end-user (Fig. 2) is generated by applying separately each of the proposed pipelines (IPP_1, IPP_2, IPP_3) onto the CFA image z. To evaluate the performance of the proposed solutions, image quality was measured by comparing $\mathbf{o}$ and $\mathbf{x}$ using four criteria defined in three color spaces. Namely, the image quality was evaluated in the RGB color space (commonly used for storage/displaying) using the mean absolute error (MAE) [9] and the peak signal-to-noise ratio (PSNR) [23] defined as follows:

$$\text{MAE}=\frac{1}{3K_1K_2}\sum_{r=1}^{K_1}\sum_{s=1}^{K_2}\sum_{k=1}^{3}\left|o_{(r,s)k}-x_{(r,s)k}\right| \tag{1}$$

$$\text{PSNR}=10\log_{10}\left(255^2\Big/\left(\frac{1}{3K_1K_2}\sum_{k=1}^{3}\sum_{r=1}^{K_1}\sum_{s=1}^{K_2}\left(o_{(r,s)k}-x_{(r,s)k}\right)^2\right)\right) \tag{2}$$

where (r,s) denotes the spatial position in a $K_1\times K_2$ image, k characterizes the color channel, $\mathbf{o}_{(r,s)}=[o_{(r,s)1},o_{(r,s)2},o_{(r,s)3}]$ is the original RGB pixel, and $\mathbf{x}_{(r,s)}=[x_{(r,s)1},x_{(r,s)2},x_{(r,s)3}]$ is the restored RGB pixel.

Since RGB is not a perceptually uniform color space, i.e. the measured units do not correspond to the human perception, two additional criteria defined in perceptually uniform CIE Luv and CIE Lab color spaces [32] with the white point D65 were used. The perceptual similarity between the images $\mathbf{o}$ and $\mathbf{x}$ is quantified using the normalized color difference (NCD) criterion [9]:

$$\text{NCD}=\frac{\sum_{r=1}^{K_1}\sum_{s=1}^{K_2}\sqrt{\sum_{k=1}^{3}\left(\bar{o}_{(r,s)k}-\bar{x}_{(r,s)k}\right)^2}}{\sum_{r=1}^{K_1}\sum_{s=1}^{K_2}\sqrt{\sum_{k=1}^{3}\left(\bar{o}_{(r,s)k}\right)^2}} \tag{3}$$

where $\bar{\mathbf{o}}_{(r,s)}=[\bar{o}_{(r,s)1},\bar{o}_{(r,s)2},\bar{o}_{(r,s)3}]$ and $\bar{\mathbf{x}}_{(r,s)}=[\bar{x}_{(r,s)1},\bar{x}_{(r,s)2},\bar{x}_{(r,s)3}]$ are the vectors representing respectively the RGB vectors $\mathbf{o}_{(r,s)}$ and $\mathbf{x}_{(r,s)}$ in the CIE LUV color space.

Another color-based criterion is the so-called Δ_{Lab} measure defined as follows [32]:

$$\Delta_{Lab}=\frac{1}{K_1K_2}\sum_{r=1}^{K_1}\sum_{s=1}^{K_2}\sqrt{\sum_{k=1}^{3}\left(\bar{o}_{(r,s)k}-\bar{x}_{(r,s)k}\right)^2} \tag{4}$$

where $\bar{\mathbf{o}}_{(r,s)}=[\bar{o}_{(r,s)1},\bar{o}_{(r,s)2},\bar{o}_{(r,s)3}]$ and $\bar{\mathbf{x}}_{(r,s)}=[\bar{x}_{(r,s)1},\bar{x}_{(r,s)2},\bar{x}_{(r,s)3}]$ are CIE Lab equivalents of the RGB vectors $\mathbf{o}_{(r,s)}$ and $\mathbf{x}_{(r,s)}$, respectively. An Euclidean distance value of approximately 2.3 between two color stimuli in the CIE Lab color space corresponds to a just noticeable difference (JND).

C. *Achieved Results*

Results reported in Figs. 6-8 are achieved for a wide range of compression ratio values (eight values per curve). Since the error values are calculated as aggregated measures averaged over the images in the test database shown in Fig. 5, these results indicate the solutions' robustness (or its lack).

For the demosaicked image compression (Fig. 6), the selection of the demosaicking algorithm practically does not have significant impact for JPEG 2000 with compression ratio values over 80. The best performance for JPEG with compression ratio values over 60 was achieved by the BI demosaicking scheme. At low compression ratios, both JPEG and JPEG 2000 produced the best results in conjunction with the powerful ED and CCA schemes.

Figs. 7 and 8 summarize results corresponding respectively to the plain and structure conversion-based CFA image

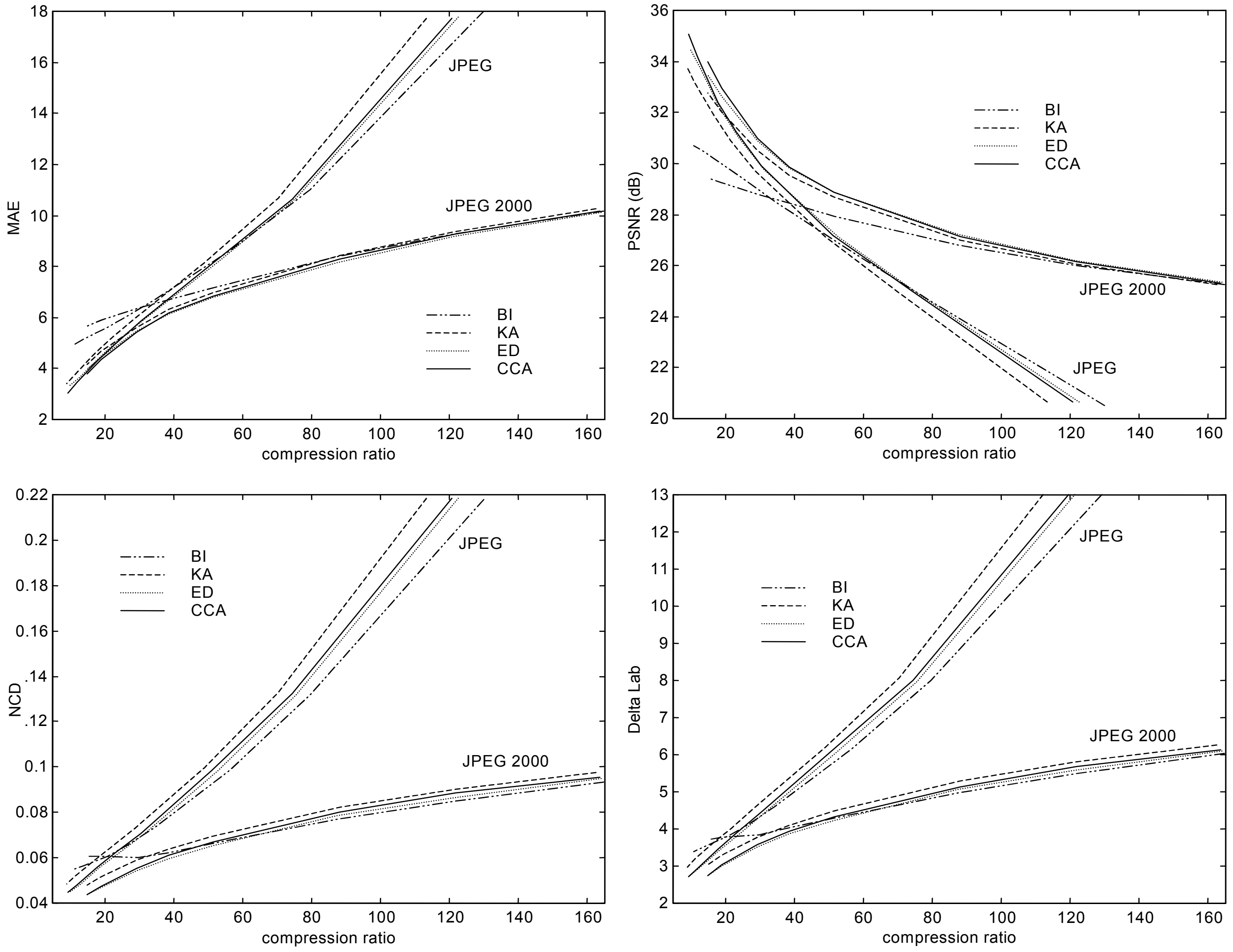


Fig. 6. Performance of the IPP$_1$ solution expressed for various compression ratios and error criteria averaged over the database in Fig. 5.

compression. As it can be seen, scaling down compression ratios, the image quality for both JPEG and JPEG 2000 compression critically depends on the performance of the demosaicking solution. The best results were achieved using sophisticated (CCA, ED) demosaicking solutions at low compression ratios.

The comparison of Figs. 6-8 shows that the use of JPEG 2000 significantly outperforms conventional JPEG in terms of both the measured quality and achieved compression ratios. This behavior was observed for all four considered error criteria. Finally, it should be noted that although the proposed IPP$_1$, IPP$_2$ and IPP$_3$ pipelines had similar performance at low compression ratios, the difference in performance of these solutions became obvious at high compression ratios where IPP$_2$ (straightforward CFA image compression) produced the worst results.

Figs. 9-11 depict enlarged parts of the test images and the output images cropped in areas with significant structural contents. Visual inspection of these images and the corresponding compression ratios listed in the figure captions reveals that the solutions equipped with JPEG 2000 clearly outperformed their JPEG-based variants in terms of the image sharpness, true coloration and higher compression ratios. Even for extremely high compression ratios, both IPP$_1$ and IPP$_3$ solutions produced modest visual quality using the JPEG 2000 coding scheme, whereas images obtained using the conventional JPEG scheme contained various visual impairments, such as blurred edges, block effects, shifted colors and other compression artifacts.

In the summary, the following conclusions can be drawn: i) the use of JPEG 2000 instead of the conventional JPEG scheme in the single-sensor imaging pipeline results in significantly higher compression ratios and quality of the captured images, ii) the proposed processing solutions produce images with the reasonable image quality at high compression ratios and visually pleasing images at compression ratios ranging from modest to low values, iii) powerful demosaicking solutions should be employed in the proposed processing pipelines to produce the highest visual quality at low and modest compression ratios, and iv) cost-effective demosaicking solutions should be used at higher compression ratios.

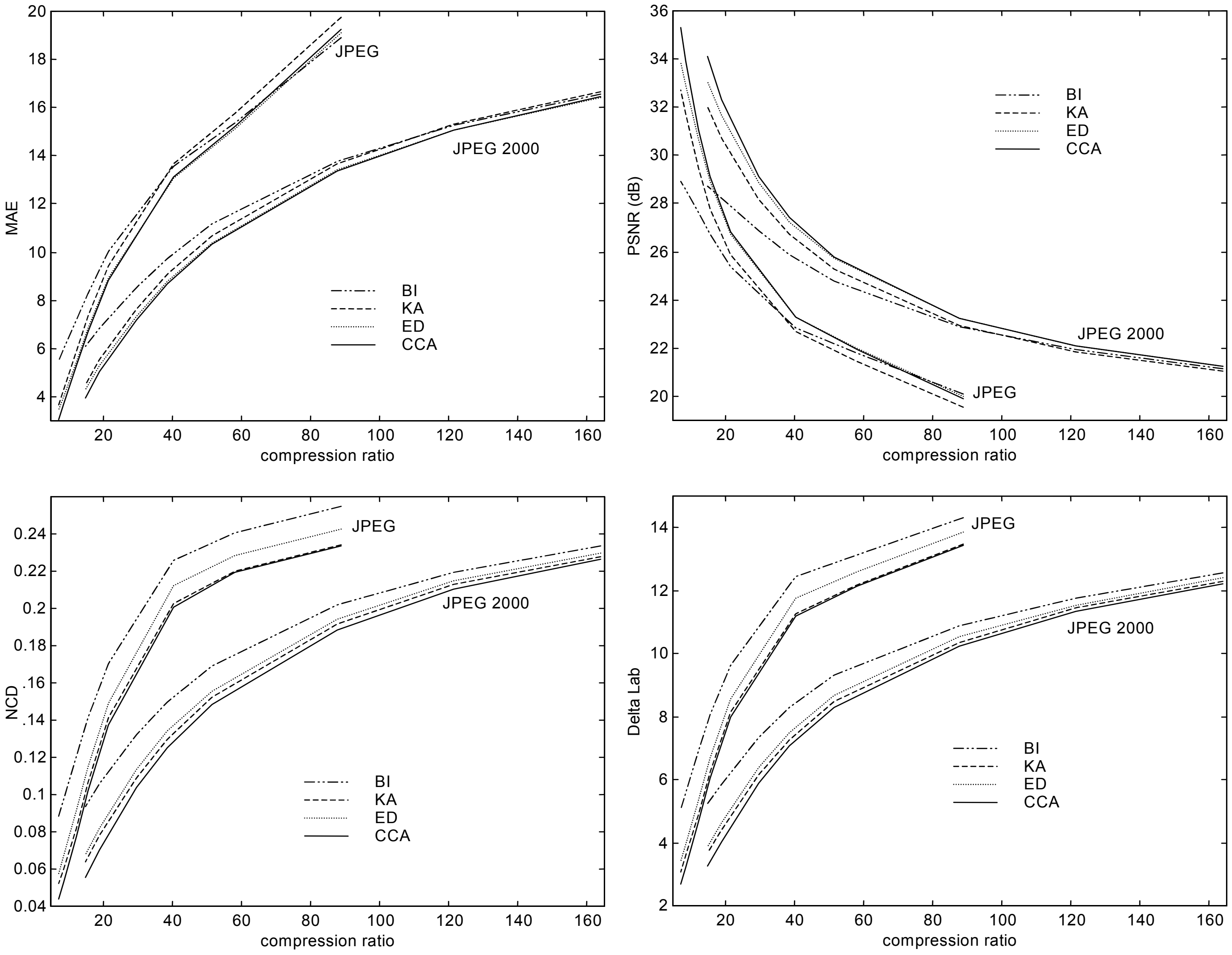


Fig. 7. Performance of the IPP$_2$ solution expressed for various compression ratios and error criteria averaged over the database in Fig. 5.

IV. CONCLUSION

A camera image compression framework suitable for single-sensor devices was presented. Using the single-sensor imaging pipeline equipped with the Bayer CFA, the proposed solutions can store either the CFA data or the demosaicked full-color data. Extensive experimentation reported in this paper indicates that the use of CFA image coding solutions as well as the introduction of JPEG 2000 as a new image compression standard for digital photography formats (EXIF, TIFF-EP) can have a key role in the development of new, powerful, consumer electronic devices.

ACKNOWLEDGEMENT

The authors gratefully thank Leo Hwang for his help with the preparation of the test tools.

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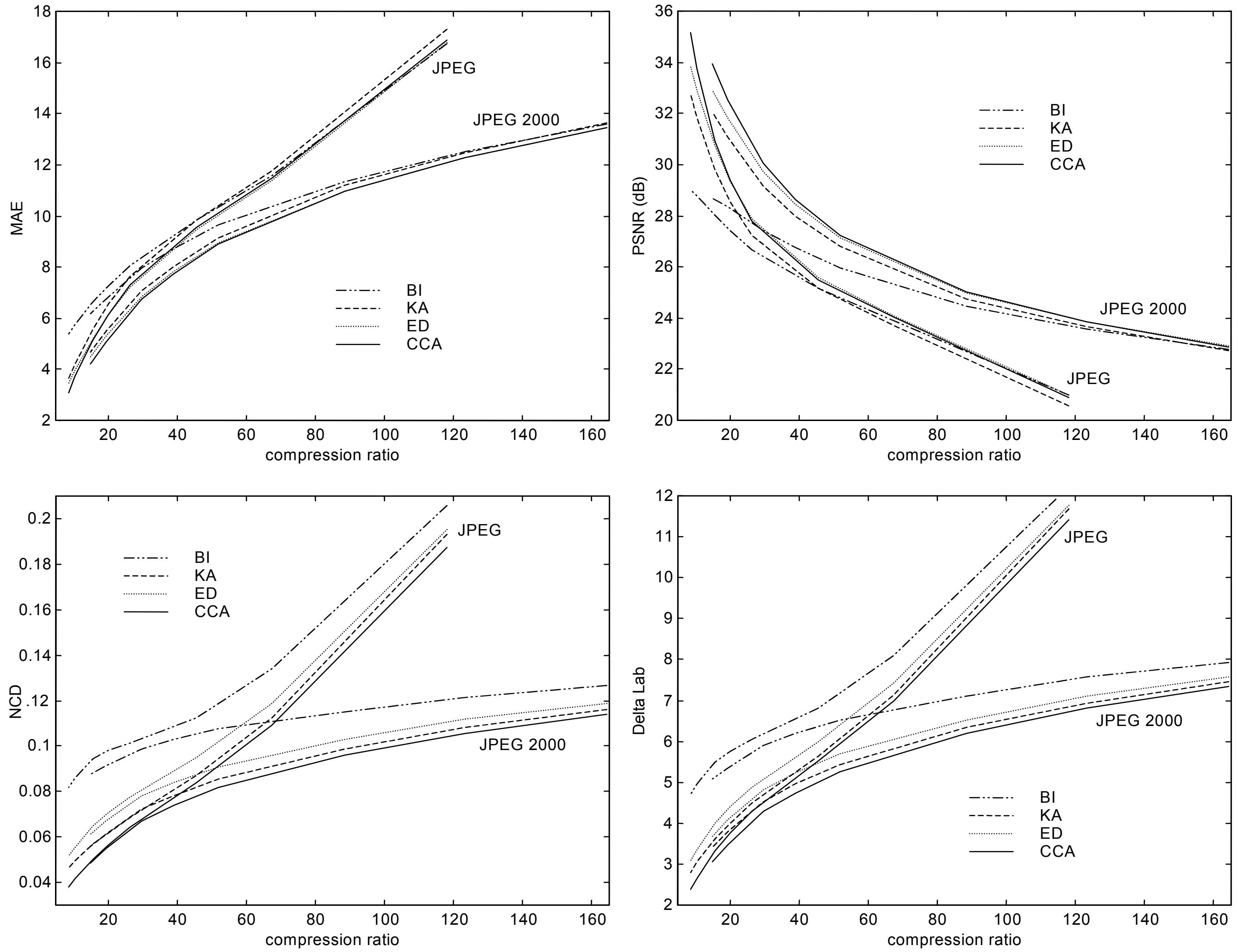

Fig. 8. Performance of the IPP$_3$ solution expressed for various compression ratios and error criteria averaged over the database in Fig. 5.

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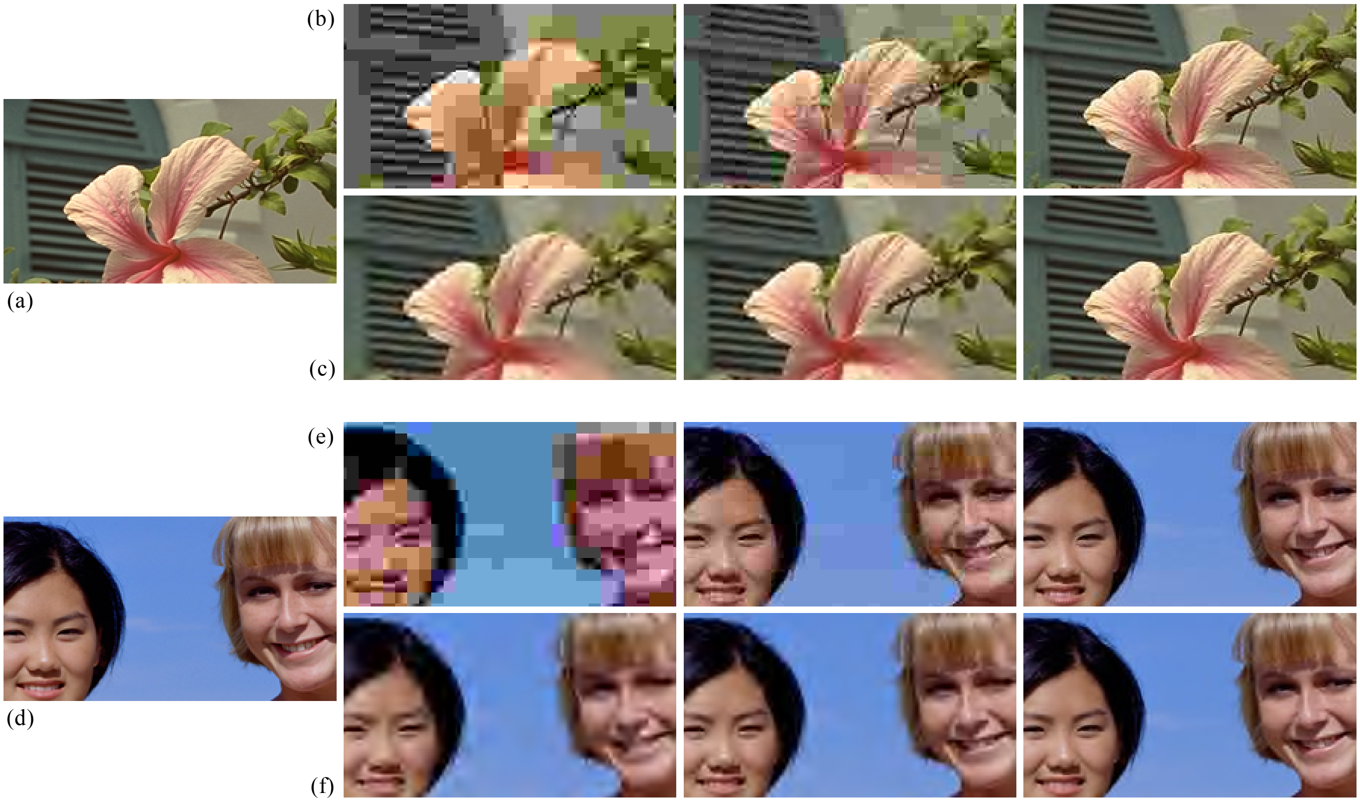

Fig. 9. Performance of the IPP$_1$ solution (demosaicked image compression) using the CCA demosaicking scheme: (a) original image Flower, (b) JPEG at compression ratios 130.05, 80.91, and 26.20, (c) JPEG 2000 at compression ratios 163.63, 122.46, and 38.93, (d) original image Girls, (e) JPEG at compression ratios 124.79, 56.58, and 20.33, (f) JPEG 2000 at compression ratios 162.79, 89.18, and 29.46.

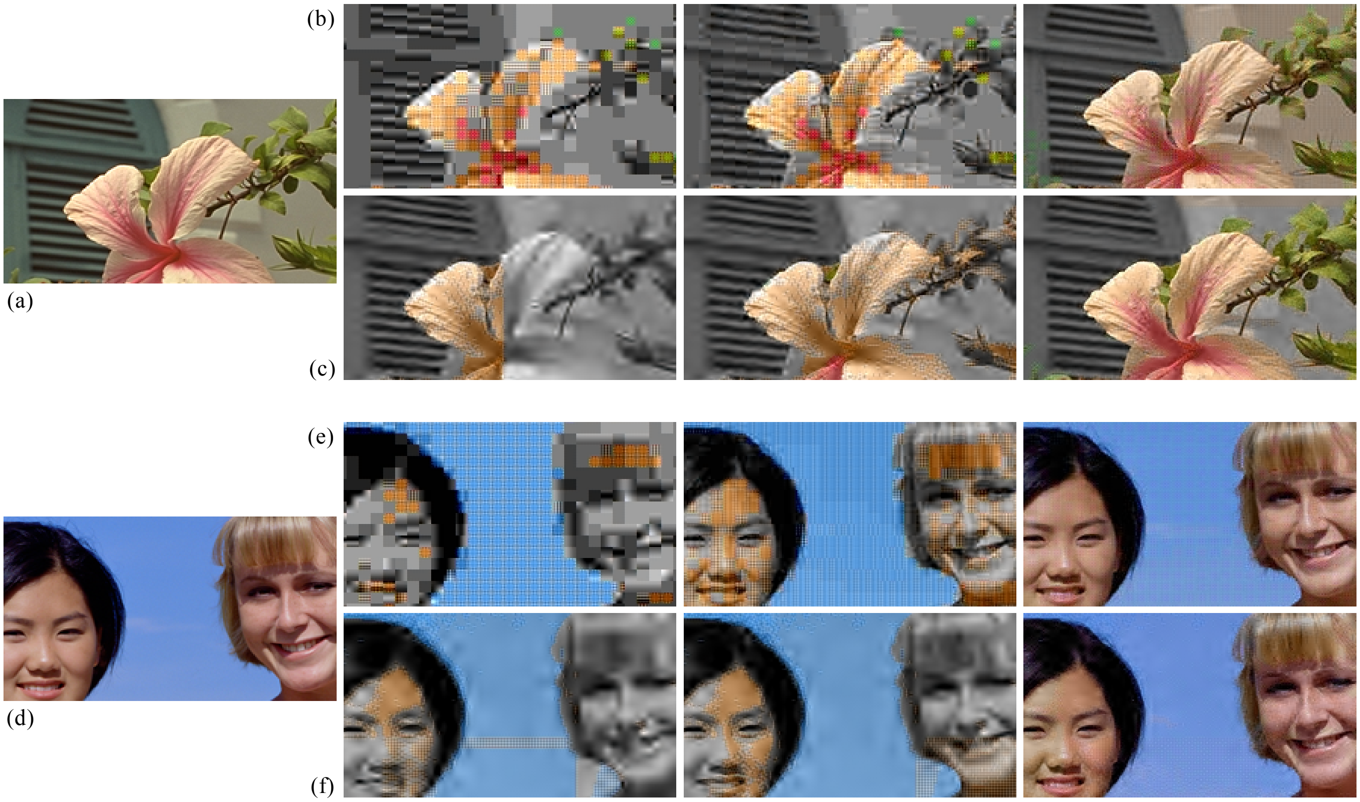

Fig. 10. Performance of the IPP$_2$ solution (CFA image compression) using the CCA demosaicking scheme: (a) original image Flower, (b) JPEG at compression ratios 116.49, 75.34, and 18.37, (c) JPEG 2000 at compression ratios 163.12, 124.49, and 38.79, (d) original image Girls, (e) JPEG at compression ratios 62.46, 33.97, 11.57, (f) JPEG 2000 at compression ratios 164.73, 86.97, and 29.57.

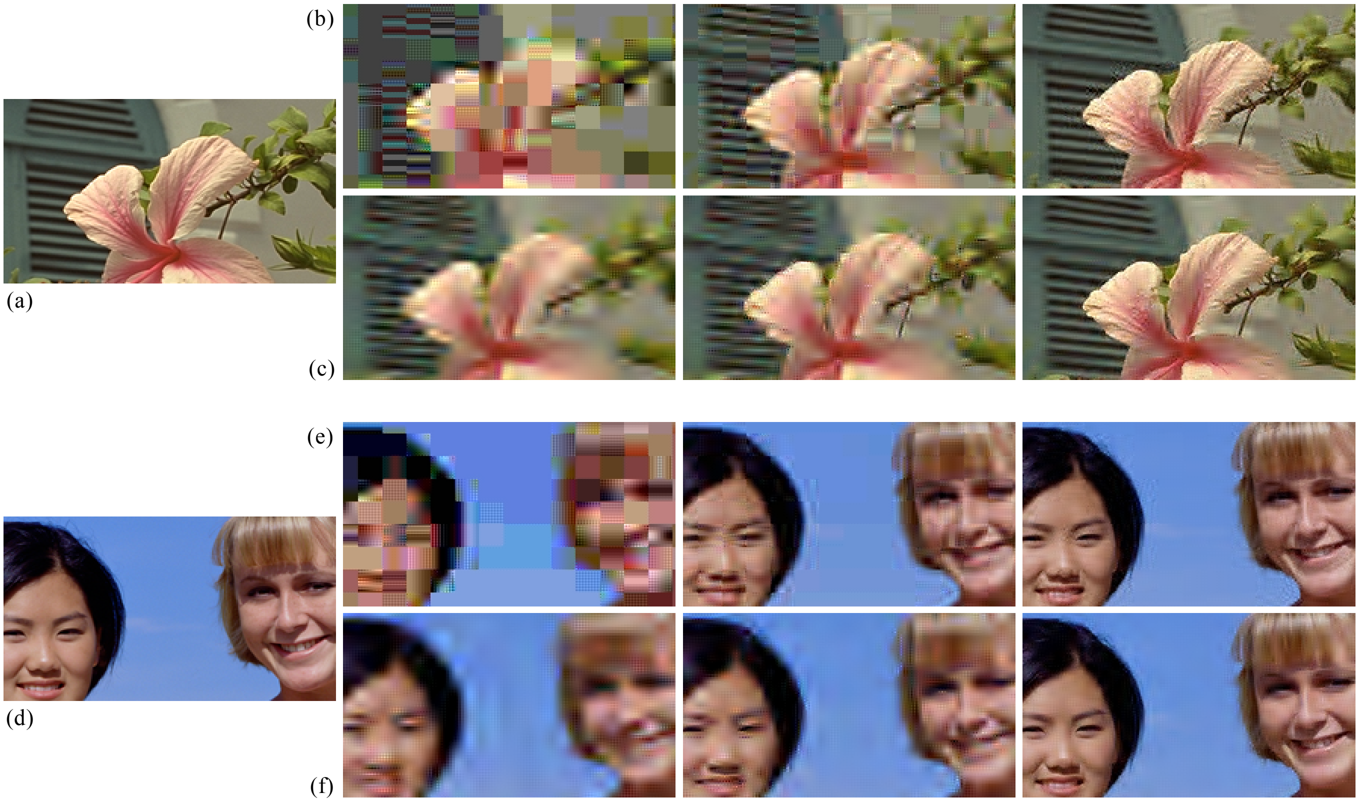

Fig. 11. Performance of the IPP$_3$ solution (structure conversion-based CFA image compression) using the CCA demosaicking scheme: (a) original image Flower, (b) JPEG at compression ratios 131.64, 47.05, and 16.95, (c) JPEG 2000 at compression ratios 162.32, 125.09, and 39.53, (d) original image Girl, (e) JPEG at compression ratios 123.38, 46.77, and 17.10, (f) JPEG 2000 at compression ratios 163.74, 87.30, and 29.58.

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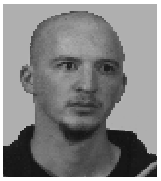

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