# Hybrid color filter array demosaicking for effective artifact suppression 

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#### Abstract

Color filter array (CFA) demosaicking is an essential process for restoring full-color images from incomplete color samples acquired by single-sensor digital cameras. We present two main contributions to CFA demosaicking. First, we analyze the causes of two main types of CFA demosaicking artifacts and examine the schemes that are effective in suppressing them, respectively. Second, by combining and extending the core merits of the schemes examined, we compose a new CFA demosaicking algorithm to suppress as many demosaicking artifacts as possible and obtain fullcolor images of high quality. Experiments using a large variety of test images have been conducted, and the results show that the proposed method outperforms the existing state-of-the-art methods both visually and in terms of peak signal-to-noise ratio. © 2006 SPIE and IS\&T. [DOI: 10.1117/1.2183325]


## 1 Introduction

Most digital still cameras acquire imagery by using a single electronic sensor (CCD or CMOS) overlaid with a color filter array (CFA). The CFA is configured in such a way that each sensor pixel samples only one of the three primary colors (e.g., red, green, and blue) or complementary colors (e.g., cyan, magenta, and yellow). The most commonly used CFA configuration today is the "Bayer" pattern, ${ }^{1}$ a schematic of which is shown in Fig. 1. In this pattern, the green (G) values are sampled on a quincunx lattice, while the red ( $R$ ) and blue (B) values are obtained on two separate rectangular lattices, respectively. Furthermore, the number of the green values is twice as many as that of the red (or blue) values.

To restore a full-color image from its CFA samples, the two missing color values at each pixel are usually estimated from their neighboring CFA samples. This process is commonly referred to as CFA demosaicking (or CFA interpolation), and it has a substantial impact on the quality of the color images produced by single-sensor digital cameras. If demosaicking is not performed properly, the restored images will suffer from visible artifacts, mostly dominated by zipper effects and false colors.

Zipper effects refer to abrupt or unnatural changes of intensities over a number of neighboring pixels, manifesting as an "on-off" pattern in regions around edges, as shown in Fig. 2(a). They are primarily caused by improper

[^0]averaging of neighboring color values across edges. False colors are spurious colors which are not present in the original image scene, as illustrated in Fig. 2(b). They appear as sudden hue changes due to inconsistency among the three color planes and usually around fine image details and edges. More details about these two types of demosaicking artifacts will be provided in the next section.

To suppress these artifacts and restore more visually pleasing images, a large number of demosaicking methods have been proposed in the literature. ${ }^{2-18}$ Most of these methods exploit the property of high spatial or spectral correlation, or both, of color images. The high spatial correlation of a color image refers to the fact that within a small, homogenous region of an image object or scene, the pixels assume similar color values. Such spatial correlation can be exploited by identifying appropriate neighboring samples based on local image spatial structure and performing demosaicking along rather than across edges. The high spectral correlation of a color image dictates that within a small image region, there is a strong dependency among the pixel values of different color planes. ${ }^{6,10}$ This spectral correlation is generally exploited by using the assumption that the differences (or ratios) between the values in two color


Fig. 1 Bayer color filter array pattern.


Fig. 2 Two common types of CFA demosaicking artifacts.
planes are likely to be constant within a local image region. ${ }^{9,14}$ However, such an assumption may not hold in the presence of complex edges or fine details. In particular, by comparing the results obtained using various existing demosaicking methods, we have observed that methods which do not well exploit the spatial correlation often produce more zipper effects, and those which inaccurately utilize the spectral correlation often result in excessive false colors.

Based on how the two types of image correlations are exploited, existing demosaicking methods can be grouped into four classes. The methods in the first class exploit neither correlation, applying the same interpolation scheme in each individual color plane. Typical methods of this class include nearest-neighbor replication, which fills in each
missing color value by replicating that of the nearest available sample; ${ }^{6}$ bilinear interpolation, which estimates each missing color value by the average value of a few neighboring samples; ${ }^{6,10}$ and cubic spline interpolation, which performs cubic convolution in each color plane. ${ }^{19,20}$ Although these methods can obtain rather satisfying results in smooth image regions, they are prone to severe demosaicking artifacts in regions with ample edges and details.

The methods in the second class mainly exploit spatial correlation but little or no spectral correlation; they usually apply some adaptive interpolation scheme in each color plane separately. Examples of this class include Cok's pattern recognition interpolation (PRI), ${ }^{2}$ which estimates the missing color values according to different local intensity patterns, and Adams's edge-sensing (ES) method, ${ }^{6}$ which


Fig. 3 Artifacts in the results obtained by different CFA demosaicking methods.


Fig. 4 Zipper effects in the results obtained by different CFA demosaicking methods.
performs interpolation along the direction determined by some edge indicators. These adaptive schemes can suppress zipper effects effectively but result in inordinate false colors. For example, see Fig. 3(a) for a cropped image region obtained by Cok's PRI method.

The methods in the third class mainly exploit image spectral correlation. Examples are Cok's constant-hue interpolation, ${ }^{3}$ which performs bilinear interpolation on color ratio values; Freeman's median interpolation, ${ }^{4}$ which estimates the missing color values by median filtering color difference planes (green minus red and green minus blue
planes) obtained by bilinear interpolation; Pei's effective color interpolation (ECI), ${ }^{15}$ which applies bilinear interpolation in color difference planes; and Gunturk's alternating projections (AP) method, ${ }^{13}$ which alternately substitutes the high-frequency subbands between different color planes. Although capable of alleviating false color artifacts, these methods normally produce visible zipper effects around edges and details, as can be seen in Fig. 3(b) and Fig. 3(c).

The methods of the last class exploit both spatial and spectral correlations by employing adaptive interpolation schemes and intercolor plane information. These methods


Fig. 5 (a), (b): Two synthetic images with vertical and diagonal edges; (c), (d): demosaicking artifacts due to bilinear interpolation.


Fig. 6 CFA samples of the (a) vertical and (e) diagonal edges; (b)-(d), (f)-(h): demosaicked results obtained by bilinear interpolation, where H and L denote pixels with large and small intensity values, respectively.
include Laroche's gradient-based interpolation (Laroche), ${ }^{5}$ which applies an adaptive interpolation scheme in the green plane and interpolates color difference values to fill in the red and blue planes; Li's new edge-directed interpolation, ${ }^{12}$ which performs edge-directed interpolation in color difference planes; Kimmel's method, ${ }^{9}$ which combines the edgedirected interpolation from Ref. 21 and the constant-hue interpolation from Ref. 3 in an iterative process; Hamilton's adaptive color-plane interpolation (Hamilton), ${ }^{8}$ which exploits adaptive schemes to accommodate information from different color planes; Wu's primary-consistent softdecision (PCSD) method, ${ }^{16}$ which relies on training and reconstructs the missing values of each pixel using consistent horizontal and vertical interpolations as suggested by the training results; and Hirakawa's adaptive homogeneitydirected demosaicking algorithm (AHD), ${ }^{18}$ which first interpolates the missing color values by performing filterbank interpolation in the horizontal and vertical directions
separately, selects the proper interpolated value using some homogeneity criteria, and then suppresses the interpolation artifacts using an iterative median process on color difference planes. The last two algorithms are among the most recent ones. Although these methods attempt to exploit both types of image correlations, they obtain suboptimal results as many visible artifacts still reside in the demosaicked images; some examples are shown in Figs. 3(d)-3(f).

After evaluating the above existing methods, we identify some elementary schemes that are effective in suppressing the two main types of demosaicking artifacts. For example, Hamilton's adaptive color-plane interpolation ${ }^{8}$ can greatly reduce zipper effects along image edges, especially in the horizonal and vertical directions. On the other hand, Freeman's median interpolation ${ }^{4}$ can remove false colors more effectively. Combining and extending the core merits of these schemes, we present in this paper a hybrid demosaicking method capable of reconstructing full-color images


Fig. 7 (a), (b): Vertical and diagonal edges reconstructed by the ECI method; (c), (d): the corresponding results reconstructed by Hamilton's method.


Fig. 8 Reference neighboring samples: G's denote the green samples and C's designate the red (or blue) samples available.
with sharper edges and fewer demosaicking artifacts, leading to improvement in image quality both visually and in terms of peak-signal-to-noise ratio (PSNR), as compared with the existing state-of-the-art methods.

The remainder of this paper is organized as follows. Section 2 provides the details of the two main types of demosaicking artifacts, and reviews some effective demosaicking schemes as well as our modification to further improve their performance. Section 3 describes the procedure of our proposed demosaicking method. Section 4 presents the experimental results and computational complexities in comparison with the existing state-of-the-art methods. In Sec. 5, we conclude the paper by summarizing our contributions.

## 2 Demosaicking Artifacts

Figure 4 shows a challenging region for demosaicking from a popular test image "Lighthouse" (image 19 in Fig. 15) and the results obtained by several existing CFA demosaicking methods. The zipper effects which appear as spurious grid pattern in this region are quite obvious and objectionable for two reasons. First, the human visual system is more sensitive to edges and textures in the horizontal and vertical directions than that in other directions (sensory perception). ${ }^{22,23}$ Second, the spurious grid pattern in these well-aligned fence strips are against our common knowledge of such scene content (cognitive perception). ${ }^{22,23}$ To the best of our knowledge, few existing demosaicking methods can reconstruct this region without noticeable zipper effects.

### 2.1 Zipper Effects

A closer examination shows that such zipper effects are mainly caused by the improper interpolation in the quincunx-sampled green plane. To see this, Fig. 4(a)-4(d) show the demosaicked result of the "Lighthouse" image and the corresponding red, green, and blue planes obtained by bilinear interpolation. We can see that only the green plane [Fig. 4(c)] possesses the annoying grid error pattern corresponding to that in the demosaicked image [Fig. 4(a)]. The result shows that zipper effects are more likely to occur around edges not aligned in the diagonal directions along which the green values are fully sampled. To illustrate this point, Fig. 5 shows two synthetic test images with a vertical edge and a diagonal edge, respectively, and the corresponding demosaicked results obtained by bilinear interpolation. It can be seen that only the vertical edge possesses zipper effects. The reason for this is further depicted in Fig. 6. Figure 6(a) and Fig. 6(e) show the CFA samples of two synthetic images in Fig. 5. As the images are achromatic, their three color planes have the same intensity and hence perfect spectral correlation. The bilinear interpolated red, green, and blue planes of Fig. 6(a) and Fig. 6(e) are shown in Fig. 6(b)-6(d) and Fig. 6(f)-6(h), respectively. It can be seen that the three interpolated color planes suffer from different errors due to their different sampling patterns. For the vertical edge [Fig. 6(a)], the green plane gives rise to the objectionable grid error pattern. The red and blue planes, however, just produce an intermediate level between the two low and high intensity levels, resulting in a blurred edge. On the other hand, the green plane of the diagonal edge only induces a blurred effect like that in the red and blue planes of the vertical edge, while the red and blue planes result in coarse jagged edges. Note that since the demosaicking artifacts are not the same in different color planes, they result in obvious false colors: the bluish tint in Fig. 5(c) and the pinkish tint in Fig. 5(d).

Similar zipper effects also appear in the results obtained by other demosaicking methods adopting bilinear interpolation. For example, Fig. 4(e) shows the result of the ECI method, ${ }^{15}$ which attempts to exploit the high spectral correlation by assuming that the color difference planes are smooth in local image regions and applying bilinear interpolation in the color difference planes. However, it does not perform well even in the case of perfect spectral correlation. This can be seen from the results [Fig. 7(a) and Fig. 7 (b)] of the two synthetic images shown in Fig. 6, for which the color difference values are all zero (i.e., perfect


Fig. 9 Four neighborhood patterns (unique up to a rotation), where $H / L$ denotes that the green value of the pixel is larger/smaller than the average of all four green values.


Fig. 10 Original image region (from image 27 in Fig. 15) and its demosaicked results obtained by (b) bilinear interpolation and (c) Freeman's method. The corresponding color difference planes (green minus red) are shown in (d), (e), and (f), respectively.
spectral correlation). Also, since the green planes reconstructed by the ECI method suffer from the grid errors as shown in Fig. 7(a), the demosaicked results possess the zipper effects, as in Fig. 4(e). Furthermore, the errors in the green plane can also propagate to the red and blue planes due to interpolation in the color difference planes, as can be seen in Fig. 4(f) and Fig. 4(h). To avoid zipper effects, the green plane needs to be more carefully and accurately reconstructed by exploiting both spatial and spectral correlations.

Several existing methods are capable of obtaining results with fewer zipper effects. The first one is the adaptive color-plane interpolation proposed by Hamilton, ${ }^{8}$ which interpolates along edges, leading to fewer zipper effects as seen in Fig. 4(i) and Fig. 7(c). Specifically, Hamilton's method estimates the missing green value $G_{i, j}$ in Fig. 8 by

$$
\widehat{G}_{i, j}= \begin{cases}\frac{G_{i, j-1}+G_{i, j+1}}{2}+\frac{-C_{i, j-2}+2 C_{i, j}-C_{i, j+2}}{2} & D H<D V  \tag{1}\\ \frac{G_{i-1, j}+G_{i+1, j}}{2}+\frac{-C_{i-2, j}+2 C_{i, j}-C_{i+2, j}}{2} & D H>D V \\ \frac{G_{i-1, j}+G_{i, j-1}+G_{i, j+1}+G_{i+1, j}}{4} & \\ +\frac{-C_{i-2, j}-C_{i, j-2}+4 C_{i, j}-C_{i, j+2}-C_{i+2, j}}{8} & D H=D V\end{cases}
$$

where DH and DV are the edge indicators in horizontal and vertical directions, respectively; the smaller the value of the $\mathrm{DH} / \mathrm{DV}$ indicator, the more likely the edge is along the horizontal/vertical direction.


Fig. 11 (a) Original image region (from image 27 in Fig. 15); (b) bilinear interpolated result; the results of applying the median filter to (c) the entire image and (d) smooth image regions only.

```
Input : An CFA image
Method :
    I. Reconstruction Process :
        A. Initialization step
            1) Fill in the G plane using adaptive color-plane interpolation;
            2) Fill in the R and B planes using pattern adaptive interpolation;
            B. Enhancement step
            1) Enhance the G plane using edge-weighted interpolation;
            2) Enhance the R and B planes using pattern adaptive interpolation;
```


## II. Refinement Process:

```
A. Edge-adaptive median filtering
1) Perform median filtering to remove spurious edges due to demosaicking;
2) Perform edge detection to differentiate edge regions from smooth regions;
3) Perform median filtering in smooth regions;
B. Updating step
1) Update the \(R\) and \(B\) values in smooth regions using pattern adaptive interpolation;
2) Update the \(G\) values in smooth regions using pattern adaptive interpolation;
```

Output : A full-color image

Fig. 12 Procedure of the proposed hybrid CFA demosaicking method.

In the case of $D H=D V$, which is more likely in smooth region, the missing green value is estimated by

$$
\begin{align*}
\widehat{G}_{i, j}= & C_{i, j}+G_{i, j-1}-\frac{C_{i, j-2}+C_{i, j}}{2} \\
& +G_{i, j+1}-\frac{C_{i, j}+C_{i, j+2}}{2}+G_{i-1, j}-\frac{C_{i-2, j}+C_{i, j}}{2}+G_{i+1, j} \\
& -\frac{C_{i, j}+C_{i+2, j}}{2} / 4 \\
= & C_{i, j}+\widehat{g c_{i, j-1}}+\widehat{g}_{i, j+1}+\widehat{g \widehat{c}_{i-1, j}}+\widehat{g}_{i+1, j} / 4 \tag{2}
\end{align*}
$$

which is the same as the formula of the ECI method, where $\widehat{g c}_{i, j-1}=G_{i, j-1}-\left(C_{i, j-2}+C_{i, j}\right) / 2$ is the estimate of the color difference value at location $(i, j-1)$, while $\widehat{g c}_{i, j+1}, \widehat{g c}_{i+1, j}$, and $g \widehat{c}_{i-1, j}$ are the corresponding estimates at locations $(i, j+1),(i+1, j)$, and $(i-1, j)$, respectively. For the other two cases $(D H \neq D V)$, the estimates obtained by Hamilton's method are different from those by ECI method. For example, by regrouping the terms in Eq. (1), we can see that when $D H<D V$, Hamilton's method computes the missing green value as

$$
\begin{align*}
\widehat{G}_{i, j} & =C_{i, j}+\frac{G_{i, j-1}-C_{i, j-2}+G_{i, j+1}-C_{i, j+2}}{2} \\
& =C_{i, j}+\frac{g \widehat{c}_{i, j-1}+\widehat{g c_{i, j+1}}}{2} \tag{3}
\end{align*}
$$

where $\widehat{g c}_{i, j-1}=G_{i, j-1}-C_{i, j-2}$ and $\widehat{g c}_{i, j+1}=G_{i, j+1}-C_{i, j+2}$ can be regarded as the estimates of color difference values in the two neighboring locations $(i, j-1)$ and $(i, j+1)$, respectively. Such interpolation is indeed the ECI's color difference interpolation in the chosen direction. Thus, the enhanced capability of Hamilton's method in reducing the zipper effects can be distributed to the use of an edge directed interpolation.

Besides the adaptive color-plane interpolation described above, another type of efficient demosaicking scheme for suppressing zipper effects is weighted interpolation. One example is the adaptive weighted method proposed by Kimmel in Ref. 9, which obtains a missing green value by combining the weighted estimates as

Table 1 Performance comparison: PSNR values (in dB) of the red, green, and blue planes are listed in the 1st, 2nd, and 3rd rows after each method.

|  | Image | Image |  |  |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| Method | Image |  |  |  |  |  |
| 8 | Image | Image | Image |  |  |  |
| Mamilton | 33.19 | 34.80 | 31.70 | 39.40 | 36.67 | 29.78 |
|  | 34.70 | 36.09 | 33.50 | 41.54 | 38.42 | 30.99 |
|  | 33.32 | 34.33 | 31.70 | 40.04 | 37.01 | 29.08 |
| Initialization | 34.09 | 36.09 | 32.75 | 40.15 | 37.49 | 30.45 |
|  | 34.70 | 36.09 | 33.50 | 41.54 | 38.42 | 30.99 |
|  | 34.32 | 35.37 | 32.80 | 40.61 | 37.76 | 29.54 |
| Enhancement | 35.80 | 37.74 | 34.30 | 41.09 | 38.84 | 31.58 |
|  | 37.46 | 38.87 | 36.41 | 43.40 | 40.62 | 33.30 |
|  | 36.12 | 36.76 | 34.40 | 41.62 | 39.14 | 30.55 |
|  | 37.93 | 38.82 | 35.66 | 41.81 | 39.54 | 32.57 |
| Refinement | 41.60 | 41.62 | 39.76 | 45.35 | 42.81 | 35.91 |
|  | 38.61 | 37.65 | 35.97 | 42.76 | 40.36 | 31.36 |



Fig. 13 Improvement of the enhancement step.
$\widehat{G}=\frac{\sum_{k} w_{(k)} \times \widehat{G}_{(k)}}{\sum w_{(k)}}$,
where $\widehat{G}_{(k)}$ denotes the estimate of the missing green value and $w_{(k)}$ designates the corresponding weight along the direction $k$, respectively. Intuitively, the higher the spatial correlation among pixels along a particular direction, the more accurate the estimate can be obtained from that direction. Hence, the weights are usually set to be proportional to the spatial correlation in the respective directions. In our empirical studies, we extended the ECI method by introducing the weighted interpolation scheme with the intention of suppressing more zipper effects; Fig. 4(m) shows one of the results obtained. Compared to Fig. 4(e), it is evident that the weighted interpolation could suppress zipper effects more effectively. In particular, it performs better in regions with complex edges and fine details, which will be further demonstrated in Sec. 3.

Another effective scheme for suppressing zipper effects is Cok's pattern recognition interpolation, which performs adaptive estimation based on the intensity patterns formed by neighboring green samples. ${ }^{2}$ As depicted in Fig. 9, there are four possible intensity patterns-edge I, edge II, stripe, and corner patterns-formed by samples $G_{i-1, j}, G_{i, j-1}, G_{i, j+1}, G_{i+1, j}$. In each pattern, different estimation is performed to obtain the missing green value $G_{i, j}$ of the central pixel. For the edge I or edge II pattern, the neighboring pattern is considered covering a horizontal edge, and the median of the four neighboring green values is taken as the estimate. For the stripe pattern and corner pattern, the pattern is more complex and a larger neighborhood $(5 \times 5)$ is used to resolve the inherent ambiguity for a better estimate (see Ref. 2 for further details). From our empirical studies, we found that this method works well in smooth regions but produces some errors in high-frequency regions such as those shown in Fig. 3(a). This deficiency is
mainly due to the errors made in selecting the interpolation direction. Although the problem can be alleviated by using a larger neighborhood to determine the proper interpolation direction, it would increase the computational complexity. To strike a good balance between the computational cost and demosaicking efficiency, a $5 \times 5$ neighborhood is generally used to process a color plane. For color difference planes, a $3 \times 3$ neighborhood is usually sufficient for two reasons. First, owing to the high spectral correlation, the color difference planes are smoother than the original color planes; thus a smaller neighborhood is enough to determine the proper interpolation direction. Second, as the color difference values are estimated from their neighboring samples, a $3 \times 3$ neighborhood in the color difference planes cover approximately the same support as what a 5 $\times 5$ neighborhood does in the original color planes.

### 2.2 False Colors

As also illustrated by the synthetic test images shown in Fig. 5 and Fig. 6, false colors are mainly due to inconsistency among the three color planes. Such inconsistency usually results in spurious intensity changes in the color difference planes. As shown in Fig. 10(e), the color difference plane of the bilinear interpolated result is blemished by some spurious edges, as compared with the color difference plane of original image in Fig. 10(d). Such spurious edges lead to false colors in Fig. 10(b), especially around edges of the wheel and the plant.

Because performing median filtering can force pixels with distinct intensities to be more similar to their neighbors while preserving sharp edges, ${ }^{24}$ Freeman proposes the use of a median filter for smoothing the color difference planes obtained by bilinear interpolation. ${ }^{4}$ As observed in Fig. 10(f), such median filtering can remove many artifacts in the color difference planes, particularly the "speckles" in the plant region, leading to fewer false colors in the result image, as shown in Fig. 10(c).


Fig. 14 Improvement of the refinement process.


Fig. 15 Test images (image 1 to image 30, enumerated from left to right and top to bottom).

Since zipper effects also appear as pixels with distinct intensities, part of them can also be removed by median filtering. For example, examining the strip patterns inside the ellipse marked in Fig. 10(b) and Fig. 10(c), the zipper effects in the result obtained by bilinear interpolation are much reduced after median filtering. However, performing median filtering indiscriminately may induce new zipper effects or jagged edges along shape edges or object boundaries. Figure 11(b) shows the demosaicked result obtained by bilinear interpolation, in which the boarders of the fruits are smooth and blurred. After performing median filtering in the color difference planes, some noticeable zipper effects are generated around the boarders of the fruits, as can be seen in Fig. 11(c). This is partly due to the fact that the color difference planes still consist of some textures around the edge regions, and these textures will be smeared if median filtering is applied indiscriminately. To strike a good balance between suppression of false colors and preservation of sharp edges, we need to avoid performing median filtering across the edges in the color difference planes.

Specifically, our proposed method first locates edge regions with an edge detector so that only smooth image regions are subject to median filtering. The difference between the original median filtering and our proposed edge-adaptive median filtering is illustrated in Fig. 11(c) and Fig. 11(d), respectively. Observably, our result possesses sharper edges with fewer zipper effects around edges.

## 3 Proposed Hybrid CFA Demosaicking Method

Our proposed hybrid demosaicking method consists of two main processes: reconstruction and refinement, as shown in Fig. 12. In particular, the two processes modify, extend, and integrate the effective artifact suppression schemes discussed in Sec. 2 to achieve an improved demosaicking performance. The procedure of the proposed method is described in detail below.

### 3.1 Reconstruction Process

The reconstruction process comprises an initialization step, which obtains an initial full-color image, and an enhancement step, which updates the color planes of the initial estimate.

### 3.1.1 Initialization

In this step, the green plane is the first to be interpolated; once fully populated, it is used to help interpolate the red and blue planes.
3.1.1.1 Green plane. (using adaptive color-plane interpolation). As described in Sec. 2.1, adaptive color-plane interpolation can reconstruct a green plane with fewer zipper effects, especially in image regions with horizontal and vertical edges. Hence, in this step we first fill in the missing green values using adaptive color-plane interpolation. Referring to Fig. 8, we define the two edge indicators as


Fig. 16 Original and demosaicked results of a cropped region from image 19.


Fig. 17 Original and demosaicked results of a cropped region from image 27.

$$
\begin{align*}
& D H=\left|-C_{i, j-2}+2 C_{i, j}-C_{i, j+2}\right|+\left|G_{i, j-1}-G_{i, j+1}\right|  \tag{5}\\
& D V=\left|-C_{i-2, j}+2 C_{i, j}-C_{i+2, j}\right|+\left|G_{i-1, j}-G_{i+1, j}\right| \tag{6}
\end{align*}
$$

Each missing green value is then estimated along the chosen direction using Eq. (1).
3.1.1.2 Red and blue planes. (using pattern adaptive interpolation). While adaptive color-plane interpolation can suppress some zipper effects and obtain satisfying results, it can be further improved. In particular, since it mainly relies on the edge information along the horizontal or vertical directions, it is prone to producing jagged edges in the other directions, as shown in Fig. 3(e) and Fig. 7(d). Furthermore, the edge information estimated in regions with complex edges may not be accurate, as evidenced by the persisting artifacts seen in Fig. 4(i). Thus, the red and blue plane interpolation in our initial step does not apply the adaptive color-plane interpolation but a pattern adaptive interpolation scheme. This scheme is similar to Cok's pattern recognition interpolation (see Section 2.1), which estimates
the missing color values according to the different neighborhood patterns. Different from Cok's method, we apply the pattern adaptive interpolation in the color difference planes to exploit both spatial and spectral correlations effectively. As the same procedure is used to interpolate both the red and blue planes, we shall only describe the red plane interpolation below.

Because the red plane is sampled more sparsely than the green plane, its interpolation requires two subprocesses:

1. Interpolating the missing red values at blue pixels: The missing red values at blue pixels (i.e., pixels with blue CFA samples) are first interpolated because at this point only the blue pixels have the four neighboring color difference ( $g r=G-R$ ) values at the cross locations $(i-1, j-1),(i-1, j+1),(i+1, j-1)$, and ( $i$ $+1, j+1$ ) forming a 4 -neighbor pattern, while the green pixels have only two neighboring $g r$ values (see Fig. 1). Furthermore, the pattern formed by these four $g r$ values can be used to obtain the edge information along the diagonal direction. The interpola-


Fig. 18 Original and demosaicked results of a cropped region from image 9.
tions for different types of neighboring patterns are as follows. First the color difference $g r$ value of the blue pixel at $(i, j)$ is obtained as:
(a) Edge pattern [a 45-deg variant of Fig. 9(a) or Fig. 9(b)] and corner pattern [a 45-deg variant of Fig. 9(d)]:

$$
\begin{equation*}
\widehat{g r_{i, j}}=\operatorname{median}\left\{g r_{i-1, j-1}, g r_{i-1, j+1}, g r_{i+1, j-1}, g r_{i+1, j+1}\right\} . \tag{7}
\end{equation*}
$$

(b) Stripe pattern [a 45-deg variant of Fig. 9(c)]: compute the average color difference value along the edge direction determined by two edge classifiers defined as $D 1=\left|R_{i-1, j-1}-R_{i+1, j+1}\right|$ and $D 2$ $=\left|R_{i-1, j+1}-R_{i+1, j-1}\right|$ :
$\widehat{g r_{i, j}}=\left\{\begin{array}{lc}\left(g r_{i-1, j-1}+g r_{i+1, j+1}\right) / 2 & D 1<D 2 \\ \left(g r_{i-1, j+1}+g r_{i+1, j-1}\right) / 2 & D 1 \geqslant D 2 .\end{array}\right.$
The missing red values at blue pixels can then be obtained by using the estimated color difference values $\widehat{g r}_{i, j}$ and the green values estimated in the previous step as $\widehat{R}_{i, j}=\widehat{G}_{i, j}-\widehat{g} \widehat{r}_{i, j}$.
2. Filling in the missing red values at green pixels: This process is similar to the preceding one, except that the neighboring pattern is now formed by the available $g r$ values at locations $(i-1, j),(i, j+1),(i+1, j)$, and $(i, j-1)$. As the blue plane can be estimated similarly, at the end of the initialization step, we obtain the complete red, green, and blue planes as well as the full color difference planes $(g r$ and $g b)$. The first
two rows of Table 1 show the PSNR performance of Hamilton's method and the proposed initialization step. On average, our initialization step outperforms Hamilton's method by an average of about 0.7 dB in the red and blue planes.

### 3.1.2 Enhancement

This step further reduces the remaining artifacts in the diagonal edges and high-detail regions of each image by updating the green plane using an edge-weighted interpolation and then updating the red and blue planes using the more accurate green plane obtained.
3.1.2.1 Green plane. (using edge-weighted interpolation). Referring to Fig. 8, we obtain the estimates of $G_{i, j}$ in the four interpolation directions (top, down, left, and right) as
$\widehat{G}_{(1)}=C_{i, j}+\overparen{g} \widehat{c}_{i-1, j}$
$\widehat{G}_{(2)}=C_{i, j}+\widehat{g}_{i+1, j}$
$\widehat{G}_{(3)}=C_{i, j}+\widehat{g}_{i, j-1}$

(a) Original

(d) Freeman

(g) NEDI

(b) Bilinear

(c) Hamilton

(h) AP

(c) PRI

(f) ECI

(i) Proposed

Fig. 19 Original and demosaicked results of a cropped region from image 8.
$\widehat{G}_{(4)}=C_{i, j}+\widehat{g}_{i, j+1}$,
respectively, where $\widehat{g c}$ denotes a color difference value $(g r$ or $g b$ ) obtained in the previous step. The weights in the four directions are calculated as
$\alpha_{(1)}=\left|C_{i-2, j}-C_{i, j}\right|+\left|G_{i-1, j}-G_{i+1, j}\right|+\left|C_{i-1, j}-C_{i, j}\right|$
$\alpha_{(2)}=\left|C_{i+2, j}-C_{i, j}\right|+\left|G_{i+1, j}-G_{i-1, j}\right|+\left|C_{i+1, j}-C_{i, j}\right|$
$\alpha_{(3)}=\left|C_{i, j-2}-C_{i, j}\right|+\left|G_{i, j-1}-G_{i, j+1}\right|+\left|C_{i, j+1}-C_{i, j}\right|$
$\alpha_{(4)}=\left|C_{i, j+2}-C_{i, j}\right|+\left|G_{i, j+1}-G_{i, j-1}\right|+\left|C_{i, j+1}-C_{i, j}\right|$.
The green value $G_{i, j}$ is then updated as
$\widehat{G}_{i, j}=\sum_{k=1}^{4} \frac{\widehat{G}_{(k)}}{1+\alpha_{(k)}} / \sum_{i=k}^{4} \frac{1}{1+\alpha_{(k)}}$,
where the addition of one in each denominator is included to avoid division by zero.
3.1.2.2 Red and blue planes. (using pattern adaptive interpolation). In this step, we employ the same method used in the initialization step to update the red and blue planes using the more accurate green plane obtained in the previous step.

By exploiting the spatial and spectral information in the four directions, this step works well in regions with sharp edges and fine details. It also rectifies the wrong judgements made by the adaptive interpolation performed in the initialization step, as evidenced by the sample results shown in Fig. 13. Compared with that of the initialization step, the image fidelity is further improved by an average of 1.6 dB , as listed in the second and third rows of Table 1.


Fig. 20 Original image regions and demosaicked results obtained by the PCSD method and our proposed method.

Table 2 Performance comparison: PSNR results (in dB) of the red, green, and blue color planes are listed in the 1st, 2nd, and 3rd rows of each image. The best PSNR result of each row is underlined.

Image Bilinear PRI Freeman ECI NEDI AP PCSD AHD Proposed Image Bilinear PRI Freeman ECI NEDI AP PCSD AHD Proposed

| 1 | 25.31 | 25.31 | 30.75 | 33.21 | 33.77 | 37.17 | 32.89 | 34.38 | 37.93 | 16 | 30.30 | 30.30 | 35.37 | 37.51 | 39.41 | 41.46 | 40.23 | 41.04 | 42.50 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 29.58 | 30.80 | 37.08 | 35.65 | 35.95 | 40.02 | 38.74 | 35.97 | 41.60 |  | 34.73 | 35.94 | 41.78 | 40.14 | 41.43 | 44.39 | 44.99 | 42.44 | 45.38 |
|  | 25.35 | 25.35 | 30.90 | 33.38 | 34.33 | 36.96 | 33.04 | 34.68 | 38.61 |  | 30.39 | 30.39 | 35.56 | 37.32 | 39.30 | 40.46 | 39.87 | 40.46 | 41.75 |
| 2 | 31.89 | 31.89 | 35.95 | 36.85 | 37.24 | 38.29 | 36.70 | 36.59 | 37.72 | 17 | 31.63 | 31.63 | 38.02 | 39.14 | 36.53 | 41.48 | 38.39 | 38.83 | 41.14 |
|  | 36.26 | 36.76 | 42.36 | 41.28 | 41.37 | 40.20 | 42.48 | 41.42 | 43.51 |  | 34.54 | 34.68 | 41.94 | 40.35 | 39.22 | 43.65 | 42.17 | 40.16 | 43.38 |
|  | 32.36 | 32.36 | 37.77 | 39.35 | 39.87 | 38.73 | 38.82 | 40.22 | 41.64 |  | 30.86 | 30.86 | 37.22 | 38.59 | 36.82 | 40.13 | 38.05 | 38.23 | 40.16 |
| 3 | 33.45 | 33.45 | 39.02 | 40.51 | 39.57 | 41.29 | 40.75 | 40.16 | 42.23 | 18 | 27.32 | 27.32 | 33.39 | 34.92 | 33.35 | 36.74 | 33.46 | 33.72 | 35.73 |
|  | 37.17 | 37.66 | 44.27 | 43.11 | 41.67 | 43.23 | 44.46 | 43.12 | 45.86 |  | 30.54 | 30.62 | 37.48 | 36.54 | 36.05 | 39.47 | 37.76 | 35.54 | 39.10 |
|  | 33.83 | 33.83 | 39.08 | 40.07 | 39.20 | 39.82 | 40.42 | 39.99 | 41.63 |  | 26.82 | 26.82 | 32.88 | 34.82 | 34.03 | 35.95 | 33.46 | 33.87 | 36.35 |
| 4 | 32.61 | 32.61 | 37.07 | 36.88 | 36.89 | 37.70 | 36.49 | 35.78 | 36.98 | 19 | 26.78 | 26.78 | 31.75 | 34.53 | 36.37 | 39.44 | 36.39 | 37.40 | 39.54 |
|  | 36.53 | 36.64 | 43.44 | 42.16 | 41.58 | 42.15 | 42.89 | 41.13 | 43.82 |  | 31.74 | 34.21 | 39.23 | 37.23 | 38.81 | 42.58 | 41.26 | 39.21 | 42.81 |
|  | 32.91 | 32.91 | 39.44 | 40.77 | 40.09 | 41.29 | 39.68 | 40.36 | 42.28 |  | 26.95 | 26.95 | 32.11 | 34.76 | 37.29 | 39.11 | 36.80 | 37.74 | 40.36 |
| 5 | 25.75 | 25.75 | 32.88 | 35.04 | 31.45 | 37.70 | 34.69 | 34.96 | 37.53 | 20 | 30.81 | 30.81 | 37.08 | 38.93 | 37.15 | 41.10 | 38.04 | 38.61 | 41.48 |
|  | 29.32 | 29.90 | 38.82 | 36.84 | 33.70 | 39.42 | 39.69 | 37.17 | 41.00 |  | 34.58 | 35.50 | 42.38 | 40.56 | 39.69 | 43.20 | 42.43 | 40.16 | 44.13 |
|  | 25.92 | 25.92 | 33.02 | 34.74 | 31.13 | 35.53 | 34.35 | 34.34 | 36.68 |  | 30.59 | 30.59 | 36.35 | 37.48 | 36.44 | 38.20 | 36.95 | 37.39 | 39.53 |
| 6 | 26.70 | 26.70 | 32.14 | 34.65 | 35.59 | 38.34 | 36.11 | 37.17 | 38.82 | 21 | 27.63 | 27.63 | 33.33 | 35.63 | 34.69 | 38.85 | 34.85 | 36.35 | 39.18 |
|  | 31.05 | 32.08 | 38.56 | 36.98 | 37.67 | 41.21 | 41.36 | 38.65 | 41.62 |  | 31.54 | 32.34 | 39.06 | 37.57 | 37.15 | 41.53 | 39.93 | 37.63 | 41.91 |
|  | 27.00 | 27.00 | 32.30 | 34.12 | 35.17 | 37.07 | 35.54 | 36.38 | 37.65 |  | 27.53 | 27.53 | 33.20 | 34.97 | 34.34 | 37.27 | 35.12 | 35.48 | 37.80 |
| 7 | 32.57 | 32.57 | 39.10 | 40.31 | 38.58 | 41.85 | 39.96 | 39.81 | 41.86 | 22 | 29.84 | 29.84 | 34.92 | 36.41 | 35.76 | 37.71 | 35.26 | 35.38 | 37.42 |
|  | 36.47 | 37.20 | 44.18 | 42.16 | 41.14 | 43.32 | 43.63 | 42.30 | 45.32 |  | 33.34 | 33.97 | 39.52 | 38.64 | 38.49 | 39.79 | 39.46 | 38.24 | 40.69 |
|  | 32.58 | 32.58 | 38.84 | 39.69 | 38.83 | 39.54 | 39.47 | 39.28 | 41.21 |  | 29.22 | 29.22 | 34.05 | 35.74 | 35.90 | 36.29 | 35.12 | 35.58 | 37.39 |
| 8 | 22.53 | 22.53 | 27.40 | 30.16 | 30.58 | 35.36 | 31.25 | 33.05 | 35.66 | 23 | 34.43 | 34.43 | 40.1 | 40.84 | 40.12 | 41.90 | 40.74 | 40.18 | 41.63 |
|  | 27.40 | 29.82 | 34.87 | 33.09 | 33.61 | 37.99 | 37.38 | 35.07 | 39.76 |  | 37.98 | 38.67 | 44.88 | 43.84 | 42.46 | 43.38 | 44.64 | 43.70 | 45.47 |
|  | 22.48 | 22.48 | 27.40 | 29.87 | 30.27 | 34.26 | 31.25 | 33.14 | 35.97 |  | 34.12 | 34.12 | 40.08 | 41.68 | 40.75 | 39.84 | 41.33 | 41.11 | 42.78 |
| 9 | 31.56 | 31.56 | 36.86 | 38.66 | 39.53 | 41.37 | 39.43 | 39.96 | 41.81 | 24 | 26.40 | 26.40 | 32.73 | 34.37 | 30.84 | 34.90 | 33.12 | 32.04 | 34.27 |
|  | 35.72 | 37.29 | 43.09 | 41.37 | 41.68 | 44.00 | 43.73 | 42.20 | 45.35 |  | 29.38 | 29.35 | 36.62 | 35.54 | 33.74 | 37.27 | 37.14 | 34.30 | 37.11 |
|  | 31.38 | 31.38 | 37.09 | 39.32 | 40.07 | 40.81 | 40.14 | 40.10 | 42.76 |  | 25.29 | 25.29 | 30.37 | 31.94 | 30.13 | 32.59 | 31.55 | 31.29 | 32.63 |
| 10 | 31.84 | 31.84 | 38.02 | 39.37 | 38.14 | 41.44 | 39.01 | 39.30 | 41.02 | 25 | 25.90 | 25.90 | 30.36 | 31.92 | 27.04 | 32.48 | 33.44 | 33.32 | 33.33 |
|  | 35.37 | 36.27 | 43.66 | 42.07 | 40.02 | 44.30 | 43.97 | 42.21 | 45.24 |  | 30.28 | 30.97 | 36.97 | 35.62 | 30.23 | 36.75 | 38.18 | 37.94 | 37.86 |
|  | 31.23 | 31.23 | 37.51 | 39.43 | 38.10 | 40.63 | 39.26 | 39.43 | 41.68 |  | 26.01 | 26.01 | 30.22 | 31.72 | 27.10 | 32.37 | 33.23 | 33.05 | 32.12 |
| 11 | 28.17 | 28.17 | 33.70 | 35.62 | 34.98 | 38.66 | 35.61 | 36.37 | 38.33 | 26 | 29.65 | 29.65 | 34.31 | 34.41 | 33.76 | 35.37 | 33.17 | 33.38 | 36.66 |
|  | 32.22 | 32.99 | 39.80 | 38.06 | 37.70 | 40.93 | 40.84 | 38.61 | 41.96 |  | 32.72 | 32.35 | 38.51 | 36.73 | 35.99 | 39.05 | 37.13 | 35.20 | 40.41 |
|  | 28.34 | 28.34 | 34.20 | 36.09 | 35.32 | 38.36 | 36.05 | 37.29 | 39.53 |  | 29.58 | 29.58 | 34.66 | 34.98 | 34.22 | 36.33 | 33.49 | 33.96 | 37.86 |
| 12 | 32.67 | 32.67 | 37.77 | 39.22 | 40.17 | 42.08 | 40.13 | 40.24 | 41.85 | 27 | 22.47 | 22.47 | 28.01 | 29.28 | 28.59 | 30.77 | 30.56 | 30.56 | 32.57 |
|  | 36.82 | 38.07 | 43.74 | 42.40 | 42.87 | 44.30 | 45.18 | 43.06 | 46.04 |  | 26.10 | 26.49 | 33.12 | 31.22 | 30.48 | 33.35 | 34.29 | 32.67 | 35.91 |
|  | 32.35 | 32.35 | 37.70 | 39.38 | 40.40 | 41.17 | 40.54 | 41.03 | 42.79 |  | 22.32 | 22.32 | 27.56 | 28.62 | 27.97 | 30.21 | 29.70 | 29.64 | 31.36 |
| 13 | 23.09 | 23.09 | 29.52 | 31.43 | 29.52 | 34.40 | 29.96 | 31.11 | 34.25 | 28 | 25.70 | 25.70 | 31.49 | 33.22 | 32.42 | 35.57 | 34.20 | 35.05 | 36.89 |
|  | 26.49 | 26.47 | 34.20 | 32.64 | 32.00 | 36.79 | 34.83 | 31.97 | 36.43 |  | 29.76 | 30.77 | 37.68 | 35.29 | 35.34 | 38.49 | 38.62 | 37.32 | 40.40 |
|  | 23.00 | 23.00 | 29.14 | 30.64 | 29.37 | 33.01 | 29.54 | 30.35 | 33.00 |  | 25.94 | 25.94 | 31.64 | 32.91 | 32.65 | 34.98 | 33.91 | 34.51 | 36.22 |
| 14 | 28.15 | 28.15 | 33.54 | 34.78 | 34.41 | 35.81 | 34.06 | 33.99 | 36.45 | 29 | 32.75 | 32.75 | 38.06 | 38.55 | 38.22 | 39.43 | 39.27 | 39.54 | 40.27 |
|  | 32.01 | 32.58 | 38.91 | 37.87 | 37.56 | 37.75 | 38.21 | 37.78 | 41.22 |  | 36.34 | 36.92 | 43.20 | 41.14 | 41.39 | 42.78 | 43.25 | 43.45 | 44.52 |
|  | 28.60 | 28.60 | 34.24 | 35.15 | 34.70 | 34.12 | 34.56 | 34.80 | 36.89 |  | 33.49 | 33.49 | 39.33 | 39.63 | 39.10 | 40.39 | 40.08 | 40.28 | 41.51 |
| 15 | 31.05 | 31.05 | 35.13 | 36.33 | 34.76 | 38.02 | 36.04 | 35.28 | 36.65 | 30 | 27.01 | 27.01 | 29.54 | 28.99 | 29.19 | 28.38 | 28.73 | 28.58 | 29.89 |
|  | 35.36 | 35.54 | 42.35 | 41.11 | 39.43 | 40.09 | 41.71 | 39.87 | 42.69 |  | 29.46 | 29.47 | 32.38 | 31.48 | 31.55 | 30.72 | 31.38 | 31.56 | 32.83 |
|  | 32.26 | 32.26 | 38.17 | 39.31 | 37.48 | 38.70 | 38.46 | 38.26 | 40.38 |  | 24.09 | 24.09 | 26.63 | 26.58 | 26.83 | 26.50 | 26.83 | 26.64 | 27.62 |
|  |  |  |  |  |  |  |  |  |  |  | 28.87 | 28.87 | 34.24 | 35.72 | 34.56 | 37.83 | 36.08 | 36.07 | 38.05 |
|  |  |  |  |  |  |  |  |  |  | Mean | 32.69 | 33.41 | 39.80 | 38.29 | 37.34 | 40.40 | 38.74 | 38.67 | 41.78 |
|  |  |  |  |  |  |  |  |  |  |  | 28.76 | 28.76 | 34.29 | 35.77 | 34.76 | 37.02 | 36.19 | 36.29 | $\underline{38.30}$ |



Fig. 21 Original image regions and demosaicked results obtained by the AHD method and our proposed method.

### 3.2 Refinement Process

The refinement process aims to suppress false colors residing in the results obtained by the reconstruction process. It comprises an edge-adaptive median filtering and an updating step, both applied to the color difference planes.

### 3.2.1 Edge-adaptive median filtering

To locate the genuine edge regions, we first apply a $5 \times 5$ median filter on the color difference planes to suppress spurious edges stemming from the demosaicking artifacts generated in the previous steps. Then, we detect the edge regions by convolving the median-filtered color difference planes ( $G c$ ) with a discrete Laplacian filter, defined as
$H=\left[\begin{array}{ccc}0.0909 & 0.8182 & 0.0909 \\ 0.8182 & -3.6364 & 0.8182 \\ 0.0909 & 0.8182 & 0.0909\end{array}\right]$.
The output of the convolution $E=G c^{*} H$ is compared against a threshold to obtain a binary edge map, given by
$B(i, j)= \begin{cases}1 & \text { if }|E(i, j)|>T \\ 0 & \text { otherwise },\end{cases}$
where $T$ is a threshold for identifying image regions with high variances, and it is set to 10 in our implementation. The pixels indicated as 1 are considered to be located at edge regions; otherwise, smooth regions.

An edge-adaptive median filtering is then applied to the smooth regions in the color difference planes to remove demosaicking artifacts, as discussed in Sec. 2.2.

### 3.2.2 Updating

In this step, we update the three color planes by using the color difference values in the smooth regions identified in the previous step. This step consists of the two following substeps.

1. Update the red and blue planes in smooth regions: Obtain the red/blue values at each green pixel by averaging the two $g r / g b$ values at the neighboring red/blue pixels. Referring to Fig. 8, the C value at $G_{i-1, j}$ is updated as:
$\widehat{C}_{i-1, j}=G_{i-1, j}-\frac{\left(\widehat{g c_{i-2, j}}+\widehat{g c_{i, j}}\right)}{2}$.

Similarly, update the red values at blue pixels, and vice versa, by applying the pattern adaptive interpolation to the four neighboring $g r / g b$ values (top, down, left, and right), as described in Eqs. (7) and (8) of the initialization step.
2. Update the green plane in smooth regions: Obtain the green values at red/blue pixels by applying the pattern adaptive interpolation to the four neighboring $g r / g b$ values (top, down, left, and right), as described in Eqs. (7) and (8) of the initialization step.

After updating, the false colors can be effectively suppressed in the demosaicked images, as shown in Fig. 14. Compared with that obtained by the reconstruction process, the image fidelity can be further improved by another 1.2 dB (on average), as shown in the last two rows of Table 1.


Fig. 22 Differences (with respective to the originals) in the red, green, and blue planes after each main step.

## 4 Experimental Results

To evaluate the performance of our proposed method, we compare our demosaicked results with those obtained by one early method (bilinear interpolation) and several representative and state-of-the-art methods, including Cok's pattern recognition interpolation (PRI), ${ }^{2}$ Freeman's median filtering (Freeman), ${ }^{4}$ Hamilton's adaptive color plane interpolation (Hamilton), ${ }^{8}$ Pei's effective color interpolation (ECI), ${ }^{15}$ Li's new edge directed interpolation (NEDI), ${ }^{12}$ Gunturk's alternating projections (AP), ${ }^{13}$ Wu's primary-consistent soft-decision (PCSD) method, ${ }^{16}$ and Hirakawa's adaptive homogeneity-directed demosaicking algorithm (AHD). ${ }^{18}$

Among the methods under comparison, bilinear interpolation is the simplest and also the most common benchmark for performance comparison in demosaicking literature. Cok, Hamilton, and Freeman's methods have their respective strengths as discussed in Sec. 2. Pei, Li, Gunturk, Wu, and Hirakawa's methods are five recently proposed methods that can obtain superior results. Figure 15 shows our
image test set; most of the images in the test set have been widely used for CFA demosaicking researches and experiments in the literature. ${ }^{10,12,13,15-18}$

In what follows, we evaluate the performance of the proposed hybrid method from two aspects: subjective visual evaluation and objective PSNR comparison.

### 4.1 Visual Evaluation

Figures 16-19 show the cropped regions of four test images and their corresponding demosaicked results obtained by our proposed hybrid method and other methods under comparison. Observably, our proposed method incurs fewer zipper effects and false colors.

In particular, Fig. 16 shows the demosaicking performance in regions with vertical edges. As illustrated in Sec. 2.1 , this region is prone to artifacts especially for those methods without directional interpolation, such as bilinear interpolation, Freeman's method, and the ECI method. As observed, Hamilton's method can reduce the zipper effects effectively, and it also helps improve the performance of the AP method and our proposed hybrid method. Since the AP method and the NEDI method attempt to exploit both spatial and spectral correlations, they result in fewer artifacts in this challenging region. Our proposed method produces the most visually appealing results by further suppressing most false colors with effective exploitation of both spatial and spectral correlations.

Figure 17 illustrates the demosaicking performance in edge regions that do not have high spectral correlation. As seen, the AP, ECI, and NEDI methods result in excessive zipper effects, while bilinear interpolation and the PRI method produce blurred edges. Hamilton and Freeman's methods produce decent results in this region except some slight false colors around axles. Our proposed method recovers the sharp edges the best and suppresses the false colors the most.

Figure 18 shows the image region with fine details and edges in various directions. As bilinear interpolation and the PRI method average pixel values across edges and interpolate the three color planes separately, they produce blurred results with most false colors. Similarly, Freeman's method and the ECI method also fuse pixels across edges, resulting in objectionable zipper effects. Moreover, as the three color planes are not highly correlated, the ECI, NEDI, and AP methods all produce false colors. Observably, the result of our proposed method is the most similar to the original image.

The region in Fig. 19 has fine details and highly correlated color planes. As observed, those methods that do not exploit spectral correlation, such as bilinear interpolation, PRI, and Freeman's method, result in more false colors than others. In addition, those methods that do not exploit spatial correlation, such as bilinear interpolation, Freeman's method, and the ECI method, produce more zipper effects. Our proposed hybrid method underlines the point that better demosaicked results can be obtained by exploiting both spatial and spectral correlations.

Figure 20 presents the demosaicked results of test images 13, 21, and 18 obtained by the PCSD method and our proposed method. By using a training process, the PCSD method can obtain satisfying demosaicked results, especially for images in the training set (e.g., image 25 in Fig.


Fig. 23 PSNR results of the red, green, and blue planes obtained after each main step.

15 and Table 2). However, the method is prone to producing false colors in regions with complex edges and fine details, as shown in Figs. 20(b), 20(e), and 20(h). Compared with the PCSD's results, the demosaicked results of our proposed algorithm have fewer false colors.

As reported in Gunturk's review paper, ${ }^{17}$ the AHD method can produce perceptually favorable image results with fewer artifacts than other existing algorithms compared in that paper. Our experiments also demonstrate the effectiveness of the AHD method. By exploiting both the

Table 3 Average PSNR results (in dB ) when one of the three main steps is not included in the proposed method.

| Image | R | G | B |
| ---: | :---: | :---: | :---: |
| With all steps | 37.94 | 41.58 | 38.06 |
| Without step 1 | 37.69 | 41.14 | 37.74 |
| Without step 2 | 37.27 | 40.43 | 37.32 |
| Without step 3 | 37.38 | 40.58 | 37.48 |

image spatial and spectral correlations, the AHD algorithm can generally reconstruct images with fewer false colors and sharper edges. However, it performs less effectively in regions with fine textures or patterns. Two examples are shown in Fig. 21, where we can see that the AHD algorithm blurs the fine textures and produces more aliasing artifacts as compared with our proposed method.

To see the merit of each step of the proposed method, we examine the differences (respective to the originals) in the three color planes after each main step. For ease of analysis, we partition our method into three main steps: step 1-initialization; step 2-enhancement; step 3 -refinement. Figure 22 shows the differences obtained by subtracting the demosaicked images from their originals to depict the amounts of demosaicking errors. Also shown below each difference image is the percentage of pixels with difference values larger than 8 intensity level, which is considered visible at close inspection. We can see that the demosaicking artifacts are reduced step by step.

### 4.2 Objective Comparison

The PSNR performances of the methods under comparison are listed in Table 2. The table shows that our proposed method outperforms others in terms of PSNR results over most of the test images. In particular, the PSNR results obtained by our proposed method on the 30 test images are, on average, 1.29 dB and 2.37 dB better than that of the AP method and the AHD method, respectively.

Figure 23 shows the contribution of each step to the overall PSNR results in the red, green, and blue planes, respectively. We can see that the image fidelity is enhanced progressively after applying each step. To illustrate the necessity of each step, Table 3 shows the degradation in the average PSNR values of three color planes if one of the three main steps is not included in the proposed method.

### 4.3 Computational Complexity

In our implementation, the proposed method requires about 80 additions, 15 multiplications, 14 bit-shifts, 33 absolute operations, 8 comparisons, and 4 median operations ( 2 with $2 \times 2$ values and 2 with $5 \times 5$ values) for each pixel. These operation counts are obtained under the assumption that the probabilities of occurrences of the three neighborhood patterns (edge pattern, corner pattern, and stripe pattern) considered in the pattern adaptive interpolation process are equal, and $2 / 3$ of the pixels are judged to be in smooth regions. The operation counts may vary moderately according to the content of the image being processed. With ref-
erence to Ref. 18, the AHD method requires 97 additions, 48 multiplies (including bit-shifts), 12 absolute operations, and 8 median operations ( 4 with $2 \times 2$ values and 4 with $3 \times 3$ values) per pixel. As for the AP method, it was estimated in Ref. 13 that 384 additions and multiplications per pixel are required for the implementation with 3 iterations. Hence, the computational complexity of the proposed algorithm is close to that of the AHD method and lower than that of the AP method.

## 5 Conclusion

In this paper, we have analyzed the causes of two main types of CFA demosaicking artifacts-zipper effects and false colors-and examined the schemes which are effective in suppressing them. By combining and extending the strengths of the schemes examined, we have proposed a hybrid CFA demosaicking method. The method incorporates the core merits of these effective schemes to suppress zipper effects and false colors by adaptively exploiting both the image spatial and spectral correlations. Experimental results suggest that the proposed method not only can greatly suppress the demosaicking artifacts, but also produce the best PSNR results, on average, over a large variety of popular test images.

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