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# Double Binnable RGB, RGBW and LMS Color Filter Arrays

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## Abstract

*New, high-resolution CMOS image sensors for mobile phones have moved beyond the single-binnable Quad Bayer and RGBW-Kodak patterns to the double binnable Hexadeca Bayer pattern featuring 4x4 tiles of like-colored pixels. Pixel binning enables high-speed, low-power readout in low-resolution modes and, more importantly, a reduction of read noise via floating diffusion binning.*

*In this paper, we present the non-intuitive result that Nona and Hexadeca Bayer can be superior to Quad Bayer in demosaicking quality due to degeneracies in the latter's spectrum. However, Hexadeca Bayer suffers from the weakness of generating Quad Bayer after one round of binning.*

*We introduce novel double binnable RGBW and LMS CFAs, composed of 2x2 tiles capable of 4:1 floating diffusion binning, that are free from spectral degeneracies and thus demosaic well in full resolution and both binned modes. RGBW offers a 6 dB low-light, read noise-limited, SNR advantage over Quad and Hexadeca Bayer in all resolution modes, while for LMS, the corresponding advantage is 4.2 dB.*

## Introduction

The rapid shrinkage of mobile CMOS image sensors' pixel pitch, triggered by advancements in stacked die technology, has resulted in sensors with a very large number of low SNR pixels, leading to the popularity of pixel binning [1]. In addition to the obvious benefits of high-speed, low-power readouts in low-resolution modes, pixel binning also helps reduce read noise by accumulating charge from the binned pixels in their common floating diffusion - a noiseless process - before encountering the noisy source follower and the downstream read circuit [2].

Binning of 4 pixels to 1 results in a 6 dB SNR improvement in low-light, read noise limited settings if the pixel values are summed in the voltage or digital domains. This is comparable to the SNR improvement expected by reading out the full-resolution image followed by downsizing to half resolution. Floating diffusion binning, on the other hand, can deliver a 12 dB SNR improvement in low-light, read noise-limited settings by replacing 4 trips through the noisy source follower for every binned pixel read with 1. In bright light, photon shot noise-limited settings, all binning methods provide similar SNR improvement, which is also broadly similar to that obtained by reading out the full-resolution image followed by downsizing.

Floating diffusion binning is only possible for pixels that share a readout circuit. Tiles of 2x2 pixels share a readout circuit in most high-resolution CMOS sensors, limiting floating diffusion binning to 4:1 binning. Variants include a mode that restricts floating diffusion binning to 2:1 to avoid integration times short enough to interfere with LED flicker. Another variant uses a switchable bank of floating diffusions to provide variable capacitance - or conversion gain - in order to avoid saturation and extend the dynamic range of the pixel [3, 4].

### *Popular Binnable Color Filter Arrays*

The most popular binnable CFA is the Quad Bayer pattern, shown in Figure 3, which replaces each pixel of the Bayer pattern with a 2x2 tile of 4 pixels of the same color. Extensions of the Quad Bayer pattern are the newer Nona Bayer and Hexadeca Bayer patterns that replace each Bayer pixel with a tile of 3x3 and 4x4 pixels, respectively. The Hexadeca Bayer pattern allows for two rounds of binning, generating the Quad Bayer pattern after the first round of binning and the Bayer pattern after the second round.

A much less popular CFA is the RGBW-Kodak pattern [5], see Figure 4, which allows 2:1 pixel binning along the diagonal direction. While the RGBW-Kodak CFA yields a 6 dB SNR improvement over Quad Bayer in full resolution, low-light read noise-limited settings, the problem is that full-resolution mode is typically not used in low light. Noise obscures fine detail in low light, making the lower resolution, higher SNR, floating diffusion binned images visually superior - even after upscaling to full resolution. The SNR lead of RGBW-Kodak over Quad Bayer shrinks to 3 dB after one round of binning since the former is limited to 2:1 floating diffusion binning while the latter is capable of 4:1 floating diffusion binning. Furthermore, the RGBW-Kodak requires the readout of twice as much data in the binned mode as Quad Bayer. The combination of RGBW-Kodak's modest 3 dB SNR improvement over Quad Bayer at the expense of higher power consumption by both the sensor's readout circuit and the demosaicker has hampered its prospects in the mobile market.

## Spectral Analysis of Color Filter Arrays

Color Filter Arrays can be analyzed in the frequency domain according to the method of [6] which allows the CFA to be represented as the sum of modulated chrominance signals and a baseband luminance signal.

In the spectrum of each CFA analyzed in the following sections, the luminance and chrominance signals are plotted as circles since the resolution of the camera lens is assumed to be equal in all directions. Furthermore, the radius of each chrominance band is plotted as half that of the luminance band in keeping with the "half bandwidth chrominance" assumption of most demosaickers. This assumption is fair in most cases due to the high correlation between the R, G, and B color planes. Furthermore, adaptive demosaickers assume both luminance and chrominance bandwidths to be locally low along the direction of edges - a fact not depicted in the following figures.

## The Bayer Family

The Quad Bayer, Nona Bayer and Hexadeca Bayer CFAs and their spectra are shown in Figures 1, 2 and 3. In each case, the luminance $l = R+2G+B$, and the chrominances $c_1 = 2G-R-B$ and $c_2 = R-B$.

### *Nona and Hexadeca Bayer*

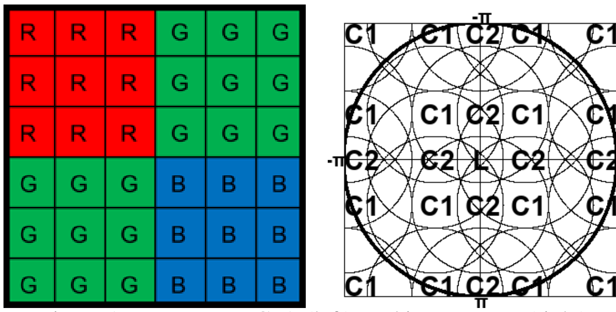



Figure 1: Nona Bayer CFA (left), and its spectrum (right).

Nona [7] and Hexadeca Bayer spectra contain a larger number of chrominance signals modulated at various carrier frequencies, some of which are close to each other or to the luminance. The large number of chrominance signals themselves is not a problem since, along with the luminance, they have only three degrees of freedom - that of red, green, and blue.

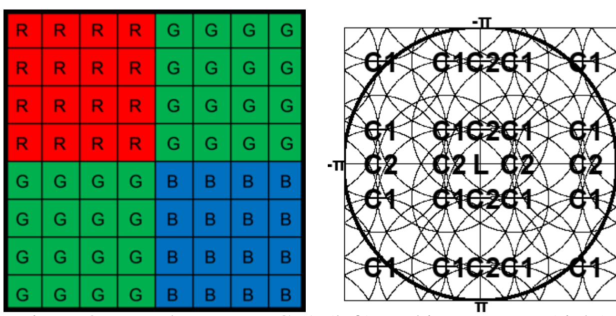



Figure 2: Hexadeca Bayer CFA (left), and its spectrum (right).

The low separation and the resulting overlap of the chrominance spectra is not a problem either. As [8] shows, spectral overlap can be disregarded except under certain degenerate conditions. A simple necessary, though not sufficient, condition for good recovery of chrominance signals is for at least one copy of the linearly independent chrominance signals to be sufficiently separated from each other and from the luminance.

Both Nona and Hexadeca Bayer can be demosaicked with good resolution and low false color using the technique of [8], with the residual false color being amenable to removal by post processing.

### *The Unfortunate Case of Quad Bayer*

The Quad Bayer spectra, shown in Figure 3, has carriers in the interior of the spectrum, located at $(\pm\frac{\pi}{2}, 0)$, $(\pm\frac{\pi}{2}, \pm\frac{\pi}{2})$ and $(0, \pm\frac{\pi}{2})$. The absence of any chrominance carriers sufficiently removed from luminance makes it impossible for any demosaicker that relies on the half chrominance bandwidth assumption to perform well. Since most demosaickers, directly or indi-

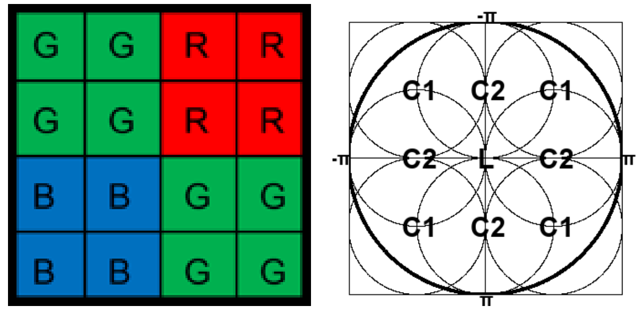



Figure 3: Quad Bayer CFA (left), and its spectrum (right).

rectly, make this assumption, they generate artifacts that can be traced to luminance-chrominance confusion at the chrominance carrier frequencies.

## Binnable RGBW CFAs

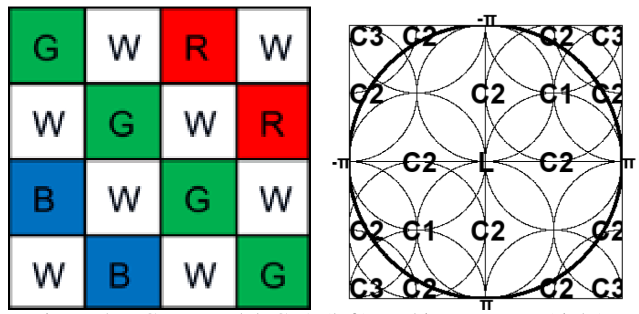



Figure 4: RGBW-Kodak CFA (left), and its spectrum (right).

The only binnable RGBW CFA in production is the RGBW-Kodak pattern [5] shown in Figure 4. RGBW-Kodak outputs 2 pixels for each 2x2 tile after binning, instead of the one output by Quad Bayer. This results in two images: a Bayer mosaic and a W color plane. The W color plane has the following uses:

1. the (Bayer mosaic minus W) difference image is easier to demosaic than the Bayer mosaic alone and results in better resolution and fewer artifacts
2. a fusion algorithm can use the higher SNR W color plane to clean up the noisier demosaicked RGB color planes.

RGBW has higher SNR than RGB systems on image features with relatively unsaturated colors owing to the greater radiant energy captured by W pixels than either of R, G, or B. On highly saturated red, green and blue features, W pixels do not capture much more energy than R, G, B pixels, and the SNR improvement stems from the greater density of pixels sensitive to the color in question. Since half the pixels are W, 3/4 of all pixels are sensitive to G and 5/8 to R or B instead of 1/2 and 1/4 respectively for the Bayer family of CFAs.

The spectrum of full resolution RGBW-Kodak, shown in Figure 4, consists of the luminance $l = R+2G+B+4W$ and the three chrominance signals $c_1 = R-2G+B$, $c_2 = R-B$, $c_3 = R+2G+B-4W$ together accounting for the four degrees of freedom of R, G, B, W. RGBW has been conjectured to have just three degrees of freedom [9, 10], but this has not been borne out in practice as W is not a linear combination of R, G, B as realized by practical color filters.

The problem with RGBW-Kodak is that chrominance $c_1 = R - 2G + B$ has only one copy and it is modulated at the relatively low carrier frequency of $\pm(\frac{\pi}{2}, \frac{\pi}{2})$. This creates confusion between luminance and chrominance resulting in substantial false color in the presence of diagonal luminance features of approximately $\pm(\frac{\pi}{2}, \frac{\pi}{2})$ frequency.

### A Novel Single Binnable RGBW CFA

We propose the novel RGBW-IA pattern shown in Figure 5 that redistributes RGBW-Kodak's 2x2 tiles so as to break up the green diagonal and thus generate more chrominance carriers.

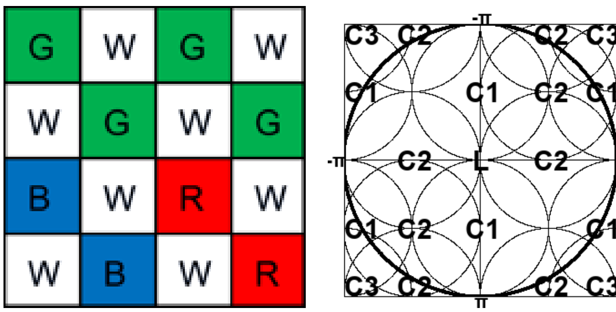



Figure 5: RGBW-IA CFA (left), and its spectrum (right).

Its spectrum is also shown in Figure 5. The definition of $l = R+2G+B+4W$, $c_1 = R-2G+B$, $c_2 = R-B$, $c_3 = R+2G+B-4W$ are identical to those of the RGBW-Kodak CFA. Having at least one copy of $c_1$, $c_2$, $c_3$ removed from the luminance $l$ reduces crosstalk with it; having multiple copies each of $c_1$, $c_2$ allows the demosaicker to adaptively pick the cleaner copy depending on edge orientation. The method of [8] reconstructs images with high resolution and false color that is low enough to be removable by post-processing. False color removal algorithms are a topic of research in themselves and out of the scope of this paper.

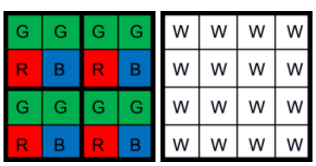



Figure 6: Binned RGBW-IA, tiled 4 times.

Like RGBW-Kodak, RGBW-IA can be binned by summing the pair of diagonally placed W pixels and the pair of diagonally placed R, G or B pixels in each 2x2 tile yielding an RGB mosaic and a W color plane. Unlike RGBW-Kodak, the mosaic generated by binning RGBW-IA is not the Bayer pattern; instead it is the less demosaicking friendly pattern shown in Figure 6. However, the availability of the W color plane allows the easy to demosaic (mosaic minus W) color difference to be computed, demosaicked and the R, G, B color planes to be reconstructed by adding back W. The SNR performance of RGBW-IA is similar to RGBW-Kodak.

### A Novel Double Binnable RGBW CFA

We generate the novel Quad-RGBW pattern, shown in Figure 7, by replacing each pixel of the single binnable RGBW-IA pattern with a 2x2 tile of pixels of the same color. The result is a double binnable CFA with the first round supporting 4:1 floating diffusion binning.

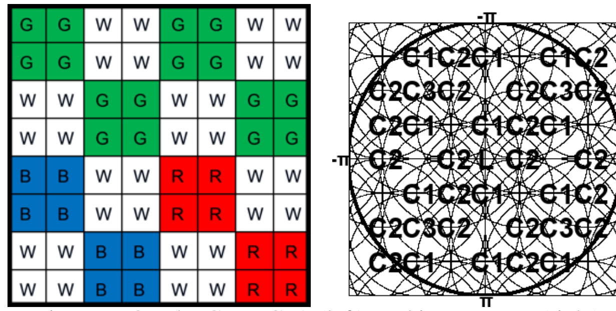



Figure 7: Quad-RGBW CFA (left), and its spectrum (right).

The spectrum of the Quad-RGBW pattern, shown in Figure 7, has the same definition of $l = R+2G+B+4W$, $c_1 = R-2G+B$, $c_2 = R-B$, $c_3 = R+2G+B-4W$ as the RGBW-IA and the RGBW-Kodak CFAs. While the spectrum contains a large number of closely spaced chrominance signals, they have at least one copy removed from the luminance $l$ which reduces their crosstalk with luminance. Multiple copies of $c_1$, $c_2$, $c_3$ allows the demosaicker to adaptively pick the cleaner copies depending on edge orientation. The method of [8] reconstructs images with high resolution and false color that is low enough to be removable by post-processing.

The first round of 4:1 diffusion binning gives Quad-RGBW a 3 dB low light, read noise limited, SNR advantage over binned RGBW-Kodak. At full resolution, and all bin modes, Quad-RGBW has a 6 dB low light, read noise limited and 3 dB bright light, shot noise limited SNR advantage over Quad Bayer and Hexadeca Bayer.

## Binnable LMS CFAs

In this section we develop binnable versions of the LMS CFAs proposed in [11]. The spectral responses of the L, M, S pixels are identical to those of the the (L)ong, (M)edium and (S)hort cones of the human retina. Additionally, like the retina, the LMS CFA contains a larger number of L, M pixels but fewer S pixels.

While M, S pixels are close analogs of the G, B pixels of Bayer sensors, L is a shade of yellow. The spectral response of L is responsible for the improved color accuracy as well has the SNR and dynamic range advantage of LMS over Bayer.

### A Novel Single Binnable LMS CFA

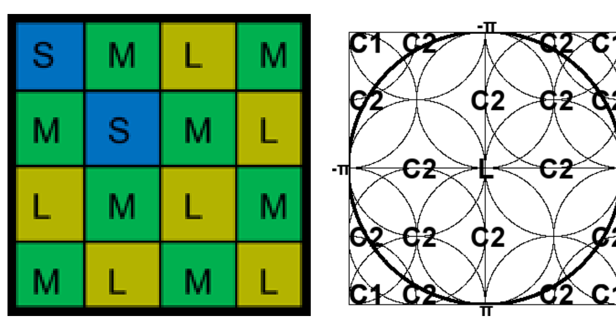



Figure 8: Single binnable LMS CFA (left), and its spectrum (right).

We propose the novel single-binnable LMS CFA shown in

Figure 8. The pattern is composed of pixel pairs of like color arranged along diagonals thereby allowing for 2:1 diagonal binning.

The spectrum of the single binnable LMS CFA consists of $l = 3L + 4M + S$, $c_1 = 6L - 8M + 2S$, $c_2 = L - S$. Both chrominances, $c_1$, $c_2$ have copies near the periphery of the spectrum and sufficiently removed from luminance to prevent crosstalk with it. Having multiple copies of $c_2$ allows the demosaicker to adaptively pick the cleaner copy depending on edge orientation. The method of [8] demosaicks the single binnable LMS with high resolution and low false color.

### *A Novel Double Binnable LMS CFA*

We generate the novel Quad-LMS pattern, shown in Figure 7, by replacing each pixel of the single binnable LMS pattern with a 2x2 tile of pixels of the same color. The result is a double binnable CFA with the first round supporting 4:1 floating diffusion binning.

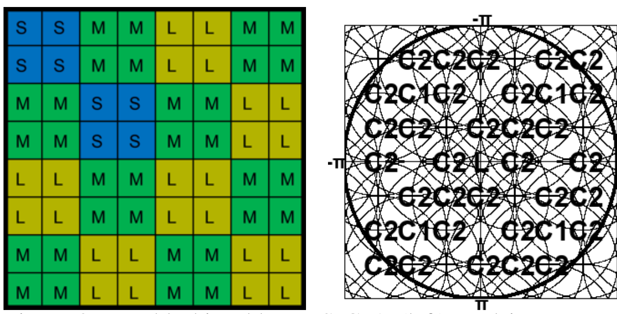



Figure 9: Double binnable LMS CFA (left), and its spectrum (right).

The spectrum of the Quad-LMS pattern, shown in Figure 9, has the same definition of $l = 3L + 4M + S$, $c_1 = 6L - 8M + 2S$, $c_2 = L - S$ as the single binnable LMS CFA. While the spectrum contains a large number of closely spaced chrominance signals, they have at least one copy removed from the luminance $l$ which reduces their crosstalk with luminance. Multiple copies of $c_1$, $c_2$ allows the demosaicker to adaptively pick the cleaner copies depending on edge orientation. High quality demosaicking of Quad LMS is possible with the algorithm of [8].

## Experimental Results

We conducted a simulation study to compare the performance of the CFAs in the noiseless case. Starting with the sRGB ground truth images, we linearized the images by reversing the sRGB tone map, applied a diffraction-limited lens model with an Airy diameter of 2 pixels, followed by conversion to the image sensor color space by applying the inverse of the following typical mobile image sensor color correction matrix:

$$\begin{bmatrix} 1.81 & -0.53 & -0.28 \\ -0.30 & 1.38 & -0.08 \\ -0.13 & -0.33 & 1.46 \end{bmatrix}$$

Finally, we mosaicked the images with the CFA pattern in question to generate the raw data.

Our processing pipeline consisted of demosaicking with the method of [8], followed by post-processing to remove false color, and finally, chrominance denoising. Chrominance denoising in the W, R-W, G-W, B-W color space is an essential step for an RGBW system as it enables it to clean up R, G, B channels with the high SNR W channel. While chrominance denoising is not an essential step for some CFAs, we employed it in pipelines for all CFAs to ensure fair comparisons.

We then converted to the sRGB color space and applied the sRGB tone map. We did not perform luminance denoising or any other post-processing.

We tested on Kodak's "kodim" image set and also the following test charts popular in industry: TE42, ISO 12233 resolution target, Circular Zone Plate. Finally, we stress-tested each CFAs ability to capture fine, irregular features with a newsprint image.

We employed the PSNR metric to measure the demosaicking quality of the CFAs. The results for single binnable CFAs are summarized in table 1 and those for double binnable CFAs are summarized in table 2.

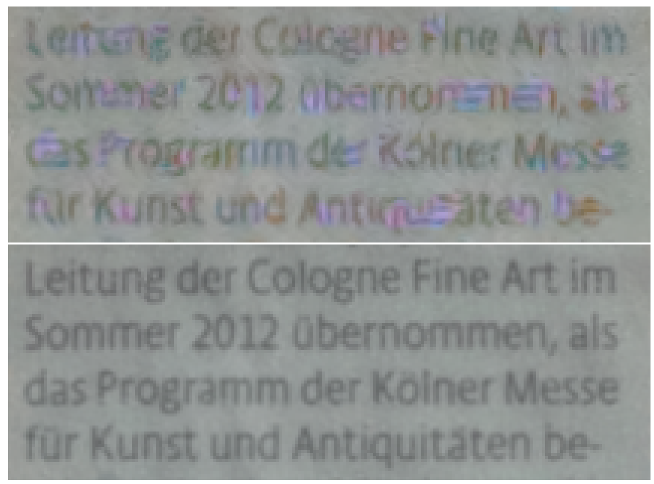



Figure 10: Newsprint (top), captured by a smartphone Quad Bayer CFA, converted to Bayer by the on-sensor remosaicker and then demosaicked by the state of the art algorithm of [12]. The same newsprint (bottom) captured by an equivalent sensor with the RGBW CFA and demosaicked with the algorithm of [8]. Note the poor legibility and severe artifacting in the Quad Bayer image.

Figure 11 shows a crop of the aforementioned newsprint image after mosaicking with both single and double binnable CFAs followed by demosaicking with the method of [8]. Figure 10 shows crops of the same newsprint image captured by actual smartphone camera modules with Quad Bayer and RGBW-Kodak CFA patterns. The Quad Bayer raw data was translated to Bayer raw data by the on-sensor remosaicker followed by Bayer demosaicking using the state-of-the art algorithm of [12]. The RGBW-Kodak raw data was demosaicked by the method of [8].

Note the poor legibility of the Quad Bayer image in Figure 10, despite several generations of commercial algorithm development. Its poor performance is also reflected in its lower PSNR. Other binnable CFAs are free of such problems and yield higher PSNRs.

## Conclusion

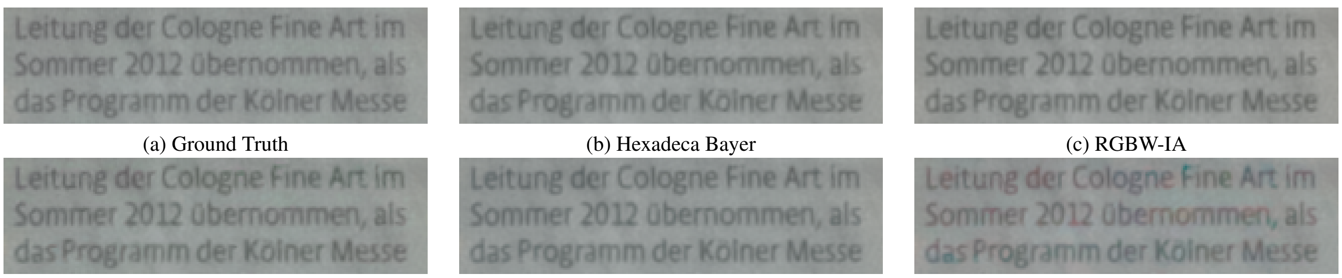
We analyzed the Quad Bayer CFA and revealed a degeneracy in its spectrum that limits its demosaicking quality. This issue was illustrated by capturing a newsprint image with a commercial smartphone sensor employing the Quad Bayer pattern. Furthermore, we examined the upcoming Nona and Hexadeca Bayer

| CFA | Kodim Image Set | ISO 12233 Chart | CZP Chart | TE42 Chart | Newsprint Image |
|---|---|---|---|---|---|
| **Quad Bayer** | 38.4 | 44.4 | 38.6 | 44.1 | 37.5 |
| **RGBW-Kodak** | 38.9 | 47.4 | 41.6 | 45.7 | 45.2 |
| **RGBW-IA** | **42.4** | **47.6** | **43.9** | **46.6** | 45.1 |
| **LMS** | 39.6 | 47.3 | 43.7 | 46.4 | **46.7** |

Table 1: Demosaicking Performance of single binnable CFAs (PSNR in dB).

| CFA | Kodim Image Set | ISO 12233 Chart | CZP Chart | TE42 Chart | Newsprint Image |
|---|---|---|---|---|---|
| **Hexadeca Bayer** | 38.4 | 45.1 | 41.0 | 44.1 | 39.7 |
| **Quad-RGBW-IA** | 38.4 | 46.0 | 41.3 | 44.0 | **42.8** |
| **Quad LMS** | **39.8** | **46.1** | **44.2** | **44.5** | 42.4 |

Table 2: Demosaicking Performance of double binnable CFAs (PSNR in dB).




(a) Ground Truth (b) Hexadeca Bayer (c) RGBW-IA
(d) Quad-RGBW (e) LMS (f) Quad-LMS

Figure 11: Simulated mosaicking of the Newsprint image with the Hexadeca Bayer and proposed CFAs followed by demosaicking with the algorithm of [8].

| Color Filter Array | Bin Mode | Low Light SNR Advantage | Bright Light SNR Advantage | Power Consumption | Frame Rate |
|---|---|---|---|---|---|
| **Quad Bayer** | full resolution | 0 dB (reference) | 0 dB (reference) | **100%** (reference) | **1x** (reference) |
| | binned once | 12 dB | 6 dB | **25%** | **4x** |
| **RGBW-Kodak** | full resolution | **6** dB | **3** dB | **100%** | **1x** |
| | binned once | **15** dB | **9** dB | 50% | 2x |
| **RGBW-IA** | full resolution | **6** dB | **3** dB | **100%** | **1x** |
| | binned once | **15** dB | **9** dB | 50% | 2x |
| **LMS** | full resolution | 4.2 dB | 2.1 dB | **100%** | **1x** |
| | binned once | 13.2 dB | 8.1 dB | 50% | 4x |

Table 3: Single Binnable Color Filter Array Summary

| Color Filter Array | Bin Mode | Low Light SNR Advantage | Bright Light SNR Advantage | Power Consumption | Frame Rate |
|---|---|---|---|---|---|
| **Hexadeca Bayer** | full resolution | 0 dB (reference) | 0 dB (reference) | **100%** (reference) | **1x** (reference) |
| | binned once | 12 dB | 6 dB | **25%** | **4x** |
| | binned twice | 18 dB | 12 dB | **6.25%** | **16x** |
| **Quad-RGBW** | full resolution | **6** dB | **3** dB | **100%** | **1x** |
| | binned once | **18** dB | **9** dB | **25%** | **4x** |
| | binned twice | **24** dB | **15 dB** | 12.5% | 8x |
| **Quad-LMS** | full resolution | 4.2 dB | 2.1 dB | **100%** | **1x** |
| | binned once | 16.2 dB | 8.1 dB | **25%** | **4x** |
| | binned twice | 22.1 dB | 14.1 dB | 12.5% | 8x |

Table 4: Double Binnable Color Filter Array Summary

CFAs and demonstrated their freedom from the problem faced by the Quad Bayer.

Our analysis extended to the less popular RGBW-Kodak CFA, where we identified a spectral issue leading to confusion between luminance and chrominance signals on diagonal image features. Additionally, we noted that its 2:1 floating diffusion binning reduced its binned-mode SNR advantage over the 4:1 binned Bayer from 6 dB to 3 dB.

Finally, we introduced a pair of single and double binnable RGBW CFAs, as well as a pair of single and double binnable LMS CFAs. We demonstrated that their spectra are free from issues and experimentally verified their good demosaicking performance. Both double binnable CFAs are composed of 2x2 tiles of like-colored pixels, enabling 4:1 floating diffusion binning, leading to high SNR. The single binnable CFAs are summarized in table 3 and the double binnable CFAs are summarized in table 4.

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## Author Biography

*Tripurari Singh received his Bachelors in Computer Science from the Indian Institute of Technology, Delhi, (1993) and his PhD in Computer Science from the Johns Hopkins University (1999). Thereafter he worked in the Operations Research industry, developing stochastic optimization algorithms, before switching to image processing. His work has focused on CFA design and the processing of raw sensor data in the presence of white/clear pixels, infrared pixels, chromatic aberration, multiple rounds of pixel binning and high chrominance resolution.*

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