TWICE BINNABLE COLOR FILTER ARRAYS

Mritunjay Singh, Tripurari Singh

Image Algorithmics
Bethesda, MD 20816
USA

ABSTRACT

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

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. Hexadeca Bayer, nevertheless, suffers from the weakness of generating Quad Bayer after one round of binning.

We present a novel twice binnable RGBW CFA, composed of 2x2 tiles capable of 4:1 floating diffusion binning, that is free from spectral degeneracies and thus demosaick well in full resolution and both binned modes. It also has a 4 dB low light SNR advantage over Quad and Hexadeca Bayer in the full resolution mode, and 6 dB SNR advantage in both the binned modes.

***Index Terms*—** Binning, Floating Diffusion Binning, Charge Domain Binnning, Color Filter Array, RGBW, RGBC.

1. INTRODUCTION

The rapid shrinkage of mobile CMOS image sensors' pixel pitch, triggered by advancements in stacked die technology, has resulted in a very large number of low SNR pixels and has led 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 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 [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 it to half resolution. Floating diffusion binning, on the other hand, can deliver 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, the SNR improvement of floating diffusion is identical to those of voltage, digital domain binning and reading out the full resolution image followed by downsizing.

Floating diffusion binning is only possible for pixels that share a readout circuit. 4 pixels share a readout circuit in most high resolution CMOS sensors limiting floating diffusion binning to the first round of 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 so extend the dynamic range of the pixel [3, 4].

1.1. Popular Binnable Color Filter Arrays

The most popular binnable CFA is the Quad Bayer pattern, shown in figure 3, that 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 2 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, that allows 2:1 pixel binning along the diagonal direction. While the RGBW-Kodak CFA allows for 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 as the Quad Bayer in the binned mode The combination of RGBW-Kodak's low 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 hamstrung its prospects in the mobile market.

2. SPECTRAL ANALYSIS OF THE BAYER FAMILY

The Quad Bayer, Nona Bayer and Hexadeca Bayer CFAs and their spectra are shown in figures 1, 2 and 3. Most demosaickers assume reasonably high correlation between the R, G, B color planes leading to the so called "half bandwidth chrominance" assumption of chrominance bandwidths being half that of luminance. Both luminance and chrominance bandwidths are also assumed by most demosaickers to be locally low in the direction of edges.

2.1. Nona and Hexadeca Bayer

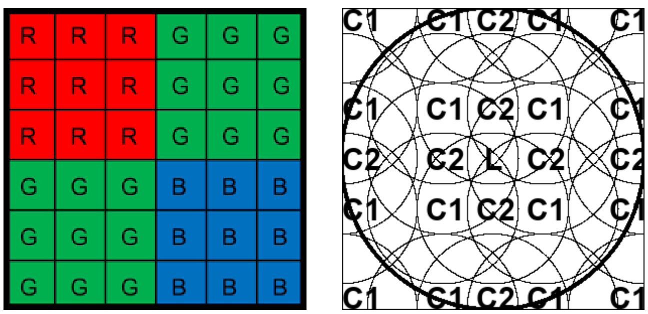

Fig. 1. Nona Bayer CFA and its spectrum.

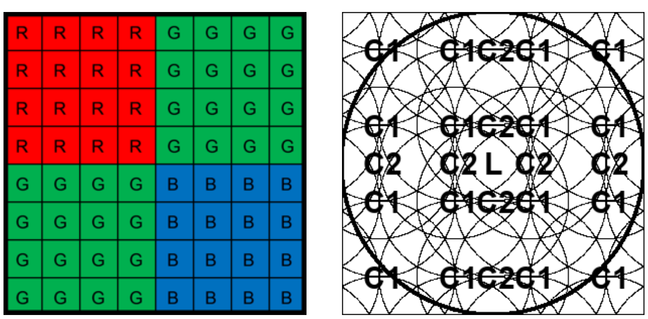

Fig. 2. Hexadeca Bayer CFA and its spectrum.

Nona [6] and Hexadeca Bayer spectra show a larger number of chrominance signals modulated at a variety of carrier frequencies, some of which are close to each other or to the luminance. The large number of chrominance signals itself is not a problem since, along with the luminance, they have only 3 degrees of freedom - that of R, G, B.

Nor is the low separation and the resulting overlap of the chrominance spectra a problem. As [7] 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 two linearly independent chrominance signals to be sufficiently separated from each other and from luminance.

Both Nona and Hexadeca Bayer can be demosaicked with good resolution and low false color using the technique of [7], with the residual false color being amenable to removal by post processing.

2.2. The Unfortunate Case of Quad Bayer

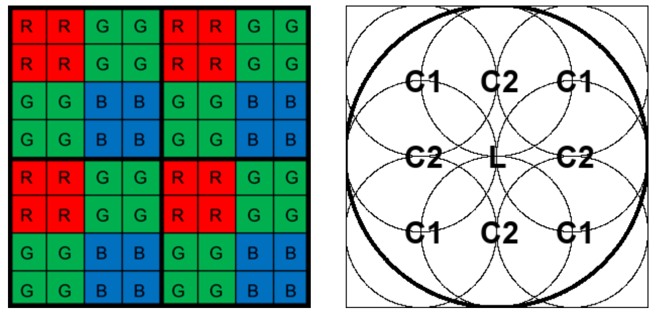

Fig. 3. Quad Bayer CFA, tiled 4 times, and its spectrum.

The Quad Bayer spectra, show 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 indirectly, make this assumption, they generate artifacts that can be traced to luminance-chrominance confusion at the chrominance carrier frequencies.

3. BINNABLE RGBW CFAS

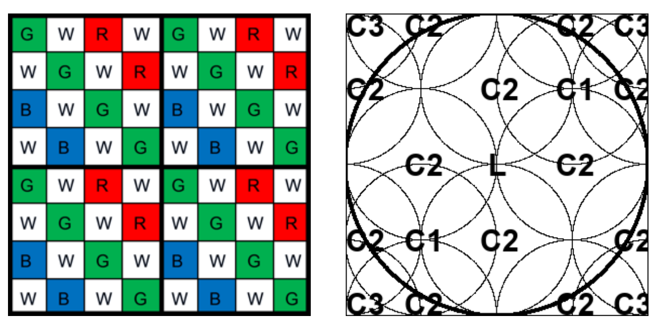

Fig. 4. RGBW-Kodak CFA, tiled 4 times, and its spectrum.

The only binnable RGBW CFA in production is the RGBW-Kodak pattern [5] shown in figure 4. RGBW-Kodak outputs 2 pixels per 2x2 tile after binning, instead of the 1 output by Quad Bayer, resulting in 2 images: a Bayer mosaic and a W color plane. The W color plane has the following uses:

1. the (Bayer mosaic - W) difference image is easier to demosaick 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 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 R, G, B color 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 a luminance and 3 chrominance signals together accounting for the 4 degrees of freedom of R, G, B, W. RGBW has been conjectured to have just 3 degrees of freedom [8, 9], but this has not been borne out in practice as W is not a linear combination of the R, G, B realized by practical filters.

The problem with RGBW-Kodak is that chrominance C2 = R-B has only one copy and it is modulated at the relatively low carried frequency of $(\frac{\pi}{2}, \frac{\pi}{2})$. This creates confusion between luminance and chrominance resulting in substantial false color in the presence of diagonal luminance features of that frequency.

3.1. A Novel Once Binnable RGBW CFA

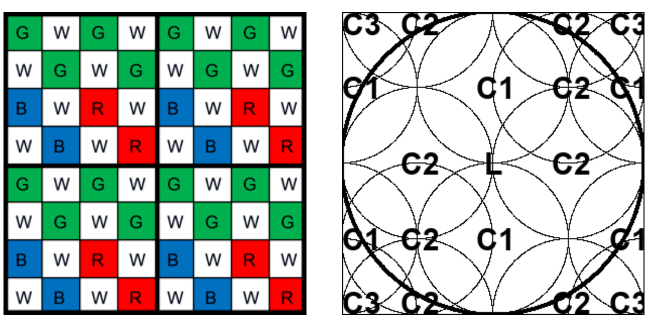

Fig. 5. RGBW-IA CFA, tiled 4 times, and its spectrum.

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. It's spectrum is is also shown in figure 5. Being removed from the luminance reduces C1, C2's crosstalk with it; having 2 copies each of C1, C2 allows the demosaicker to adaptively pick the cleaner copy. The method of [7] reconstructs images with high resolution and sufficiently low false color 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.

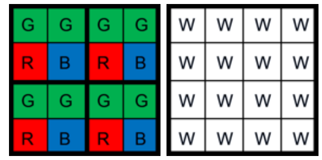

Fig. 6. Binned RGBW-IA, tiled 4 times.

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 a 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-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.

3.2. A Novel Twice Binnable RGBW CFA

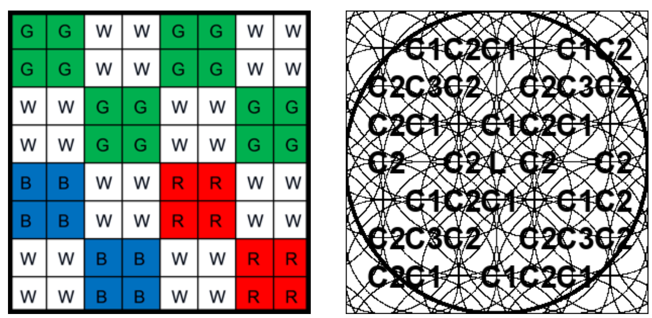

Fig. 7. Quad-IA CFA and its spectrum.

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

The spectrum of the Quad-IA pattern, shown in figure 7, has a large number of closely spaced chrominance signals. Crucially, though, enough of them are near the periphery of the spectrum and sufficiently separated from luminance to allow for good quality demosaicking using techniques of [7] followed by a post processing step to remove the residual false color.

The first round of 4:1 diffusion binning gives Quad-IA a 3 dB low light, read noise limited, SNR advantage over binned RGBW-Kodak and a 6 dB low light, read noise limited, SNR advantage over binned Quad Bayer and once binned Hexadeca Bayer. After the second round of binning Quad-IA maintains its 6 dB low light, read noise limited, SNR advantage over Hexadeca Bayer.

At full resolution, Quad-IA has a 4 dB low light, read noise limited and 2dB bright light, shot noise limited SNR advantage over Hexadeca Bayer, but a 2 dB low light and a 1 dB bright light SNR disadvantage compared to RGBW-Kodak and RGBW-IA. Since binned SNR is more important than full resolution SNR in modern, high resolution CMOS image sensors for mobile phones, Quad IA is the highest performance CFA for this application.

4. EXPERIMENTAL RESULTS

We conduct a simulation study to compare the performance of the CFAs in the noiseless case using PSNR as the metric.

Starting with the sRGB ground truth images, we linearize the image by reversing the sRGB tone map, apply a diffraction limited lens model with a 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 mosaic the image with the CFA pattern in question to generate the raw data.

Our processing pipeline consists of demosaicking with the method of [7] followed by post processing to remove false color and chrominance denoising. Chrominance denoising is essential for RGBW systems to clean up R, G, B color planes with the high SNR W color plane. We also apply chrominance denoising to the Bayer family images to make the comparisons fair. We then convert to the sRGB color space and apply the sRGB tone map. We do not perform luminance denoising or any other post processing.

We use the following test charts popular in industry: TE42, ISO 12233 resolution target, Circular Zone Plate.

CFA	TE42	ISO 12233	CZP
Hexadeca Bayer	45.1 dB	47.6 dB	42.6 dB
Quad-IA	46.4 dB	48.6 dB	44.1 dB
RGBW-IA	49.5 dB	50.2 dB	47.6 dB

Table 2. Demosaicking Performance (PSNR). PSNR is higher than usually reported for demosaicking because of simulation of optics and the use of image sensor color space.

We use the PSNR metric to measure the demosaicking quality of the CFAs. The results are summarized in table 2.

5. CONCLUSION

Our findings are summarized in table 1. The proposed Quad-IA CFA has the highest SNR, except in the full resolution mode where it is surpassed by once binnable RGBW CFAs. Quad-IA also has the lowest power consumption and highest speed except in the twice binned mode where it is surpassed by Hexadeca Bayer. The performance of Quad-IA is very good even in categories where it is not the best making it the top choice for high megapixel sub-micron mobile image sensors.

Color Filter Array	Bin Mode	Demosaic Quality	Low Light SNR Advantage	Bright Light SNR Advantage	Power Consumption	Frame Rate
Quad Bayer	full resolution	poor	0 dB (reference)	0 dB (reference)	**100%** (reference)	**1x** (reference)
	binned once	good	12 dB	6 dB	**25%**	**4x**
RGBW-Kodak	full resolution	fair	**6** dB	**3** dB	**100%**	**1x**
	binned once	good	15 dB	**9** dB	50%	2x
RGBW-IA	full resolution	good	**6** dB	**3** dB	**100%**	**1x**
	binned once	good	15 dB	**9** dB	50%	2x
Hexadeca Bayer	full resolution	good	0 dB	0 dB	**100%**	**1x**
	binned once	poor	12 dB	6 dB	**25%**	**4x**
	binned twice	good	18 dB	12 dB	**6.25%**	**16x**
Quad-IA RGBW	full resolution	good	4 dB	2 dB	**100%**	**1x**
	binned once	good	**18** dB	**9** dB	**25%**	**4x**
	binned twice	good	**24** dB	**15 dB**	12.5%	8x

Table 1. Summary of Binnable Color Filter Array Performance

6. REFERENCES

[1] Sandor L Barna, Scott P Campbell, and Gennady Agranov, "Method and apparatus for improving low-light performance for small pixel image sensors," June 11 2013, US Patent 8,462,220.

[2] Failop Chu, Robert M Guidash, J Compton, S Coppola, and W Hintz, "Improving low-light cmos performance with four-transistor four-shared pixel architecture and charge-domain binning," in *Digital Photography II*. SPIE, 2006, vol. 6069, pp. 25–33.

[3] Vincent C Venezia, Alan Chih-Wei Hsiung, Kelvin Ai, Xiang Zhao, Zhiqiang Lin, Duli Mao, Armin Yazdani, Eric AG Webster, and Lindsay A Grant, "1.5 μ dual conversion gain, backside illuminated image sensor using stacked pixel level connections with 13ke-full-well capacitance and 0.8 e-noise," in *2018 IEEE International Electron Devices Meeting (IEDM)*. IEEE, 2018, pp. 10–1.

[4] Donghyuk Park, Seung-Wook Lee, Jinhwa Han, Dongyoung Jang, Heesang Kwon, Seungwon Cha, Mihye Kim, Haewon Lee, Sungho Suh, Woong Joo, et al., "A 0.8 μm smart dual conversion gain pixel for 64 megapixels cmos image sensor with 12k e-full-well capacitance and low dark noise," in *2019 IEEE International Electron Devices Meeting (IEDM)*. IEEE, 2019, pp. 16–2.

[5] Mrityunjay Kumar, Efraín O Morales, James E Adams, and Wei Hao, "New digital camera sensor architecture for low light imaging," in *2009 16th IEEE International Conference on Image Processing (ICIP)*. IEEE, 2009, pp. 2681–2684.

[6] Youngsun Oh, Munhwan Kim, Wonchul Choi, Hana Choi, Honghyun Jeon, Junho Seok, Yujung Choi, Jaejin Jung, Kwisung Yoo, Donghyuk Park, et al., "A 0.8 μm nonacell for 108 megapixels cmos image sensor with fd-shared dual conversion gain and 18,000 e-full-well capacitance," in *2020 IEEE International Electron Devices Meeting (IEDM)*. IEEE, 2020, pp. 16–2.

[7] T. Singh and M. Singh, "Disregarding Spectral Overlap - a unified approach for Demosaicking, Compressive Sensing and Color Filter Array Design," in *Proc. of IEEE ICIP*, 2011.

[8] J. Wang, C. Zhang, and P. Hao, "New Color Filter Arrays of High Light Sensitivity and High Demosaicking Performance," in *Proc. of IEEE ICIP*, 2011.

[9] Mina Rafinazari and Eric Dubois, "Demosaicking algorithm for the kodak-rgbw color filter array," in *Color Imaging XX: Displaying, Processing, Hardcopy, and Applications*. SPIE, 2015, vol. 9395, pp. 27–32.