MULTI-LEVEL COLOUR HALFTONING ALGORITHMS

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ABSTRACT

Methods for the halftoning of images on multi-level printing devices such as multi-level inkjet printers are presented. Due to the relatively large size of single droplets, halftoning algorithms are still needed. However, since halftoning occurs between the basic levels attainable by printing one, two or several droplets at the same position, artefacts are less visible than in equal resolution bilevel printers. When dithering algorithms are used for the halftoning task, the dither threshold tiles should have oblique orientations so as to make the halftoning artifacts less visible. They should be designed so as to break up the inherent artifacts of variable dot size printers, such as for example continuous lines made up of elongated elliptic dots. Error-diffusion in colour space is also appropriate for multi-level halftoning. Visual artifacts can be reduced by introducing dot over dot colour inhibiting constraints.

1. INTRODUCTION

In the last two years, 300 dpi to 600 dpi high-quality ink jet printers have been offered for desktop publishing at very low cost (below 300 dollars). New halftoning algorithms based on dispersed-dot dithering [1], [2], on improved error-diffusion schemes [3], [12] or on combinations of error-diffusion and dithering techniques [4] have provided the means to reproduce both grayscale and colour images.

Currently, ink-jet device manufacturers are making efforts to put on the market low-cost variable dot size ink-jet printers able to reproduce multiple intensity levels. Multi-level inkjet printers seem easier and cheaper to develop than devices having a significantly higher resolution. The main effort resides in ensuring a constant, repetitive small droplet diameter and at the same time a minimal dot gain by minimizing the ink spread on paper.

Multiple intensity levels per pixel are achieved by printing one, two or several droplets at the same position. Experience shows that if a single droplet has a minimal diameter, say 50% of the diameter of the largest printable dot size, the first darkness level (or surface coverage level) an ink-jet printing device may print is at least 25%, the second darkness level is at least 45%, and the remaining levels cover the darker levels between 45% and 100% darkness. It is therefore of capital importance to use halftoning algorithms in order to obtain additional intermediate intensity levels (Fig. 1), e.g. levels between 0 and 25% darkness, levels between 25% darkness and 45% darkness, etc.

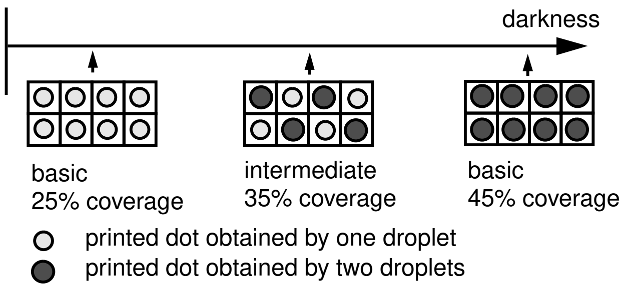


Figure 1. Intermediate darkness levels obtained by dithering between basic levels

The quality criteria for judging and comparing halftoning algorithms are the following:
- visibility of individual dots or screen elements should be minimized
- the number of intensity levels should be large enough (> 40) to avoid banding effects
- structure artifacts, i.e. repetitive or semi-repetitive visible structures should be avoided

Int. Symposium on Advanced Imaging and Network Technologies, October 96, Berlin, SPIE Vol. 2949, 332-340.

- false contours due to sharp halftone structure changes should be avoided

This paper presents dither-based and error-diffusion methods for the halftoning of images on multi-level printing devices. The resulting visual effects are shown by simulating the printed dots of a multi-level inkjet printer.

2. DITHER TILE BASED MULTI-LEVEL HALFTONING

As mentioned in the introduction, multi-level halftoning aims at generating additional intensity levels between the levels produced by printing successive ink drops on paper. When the set of available ink drops produces round dots, and when the colour inks are near to ideal inks or when colour layers can be placed without phase shifts one on top of the other, colour layers can be halftoned separately by a dispersed-dot dithering method such as Bayer dispersed-dot dithering [5], rotated dispersed dither [2] or with the help of any adequate dispersed-dot dither threshold array.

Dither-based halftoning methods [6],[7],[8] are based on dither tiles paving the plane. Parallelogram or hexagonal dither tiles for dispersed-dot dither can be generated recursively with two-fold (Fig. 2a) or respectively three-fold dispersion (Fig. 2b) of threshold levels [9].

The number of additional intensity levels which may be produced between two levels given by k and k+1 droplets printed on a single pixel depends on the size of the dither tile. One has to be careful to select a small dither tile, since a large dither tile induces low frequency components and therefore generates more visible artifacts at low and middle resolution. Between the highest intensity level (no droplet printed) and the next lowest intensity level (one droplet printed), the dither array based multi-level dithering method behaves in the same way as bi-level dithering and produces similar artifacts, but at a reduced intensity.

At an intermediate level between k and $k+1$ droplets printed on a single pixel, artifacts are still visible, especially for k=1 or k=2. Figure 9 illustrates the halftones produced between the intensity levels associated with k=1 and k=2 droplets for a Bayer dither array, a parallelogram dither tile and a hexagonal dither tile. It is immediately apparent that the Bayer dither array generates visually disturbing artifacts such as horizontal and diagonal crosses. Artifacts are less visible with parallelogram and hexagonal dither arrays since they all have an oblique orientation.

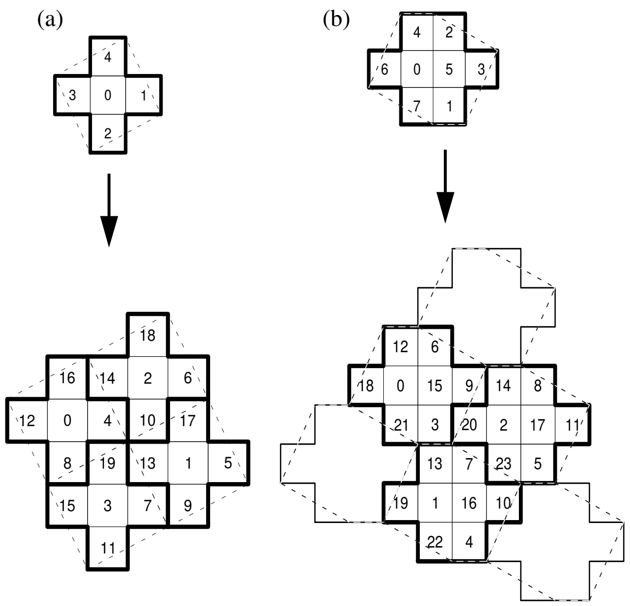
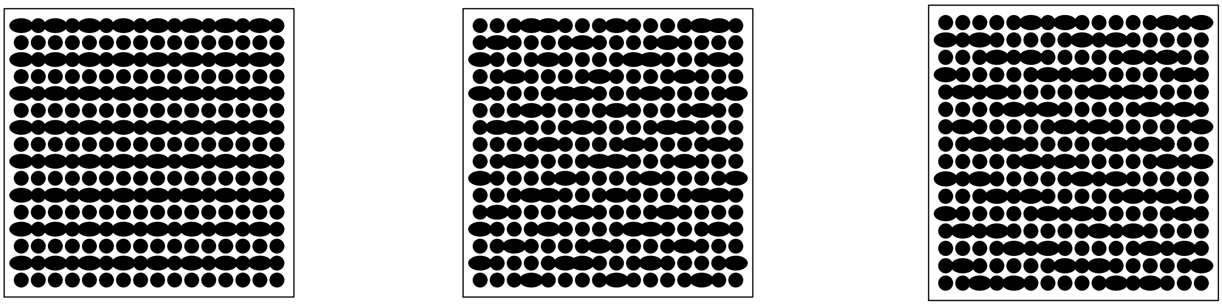


Figure 2. Recursive generation of a parallelogram (a) and hexagonal (b) dispersed dither tiles

In some cases, due to the displacement of the ink-jet head, successive droplets are not printed exactly at the same place, but in a slightly eccentric manner. The resulting printed dot has an elliptic shape. Since the elliptic dot touches neighbouring elliptic dots first in one direction and only after a certain number of intensity levels in the other direction, at certain levels, bands between elliptic dots become visible (Fig. 3a). In order to break these bands, the dither threshold levels should be arranged to produce an elliptic dot growing pattern breaking the continuity of the bands (Figs. 3b and 3c).



(a) Bayer Dispersed Dither level i+2

(b) Parallelogram Dispersed Dither level i+2

(c) HexagonalDispersed Dither level i+2

Figure 3. Breaking the horizontal bands produced by elliptic dot shapes with distributions of dither thresholds according to the tiles shown in Fig. 2a and 2b.

3. ERROR DIFFUSION BASED CONSTRAINED MULTI-LEVEL HALFTONING

Error-diffusion in colour space has been proposed by Sullivan, Miller and Wetzel [10] as a means of reducing artifacts which appear when error-diffusion is applied independently to each colour channel (red, green, blue or cyan, magenta, yellow). These artifacts, also called correlated noise or "worms" become strong when separatly error-diffused halftoned layers are superimposed.

Error diffusion in colour space relies on the idea of computing for each output pixel an error diffusion vector composed of the 3 colour components and to weight and distribute this error vector to neighbouring pixels. At each ouput device pixel, the choice of the ouput colour is made by computing the euclidian distance between the desired ouput colour plus the error colour vector diffused from neighbouring pixels and the available output colours. The ouput colour minimizing that euclidian distance is selected.

As already pointed out by Sullivan, Miller and Wetzel [10], when the chosen output colours lie on a parallelepiped whose sides are parallel to the chosen output space axes, separate error-diffusion in each of the colour layers and vector error diffusion in 3D colour space yield the same result. Sullivan, Miller and Wetzel propose to diffuse the error vector in the non-linear CIELUV colour space and to blur the output vectors in order to minimize error-diffusion artifacts. Klassen, Eschbach and Bharat [11] propose a colour error diffusion method for printing gray tone in colour images, which reduces the intensity of artifacts by distorting the colour space so as to induce the replacement of black pixels by side by side printing of cyan, magenta and yellow pixels. The approach we present is based on inhibiting constraints used for inhibiting the apperance of combined colour variable dot size pixels in highlight and mid-tone regions.

We apply color error diffusion in a linear RGB space which is obtained by a linear transformation of the parallelepiped whose vertices are given by the CIE-XYZ coordinates of solid printed Cyan, solid printed Magenta and solid printed Yellow. Worm-like artifacts are strong when colour layers are halftoned independently or equivalently, when colour error diffusion is applied with target colours C,M,Y,R,G,B,W forming a rectilinear parallelepiped in the RGB orthogonal output coordinate space. In highlights, when ink surface coverage percentages are low, one can inhibit the use of superimposed inks forming composed colour R,G,B,K. By removing these ouput colour candidates from the choice of output colours, highlight reds, greens and blues are generated by yellow-magenta, respectively cyan-yellow and cyan-magenta side by side dot printing. Fig. 4 shows the colour error-diffusion patterns when two colour layers (layer c1 at 3% and layer c2 at 2% surface coverage) are printed (a) without constraints, i.e. with the possibility of having overlapped c1 and c2 dots, and (b) with constraints inhibiting dot over dot printing.

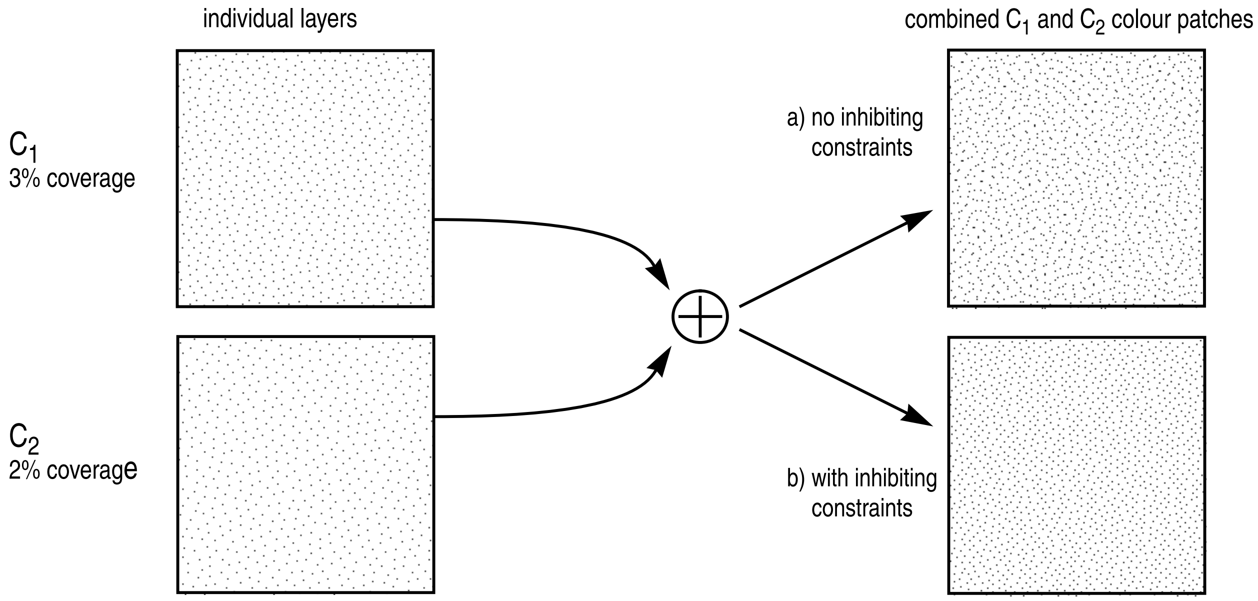


Figure 4. Colour error-diffusion (a) without and (b) with constraints inhibiting dot over dot printing

Clearly, the solution with constrainted error-diffusion provides less worm-like visual artifacts. This visual result can also be explained by the fact that constrained error-diffusion generates more printed pixels (side by side printing instead of dot over dot printing) creating thereby higher frequency artifacts which are less perceptible to human vision.

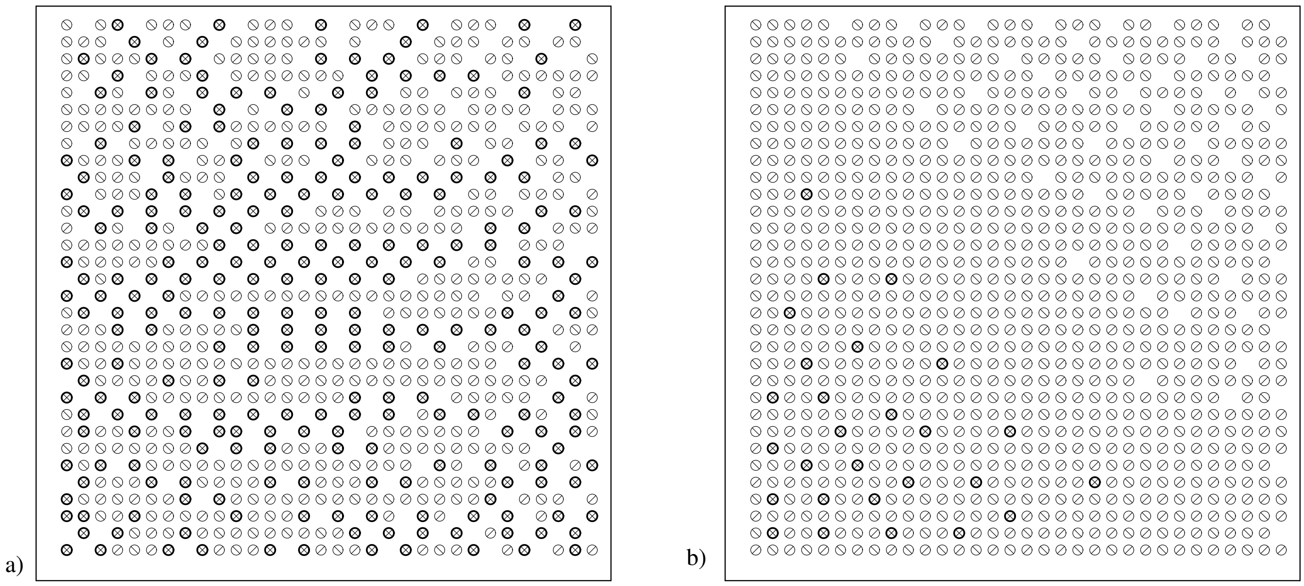


Figure 5. Bilevel colour error-diffused patch with surface coverages c1= 50%, c2=50% at the center and with 12% coverage increase/decrease towards the edges

In the next example (Fig. 5), a colour patch is error-diffused in colour space with two basic colours c1 and c2 having each at the center of the image a surface coverage of 50% which varies towards the borders of the image by 12%. One can clearly see that the patch where the dot superposition of c1 and c2 is inhibited provides less disturbing artifacts. In the patch generated without inhibiting constraints, regions with superimposed c1 and c2 colours contain larger white areas which tend to create artificial boundaries.

Error-diffusion in colour space is also appropriate for variable-dot size printing. For the sake of simplicity and without loss of generality, we consider here a printer capable of printing dots either with one droplet at 50% surface coverage or with two droplets at 100% surface coverage. When printing two colours, for example cyan and magenta, the candidate printable colours for unconstrained error-diffusion are described in Table 1

Figure 6a shows a two dimensional representation of the white-cyan- magenta-blue colour plane which is a part of the printable colour gamut in the RGB ouput colour space (Fig. 6b)

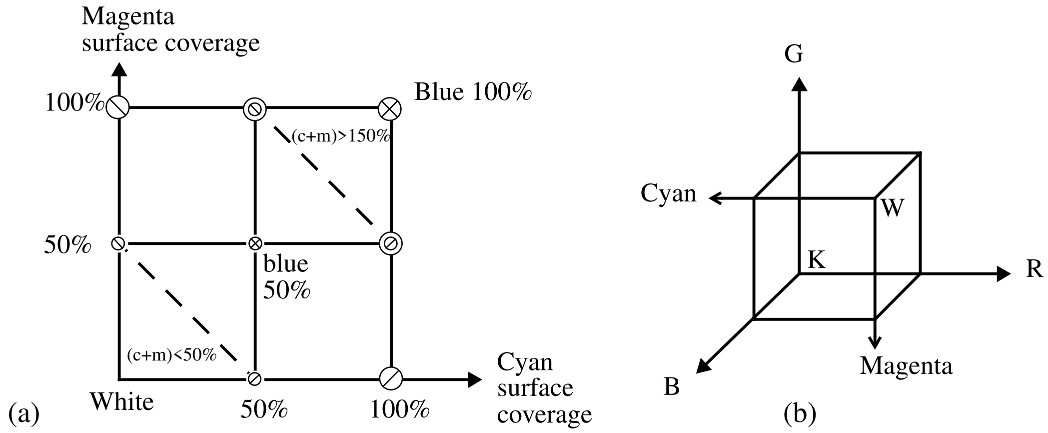


Figure 6. Two-dimensional representation of the white cyan magenta blue gamut and of corresponding error-diffusion output colours

From Fig. 6, one can see that for example Blue at 50% can be rendered in two different ways: either by printing 1 droplet of cyan (cyan50%) overlaid with 1 droplet of magenta (magenta50%), which gives a substactive blue or by printing side by side dots formed by 2 droplets of cyan (cyan 100%) and 2 droplets of magenta (magenta100%), which gives a weighted additive blue.

Table 1: Printable colours for variable dot size error-diffusion

Colour	label	droplets	symbol
White	White	no droplet	
Cyan 50%	c50%	one C-droplet	⊘
Cyan 100%	c100%	two C-droplets	⊘
Magenta 50%	m50%	one M-droplet	⦸
Magenta 100%	m100%	two M-droplets	⦸
Blue 50%	c50%m50%	overlapped one C & one M droplet	⊗
CyanBlue	c100%m50%	overlapped two C & one M droplet	⊘
MagentaBlue	c50%m100%	overlapped one C and two M droplets	⦸
Blue 100%	cyan100%m100%	overlapped two C and two M droplets	⊗

In order to reduce halftone artifacts, intensity-dependent inhibiting constraints must be introduced. At some surface coverage levels, the colour resulting from overlaid c1 and c2 colours can be inhibited and at other surface coverage levels, it must be allowed. For example, for bi-level colour printing, blue between 50% and 100% can only be achieved if a minimal amount of superimposed cyan and magenta inks are allowed. This is also true for variable dot-size printing.

Constraints which vary according to the current colour intensity can be introduced for example by enlarging the distance between the current colour to be printed and the combined colour (blue) with an intensity dependent penalty factor.

Fig. 7 shows the feasibility of constained error-diffusion in colour space for variable dot size printing. One can see that at combined surface coverages below 50% (cyan + magenta < 50%) only few superimposed half- size colour dots (blue50%) appear. Similarly, at combined surface coverage levels below 150% (cyan + magenta < 150%), only few superimposed full size colour dots appear (blue 100%).

Fig. 8 shows a different solution, where the single drop superimposed 50% cyan and 50% magenta (blue 50%) colour has been completely discarded from the choice of printable colours. Furthermore, the intensity dependent penalty function is applied to all remaining printable colours, whose euclidian distance from the current colour in RGB space is larger than 1/2, assuming colour coordinates ranging between 0 and 1. Fig. 8 shows less artifacts and provides smoother intensity transitions than Fig. 7. The intensity dependent penalty function has a heavy impact on the resulting error-diffusion halftone quality. Further research is needed to optimize the penalty functions used for the inhibiting constraints.

4. CONCLUSIONS

Variable dot size inkjet printers at moderate cost will soon be available on the market. Due to the relatively large size of single droplets, halftoning algorithms are still needed. However, since halftoning occurs between the basic levels attainable by printing one, two or several droplets at the same position, artefacts are less visible than in equal resolution bilevel printers. When dithering algorithms are used for the halftoning task, the dither threshold tiles should have oblique orientations so as to make the halftoning artifacts less visible. They should be designed so as to break up the inherent artifacts of variable dot size printers, such as for example continuous lines made up of elongated elliptic dots. In the case of error-diffusion in colour space, the introduction of dot over dot colour inhibiting constraints considerably reduces visual artifacts.

5. REFERENCES

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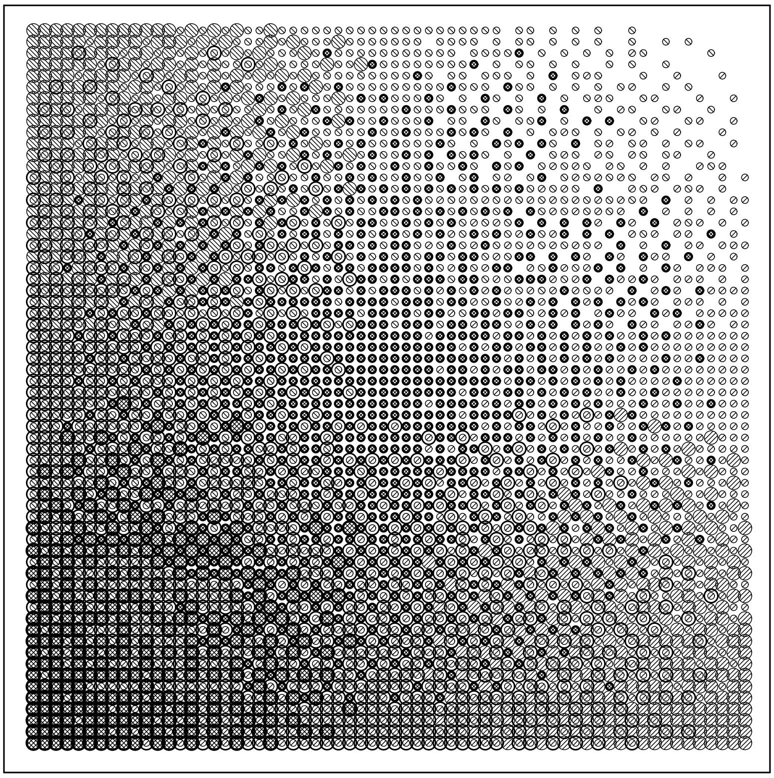

Figure 7. Variable dot size colour error-diffused cyan magenta wedge, with intensity-dependent inhibiting constaints (blue 50% allowed).

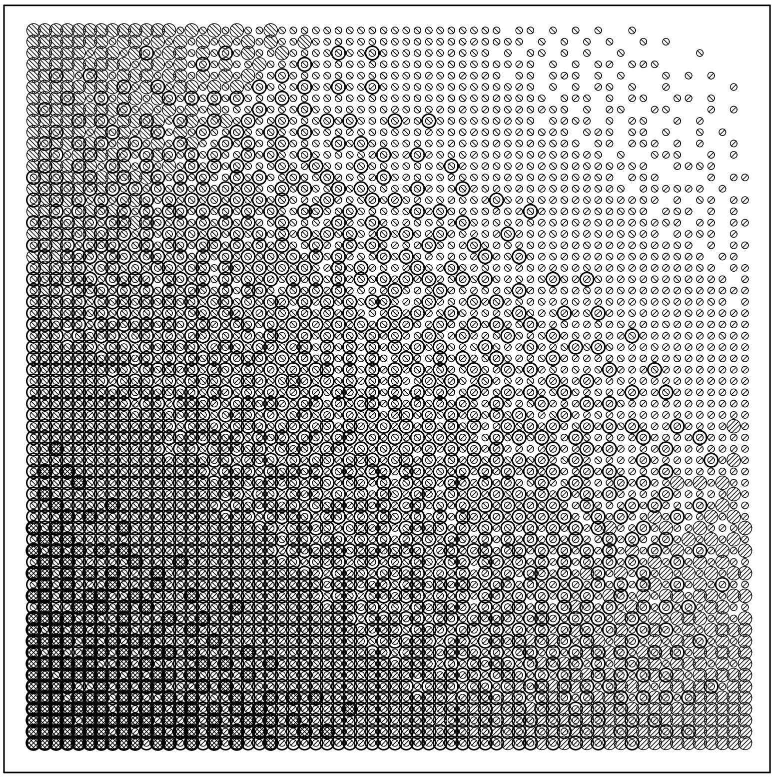

Figure 8. Variable dot size colour error-diffused cyan magenta wedge, with intensity-dependent inhibiting constaints (blue 50% discarded)

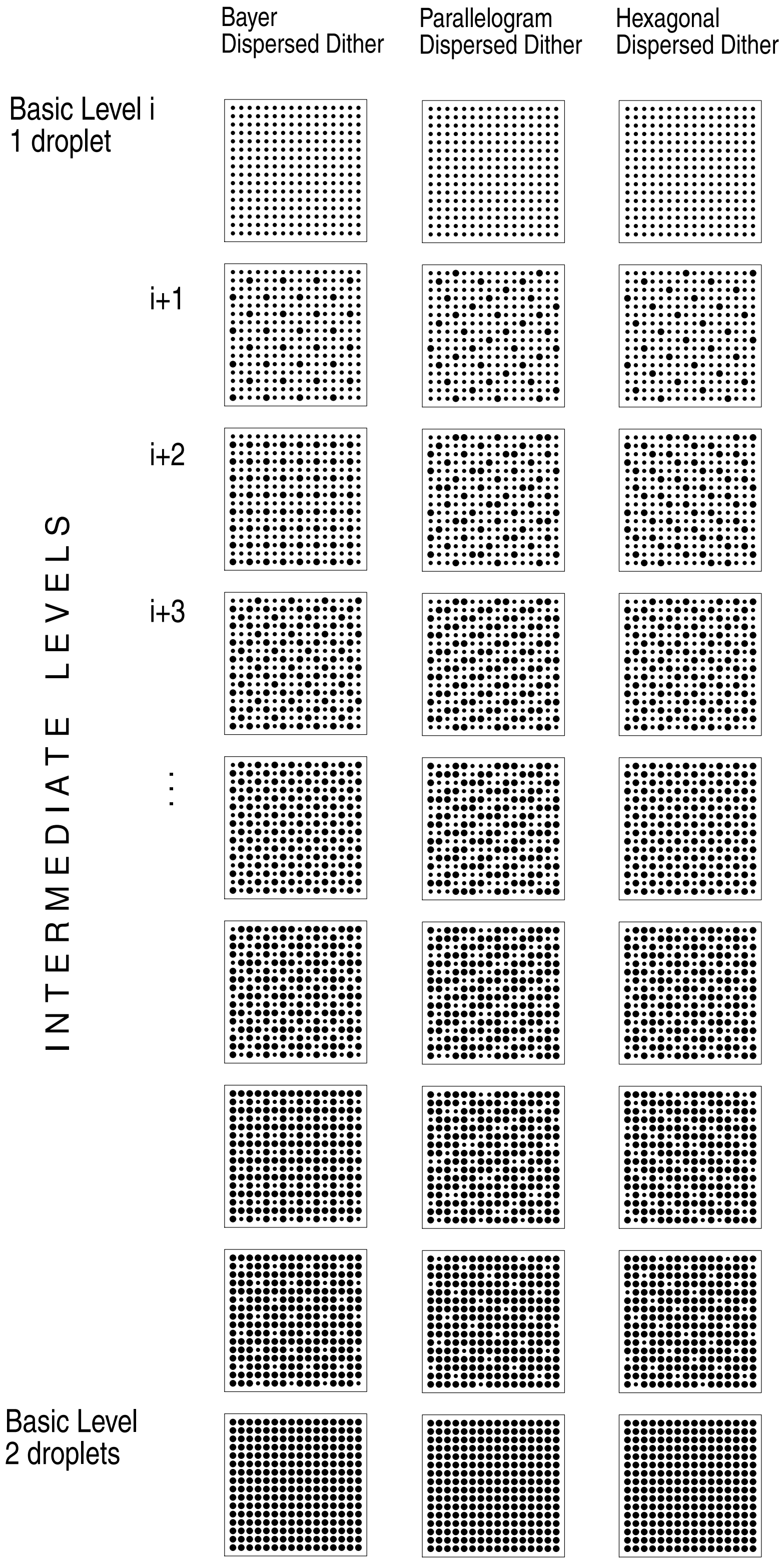

Figure 9. Intermediate intensity levels produced by dither tile based multi-level printing; the parallelogram dither corresponds to the tile shown in Fig. 2a and the hexagonal dither to the tile shown in Fig. 2b.