Multilevel halftoning applied to achromatic inks in multi-channel printing

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Abstract

Printing using more than four ink channels visually improves the reproduction. Nevertheless, if the ink layer thickness at any given point exceeds a certain limit, ink bleeding and colour accuracy problems would occur. Halftoning algorithms that process channels dependently are one way of dealing with this shortcoming of multi-channel printing. A multilevel halftoning algorithm that processes a channel so that it is printed with multiple inks of same chromatic value was introduced in our research group. Here we implement this multilevel algorithm using three achromatic inks – photo grey, grey, black – in a real paper-ink setup. The challenges lay in determining the thresholds for ink separation and in dot gain compensation. Dot gain results in a darker reproduction and since it originates from the interaction between a specific ink and paper, compensating the original image for multilevel halftone means expressing dot gain of three inks in terms of the nominal coverage of a single ink. Results prove a successful multilevel halftone implementation workflow using multiple inks while avoiding dot-on-dot placement and accounting for dot gain. Results show the multilevel halftoned image is visually improved in terms of graininess and detail enhancement when compared to the bi-level halftoned image.

Keywords: multilevel halftoning, multi-channel printing, dot gain compensation, graininess
1. Introduction

In order to achieve a colour reproduction, the initial image to be printed is firstly separated into a number of colorant channels. Traditionally, the channels used are cyan (C), magenta (M), yellow (Y) and black (K), but in the interest of reducing graininess and augmenting the colour gamut for high quality colour printing, additional channels are introduced (Jang, et al., 2005). These additional channels can be light cyan (Lc), light magenta (Lm), grey (GY), photo grey (PGY), red (R), green (G), blue (B), orange (O), or a combination of them. Introducing additional channels is a solution to achieve high quality prints in many printing technologies.

After separation, each channel is digitally adapted for the printing process before being sent to the printing device. The reason for this digital adaptation lays in the common nature of the vast majority of printing technologies, where placing ink onto a media substrate is a choice of either depositing or not depositing a drop of ink onto a specific position. The printed image is therefore a result of either printed or not printed spots – duotone impression. In order to achieve a full palette of lighter and darker tones, a digital pre-reproduction step called halftoning is performed. A halftoning algorithm converts each colorant channel of the image into microdots in smaller or greater size and/or concentration that create the illusion of tone gradation. Literature reveals a large number of halftoning algorithms (Wyble and Berns, 2000) that can mainly be categorized in amplitude modulated (AM) and frequency modulated (FM) algorithms (Sharma, 2003). In AM halftoning the size of the dots varies to create the illusion of lighter or darker tones, whereas in FM halftoning, the concentration of dots is the fluctuating factor.

Once the channels are halftoned, the printing system transfers the corresponding channel’s ink (C, M, Y, K, etc.) onto the media substrate. In inkjet this means that ink droplets are placed on the paper. A certain ink-paper interaction then happens, known as dot gain or tone value increase. In literature, dot gain is differentiated and even separated as two independent phenomena (Namedanian, et al., 2013). Physical (mechanical) dot gain is the result of ink penetration and ink spreading onto the paper. Because of this spreading, the printed dot will grow in size, resulting in a darker printed image. On the other hand, optical dot gain is the result of light scattering and light absorption. The photons of light that enter the paper through the ink layer scatter in the
paper and either get absorbed in it or exit the paper at a further point, possibly at a point with no ink layer. This light exchange between different chromatic areas is the reason for optical dot gain, which also causes the resulted printed dots to appear larger.

Dot gain is the reason there is a differentiation between the ink coverage value sent to the printing system (nominal coverage) and the resulting printed coverage (effective coverage). That is why, before halftoning, the initial image must be compensated for dot gain so that the printed image has the correct ink coverage values. Dot gain compensation is performed by applying existing mathematical models, such as Murray-Davies model (Murray, 1936), to the initial image, described in Equation 1:

\[ R = aR_t + (1 - a)R_p \]  

where \( R \) is the predicted reflectance, \( a \) the fractional ink area coverage, \( R_t \) the spectral reflectance of the full coverage ink, and \( R_p \) the paper’s spectral reflectance. Using this formula, one can calculate the amount of dot gain a printing system will produce (influenced by many factors, as ink, paper, etc.) and adjust the nominal coverage values accordingly. Since dot gain is dependent on the ink, each channel’s nominal coverage value needs to be adjusted separately.

It has already been mentioned that multi-channel printing (printing with more than four channels) increases the gamut and improves the overall image quality. Nevertheless, a high number of colorants impose new computational challenges and physical limitations, one of them being a too large number of ink layers printed on top of each other, which causes ink bleeding and colour inaccuracy (Zeng, 2000). Certain halftoning algorithms can help to overcome these issues. For instance, in channel dependent halftoning, the algorithm is applied at two or more channels dependently at the same time, so the halftone dots are placed in a manner that they have minimal overlap between colorants – dot-off-dot halftoning (Gooran, 2004).

Another example is proposed in Gooran (2006) where a multilevel halftoning algorithm combines the channels with the same chromatic values (e.g. magenta and light magenta) by firstly separating the original image into different lightness regions and then halftoning it. One of the advantages of this method is that, in the resulting image channel printed with multiple inks of the same chromatic values, dot-off-dot printing strategy is utilized. This means that only a single
Ink layer is applied while using multiple inks of same chromatic values, which is an important step in overcoming one of the challenges of multi-channel printing. Meanwhile, using multiple inks with same chromatic values instead of a single ink improves significantly the visual impression of the reproduced image. This is especially obvious in light regions, where using a single ink means placing sparse halftone dots, resulting in a visually obvious graininess in those regions. Meanwhile, the additional colorants used are the washed out versions of the main colorant. Using those inks makes it possible to place the halftone dots in a denser pattern, while maintaining the same lightness value, which results in a less grainy image.

In this paper we implement the proposed multilevel FM halftoning with three achromatic inks – PGY, GY and K, using an inkjet printer. Creating a single channel that will be printed with three different inks proves to be challenging for dot gain compensation, as each ink has a different dot gain curve. In order to perform a successful dot gain compensation, it is necessary to express the dot gain of the three inks used in terms of nominal area coverage of a single, black, ink. In order to do that, correct ink limits for colorant separation must be determined, dependent on the combination of inks, substrate, halftoning algorithm and printing resolution.

This paper is structured as follows. After this introduction the proposed halftoning method workflow is explained in section 2. Section 3, Methodology, describes the experimental setup, how the ink limits for colorant separation were located and how dot gain was compensated. In section 4, Results and discussion, the results of the dot gain compensation are shown. Results of the graininess calculations are also discussed. A conclusion is given in section 5.

2. Multilevel algorithm implementation

The multilevel halftoning algorithm was firstly proposed in Gooran (2006). Opposed to the majority of halftoning algorithms that halftone one channel for one ink, multilevel halftoning results in an image channel that can be printed with multiple inks. In one of the steps of multilevel halftoning, any bi-level halftoning algorithm can be applied. This section describes the proposed multilevel halftoning algorithm.
2.1 Multilevel halftoning

The workflow of the multilevel algorithm is displayed in Figure 1. For the sake of the argument, the figure created has low resolution so that the halftone dots are visible and the regions are clearly separated.

In the pre-processing step, the original image is separated into a number of regions, each with a range of tone values, where the number of regions depends on the number of inks. One must also set the ink limits, i.e. the thresholds where one ink stops and another one begins, explained in section 3.2. The regions within the thresholds represent parts of the image with the same tonal value ranges. For the instance of 3 inks and thresholds of 0.33 and 0.66, three regions exist: tonal values between [0, 0.33], [0.33, 0.66] and [0.66, 1], marked in Figure 1 with numbers 1 through 3. In the same pre-processing step, each of these regions is transformed to values between [0, 1] or [1, 0]; for this instance region 1 has values between [0, 1], region 2 between [1, 0], and region 3 between [0, 1]. Here, 0 means no ink and 1 means fulltone ink.

The reasoning behind setting region 2 between [1, 0] instead of [0, 1] is to avoid neighbouring opposite interval limits, since this could cause a discontinuous image. If region 1 set between [0, 0.33] would be assigned values [0, 1] and region 2 between [0.33, 0.66] would become [0, 1] as well, a problem would appear around 0.33, where there would be a jump in the border between the regions from 1 to 0. This would cause discontinuation around this area that are otherwise easily avoided by assigning values so that neighbouring regions have the same neighbouring interval limit.

In the next step, halftoning, since regions with corresponding assigned values have been separated and scaled between [0, 1], any bi-level halftoning can be applied to the pre-processed image.

In the post-processing step the 0s and 1s in the image are replaced by the limit threshold values, in our example 0, 0.33, 0.66 or 1, depending on the region the pixel belongs to. For example, in those parts corresponding to the region [0, 0.33], 0s remain 0 but 1s are replaced by 0.33.
The region corresponding to [0.33, 0.66], 1s are replaced by 0.33 and 0s by 0.66, and so on (Gooran, 2006). The result is a single image, halftoned for three different inks with the choice of K, GY, PGY or no ink.

![Image of multilevel halftoning workflow]

*Figure 1: Multilevel halftoning workflow*

### 2.2 Iterative Method Controlling the Dot Placement (IMCDP)

As this multilevel halftone workflow can use any bi-level halftoning algorithm, we chose an algorithm developed in our research group to have a better control over the whole process, named Iterative Method Controlling the Dot Placement (IMCDP) (Gooran, 2004). In this halftoning algorithm halftone dots are placed iteratively with the goal of reducing the difference between the original and the halftoned image. The generation of the halftoned image starts with a creation of a blank image with the same size as the original image. The total number of dots to be placed in the halftone image is dependent on the overall original image’s lightness/darkness and therefore is known in advance.

Starting with a blank image, in the first step, the algorithm finds the position of the darkest pixel in the original image and places the first dot at that location in the halftoned image. In the next step the low-pass filtered version of the halftoned image is subtracted from the low-pass filtered version of the original image. The low-pass filter used is Gaussian filter with standard deviation 1.3 truncated to 11 x 11 pixels. This operation is addressed in Gooran (2004: 355) as the
feedback process. The location of the maximum pixel value of the created subtracted image is found and at that location on the halftoned image the next dot is placed. The process is continued until the known number of dots is placed, thus achieving the final halftoned image.

3. Methodology

This paper deals with the implementation of multilevel FM halftoning as part of a setup for multichannel inkjet printing. For the purpose of this study the focus is on achromatic inks, i.e. photo grey (PGY), grey (GY) and black (K), aiming for a multilevel dot-off-dot halftoning with three different levels, spanning from no ink to fulltone black.

3.1 Experimental setup

The implementation challenges lie in determining the correct threshold levels used for colorant separation and in compensating for dot gain for three different inks. These thresholds are dependent on the ink combination, type of substrate, halftoning method and print resolution. In order to find proper thresholds for our setup, patches with 0% to 100% nominal ink coverage, in steps of 1%, were printed for all three inks. All prints were made using an inkjet 12-channel printer Canon imagePROGRAF iPF6450. All samples were printed on 90 g/m² uncoated office paper and on 170 g/m² matte coated paper at a resolution of 600 dpi. Nevertheless, the same workflow can be applied to other media substrates and other printing resolutions. The CIEXYZ values of the printed patches were measured using the spectrophotometer BARBIERI electronic Spectro LFP RT, light source D50 with 2° standard observer.

3.2 Locating thresholds between inks

Since achromatic inks vary in lightness (correlated with luminance), measured luminance Y values were used to find the thresholds between the inks. The thresholds are the ink coverage values at which the Y value of the black ink matches the Y value at 100% ink coverage of the lighter inks, photo grey and grey (Figure 2).
Figure 2: Y values of the three inks allow locating the thresholds between inks: (left) uncoated 90 g/m$^2$ paper, (right) matte coated 170 g/m$^2$ paper

Figure 2 shows the luminance Y values of the three inks – PGY, GY and K, plotted against their nominal ink coverages for the (left) uncoated 90 g/m$^2$ paper and (right) 170 g/m$^2$ matte coated paper. This plot also shows the Y values that match GY and PGY.

For the example of the coated paper, the Y values of fulltone GY match the Y values of 62.5% K, while the Y values of fulltone PGY correspond to the Y values of 42.5% K. Thus for this setup one can conclude that the limits between the regions should be set at 42.5% and 62.5% ink coverage. Region 1 would correspond to the light tones up to 42.5% black ink coverage, so [0, 0.425] should be printed with the lightest, PGY ink; region 2 with values from 42.5% to 62.5% black ink coverage, i.e. [0.425, 0.625], should be printed with PGY and GY inks, and region 3, between [0.625, 1], with GY and K. At each of these intervals ([0, 0.425], [0.425, 0.624], [0.625, 1]) the specific ink used spans from 0 to 100% ink coverage at that region.

### 3.3 Dot gain compensation

Paper-ink interaction causes dot gain with the result of ink areas appearing darker and larger once printed. In order to rectify this so that the final result (effective ink coverage) has the tone value intended, the nominal ink coverage for each channel has to be adjusted prior to halftoning and printing. In order to do so, the following methodology was performed.
The calculated thresholds were applied in order to multilevel halftone the patches from 0% to 100% ink coverage, with steps of 1%. The bi-level halftoning algorithm was IMCDP. Afterwards the patches were printed using all three inks simultaneously on the two paper substrates at 600 dpi. The resulting Y values of the printed patches allowed us to adjust the initial image for dot gain compensation using Murray-Davies formula. After printing, measurements were conducted to verify whether successful dot gain compensation has been accomplished.

4. Results and discussion

Thresholds were located for each of the inks and paper (Figure 2). For the 90 g/m² uncoated paper, it was found that the Y values of fulltone GY matched K at 38%, while the Y values of fulltone PGY matched K at 28%. Therefore, all tones lighter than 28% are reproduced using the PGY ink ranging from 0% to 100% ink coverage. The range between 28% and 38% is reproduced by a mixture of PGY and GY inks and the nominal ink coverage values between 38% and 100% with a mixture of GY and K inks. For the 170 g/m² matte coated paper the Y values for fulltone PGY and GY inks corresponded to the Y values of K at 42.5% coverage for PGY and 62.5% for GY.

This strategy makes the transitions between inks very smooth, which was verified by creating a continuous tone grey ramp image from 0% to 100% coverage, shown in Figure 3. Nevertheless, in order for the grey ramp to appear smooth in the printed proceedings, dot gain compensation must be performed for the specific ink and paper used. Since this information is not available, note that the ramp may not appear smooth in a printed manuscript.

Figure 3: Multilevel halftoned ramp for three achromatic inks
The dot gain curves for the three inks individually were plotted against the nominal ink coverage values using the Murray-Davies formula (Figure 4). The calculated thresholds were used to multilevel halftone the patches, print them on both papers and measure them. The dot gain curve of the three inks combined was plotted again and displayed on the same figure.

It can be seen in Figure 4 that the dot gain curves vary from ink to ink and from paper to paper. Each ink has a unique dot gain curve, and it is the three ink combination measurement values that need to be used in order to perform dot gain compensation.

![Dot gain curves for three inks individually and combined, in reference to black, in multilevel halftoning](image)

**Figure 4**: Dot gain curves for three inks individually and combined, in reference to black, in multilevel halftoning for: (left) uncoated 90 g/m² paper, (right) matte coated 170 g/m² paper

In order to verify the correctness of the dot gain compensation the Y values of the compensated patches were measured. Using Murray-Davies formula the effective area coverages were calculated. If the effective area coverage values are plotted against the nominal area coverage values, the assumption is that they will be the same, thus showing a linear response in the plot. The results are shown in Figure 5 for both papers.
As can be seen in Figure 5, the plot of the effective area coverage versus the nominal area coverage is a straight line for both papers, proving a successful dot gain compensation in our workflow.

It has already been mentioned that using three achromatic inks (PGY, GY, K) instead of only one (K) gives the advantage of a less grainy result and therefore visually more pleasant image. In order to illustrate this, a 10% black ink coverage patch was digitally created and halftoned in two different ways – once using only one, black, ink and bi-level halftoning it with IMCDP and the second time using three inks and multilevel halftoning the patch with IMCDP (Figure 6).

Note that the patches of Figure 6 are digital representations, not printed results. Therefore, it is likely that on the printed image the overall impression of the halftoned patches differ due to dot gain. Since different inks have different dot gain value, the printed images will most likely appear visually different, since this image has not been compensated for dot gain for any paper-ink setup.
Although both halftoned images have the same mean value of 10% black ink coverage on the digital representation, it can easily be seen that the multilevel halftoned patch (down) shows a less grainy result. This is because while bi-level halftone algorithms default to halftone using a single colorant (in this case K), the multilevel halftone algorithm halftones the patch under the assumption of multiple colorants. For this example, the used setup was three inks and the ink limits found for coated paper, in which 10% black ink coverage corresponds to $10% \cdot \frac{1}{0.425} = 23.5\%$ PGY ink coverage (Figure 2). The multilevel halftone algorithm then makes use of the PGY ink, with lighter tone than K, and halftones the dots in a denser configuration. Both of these factors account for the fact of a less grainy result, which was also verified by calculating the standard deviation. The standard deviation for the pixel values in the patch bi-level halftoned with IMCDP was 0.3023, while for those of the multilevel halftoning was smaller and equals 0.1815.

Similarly, standard deviation was calculated for digitally produced patches ranging from 1% to 30% black tone value, bi-level halftoned (with IMCDP) and halftoned with the multilevel algorithm. Figure 7 shows the results. It can be seen that the curve indicating the standard deviation of the patches halftoned with the bi-level algorithm is always above the curve of the

![Figure 6: 10% black ink coverage patch bi-level halftoned (up) and multilevel halftoned (down)](image)
standard deviation of the multilevel halftoned patches, which proves a less grainy result in the latter case.

Figure 7: Standard deviation of pixel values in the patch

A detail of a digital image was halftoned with the bi-level IMCDP and with the multilevel algorithm at 150 dpi (Figure 8). It is visible not only that the left (bi-level halftoned) image displays more graininess than the right (multilevel halftoned) one, but also that the latter one adds to the level of detail. This higher level of detail can be easily explained by the nature of the multilevel algorithm. Since multiple inks, each ranging from 0% to 100% ink coverage, are to be used to reproduce the image channel, it is obvious that such an image will have a higher detail reproduction than the one being reproduced with only one ink.

Figure 8: Image detail: (left) bi-level halftoned, (right) multilevel halftoned
5. Conclusions

A multilevel halftoning approach introduced in Gooran (2006) has been implemented in a multi-channel printing setup. The implementation has been done using three different achromatic inks – grey, photo grey and black. Challenges include determining the threshold between each of the ink pairs and achieving a linear dot gain response. Dot gain is ink-specific and it is necessary to calculate a joined dot gain for three different inks in relation to one. Once the initial image has been compensated for a linear dot gain response, the multilevel halftoning algorithm is again applied to the patches, which were then printed and measured. Results of the effective versus nominal area coverage shown in Figure 5 verify that the multilevel halftoning workflow for the printer, inks and substrates used was successfully controlled and can be applied to other frameworks. This means a setup in which multiple inks are used without an ink layer overlap (dot-off-dot impression). In addition, the overall image quality is improved in terms of graininess (verified by measuring the graininess by means of standard deviation) and detail enhancement.
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References


