IMPROVING VOID-AND-CLUSTER FOR BETTER HALFTONE UNIFORMITY

Hakan Ancin, Anoop K. Bhattacharjya, Joseph Shu

Epson Research and Development Inc.
3145 Porter Drive, Suite 104
Palo Alto, CA 94304

ABSTRACT

Dithering quality of the void and cluster algorithm [1] suffers due to fixed filter width and absence of a well-defined criterion for selecting among equally-likely candidates during the computation of the locations of the tightest clusters and largest voids. Various researchers have addressed the issue of fixed filter width by adaptively changing the width with experimentally determined values. This paper addresses both aforementioned issues by using a Voronoi tessellation and two criteria to select among equally likely candidates. The algorithm uses vertices of the Voronoi tessellation, and the areas of the Voronoi regions to determine the locations of the largest voids and the tightest clusters. During void and cluster operations there may be multiple equally-likely candidates for the locations of the largest voids and tightest clusters. The selection among equally-likely candidates is important when the number of candidates is larger than the number of dots for a given quantization level, or if there are candidates within the local neighborhood of one of the candidate points, or if a candidate's Voronoi region shares one or more vertices with another candidate's Voronoi region. Use of these methods lead to more uniform dot patterns for light and dark tones. The improved algorithm is compared with other dithering methods.

Keywords: void and cluster, dithering, stochastic screening, halftone, Voronoi tessellation

1. INTRODUCTION

Dispersed dithering is an efficient halftoning algorithm that does not require the processing of neighboring pixels. This method uses a dither array that consists of thresholds. The dither array is tiled periodically to cover the image to be halftoned. Each pixel in the image is compared with the corresponding threshold value from the dither array to decide whether a dot will be placed at that location. The problem with the method is that since the dither array is fixed, if a dot is present at a particular location in a light tone, it will be present at the same location in all of the darker tones. For this reason, misplacement of dots in light tones leads to artifacts in darker tones.

One of the methods to generate a dither array is the void-and-cluster algorithm [1]. The void and cluster algorithm uses a fixed width filter to compute a rank value for each dither array entry. The filter response is used to identify candidate locations in the dither array for setting the next threshold level. However, the algorithm does not have a strategy for selecting among candidates that have the same filter response. The lack of such a strategy leads to the selection of either the first candidate or random selection among the candidates. Both issues may lead to non-uniform dot patterns that are especially disturbing in light and mid tones. Problems related to fixed filter width were addressed in [2] by experimentally determining various filter widths for various gray levels.

Methods presented in this paper improve the dot placement in light and dark tones. The dither array generation begins with an initial binary pattern of 0s and 1s representing the dot pattern for a given gray level. The set of candidates for the next gray level is determined by partitioning the set of dots in the current level into Voronoi regions. The Voronoi vertices are used to determine the location of the largest void while the Voronoi regions are used to determine the location of the tightest cluster. In case of equally likely candidates three different criteria are used to determine the best candidate.

In the following sections we present the initial pattern generator, void and cluster operations. These methods improve on corresponding steps in [1]. Results illustrating improvements based on these modifications are presented in Section 4.

2. INITIAL PATTERN GENERATOR

An initial binary pattern is generated from a light uniform patch by an error diffusion algorithm [4]. Voronoi tessellation is computed on the wrapped-around initial binary pattern. If the number of dots generated by the error diffusion is less than the required nearest gray level, additional dots are added to the binary pattern. This pattern is homogenized by an algorithm similar to the one given in [1].

The initial pattern is homogenized as follows. Initially, the tightest cluster location is determined and the dot at this location is removed. After this step, the largest void location is determined and a dot is placed at this location. Successive computations of tightest clusters and largest voids continue until the tightest cluster location is same as the location of the largest void. In this paper, the location of the tightest cluster is determined by computing the area of each Voronoi region. The dot which is within the smallest of these regions determines the location of the tightest cluster. The location of the largest void is determined by the use of Voronoi vertices. Gaussian filters that are centered on these vertices are applied to the binary pattern, and the vertex with the largest filter response is selected as the location of the largest void. Since the dither array tiles the Euclidean plane infinitely along two orthogonal axes, the Voronoi tessellation is computed on a torus shaped binary pattern.

Carefully designed selection criteria are used to choose among equally-likely candidates. This selection minimizes low frequency noise in the dot distribution. The homogenized pattern is used to compute the dither array in the next section. Figure 1 shows the initial pattern that is used to generate the dither array in Section 3.

3. DITHER ARRAY GENERATION

Dither array generation consists of two operations, viz., computing the locations of the tightest clusters and the locations of the largest voids. Within each step, the best candidate among equally likely candidates is selected using three criteria. The cluster and void operations, and the candidate-selection criteria are described below.

3.1 Cluster Operation

The cluster operation assigns rank values to all dither array entries that have dots in corresponding locations in the initial binary pattern. Initially, a binary pattern with the same dot configuration as the initial binary pattern is generated. Voronoi tessellation is computed on the binary pattern. The area of each region is computed and the smallest one is determined. The dot within the smallest region denotes the location of the tightest cluster. In the dither array, a rank value is assigned for this dot and the dot is removed from the binary pattern. If there are two or more dots with the same smallest region size, one of the three criteria explained in Section 3.3 is used to determine the best candidate.

Dots that are removed by the cluster operation during the gray level transition from 244 to 245 are shown in Figure 2. These dots are removed from the densest clusters. The void operation utilizing the Voronoi tessellation adds new dots to the binary pattern as described in the next section.

3.2 Void Operation

The binary pattern is re-initialized with the initial binary pattern. Voronoi tessellation is computed on the dots of the binary pattern as long as the rank value is less than a predetermined rank value, R_1. The vertices of the Voronoi tessellation is used to locate the largest void location. At these vertices Gaussian kernels are applied on the binary pattern. The vertex with the largest filter response is selected as the location of the largest void. A rank value is assigned for this location in the dither array and 1 is inserted into this location in the binary pattern. Dots generated by the void operation is shown in Figure 3.

At the rank value of R_1, dots begin to dominate the binary pattern. After this point there is no advantage of using the Voronoi tessellation, a few Gaussian based filters are sufficient to determine the rank values of the dots up to a certain rank, R_2.

At R_2, 0s become very sparse. At this level Gaussian filters have very weak discrimination leading to large number of equally likely candidates. This problem can be resolved by interchanging the roles of 0s and 1s. With this change the problem of finding largest void in the original domain becomes equivalent to computing the tightest cluster in the new domain. The cluster operation explained in the previous section can be applied on the new binary pattern. This process continues until all entries in the dither array have valid rank values.

The determination of the largest void using filter responses may result in multiple equally-likely candidates. Candidate selection proceeds by using one of the three criteria explained in the following section.

3.3 Candidate Selection Criteria

Selection among equally-likely candidates is important when the number of the candidates is larger than the number of dots within a quantization level, or two or more dots are within an area covered by a filter kernel which is centered on one of the dots, or if a candidate's Voronoi region shares one or more vertices with another candidate's Voronoi region. In these situations, the selected dot can change the distribution of dots for the current and future quantization levels.

3.3.1 Selection Among Equally-Likely Candidates by Spatial Separation Criterion

The spatial separation criterion helps to resolve degeneracy between equally-likely candidates by selecting the candidate that leads to the most uniform dot distribution. This criterion is defined as follows.

Let the distance between any two points be defined as the minimum geodesic distance on a torus and denote the distance by D(.,.). Denote the *N* candidate locations that are found to be equally-likely under a local neighborhood criterion by the set ***X***, $\boldsymbol{X} = \{x(j); j = 0, \cdots, N-1\}$. This neighborhood can be determined by Voronoi tessellation or by the application of a small conventional kernel. The set of points that have already been ranked in the current and the previous quantization levels are denoted by $\boldsymbol{P} = \{p(j); j = 0, \cdots, M-1\}$. The index *J*, given by the following expression,

$$J = \arg\max_{j} \left\{ \min_{i} D\left(x_j, p_i\right) \right\} \tag{1}$$

is the index of the point in the set ***X*** that will be ranked next during the void operation. During void operation a dot is added into largest void region. For this reason equation (1) maximizes the minimum geodesic distance.

Similarly, the index *J* for the cluster operation is computed by,

$$J = \arg\min_{j} \left\{ \min_{i} D\left(x_j, p_i\right) \right\} \ . \tag{2}$$

The minimum geodesic distance is minimized in (2) because a dot is removed from the tightest cluster during cluster operation.

3.3.2 Selection Among Equally-Likely Candidates by Assuring Uniform Distribution of Dots Within Blocks

If the application of the previous criterion results in more than one candidate, another criterion is used to select a candidate based on the number of dots in a spatial region. The binary pattern is partitioned into blocks as shown in Figure 4. As shown in this figure, blocks **B**, **C**, and **D** are the portions of neighboring blocks of the dither array on a torus. Within each block the number of dots is counted and the new dot location is chosen to achieve the most uniform distribution of the binary pattern. During the clustering operation the candidate is chosen from the block that contains largest number of points, whereas during the void operation the candidate is chosen from the block that contains the smallest number of points. This criterion enforces a uniform distribution of dots for the dither array.

In some cases, application of both criteria may not result in a unique candidate. For these cases one of the candidates is selected randomly.

4. CONCLUSIONS

Improvements over void and cluster algorithm were presented. The presented methods generated more uniform halftones than the void and cluster algorithm that did not have a special criterion for choosing between equally-likely candidates. This improvement is illustrated in Figure 5 on a 512x512 patch with gray level 253. Figure 5(a) shows the pattern generated by using Floyd and Steinberg's error diffusion filter. Random noise has been added to the threshold during the error diffusion operation. Perceptually lower quality dot pattern was generated by this method for this specific gray level. The dot pattern in Figure 5(b) was generated by a dither array with dimensions 256x256. This array was constructed by the void and cluster algorithm which was implemented based on [1]. The initial binary pattern for this algorithm was generated by the method described in Section 2. In case of equally-likely candidates the best candidate was chosen by random selection. This dot pattern is better than the one generated by the error diffusion, but it is less uniform than the one shown in Figure 5(c). The dot pattern shown in Figure 5(c) was generated by a dither array with dimensions 256x256 and this array was generated by the algorithm described in this paper. The initial binary pattern is the same as the one used to generate the pattern in Figure 5(b). The pattern in Figure 5(c) is more uniform than both patterns and has less disturbing artifacts.

The method described in this paper generated more uniform patterns for both dark and light tones. This property was illustrated on gray scale ramps in Figure 6. The pattern generated by the described method, shown in Figure 6(c), had less white clumps in dark tones than the one generated by the standard void-and-cluster method shown in Figure 6(b).

The improved quality of the dither matrix has significant impact on the smoothness of color halftones as presented in [5].

REFERENCES

[1] R. Ulichney, "The void-and-cluster method for dither array generation," IS&T/SPIE Symposium on Electronic Imaging and Science, San Jose, CA, vol. 1913, pp. 332-343, Feb 3, 1993.
[2] Q. Lin, "Improving halftone uniformity and tonal response, IS&T Tenth Congress on Advances in Non-Impact Printing Technologies, pp. 377-380, New Orleans, Louisiana, 1994.
[3] K. Mulmuley, Computational Geometry An Introduction Through Randomized Algorithms, Prentice Hall, Englewood Cliffs, NJ, 1994.
[4] R. Ulichney, *Digital Halftoning*, The MIT Press, Cambridge, Massachusetts, 1987.
[5] J. Shu, J. Li, H. Ancin, A. Bhattacharjya, "Color stochastic screening with smoothness enhancement", NIP13:IS&T International Conference on Digital Printing Technologies, November 2-7, pp. 522-525, 1997.

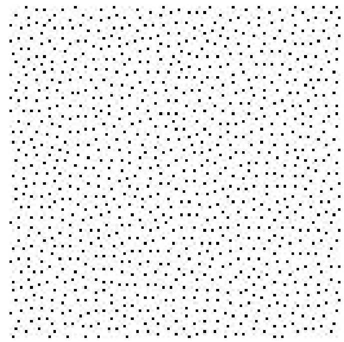
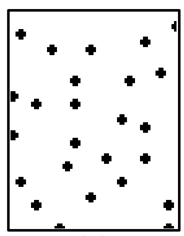
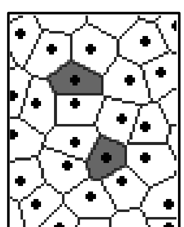


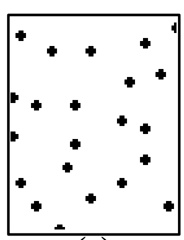
Figure 1: An initial pattern that is used to generate 256x256 dither array. The initial pattern was generated by error diffusing a patch with gray value 240. This patch is homogenized by the method described in Section 2.



(a)



(b)



(c)

Figure 2: Illustrates cluster process on a set of dots that have been cropped from a binary pattern with dimensions 256x256. During the transition from gray level 244 to 245 two dots have been removed by the cluster operation. (a) Dots at gray level 244. (b) Voronoi tessellation for the binary pattern shown in (a). Shaded Voronoi regions have smaller sizes than the other regions. (c) Dots at gray level 245. Dots in shaded regions are removed in this figure.

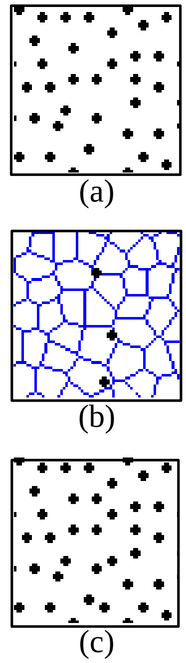


Figure 3: Illustrates void process on a set of dots that have been cropped from a binary pattern with dimensions 256x256. During the transition from gray level 235 to 234 three dots have been added by the void operation. (a) Dots at gray level 235. (b) Voronoi tessellation for the binary pattern shown in (a). Crosses in this figure denote positions of the dots that will be inserted in gray level 233. (c) Dots at gray level 233.

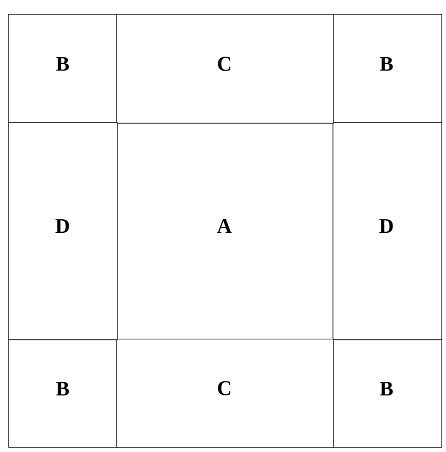
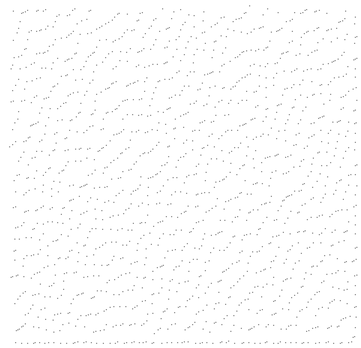
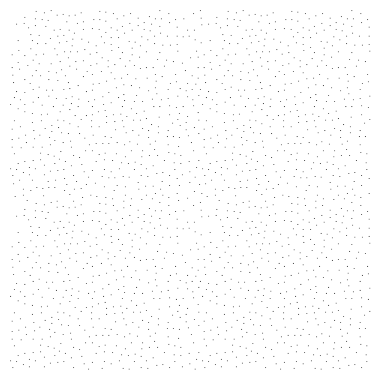


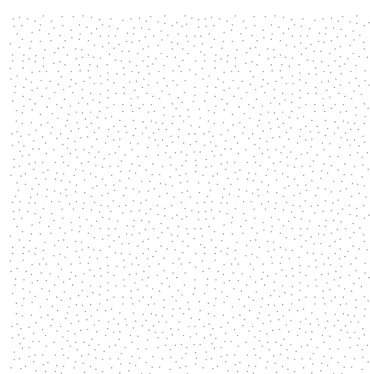
Figure 4: Shows a binary pattern that is partitioned into four equal size blocks. Blocks B, C, and D are located along the boundaries and are wrapped around as they are illustrated in the figure.



(a)

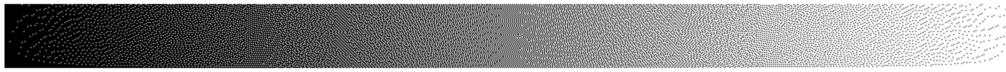


(b)

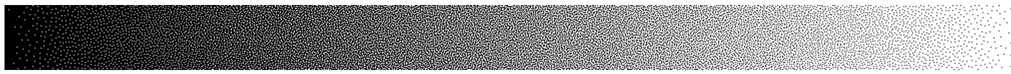


(c)

Figure 5: Illustrates the improvement in dot uniformity on 512x512 patches in light tones, e.g. gray level 253. (a) Error diffusion with Floyd and Steinberg method. Random noise has been added to the fixed threshold value. (b) Dithering with a void-and-cluster algorithm that uses random selection for equally-likely candidates and uses only one Gaussian kernel. (c) The same patch dithered with the methods described in this paper. Among the three methods the new method generates more uniform dot pattern.



(a)



(b)

(c)

Figure 6: Illustrates the improvement in dot uniformity on gray ramps. (a) Error diffusion with Floyd and Steinberg's method. Random noise has been added to the fixed threshold value. (b) Dithering with a void-and-cluster algorithm that uses random selection for equally-likely candidates and uses only one Gaussian kernel. (c) Dithering with the method described in this paper. This ramp has less white clumps in dark tones than the one shown in (b).