Yule-Nielsen approach for predicting the spectral transmittance of halftone prints

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Abstract

The transmittance spectrum of halftone prints on paper is predicted thanks to a model inspired by the Yule-Nielsen modified spectral Neugebauer model used for reflectance predictions. This model is well adapted for semi-opaque printing supports and applicable to duplex prints. Model parameters are obtained by a few transmittance measurements on calibration patches printed at one side of the paper. The model was verified with duplex specimens printed by inkjet with standard and custom inks, at different halftone frequencies and on various types of paper. Predictions are as accurate as those obtained with a previously developed reflectance and transmittance prediction model relying on the multiple reflections of light between the paper and the print-air interfaces.

Introduction

Color prediction for halftone prints has been an active subject of investigation for more than sixty years. Thanks to the recently developed spectral prediction models [1], it is now possible to predict printed halftone colors accurately for a wide range of printing technologies. However, possibly because prints are rarely illuminated from behind, their color in transmittance mode has been much less studied. Recently, a first reflectance and transmittance prediction model for recto-verso halftone prints [2, 3] was developed as an extension of the Clapper-Yule model [4], by describing the multiple reflections of light between the paper and the print-air interfaces (Figure 1). The angle-dependent attenuation of light within the colorants followed the approach of Williams and Clapper [5] and the spreading of the inks was accounted for according to the method proposed by Hersch et al. [6]. The parameters used by that model were the reflectance and the transmittance of the paper substrate, the transmittance of the colorant layers, the surface coverages of the colorants and the Fresnel coefficients corresponding to the reflection and transmission of light at the print-air interfaces. That first model illustrated the ability to extend a reflectance-only model to transmittance. In a similar manner, we now propose an extension of the Yule-Nielsen modified spectral Neugebauer model [7], which is, in respect to reflectance predictions, widely used for prepress and printing applications. The proposed extension enables predicting the transmittances of duplex prints, i.e. papers printed on their two sides. In order to verify its prediction accuracy, we tested the proposed model with recto-verso halftones printed by inkjet with standard and custom inks, at different halftone frequencies and on various types of paper.

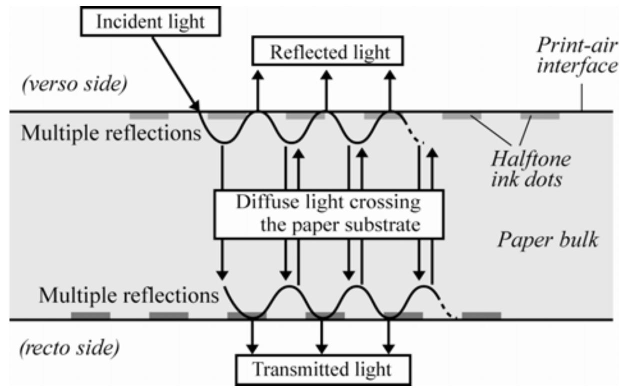

Figure 1. Physical model of the interaction of light and a duplex print on paper accounting for the multiple reflections between the paper bulk and the print-air interfaces.

Let us recall, before introducing the model, that the transmittance of a diffusing layer or multilayer does not change when flipped upside-down in respect to the light source. This property, that Kubelka called "non-polarity of transmittance" [8], remains valid when the strongly scattering layer is coated with inks and bounded by interfaces with air, provided the geometries of illumination and of observation are identical, for example directional illumination at 0° and observation at 0° [9]. When the two geometries are different, flipping the print may induce a small variation of its transmittance spectrum. Non-polarity of transmittance applies for single-sided as well as for duplex prints. There is no equivalent in reflectance mode.

Yule-Nielsen model for transmittance

A halftone is a mosaic of juxtaposed colorant areas obtained by printing the ink dot layers. The areas with no ink, those with a single ink layer, and those with two or three superposed ink layers are each one considered as a distinct colorant (also called Neugebauer primary). For three primary inks (e.g. cyan, magenta and yellow), one obtains a set of eight colorants: no ink, cyan alone, magenta alone, yellow alone, red (magenta + yellow), green (cyan + yellow), blue (cyan + magenta) and black (cyan + magenta + yellow). The paper coated with colorant k on the recto side has a transmittance spectrum $T_k(\lambda)$, which can be measured with a spectrophotometer in transmittance mode, e.g. the X-Rite Color i7 instrument in total transmittance mode (d:0° geometry).

In classical clustered-dot or error diffusion prints, the fractional area occupied by each colorant can be deduced from the surface coverages of the primary inks according to Demichel's equations [10]. For cyan, magenta and yellow primary inks with respective surface coverages *c*, *m*, and *y*, the surface coverages of the eight colorants are respectively:

$$\begin{aligned} a_w &= (1-c)(1-m)(1-y) \\ a_c &= c(1-m)(1-y) \\ a_m &= (1-c)m(1-y) \\ a_y &= (1-c)(1-m)y \\ a_{m+y} &= (1-c)my \\ a_{c+y} &= c(1-m)y \\ a_{c+m} &= cm(1-y) \\ a_{c+m+y} &= cmy \end{aligned} \quad (1)$$

Let us assume, as a first approximation, that the transmittance of the halftone print is the sum of the colorant-on-paper transmittances $T_k(\lambda)$ weighted by their respective surface coverages a_k. We obtain a transmittance expression similar to the spectral Neugebauer reflectance model [11]

$$T(\lambda) = \sum_{k=1}^{8} a_k T_k(\lambda) \quad (2)$$

However, the linear equation (2) does not predict correctly the transmittance of halftone prints due to the scattering of light within the paper bulk and the multiple reflections between the paper bulk and the print-air interface, which induce lateral propagation of light from one colorant area to another. This phenomenon, known for reflectance as the "Yule-Nielsen effect" [12, 13], also occurs in transmittance mode (see Figure 1). In order to account for this effect, we follow the same approach as Viggiano [7] by raising all the transmittances in Eq. (2) to a power of $1/n$. We obtain the Yule-Nielsen modified Neugebauer equation for the transmittance of a color halftone printed on the recto side:

$$T(\lambda) = \left[\sum_{k=1}^{8} a_k T_k^{1/n}(\lambda)\right]^n \quad (3)$$

A second phenomenon well-known in halftone printing is the spreading of the inks on the paper and on the other inks [6]. In order to obtain accurate spectral transmittance predictions, effective surface coverages need to be known. They are deduced from the measured transmittance spectra of a selection of printed halftones, called calibration patches.

Effective surface coverages

The amount of ink spreading is different for each ink and depends on whether the ink is alone on paper or superposed with the other inks. Effective surface coverages are therefore computed for all ink superposition combinations. Each ink is printed at 0.25, 0.5 and 0.75 nominal surface coverage, (a) alone on paper, (b) superposed to a solid layer of a second ink, (c) superposed to a solid layer of the third ink, and (d) superposed to a solid layer of the second and third inks. Hence, for three primary inks, 36 calibration patches are printed. The effective surface coverage $q_{i/j}$ of ink *i* superposed with the solid colorant *j* is fitted by minimizing the sum of square differences between the transmittance predicted by Eq. (3), i.e.,

$$P(\lambda) = \left[(1-x)T_j^{1/n}(\lambda) + xT_{i+j}^{1/n}(\lambda)\right]^n$$

and the measured transmittance $M(\lambda)$:

$$q_{i/j} = \underset{0 \le x \le 1}{\arg\min} \sum_{\lambda=380\text{nm}}^{730\text{nm}} \left[M(\lambda) - P(\lambda)\right]^2 \quad (4)$$

where T_j and T_{i+j} denote the colorant-on-paper transmittances for respectively the solid colorant *j* (which may be the unprinted paper) and the superposition of ink *i* and colorant *j*. It is assumed that the effective surface coverage is 0, respectively 1, when the nominal surface coverage is 0 (no ink), respectively 1 (full coverage). We obtain a list of effective surface coverages $q_{i/j}$, which by linear interpolation yields a continuous curve $q_{i/j} = f_{i/j}(q)$, where *q* is the nominal ink surface coverage (Figure 2).

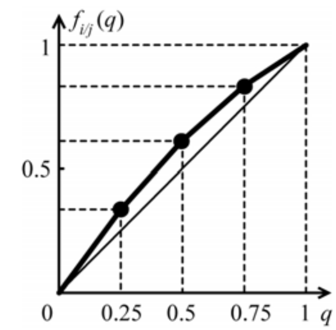

Figure 2. Example of ink spreading curve, giving the effective surface coverage of ink i when superposed on colorant j as a function of the nominal surface coverage q.

The ink spreading curves are established from patches where only one ink is halftoned. Let us now consider a halftone where cyan, magenta and yellow inks have the respective nominal surface coverages c_0, m_0, and y_0. Before using Demichel's equations (1) to obtain the surface coverages of the eight colorants, the nominal ink surface coverages c_0, m_0, and y_0 are converted into effective ink surface coverages *c*, *m* and *y*, which account for the superposition-dependent ink spreading. They are obtained by performing a few iterations with the following equations:

$$\begin{aligned} c &= (1-m)(1-y)f_c(c_0) + m(1-y)f_{c/m}(c_0) \\ &\quad + (1-m)\, y\, f_{c/y}(c_0) + m\, y\, f_{c/m+y}(c_0) \\ m &= (1-c)(1-y)f_m(m_0) + c(1-y)f_{m/c}(m_0) \\ &\quad + (1-c)\, y\, f_{m/y}(m_0) + c\, y\, f_{m/c+y}(m_0) \\ y &= (1-c)(1-m)f_y(y_0) + c(1-m)f_{y/c}(y_0) \\ &\quad + (1-c)\, m\, f_{y/m}(y_0) + c\, m\, f_{y/c+m}(y_0) \end{aligned} \quad (5)$$

For the first iteration, $c = c_0$, $m = m_0$ and $y = y_0$ are taken as initial values on the right side of the equations. The obtained values of *c*, *m* and *y* are then inserted again into the right side of the equations, which gives new values of c, m, y and so on, until the values of c, m, y stabilize. The effective surface coverages of the colorants are calculated by plugging the obtained values for c, m and y into Eq. (1).

Duplex halftone prints

A duplex print is a paper printed on its two faces, possibly with different inks. When printed with three inks on each face, the print contains 8 recto-colorants (labeled u) and 8 verso-colorants (labeled v), therefore 64 duplex-colorants (uv). In order to obtain their transmittances $T_{uv}(\lambda)$ by measurement, the 64 duplex-colorants need to be printed as uniform patches.

Since the paper is strongly scattering, we may assume that the lateral propagation of the light crossing the paper substrate is large compared to the halftone screen period. Hence, there is no correlation between the colorants traversed by the light at the recto and verso sides. The probability for light to cross the recto-colorant u and the verso-colorant v is simply the product of their respective surface coverages, i.e. $a_u a_v$.

The effective surface coverages a_u and a_v are determined separately for the recto- and verso-colorants. They are deduced from recto-only, respectively verso-only calibration patches according to the method presented in the previous section. In order to account for the Yule-Nielsen effect, all transmittances are raised to the power of $1/n$. The transmittance of the recto-verso halftone print is given by

$$T(\lambda) = \left[\sum_{u=1}^{8}\sum_{v=1}^{8} a_u a_v T_{uv}^{1/n}(\lambda)\right]^n \tag{6}$$

In order to reduce the number of colorant-on-paper transmittances to measure, we propose a variant of this model where only one-sided patches are needed: 8 recto-only colorants and the 8 verso-only colorants. Each recto- and verso-colorant (generically labeled j) is characterized by an intrinsic transmittance $t_j(\lambda)$ defined as the ratio of the measured colorant-on-paper transmittance $T_j(\lambda)$ to the unprinted paper transmittance $T_p(\lambda)$

$$t_j(\lambda) = T_j(\lambda)/T_p(\lambda) \tag{7}$$

The duplex colorant-on-paper transmittances $T_{uv}(\lambda)$ are written as

$$T_{uv}(\lambda) = T_p(\lambda) t_u(\lambda) t_v(\lambda) \tag{8}$$

and Eq. (6) becomes

$$T(\lambda) = T_p(\lambda)\left[\sum_u a_u t_u^{1/n}(\lambda)\right]^n \left[\sum_v a_v t_v^{1/n}(\lambda)\right]^n \tag{9}$$

This second formulation of the model is as accurate as the one expressed by Eq. (6) and it is more flexible because a different n factor can be applied to the recto- and the verso-colorant parameters. This may be useful when the recto and the verso are printed at different halftone frequencies.

Note that all measurements and predictions should rely on the same measuring geometry and the same position for the recto face in respect to the light source. If the print is flipped, i.e. the verso face takes the place of the recto face, its transmittance may be modified especially when the light source and the capturing device have different angular geometries [2].

Verification of the model

In order to verify the prediction model, 1875 recto-verso halftone patches were printed with the Canon PixmaPro 9500 inkjet printer at a screen frequency of 120 lpi on the super-calendered and non-fluorescent paper APCO II from Scheufelen Company, Germany. The 1875 patches correspond to the 125 combinations of cyan, magenta and yellow inks printed at the nominal surface coverages 0, 0.25, 0.50, 0.75 and 1, versus 15 different CMY colors printed on the verso. In a second experience, we used cyan, magenta and yellow inks (CMY) on the recto, and red and green custom inks (RG) on the verso. We combined 6 different CMY-halftone colors on the recto and 5 RG-halftone colors on the verso, thus yielding $6 + 5 + 30 = 41$ recto-only, verso-only or recto-verso patches. This set of patches was printed at different selected halftone frequencies and on several paper types, listed in Table 1. The transmittances of the printed patches were measured with the Color i7 instrument from X-Rite Company. They are observed at 0° on the recto-side and illuminated with diffuse light on the verso-side.

For each set of printed patches, transmittance spectra are predicted by the Yule-Nielsen transmittance model, according to Eq. (9), with an optimal n value different for each type of paper and each halftone frequency. Transmittance spectra are also predicted by the previously proposed multiple reflections transmittance model [3]. The color differences between measured and predicted spectra are expressed in CIELAB ΔE_{94} values and presented in Table 1. ΔE_{94} values are obtained by converting the predicted and measured spectra first into CIE-XYZ tristimulus values, calculated with a D65 illuminant and in respect to a 2° standard observer, and then into CIELAB color coordinates using as white reference the transmittance spectrum of the unprinted paper illuminated with the D65 illuminant [14].

At a first sight, the two models provide almost the same excellent prediction accuracy. The Yule-Nielsen model tends to provide better predictions at low halftone frequencies and slightly less accurate predictions beyond 120 lpi. In a similar manner as in the reflectance mode [6], the optimal n value increases as the halftone frequency increases. The type of paper has a strong influence on the optimal n value as well as on the prediction accuracy. The Biotop paper is a very porous paper in which inks penetrate deeply. The obtained ΔE_{94} color differences are higher than for the other types of paper, and the optimal n takes a very high value, indicating that the Yule-Nielsen approach is not the best one for this type of paper.

Table 1: Average color difference between measured and predicted transmission spectra

Set of patches	Type of paper	Frequency	*n*-value	Yule-Nielsen model[b]	Multiple reflections model[b]
1875 CMY/CMY patches	APCO II paper (T = 0.11)[a]	120 lpi	3.5	0.98 (*1.93*)	1.04 (*2.09*)
41 CMY/RG patches	APCO II paper (T = 0.11)[a]	60 lpi	1.5	0.54 (*1.07*)	0.92 (*1.81*)
		90 lpi	2	0.73 (*1.39*)	0.81 (*1.56*)
		120 lpi	1.9	1.01 (*1.83*)	0.99 (*1.56*)
		150 lpi	2.7	1.05 (*1.90*)	0.87 (*1.45*)
	Office paper (T = 0.16)[a]	120 lpi	7.2	0.71 (*1.34*)	0.63 (*1.17*)
	Biotop paper (T = 0.19)[a]	120 lpi	100	1.30 (*2.45*)	1.17 (*2.11*)

[a] Average transmittance of the paper at the wavelength range between 550 and 600 nm.
[b] Average CIELAB ΔE_{94} *(95-quantile)*.

Conclusion

The present study shows that the Yule-Nielsen modified Neugebauer model, widely used for spectral reflectance prediction, can be transposed for spectral transmittance predictions in a relatively straightforward manner. Except the fact that colorant transmittances are used in place of colorant reflectances, the model relies on the same concept: an empirical factor n, applied as $1/n$ exponent on each colorant transmittance, models the transfer of light between colorants due to the lateral propagation of the light scattered by the paper and the multiple internal reflections between the paper bulk and the print-air interface. Effective surface coverages are fitted from the transmittance of selected printed single-sided patches to account for ink spreading in each ink superposition condition. For duplex halftone prints, the parameters relative to the inks, i.e. the transmittance and the surface coverage of the colorants, are deduced from recto-only and verso-only printed calibration patches. Then, every duplex halftone combination is predicted. The tests carried out on inkjet recto-verso prints show the excellent accuracy of the model, especially at low halftone frequencies. Even though it is slightly less accurate than the previously proposed Clapper-Yule-inspired transmittance model [3] for high halftone frequencies and highly ink-absorbing papers, it has the benefit of simplicity and of a reduced number of parameters.

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