Revenge of the Physical - Mobile Color Barcode Solutions to Security Challenges

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HP Laboratories
HPL-2010-7

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Abstract:
Ubiquitous access to relatively high quality imaging - from digital cameras and phone cameras - has changed the way in which consumers and retailers interact with their environment and products. Barcodes and other printed marks containing information can be used to link interested parties to virtually any information of interest, often by re-directing their internet-enabled device to the appropriate webpage. With proper access privileges, the camera user can obtain information related to product security - from track and trace to product provenance, authentication and forensics. In this paper, we address many of the variables which must be considered when optimizing printed marks for their use in mobile applications. These variables include the choice and the optimization of the colors, the choice of error-correcting and/or calibration codes, the authentication technique deployed, and the restoration approaches chosen. We show herein that the proper design of color-based barcodes results in more than a doubling of payload density over default conditions, and so provides a more effective security solution and, if desired, branding mark. The implications to mobile applications are also discussed.

External Posting Date: January 21, 2010 [Fulltext] Approved for External Publication
Internal Posting Date: January 21, 2010 [Fulltext]

Published and presented at Optical Document Security 2010, San Francisco. January 20-22, 2010

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ABSTRACT

Ubiquitous access to relatively high quality imaging—from digital cameras and phone cameras—has changed the way in which consumers and retailers interact with their environment and products. Barcodes and other printed marks containing information can be used to link interested parties to virtually any information of interest, often by re-directing their internet-enabled device to the appropriate webpage. With proper access privileges, the camera user can obtain information related to product security—from track and trace to product provenance, authentication and forensics. In this paper, we address many of the variables which must be considered when optimizing printed marks for their use in mobile applications. These variables include the choice and the optimization of the colors, the choice of error-correcting and/or calibration codes, the authentication technique deployed, and the restoration approaches chosen. We show herein that the proper design of color-based barcodes results in more than a doubling of payload density over default conditions, and so provides a more effective security solution and, if desired, branding mark. The implications to mobile applications are also discussed.

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1. INTRODUCTION AND OVERVIEW OF THE PAPER

Security printing marks have evolved from printed marks used for other purposes—e.g product identification and point-of-sale [1]. To accommodate the need for higher density in security and other applications, 1D barcodes have been replaced by 2D barcodes such as QR, DataMatrix and Aztec in many mobile and security applications [2][3][4]. For mobile information gathering, organizations such as the OMA [2] and the GS1 Mobile Com Extended Packaging project [3] are helping to connect the consumer to the branded product through bar code enabled services. In security applications, bar codes—along with RFID chips—are used to provide EPCglobal [1] mass serialization along with other security strings (unique IDs, digital signatures of other printed information, replication of RFID information, etc.). Color barcodes (often termed 3D barcodes since more than 2 colors can be supported in a single module) are the next step in increasing barcode density. These include the ColorCode, the Microsoft High Capacity Color Barcode (HCCB) [5] and the color tile [6][7] 3D barcode deterrent described herein. These marks have helped provide the "revenge of the physical", since the adoption of mobile imaging has outpaced that of "non-physical" (i.e. electronic, such as RFID) means for interrogating product packaging and labels, signage and other physical objects and locations.

The application of color to barcodes offers more than increased density. Color is attention-getting and so can increase compliance. Color uses three channels of information (usually RGB, after scanning) and so is more suitable for steganographic, authentication and forensic purposes. In this paper, we elaborate on recent research to extend the utility of color barcodes in security applications. For example, at ODS 2008, the concept of spectral pre-compensation (SPC) was described [7]. This technique ensures that the colors are maximally dispersed after scanning, improving the authentication accuracy and thus the payload density (PD, reported in bytes per given area) of the color barcodes. Other technologies used to increase PD include the authentication algorithm chosen, the image restoration algorithms deployed (we consider saturation equalization, or SE, herein), and the type/percent of error correction code (ECC) used. We also consider alternatives to ECC (e.g. data replication and the use of calibration indicia) to increase PD. In our paper, we provide results showing the relative effectiveness of each of these approaches to increasing PD. In general, we show that the effective design of the authentication algorithm is the surest way to increase PD when different printing technologies, scanning devices and substrates are taken into account.

Next, we present results from recent investigations on optimal encoding of color barcodes to enable multiple scanners in a large, real-world ecosystem (e.g. a supply chain). Previously, we have used scaled (structural) multi-level color tiling approaches, for which tiles are logically grouped—e.g. as single tiles (authenticated by the highest quality cameras/scanners), 2x2 tile clusters, 3x3 tile clusters, etc. Recent data, however, supports the use of color-set degradation (hue-based error sensitivity), in which the number of colors disambiguated changes depending on the reading device (while all are printed in 6 colors, reading in 2 colors is robust to ≤ 90º error in hue, while reading in 6 colors is only robust to ≤ 30º error in hue).

The advantages of the many incarnations of color tiles for security are then discussed. We conclude describing color tile deployment optimization for a secure supply chain.

2. EXPERIMENTS PERFORMED

2.1 Color Tiles

All experiments performed herein are designed to optimize for real-world deployment a color barcode-like data-rich printed mark, the color tile [6][7]. The color tiles consist of six data-carrying colors: red (R), green (G), blue (B), cyan (C), magenta (M) and yellow (Y). In addition, two black (K) tiles are placed in the upper left and lower right corners to aid in registration. White (W) surrounds the color tile deterrent and is used for segmentation purposes. All images are printed and scanned in 8-bits/channel, 3-channel RGB-space, and the individual pixels P(i,j) for the images are designated as having R, G and B values in the triplet {r,g,b}.

The color tiles are arranged as in Figure 1. For the purpose of consistent comparison, the tiles are arranged on a 10x10 grid, so that if necessary, the deterrent can support 100 tiles. In the default configuration, there are 64 tiles colored one of {R,G,B,C,M,Y,K}. The color tile deterrent uses non-payload indicia (NPI) rather than error-correcting code (ECC) to provide authentication robustness (Figure 1, center) while providing high payload density (PD), in units of bytes/inch^2. When there are the default six color possibilities for each payload indicia (PI), the PD is equal to (ln(6)/ln(2))*n(PI)/8, where n(PI) is the number of payload indicia in 1.0 inch^2. In the deterrent of Figure 1, eight tiles are used to provide orientation and color calibration. Two K tiles provide "Northwest-Southeast" calibration, and the neighboring CMY ("Northwest") and RGB ("Southeast") color calibration tiles are used for 180 degree disambiguation. Note that the color opponency pairings (R-C, B-Y and G-M) are 180º apart, providing the greatest possible color differences for the NPI. Since 8 NPI are used for the 10x10 tile area, we define NPI/(PI+NPI) as 0.08 for this deterrent (area percentage).

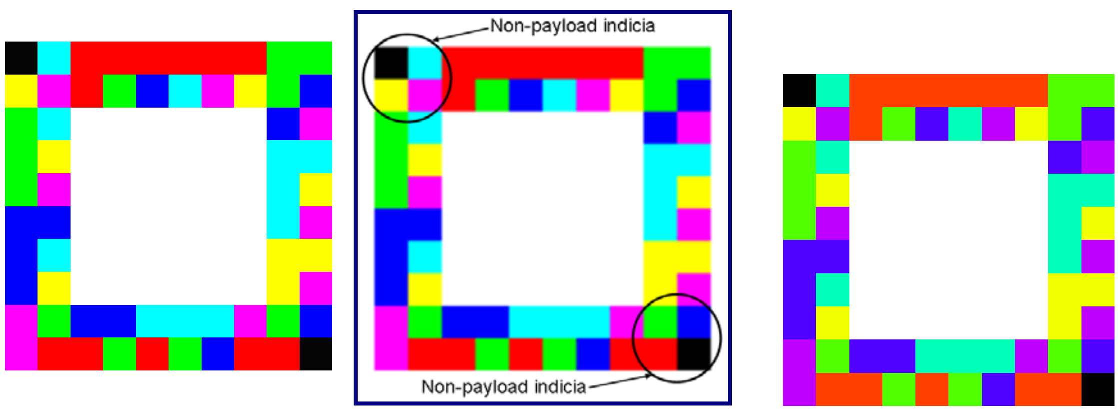

Figure 1. Color tile deterrent (left), with the non-payload indicia (NPI) indicated (center), and with spectral pre-compensation (SPC) optimized colors (right).

Test sheets of multiple color tile deterrents as described in [7][8] were printed for both uncompensated and spectrally pre-compensated color sets. Individual tiles were sized from 4x4 to 30x30 pixels, and all printing was performed at 600 dots/inch (dpi). Thus, individual tiles were sized from 1/150 to 1/20 of an inch in dimension (height = width), and the deterrents as depicted in Figure 1 were sized from 1/15 to ½ of an inch in dimension.

The color tile deterrent sheets are printed with 0.5 inch separation between any two deterrents (on each side). Due to differences in the overall deterrent size, the test sheets included 165, 150, 140, 140, 130 and 117 full deterrents, respectively, for individual tile sizes of 5x5, 6x6, 7x7, 8x8, 9x9 and 10x10 pixels, respectively (multiple sheets are printed for larger-sized tiles). This equates to 9240, 8400, 7840, 7840, 7280 and 6552, respectively, individual tiles tested.

The colors {R,G,B,C,M,Y} were chosen to map 6 of the 8 points of a color cube with {r,g,b} axes (Figure 2). The other two colors, black and white, are used for orientation calibration and background color, respectively.

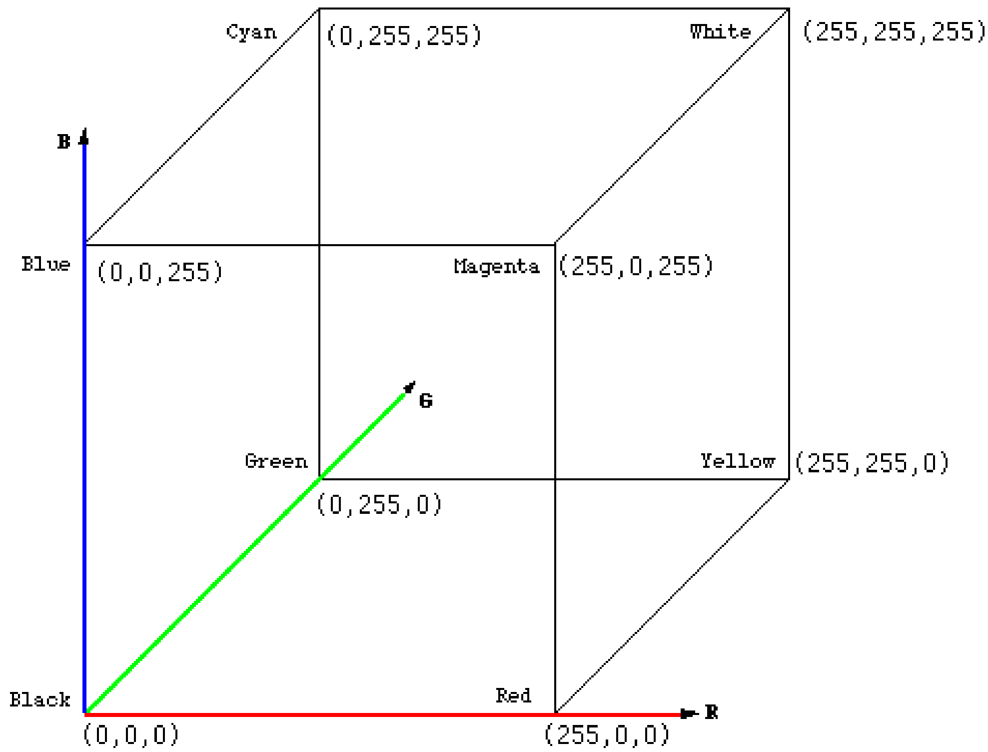

Figure 2. Illustration of the three-axis {rgb} representation and the location of the primary color tile hues (RGBCMY).

2.2 Printing Technologies

For the experiments described herein, a large variety of printers were used for testing. We report printing using the following printers: the inkjet models 6127, 6280 and 5440. The 6280 is an all-in-one device (and thus has a scanner). For each printer, multiple test sheets of deterrents covering the size range described above were printed using a {CMYK} 4-ink palette. All pages were printed at 600 dpi (dots/inch) with default (color) settings.

2.3 Substrates

Printing effects, and thus the payload density (PD) of color tiles, are also dependent on the substrates used. We tested HP Office Paper (hereafter "Plain"), Premium Plus Photo Paper, soft gloss (hereafter "Soft Gloss"), and Premium Plus Photo Gloss Paper (hereafter "Gloss") to determine the relative impact of substrate on the PD achieved.

2.4 Authentication Approaches

After printing, all pages were scanned at 600 dpi using an HP Scanjet 8350 with 24-bit {r,g,b} color default settings. The images were then segmented using custom software. Non-white (non-W) pixels were determined as having at least one {r,g,b} value < 128 and then run-length smeared using 1/150 of an inch run-length gap. Connected components were formed, and then prepared for authentication. Each connected component (verified to be a single deterrent comprising 64 tiles and whitespace in its center) was divided into 10x10 sections, which correspond to the individual tile zones (the central 36 are only whitespace). The corner tiles were checked for black pixels to ensure that the orientation was correct, and the individual data tile images (64/deterrent, of which 56 contain variable data and the other 8 are used for calibration, as shown in Figure 1 center) were eroded by 15% along each edge, resulting in, for example, 7x7 24-bit color images for each tile in a 10x10 pixel-sized tile deterrent. The colors of these tiles were determined as described next and compared to the printed sequence of tiles.

Two different authentication algorithms were used for the testing (after restoration was applied). The first, shorthanded the "RGB-Distance" approach, assigned the color of each tile based on the minimum L1 distance between the tile sub-segment's mean {r,g,b} values and the {**r,g,b**} values of the 6 color NPI. That is, it is assigned the color of the NPI minimizing the sum |r-**r**| + |g-**g**| + |b-**b**|. The second authentication approach, shorthanded the "Hue" approach, assigned the color of each tile based on the minimum angular distance between the hue of the tile sub-segment and the hues of the six color NPI. That is, the minimum of Hue(mean$\{r,g,b\}_{\text{sub-segment}}$)-Hue(mean$\{\mathbf{r,g,b}\}_{\text{NPI}}$), where before scanning Hue(mean$\{\mathbf{r,g,b}\}_{\text{NPI}}$) for NPI={R,Y,G,C,B, and M} = {0,60,120,180,240, and 300}. The actual hue angles of the NPI, of course, are somewhat different after printing and scanning.

Authentication accuracy was determined based on the number (out of 117, 130, 140, 140, 150 or 165 deterrents at tile sizes of 10, 9, 8, 7, 6 or 5 pixels, respectively) of 56-tile sequences that were correctly read in their entirety. Even one sequence color error was considered an "authentication" failure. Thus, the reported accuracy is "full deterrent accuracy", and is appropriate since no error-correcting code (ECC) is used when deploying NPI.

2.5 Restoration Approaches

Additional tests were performed with a simple image restoration pipeline. The approach used was saturation equalization (SE). For every pixel P(i,j), the pixel's scanned color representation is given by $P(r_s,g_s,b_s)$ where $c_s \in [0,255]$ is the intensity value of color c. $P(r_s,g_s,b_s)$ is then transformed to $P(r_{SE},g_{SE},b_{SE})$ where $c_{SE} \in [0,255]$ is the SE value of color c, and $\operatorname{argmax}(r_{SE},g_{SE},b_{SE})$ is always 255 (maximum saturation). Thus, $(r_{SE},g_{SE},b_{SE}) = [255/\operatorname{argmax}(r_s,g_s,b_s)]^* (r_s,g_s,b_s)$. So, a pixel with scanned values $(r_s,g_s,b_s) = (125,230,111)$ will have SE values of $(r_{SE},g_{SE},b_{SE}) = (139,255,123)$. After performing SE, all authentication tests were performed again on the restored images.

2.6 Spectral Pre-Compensation

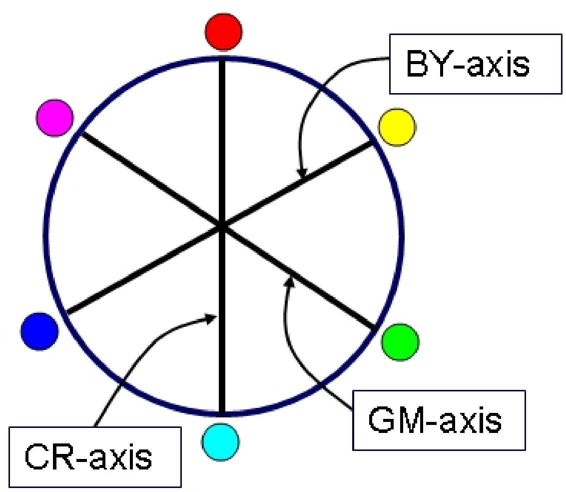

Figure 3. Illustration of the three-axis {rgb} representation and the location of the primary color tile hues (RGBCMY). In this representation, each color is 60º from its two nearest neighbors (e.g. G and R for Y).

Spectral pre-compensation [6][7][8] has been introduced as a means to improve PD. The spectral pre-compensation, or SPC, strategy involves printing a large set of color targets, scanning them and selecting the colors from this set that, *after* *printing and scanning*, result in the intended color set, {RGBCMY}, with each successive color 60º from the previous color as shown in Figure 3. The corresponding path of the color "circle" in Figure 3 on the three-axis {rgb} color cube of Figure 2 is given in Figure 4 (thick arrows).

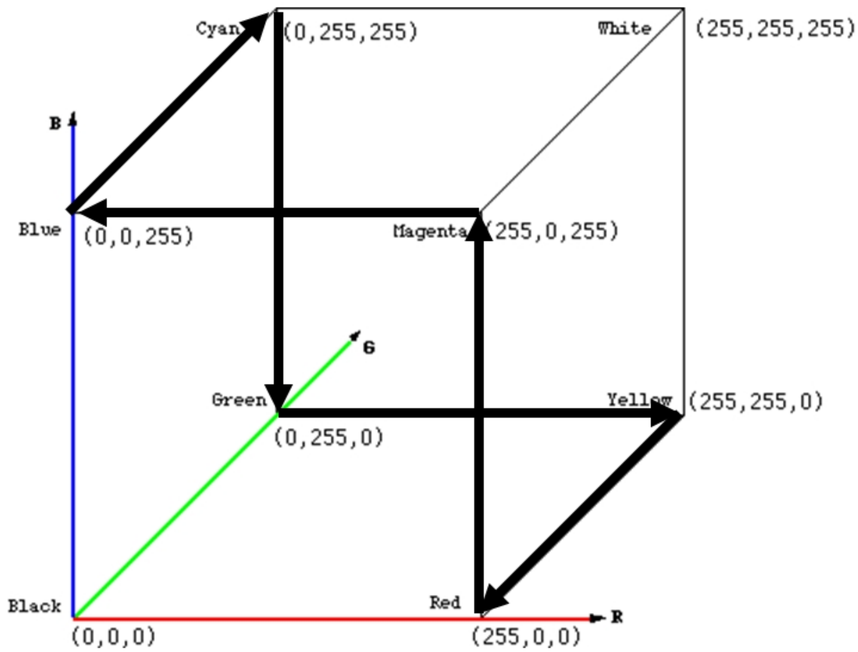

Figure 4. Illustration of the three-axis {rgb} representation and the location of the primary color tile hues (RGBCMY).

The spectral pre-compensation color set was determined for the 6127, 6280 and 5440 printers. The spectral pre-compensation colors to be printed are indicated by the triangle-tipped arrows in Figure 5. The resulting colors after printing and scanning are indicated by the uniformly separated circles in Figure 5. In general, they are quite similar. Blue (B) is pre-compensated by adding magenta (M), M by adding B, and cyan (C) by adding G for each of the three printers.

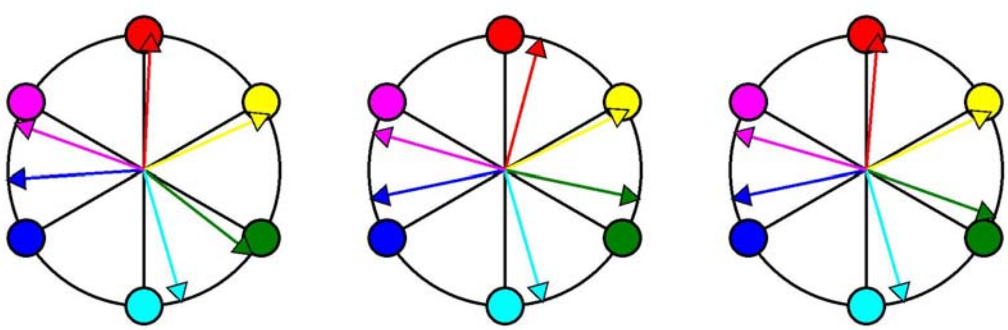

Figure 5. Spectral pre-compensation colors (triangles) printed to obtain intended colors (circles) after printing on plain paper with the 6127 and scanning (left), the 6280 and scanning (center) and the 5440 and scanning (right) (See Figures 7-9 in ref. [7]).

We then validated successful spectral pre-compensation occurred by showing that the metric side-lobe entropy, described in [8] and below, increased after applying the pre-compensated colors.

2.7 Side-lobe Entropy

As noted in reference [8], if SPC has been properly applied, the colors after printing and scanning are 60º apart in the 360º color representation of Figure 3. As such, tile substitution errors should become more entropic after pre-compensation—that is, the odds of substituting a color, C_i, for the neighboring color C_{i-1} should be of more equal probability to the odds of substituting C_i for the other neighboring color, C_{i+1}. Note that $C_{i\%6} = C_i$ for all i=1,2,…,6 where % is the modulus operator, and so $C_0=C_6$, etc. The colors C_{i-1} and C_{i+1} are termed the side-lobes for color C_i and so the side-lobe entropy, a measure of how entropic the color mistakes are, is given by:

$$e_{SL} = \sum_{i=1}^{6} K(i) \tag{1}$$

where

$$K(i) = -[p(C_{i+1})*\ln(p(C_{i+1})) + p(C_{i-1})*\ln(p(C_{i-1}))] \tag{2}$$

and

$$p(C_{i\pm1}) = \left[\frac{C_i \to C_{i\pm1}}{C_i \to C_{i+1} \,||\, C_{i-1}}\right] \tag{3}$$

In Equation (3), $p(C_{i+1})$ is the probability of incorrectly substituting (where → is the substitution operator) color C_i to C_{i+1} divided by the probability of incorrectly substituting color C_i to C_{i-1} or C_{i+1} and $p(C_{i-1})$ is the probability of incorrectly substituting color C_i to C_{i-1} divided by the probability of incorrectly substituting color C_i to C_{i-1} or C_{i+1}. To account for different error rates for each of the 6 colors, we also computed $e_{SL}(w)$, or weighted side lobe entropy, defined as:

$$e_{SL}(w) = \sum_{i=1}^{6} w(i) * K(i) \tag{4}$$

In Equation (4), w(i) is the percentage of substitution errors for color I; that is, $\sum w(i)=1.0$. The range of e_{SL} is [0,4.159] and the range of $e_{SL}(w)$ is [0,0.693]. If the more traditional $\log_2(\cdot)$ were used to compute entropy in Equation (2), these ranges become [0,6] and [0,1], respectively. Alternatively, we compute the entropy measurements by comparing the side lobes of the diagonals of the confusion matrix, **C**. Thus, diagonal-adjacent matrix elements **C**(i,j) and **C**(j,i) for each adjacent pairing of colors i and j are the pairings used for the K(i) in Equations 1, 2 and 4. Normalizing e_{SL} and $e_{SL}(w)$ to the range of [0,1] provides a measure of percent maximum entropy, e_{PM}, and weighted percent maximum entropy, $e_{PM}(w)$.

2.8 Dual-Channel Approaches

Because the color tiles are composed of six different hues, they can be used for a dual-channel approach. This is because there are two different classes of error possible when using color such as the circular model for (fully saturated) hue given in Figures 3 and 5. The first is when the correct color is substituted for one of its two neighboring colors (e.g. "M" or "C" in place of the correct "B"), and the second is when the substitution error is not a neighbor (e.g. "R", "Y", or "G" for "B"). The first type requires a hue error of ≥ 30º, while the second requires a hue error of ≥ 90º. In the general case, the color tile deterrent uses a multiplicity, M, of colors, to provide ln(M)/ln(2) bits of information per data tile (ignoring error-correcting and/or calibration tiles).

Color information can be encoded in a wide variety of set sizes—that is, M=2, 3, 4, …, and up to 256 colors distinguished for 8-bit paletted images (for real-world/mobile applications, M is typically ≤ 16). However, whenever M ≥ 6, the printed deterrent can be simultaneously read with different implicit values for M. A scanner capable of resolving all six different colors can read ln(6)/ln(2)=2.585 bits/tile, but a mobile camera capable only of resolving two different colors—e.g. along one of the color axes shown in Figure 3—can read only 1 bit/tile.

In some cases, assuming a lower value for M can actually increase payload density—e.g. when the hue stability is poor but the "structural" integrity of the tiles is of sufficient quality. This may be the case for a high-end printer and substrate. In other cases—such as inkjet printing on office paper, in which "paper fiber bleed" of the inks into the paper occurs—the hue stability may be better than the effect of tile-to-tile hue blurring, and so a higher-M strategy may be deployed. The latter generally requires the printing of larger tiles. For the case of 6-hue color tiles, then, the higher-M strategy is supported if and only if the size need only be increased by a value of less than or equal to the square root of 2.585, or 1.608. In the general case, the number of different reading strategies, N_{rs}, that can be defined for M colors is:

$$N_{rs} = (\mathrm{int})((M-2)/4) \tag{5}$$

That is, $N_{rs} = 2$ if $6 \le M \le 9$; 3 if $10 \le M \le 13$, etc.

3. RESULTS

3.1 Determination of Payload Density

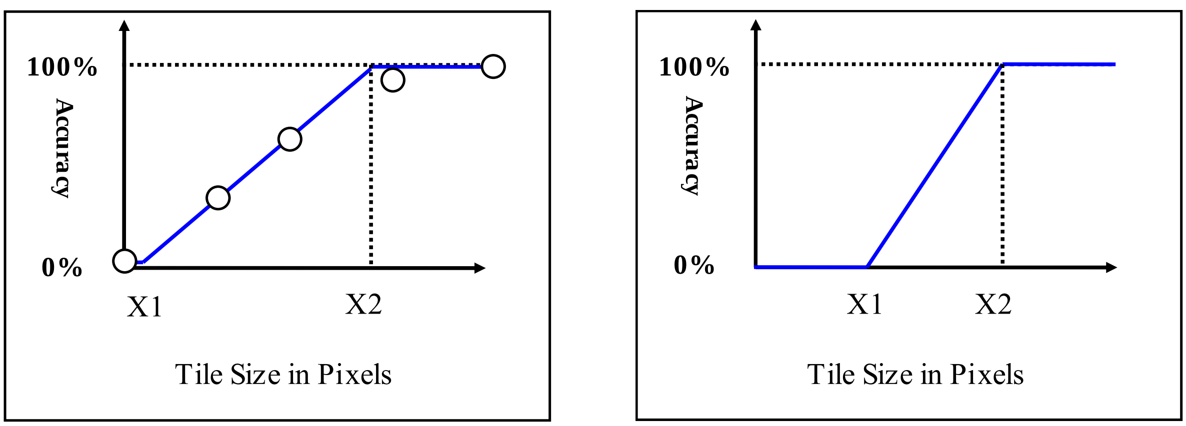

Figure 6. Piecewise-linear model (left) for authentication data taken using the 6127 printer, plain paper with SPC applied. The circles showed the measured authentication accuracies at 5, 6, 7, 8 and 9 pixels. The general piecewise-linear model for authentication used to fit authentication data for the determination of SPD-fA-PL (Equation 6) is shown to the right.

In order to compare the relative effects of each color tile technology, we require a single, unambiguous metric for comparison. This is payload density (PD). However, PD is not unambiguous, as different color barcode researchers report PD with widely different reading error rates [5][9][10][11][12]. As such, we define SPD-fA-PL, the security payload density at full (100%) authentication using the piecewise linear model of Figure 6.

$$SPD - fA - PL = \frac{\ln(6)}{\ln(2)} * \frac{PI}{(PI + NPI)} * \frac{bytes}{bit} * \frac{DPI^2}{X2^2} \quad (6)$$

In Equation 6, the bits per tile is given by ln(6)/ln(2), since there are 6 different payload colors. The percentage of payload-carrying indicia is PI, and the percentage of non-payload, or calibrating, indicia, is NPI. There is 1 byte for every 8 bits, and DPI is the printed dots per inch (600 for all of our experiments). As in Figure 6, X1 is the 0% authentication point and X2 is the 100% authentication point in the piecewise-linear model. The line segments are those that provide the minimum squared error difference from the actual data points. Thus, SPD-fA-PL is a single, unambiguous—and unbiased—parameter allowing for the comparison of PD for any set of test variables (printer, paper, SPC, restoration, choice of NPI, etc.) and will be reported in the Tables that follow.

3.2 SPD-fA-PL Results for the 6127, 6280, 5440 Printers, When Varying Substrate, Authentication Approach and the Use of Spectral Pre-Compensation (SPC)

Table 1. Color tile estimated security payload density (bytes/in^2) at full (100%) authentication, piecewise-linear model (SPD-fA-PL), printed on the 6127 printer. SPC=spectral pre-compensation if YES, no spectral pre-compensation if NO.

Paper (SPC)	**RGB-Distance**	**Hue**
Plain (NO)	1290	1570
Plain (YES)	1630	1830
Gloss (NO)	2620	2180
Gloss (YES)	2840	2900
Soft Gloss (NO)	2460	1490
Soft Gloss (YES)	2780	2870

The data in Table 1 (for the 6127 printer) illustrates that the best results on all paper types are obtained when both SPC and the Hue authentication algorithm are used together. Without SPC, however, the results vary with the paper type: RGB-Distance authentication outperforms Hue authentication for soft and gloss papers, while Hue authentication outperforms RGB-Distance on plain paper. Overall, averaging all comparative values, Hue resulted in a mean 2.8% decrease in SPD-fA-PL compared to RGB-Distance; SPC resulted in a mean 31.7% increase in SPD-fA-PL compared to no compensation; and the two glossy papers resulted in a mean 59.3% increase in SPD-fA-PL compared to Plain.

Table 2. Color tile estimated security payload density (bytes/in^2) at full (100%) authentication, piecewise-linear model (SPD-fA-PL), printed on the 6280 printer. SPC=spectral pre-compensation if YES, no spectral pre-compensation if NO.

Paper (SPC)	**RGB-Distance**	**Hue**
Plain (NO)	1640	1830
Plain (YES)	2620	2780
Gloss (NO)	2460	1290
Gloss (YES)	2680	2560
Soft Gloss (NO)	2110	1270
Soft Gloss (YES)	1930	1960

Similar trends for SPD-fA-PL are observed for the 6280 printer (Table 2). RGB-Distance authentication outperforms Hue authentication for soft and gloss papers, especially without SPC, while Hue authentication outperforms RGB-Distance on plain paper. Overall, averaging all comparative values, Hue resulted in a mean 12.1% decrease in SPD-fA-

PL compared to RGB-Distance; SPC resulted in a mean 44.1% increase in SPD-fA-PL compared to no compensation; and the two glossy papers resulted in a mean 8.3% decrease in SPD-fA-PL compared to Plain.

The results for SPD-fA-PL for the 5440 printer are provided in Table 3. Again, the best results were obtained for the Hue+SPC combination, and without SPC the RGB-Distance approach outperformed the Hue approach on soft and gloss paper. RGB-Distance authentication again outperforms Hue authentication for soft and gloss papers when no SPC is applied, while Hue authentication outperforms RGB-Distance on plain paper. Overall, averaging all comparative values, Hue resulted in a mean 1.7% increase in SPD-fA-PL compared to RGB-Distance; SPC resulted in a mean 52.3% increase in SPD-fA-PL compared to no compensation; and the two glossy papers resulted in a mean 61.9% increase in SPD-fA-PL compared to Plain.

Table 3. Color tile estimated security payload density (bytes/in^2) at full (100%) authentication, piecewise-linear model (SPD-fA-PL), printed on the 5440 printer. SPC=spectral pre-compensation if YES, no spectral pre-compensation if NO.

Paper (SPC)	RGB-Distance	Hue
Plain (NO)	1100	1120
Plain (YES)	1210	2500
Gloss (NO)	2840	1540
Gloss (YES)	2640	2800
Soft Gloss (NO)	2900	1220
Soft Gloss (YES)	2640	2620

Table 4. Color tile estimated security payload density (bytes/in^2) at full (100%) authentication, piecewise-linear model (SPD-fA-PL), mean values for Tables 1-3. SPC=spectral pre-compensation if YES, no spectral pre-compensation if NO.

Paper (SPC)	RGB-Distance	Hue
Plain (NO)	1340	1510
Plain (YES)	1820	2370
Gloss (NO)	2640	1670
Gloss (YES)	2720	2750
Soft Gloss (NO)	2490	1330
Soft Gloss (YES)	2450	2480

The mean values for Tables 1-3 are presented in Table 4. Maximum overall PD is obtained when SPC is used on Gloss paper. On Plain paper, Hue authentication increases SPD-fA-PL by 21.5% over RGB-Distance authentication, and SPC increases SPC by 46.4%. The data in Table 4 support the following interpretations:

(1) In the absence of spectral pre-compensation, RGB-Distance based authentication should be employed for Soft and Gloss paper.

(2) Hue based authentication should be deployed on non-glossy (e.g. Plain) paper.

(3) The use of SPC is in general advantageous, and so when possible should be deployed. The SPC effects are relatively consistent across printer models.

(4) The best overall results are consistently attained when deploying Hue authentication and SPC. Payload densities from 2400-2800 bytes/in^2 are observed on the three paper types.

3.3 SPD-fA-PL Results and the Use of Saturation Equalization (SE) Image Restoration

Table 5 presents data for the 5440 printer with the SE restoration pipeline removed from the authentication software. The effect of removing the restoration pipeline is obvious. A statistical significant 26.8%±14.0% ($p<0.001$, z-test) decrease in SPD-fA-PL was observed, indicating that the restoration pipeline contributes to 21.1% of the final SPD-fA-PL value.

Table 5. Percent change in the SPD-fA-PL (bytes/in^2), 5440 printer, when the saturation equalization (SE) restoration is not used.

Paper (SPC)	RGB-Distance	Hue
Plain (NO)	-14.7%	-24.2%
Plain (YES)	-31.3%	+4.9%
Gloss (NO)	-23.3%	-49.5%
Gloss (YES)	-33.5%	-26.2%
Soft Gloss (NO)	-18.3%	-26.8%
Soft Gloss (YES)	-42.8%	-35.9%

3.4 SPD-fA-PL Results when Using 2-color and 6-color Authentication Approaches, 6280 Printer and Plain Paper, When Varying Authentication Approach, the Use of Spectral Pre-Compensation (SPC), the Use of Saturation Equalization (SE) Image Restoration, and the Number of Print-Scan (PS) Cycles

Table 6 shows the effects of SPC, SE-based restoration, and the differential usage of RGB-Distance and Hue authentication approaches on SPD-fA-PL. These results are for the 6280 printer, using Plain paper. Highest PD is obtained using the Hue authentication, SPC and no SE restoration. Interestingly, this is with a 2-color authentication approach. For the usual 6-color approach, SPC results in consistent 40-80% increase in SPD-fA-PL. The effects of SPC are mixed for the 2-color approach. Restoration using SE does not improve PD in any predictable fashion. Hue authentication has a widely varying effect, but is generally ameliorative for SPD-fA-PL.

Table 6. SPD-fA-PL values (bytes/in^2), using either RGB-Distance or Hue based authentication, with or without saturation equalization (SE) of images prior to authentication, and with or without spectral pre-compensation. Data shown is for the 6280 printer/8350 scanner combination.

	No Spectral Pre-Compensation (SPC)				Spectral Pre-Compensation (SPC)			
Approach	RGB-no	RGB-SE	Hue-no	Hue-SE	RGB-no	RGB-SE	Hue-no	Hue-SE
6-color	1020	1020	1200	1100	1590	1810	1910	1910
2-color	1260	960	1300	900	1130	740	2460	740

We then considered the impact of additional copying, or print-scan (PS), cycles on the SPD-fA-PL (Table 7). The original printing and scanning, shown in Table 6, represent a single PS cycle. Two additional cycles (accomplished by scanning and printing—that is, copying—on the 6280) resulted in an additional 32 measurements of SPD-fA-PL after all of the scanned sheets were analyzed.

Table 7. SPD-fA-PL values (bytes/in^2), using either RGB-Distance or Hue based authentication, with or without saturation equalization (SE) of images prior to authentication, and with or without spectral pre-compensation. Data shown is for the 6280 printer/8350 scanner combination. 3 print-scan (PS) cycles (two additional copies after original printing and scanning), all using the 6280 all-in-one, are shown.

	No Spectral Pre-Compensation (SPC)				Spectral Pre-Compensation (SPC)			
Approach	RGB-no	RGB-SE	Hue-no	Hue-SE	RGB-no	RGB-SE	Hue-no	Hue-SE
1 PS, 6-color	1020	1020	1200	1100	1590	1810	1910	1910
1 PS, 2-color	1260	960	1300	900	1130	740	2460	740
2 PS, 6-color	360	340	610	530	600	700	1020	1020
2 PS, 2-color	510	630	590	740	600	500	830	480
3 PS, 6-color	130	140	200	190	340	300	580	500
3 PS, 2-color	260	330	340	360	270	330	470	370

Table 7 illustrates that copying causes consistent, significant reduction in SPD-fA-PL under all tested conditions—with or without SE restoration; using Hue or RGB-Distance based authentication; using either a 2-color or 6-color data reading approach; and with or without using SPC. The effect of the first additional PS cycle ("2 PS" rows in Table 7) resulted in a mean 49.8% reduction in SPD-fA-PL, and the second additional PS cycle ("3 PS" rows in Table 7) resulted in a mean 49.7% reduction in SPD-fA-PL.

3.5 Side-lobe entropy

Side-lobe entropy measurements, as described in Equations 1-4, were computed for all of the tests to assess the effectiveness of the SPC, when applied. The smallest tile sizes tested provide the highest error rate. The confusion matrices for the smallest sized tiles, the 5x5 pixel at 600 dpi tiles, are provided in Tables 8-9. These were analyzed after printing using the 6280 printer and scanning using the 8350 scanner. Numbers in bold are correctly assigned (confusion matrix diagonals), and numbers in italics/red are assigned to a side-lobe (adjacent color). It is obvious in looking at the tables that the mis-classified tiles are assigned more evenly to neighboring tiles in Table 9 (using SPC) than in Table 8 (no SPC applied).

Table 8. Confusion matrix for color assignment for color tiles without spectral pre-compensation (SPC) printed at 5x5 pixel size, 600 dpi, using the 6280 printer and scanned on the 8350 scanner. Numbers in bold are correctly assigned, in italics/red assigned to a side-lobe (adjacent color).

	Assigned Color					
Actual Color	R	Y	G	C	B	M
R	**1210**	*0*	0	0	0	*604*
Y	*12*	**1094**	*49*	0	0	0
G	14	*30*	**1515**	*8*	5	1
C	0	0	*1*	**1494**	*154*	0
B	0	0	6	*329*	**1145**	*0*
M	*160*	0	0	1	*15*	**1140**

Table 9. Confusion matrix for color assignment for color tiles with spectral pre-compensation (SPC) printed at 5x5 pixel size, 600 dpi, using the 6280 printer and scanned on the 8350 scanner. Numbers in bold are correctly assigned, in italics assigned to a side-lobe (adjacent color).

	Assigned Color					
Actual Color	R	Y	G	C	B	M
R	**1718**	*23*	1	0	0	*73*
Y	*18*	**1115**	*18*	0	0	4
G	13	*52*	**1548**	*22*	4	10
C	0	0	*29*	**1499**	*115*	4
B	0	0	1	*216*	**1305**	*68*
M	*118*	0	0	3	*135*	**1061**

Table 10. Simplified side lobe entropy, e_{SL}, weighted side-lobe entropy, $e_{SL}(w)$, percent maximum entropy, e_{PM}, and weighted percent maximum entropy, $e_{PM}(w)$, for color tiles printed at 5x5 pixel size, 600 dpi, using the 6280 printer and scanned on the 8350 scanner. Side lobe entropies are defined in Equations 1-4. Confusion matrix diagonal-adjacent elements $\mathbf{C}(i,j)$ and $\mathbf{C}(j,i)$ for each adjacent pairing of colors i and j are the pairings used for the K(i) in Equations 1, 2 and 4, and can be readily calculated from Tables 8-9.

Side Lobe Entropy	**No SPC**	**SPC**
e_{SL}	2.151	3.886
$e_{SL}(w)$	0.550	0.645
e_{PM}	0.517	0.934
$e_{PM}(w)$	0.794	0.931

Table 10 provides the side-lobe entropy values, which quantify the greater entropy in adjacent-color mis-classification indicative of successful spectral pre-compensation.

4. DISCUSSION

4.1 Summary

The results presented here emphasize the importance of choosing a high-quality substrate in order to assure a high density SPD-fA-PL. Consistently better results were observed when using (Soft, Gloss) glossy papers in comparison to Plain paper. This has been observed previously using different substrates with dry and wet electrophotographic printing technologies, as well [6][7][8]. However, we herein demonstrated that the proper combination of spectral pre-compensation (SPC), image restoration and authentication techniques can enable a similar SPD-fA-PL to be attained with printing on Plain paper. Although SPF-fA-PL density is not generally as high for thermal inkjet (TIJ) printing as for the electrophotographic printing technologies, the data here support data densities well above 2000 bytes/in^2 for Plain, Gloss and Soft paper types using TIJ technology.

The results (Tables 1-4, 6-7) indicate that SPC is a broadly useful technique for increasing SPD-fA-PL. Moreover, in instances when spectral pre-compensation was not useful for increasing authentication accuracy, the printing quality was already acceptable, and SPF-fA-PL rates above 2400 bytes/in^2 were observed. Increases in both authentication accuracy and in side-lobe entropy measurements such as $e_{SL}(w)$ and $e_{PM}(w)$ are anticipated for a print run to pass inspection.

The effect of using Hue-based authentication and SPC is of sufficient benefit to offset an entire copy (PS) cycle, as shown in Table 7 (where, coincidentally, the SPD-fA-PL values salient to show this are all exactly 1020 bytes/in^2). That is, color tiles which are not spectrally pre-compensated and use the RGB-Distance authentication method have the same payload density after a single PS cycle as those undergoing SPC and Hue authentication have after **two** PS cycles.

4.2 From Scanning to Mobile Camera Reading

The results above use either a desktop scanner (8350) or an all-in-one (6280) device. However, mobile applications will be increasingly important in the future. Some of the approaches described herein, notably spectral pre-compensation, are optimized for the combination of printer and scanning devices that will be used to produce and read the color tiles, respectively. This may not be appropriate—or even possible—in order to simultaneously support the wide array of mobile imaging devices, not to mention a wide array of printers producing them. Thus, our emphasis herein on the ability to optimize SPD-fA-PL through simultaneous optimization of SPC, restoration and authentication approach—while appropriate when using scanners and all-in-one devices—will need to be modified to support the broader set of devices used for mobile authentication. There, the device with the minimum assured SPD-fA-PL may be used to define the color tile size and other settings. The multiple-color strategy—or "M-color authentication strategy"—described herein (Figure 3, Tables 6-7) may offer a means of providing broader coverage of the mobile devices without sacrificing PD for the more capable mobile imagers.

4.3 Variable Colors/Tile Approaches

For the 6-color authentication, errors occur when the hue of a segmented tile deviates by $\geq 30^{\circ}$ from its intended hue. For the 2-color (or "color-opponency pair", see Figure 3) authentication, errors occur when the hue of a segmented tile deviates by $\geq 90^{\circ}$ from its intended hue. Cameras/scanners with lower hue quality are expected to generally work better with the 2-color tile approach, and cameras/scanners with higher hue quality will generally work better with the 6–color tile approach. The results here indicate that different imaging devices may achieve optimal SPD-fA-PL densities with different M-color authentication approaches.

4.4 Comparison to Other Approaches

The barcodes described herein were printed and scanned at 600 dpi (dots/inch). Another group [9] reports higher densities for printing of individual dots, but these are achieved when the printing settings are controlled so that halftoned dots are controllable for orientation and color. Moreover, scanning at 1200 dpi or 2400 dpi—with concomitant increase in image size—is required. At 1200 dpi scanning, the group [9] reports 3600 bytes/in^2 payload density, with a 2% error rate, and 7200 bytes/ in^2 payload density, with a 13% error rate. At 2400 dpi scanning, they report 3600 bytes/in^2 payload density, with a 0.5% error rate, and 7200 bytes/ in^2 payload density, with a 5.6% error rate. It is not obvious how to convert these data to SPD-fA-PL. The authors of [9] comment that Microsoft's Smart Tag [5][11] is dependent on finding the right colors, but since the Smart Tag uses only {CMYK} colors it is unlikely to suffer from halftoning-related color effects.

Comparing the results herein to other color barcodes, the overall payload densities (PDs) compare favorably. Table IX of reference [10], for example, cites the following bar code PD in bytes/in^2: Data Matrix, 1555; Aztec Code, 1888; QR Code, 1941; Multilevel 2D Bar Code (p_1 - s_1), 2211; and Multilevel 2D Bar Code (p_5 - s_1), 2397. Only the latter two approach the densities of 2400-2800 bytes/in^2 achieved in the work presented here. Alternative bar code approaches include the color triangle approach of reference [5]. While the PD is not provided in [5], the accompanying website mentions a PD of 2000 bytes/in^2 [11]. So, to our knowledge, the densities achieved for spectrally pre-compensated color tiles described herein meet or exceed those of other reported bar codes.

In related color barcode work, the use of visual cues enables a color barcode field, with ECC, to reach PD of 900 bytes/in^2 [12]. In [12], it is noted that "the use of proper visual cues [will enable] the system to reach much higher payloads, at least to 2500 bytes/in^2. We are working with that team to optimize the combination of non-payload indicia (NPI) and ECC to reliably reach that payload density.

5. CONCLUSIONS

The tests performed here provide support for the following set of recommendations when deploying color barcodes for high-density data reading.

1. Use glossy or other high image-quality paper when possible. This is especially indicated for the TIJ printing technology used for the tests reported here. Soft and Gloss paper types provided generally high SPD-fA-PL regardless of restoration, authentication and spectral pre-compensation approaches deployed.

2. Use SPC where indicated as means to increase SPD-fA-PL, and use side-lobe entropy metrics to validate the effectiveness of the SPC deployed.

3. Consider multiple authentication approaches. We used RGB-Distance and Hue authentication approaches herein, and found the Hue authentication approach to work best with Plain paper. The results were more mixed with the Soft and Glossy paper. We observed, not surprisingly, that the Hue authentication approach works well where SPC works well, since SPC is focused on maximal dispersion of the readable colors after scanning.

4. Consider multiple restoration approaches. We addressed only a simple restoration approach herein, the saturation equalization (SE) approach. It was effective for increasing payload density using scanners. Given the more considerable image distortion—lighting, lens-related warping, color inconsistency, planar distortion, perspective distortion, etc.—normally accompanying mobile imaging, image restoration techniques will be far more important for accurate mobile color tile imaging than they are for scanner or all-in-one based color tile imaging.

5. Consider different choices for M, the number of colors, and thus N_{rs}, the number of reading strategies available to the network of readers and reading devices. This is potentially of high value for mobile applications, in which case a workflow in which the mobile device attempts to read at the highest-density (highest number of distinguishable colors/tile), then the next highest, etc., until a successful read is obtained. This also offers a different "concept" for error-correcting code, in which payload density drops with reduced image quality of the imaging device.

6. FUTURE WORK

The color tile was deployed with HP's Smart Label and Authentication software and demonstrated at the DRUPA'08 print show. This paper represents formal consideration and systematization of the printing and reading (imaging) approaches necessary to optimize color tiles for scanners and all-in-ones (line scanners). Further work is required to optimize color tiles for mobile deployment, and that work is underway. Work to date shows that achieving SPD-fA-PL of 300 bytes/in^2 is possible using the approaches herein for a wide number of mobile cameras. We are working to increase that density so that the color tiles can provide a high-density, small "real estate" solution to the "revenge of the physical".

7. ACKNOWLEDGEMENTS

The authors thank many helpful colleagues for collaboration in this area, including but not limited to Matt Baker, Matthew Gaubatz, Shawn Gibson, Galia Golodetz, Joceli Mayer, Andrew Page, Stephen Pollard, Eddie Torres, and Juan Carlos Villa. The authors also thank Gary Dispoto, Eric Hanson and Henry Sang for their continued support of this research.

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