Color QR Codes: Increased Capacity Via Per-Channel Data Encoding and Interference Cancellation

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Abstract

Monochrome 2-D barcodes have recently become extremely popular in mobile imaging applications. To accommodate higher data rates, we present a methodology for extending these barcodes to color. We use independent per channel data encoding in cyan, magenta, and yellow print colorant channels and decode the information in the complementary red, green, and blue channels used in capture, effectively increasing the data rate by a factor of three. To overcome unavoidable inter-channel interference, our framework utilizes adaptive thresholding and model-based interference cancellation at the decoder which are facilitated by an intelligent barcode design that allows estimation of parameters required for thresholding and cancellation. We present the framework by constructing and evaluating the performance for a color version of the QR code, the most commonly deployed monochrome barcode in mobile applications. Experimental results demonstrate that the framework is effective and allows recovery of embedded data with low bit error rates, which can be readily handled by the built in error correction within the QR code standard.

1 Introduction

Two dimensional barcodes have recently become very popular in mobile applications for a couple of reasons. Firstly, the camera phones inherently capture 2-D images and can therefore be directly used with 2-D barcodes, unlike conventional laser-based 1-D barcode scanners that would require hardware modifications for capturing 2-D barcode images. Secondly, equally importantly, the 2-D codes offer high enough rates (per unit substrate area) to provide a viable mechanism for bridging between the physical world of print and the cyber world of the Internet. In particular, the most common uses of 2-D barcodes are for the purpose of facilitating access to online information about products and services advertised in print media such as magazines, posters, and billboards [1, 2]. The universal resource locator (URL) for the online information is embedded within the print as a 2-D barcode, which can be captured with a cell phone camera, and, upon decoding, allow the user to access the information without the tedium of manually entering the URL. Among the various options available for 2-D barcodes, for mobile applications, the (monochrome) quick response (QR) code [3, 4] is used most extensively in practice. The QR code standard [4] defines a flexible solution with competitive data rates, support for multiple character sets, features for rapid and robust synchronization under lighting and orientation variations, multiple data density designs, and built in variable error correction capability for handling differing application requirements [1].

Although 2D codes have higher capacity than their 1D counterparts, innovations that further increase their capacity are of considerable interest because they allow for either: a) a reduction in the substrate foot-print that these codes consume in print media, b) additional information with the same substrate foot-print, c) greater robustness, or some combination thereof. Specifically, in situations where 2-D barcodes are used to connect a user with a URL associated with a product advertisement, the additional data capacity can be utilized for encoding information on the publication or location of the advertisement, which can be invaluable for assessing effectiveness of advertisement and corresponding ad-monetization.

Because cell phone cameras inherently capture color rather than monochrome images, a natural way to increase the capacity of 2-D barcodes for mobile applications, is to exploit the "spectrum diversity" that the red (R), green (G), blue (B) camera color channels offer from a communications standpoint. This approach is also attractive because magazines, newspapers, posters, and billboards, in which barcodes are commonly embedded for providing mobile connectivity, are already printed in color, with the possible exception of the barcode region. A number of efforts have recently been initiated in this direction [5, 6]. Color variations across printers and cameras pose a challenge for these existing methods causing compromises in performance/robustness.

In this paper, we propose a simple and robust framework for extending existing monochrome barcodes to color with greater robustness, which we illustrate concretely by constructing a color QR code. We use independent per channel encoding of data in the cyan (C), magenta (M), and yellow (Y) printing colorant channels. The data in the C, M, Y colorant channels are decoded from the corresponding complementary R, G, and B camera sensor channels, respectively, thereby enabling a data rate that is three times the rate for the corresponding monochrome version. To overcome the deleterious effects of unavoidable inter-colorant interference, we use a model based interference cancellation procedure that is computationally inexpensive and provides a significant performance improvement. Because the optimal parameters for the interference cancellation process are printer and camera dependent, we use a customized design of the synchronization markers for the code that also enables estimation of the required parameters. Experimental results demonstrate that the methodology is effective and the resulting barcodes offer excellent performance.

In Section 2 we describe the construction of the color QR code in the proposed framework. Experimental results from tests performed with the constructed code are presented in Section 3 and Section 4 concludes the paper with a summary of the major results and a discussion.

Figure 1. The proposed color QR code (2cm x 2cm).

2 Color QR Code in Proposed Framework

We describe our proposed framework for extending monochrome barcodes to color by using a specific color barcode construction based on the popular QR code that is shown in Fig. 1. The code is (designed to be) printed using three layers of C, M, and Y colorants corresponding to the subtractive color primaries [7]. The three large annular squares at three of the corners along with the included solid squares are positioning marks to allow quick detection of the barcode pattern by the decoder. Combined with other marks distributed over the square footprint of the barcode, these marks enable synchronization at the decoder. We design the colors of the positioning marks to correspond to six combinations of the colorant layers, in particular C, M, Y, CM, CY, and MY, where the latter three represent the printer blue, green, and red, respectively[1]. The corresponding regions in the image captured at the decoder enable interference cancellation during the decoding, as explained later in this section.

The remainder of the barcode substrate encodes the data payload which is organized as three parts, of which, one each is embedded independently in one of the C, M, and Y printing colorant channels using the same method as the monochrome QR codes.

2.1 Data Recovery: Color Interference Cancellation

In mobile imaging applications of interest, the decoder seeks to recover the data embedded in the barcode from an image of the barcode captured with a cell phone camera. In an ideal setting, the R, G, and B channels of the captured camera images correspond to inverted versions of the complementary C, M, and Y colorant layers with no cross-interactions between the camera channels and the non-complementary colorants. The encoded data in C, M, and Y print colorants can then be extracted from R, G, and B capture channels, respectively. In reality, however, there is significant cross-channel coupling among the printer and camera color channels as is illustrated in Fig. 2, which shows an image of a printed version of the barcode in Fig. 1 captured using a cell phone camera[2]. It can be seen that the each of the R, G, and B camera sensor channels capture not only the complementary C, M, and Y printer colorant channels but also see significant interference from other non-complementary channels. In particular, the color interference seen in the blue channel is the most significant and can not be compensated by simple thresholding because, as can be seen in Fig. 2 a number of barcode regions with the yellow colorant appear lighter in the blue channel than regions which do not include the (complementary) yellow colorant.

To overcome the cross-channel color-interference, we utilize a physical model for the print and capture process. Assuming the C, M, and Y colorants are transparent (non-scattering) we model

[1] In terminology used in the context of modeling color printers, these are a subset of the so-called Neugebauer printing primaries [7].

[2] Details of the experimental set up are provided later in Section 3.

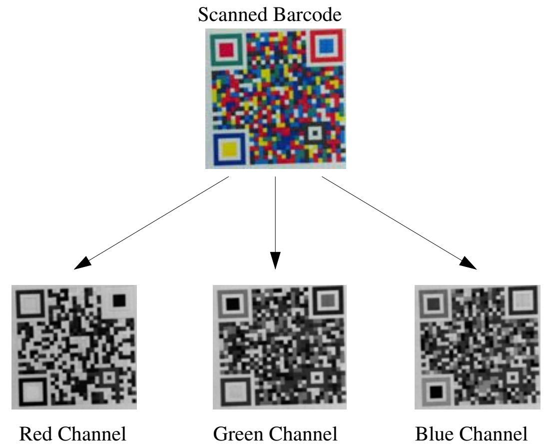

Figure 2. Color interference due to cross-channel coupling.

the print using the the transparent version of Kubelka-Munk theory [8, Chap. 7], or the Beer-Bouguer law [8, Chap. 7], as $(t_i(\lambda))^2 = 10^{-d_i(\lambda)}$, where $d_i(\lambda)$ is the optical density for the i^{th} colorant layer (under to and fro passage), where $(i \in \{C,M,Y\})$. The binary colorant layers of the barcode are represented as bi-level images $I_i(x,y)$ $(i \in \{C,M,Y\})$, where $I_i(x,y)$ is 1 in regions where the i^{th} colorant is printed and 0, otherwise. The spatial pattern of spectral reflectance of the printed barcode can then be approximated as [7]:

$$r(x,y;\lambda) = r_w(\lambda) 10^{-\sum_{i\in\{C,M,Y\}} d^i(\lambda) I_i(x,y)} \quad (1)$$

where $r_w(\lambda)$ is the spectral reflectance of the barcode substrate (paper).

If the spectral sensitivity of the R, G, B capture channels is represented by $s_k(\lambda)$, $k \in \{R,G,B\}$, the three channels in the image captured by the digital camera can be expressed as[3]. $I_k^s(x,y) = \int s_k(\lambda) r(x,y;\lambda) d\lambda$, $k \in \{R,G,B\}$. We further approximate the spectral sensitivities of R, G, B camera color channels as Dirac delta functions $s_k(\lambda) = \alpha_k \delta(\lambda - \lambda_k)$ at corresponding wavelengths λ_k, $k \in \{R,G,B\}$, which, with allows us to write the normalized optical densities corresponding to the three captured channels as

$$\begin{aligned} d_k(x,y) &\stackrel{\text{def}}{=} -\log_{10}\left(\frac{I_k^s(x,y)}{I_k^s(W)}\right) \\ &= \sum_{i\in\{C,M,Y\}} d_k^i I_i(x,y) \end{aligned} \quad (2)$$

where $I_k^s(W)$ is the captured image value corresponding to the paper substrate in the k^{th} camera channel and $d_k^i = d^i(\lambda_k)$. Note that the linear relation in Eq. (2) between the densities corresponding to camera responses and print colorant channels allows us to perform *interference cancellation* and estimate the print colorant channels from the camera color channels provided that the optical density of the colorant layers in the camera channels d_k^i's

[3] In actual practice, due to variations in lighting the model does not apply on an absolute basis. The spatial variations in lighting, however, impact all colorant channels identically and can be handled after our proposed processing in much the same way as they are currently tackled for monochrome barcodes [5, 9, 10].

for all $k \in \{R,G,B\}$ and $i \in \{C,M,Y\}$ are available[4]. Specifically, denoting by $\mathbf{D}$ the matrix whose i^{th} column is $[d_R^i, d_G^i, d_B^i]^T$, we see that under the model of (2) the printed binary channels $\mathbf{I} = [I_C, I_M, I_Y]^T$ at a given location (x,y) are obtained from the recorded density $\mathbf{d} = [d_R^i, d_G^i, d_B^i]^T$ at that location by $\mathbf{I} = \mathbf{D}^{-1}\mathbf{d}$. Although the model of (2) makes several simplifying assumptions, it captures the first-order behavior of the print and capture processes. Its utility has recently also been demonstrated in an alternate application [11] for the more conventional four-colorant printing scenario.

To cancel the color interference, we require an estimate of $\mathbf{D}$. For obtaining this estimate, we use the R, G, B values sensed by the digital camera for the positioning marks at the corners of our color QR code shown in Fig. 1 that correspond to printing of the colorant combinations C, M, Y, CM, CY, and MY. After finding the positioning marks in the barcode the normalized R, G, B channel optical densities are computed for each pixel contained inside the positioning marks and an estimate of $\mathbf{D}$ is obtained from these observed values and the known input values I_C, I_M, and I_Y for these pixels via a least-squares fit to the model of 2.

3 Experimental results

In order to evaluate the performance of the proposed color barcode, we conducted a number of experiments using color printers and cell phone cameras available to us. First we generated an instance of the proposed color QR code, where three different URLs were individually encoded within each of the C, M, and Y color separations. Each separation's data was encoded in the form of a monochrome QR code using the open source Zint[5] toolkit. The three monochrome barcodes were combined by incorporating these as C, M, and Y separations in a color image. In this process, the positioning markers were also mapped to appropriate Neugebauer primaries mentioned previously, resulting in the color QR code shown in Fig. 1. Data embedded in each of the individual separations was encoded for error correction using the designated "L level" of error protection specified in the QR code standard, which uses Reed-Solomon codes intended to offer protection against approximately 7% errors. In each case, the resulting bit stream obtained after the error correction encoding procedure was also recorded to enable computation of bit error rates prior to the use of the error correction decoding. The generated QR color barcode was then printed on two laser printers (HP LaserJet 5640 and 4700), one inkjet printer (HP OfficeJet 6500) and two color copiers (Ricoch Afficio MP C2550, Xerox Work Centre 7665) in three different sizes: 15 x 15 mm, 20 x 20 mm and 30 x 30 mm.

Images of each of the printed color QR barcodes were captured in typical office lighting conditions (indoor, fluorescent lighting) with two mobile phones, an iPhone 4 with a 5 megapixel camera and an iPhone 3GS with a 3 megapixel camera. An example image from the set of captured images for a $2cm \times 2cm$ version is shown in Fig. 2. Because of the color interference, decoding of the embedded data fails if the individual R, G, and B colorant channels are used in a monochrome decoder. The specially designed colorant combinations of the positioning marks in the QR code, were used to estimate the color-interference parameters $\mathbf{D}$ and cancel the interference as indicated in Section 2. The resulting estimate of print colorant channels are shown in Fig. 3. Note that the color interference cancellation algorithm removes most of the cross-interference between print-colorant and camera channels (see the estimated yellow channel in Fig. 3 with the blue channel in Fig. 2.)

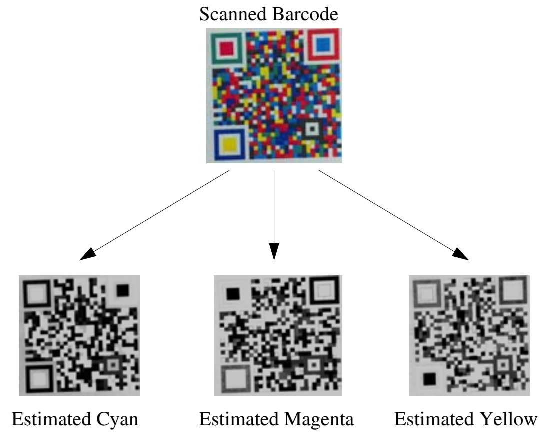

Figure 3. Color interference cancellation.

The effectiveness of the interference cancellation procedure was also verified by testing the barcode decoding. Individual barcodes in each of the colorant layers decoded correctly when the images estimated using the interference cancellation procedure were displayed on screen and captured using a QR code reader application and also when these images were input to a monochrome QR barcode decoder, specifically the ZXing Java-based decoder[6]. Furthermore, to obtain estimates of the bit error rates, we also obtained the decoded bit-stream from the decoder prior to the error correction decoding procedure and computed the bit error rate by comparing this bit stream against the corresponding bit stream at the encoder. The resulting bit error rates are summarized in Table 1, where we can see that these error rates are well within the error correction capability of the L level error protection, which allows recovery from approximately 7% errors. For comparison, we also used an alternative method that is enabled by our proposed color QR code design. In this alternative method, we attempt to eliminate the color interference by adaptively thresholding each layer by using a threshold value for each of the R, G, and B channels, where the threshold is set as the midpoint between the average value for the corresponding complementary colorant and the two colorant combination that does not include the complementary colorant. The resulting estimated barcodes decoded successfully for the R and G channels but not for the B channel. The bit error rates obtained with the adaptive thresholding process were also evaluated and are listed in Table 2. It can be seen from these tabulated bit error rates that the adaptive thresholding approach while successful for the R and G channels fails for the B channel. The interference cancellation approach on the other hand can successfully recover the data in all three channels.

[4] Also note that the model is not impacted by a power-law transform, commonly employed for "gamma correction".

[5] http://www.zint.org.uk

[6] http://code.google.com/p/zxing/

Size, mm	Cancellation		
	Cyan	Magenta	Yellow
15 x 15	0	0.0515	0.0363
20 x 20	0.0005	0.0392	0.0226
30 x 30	0.0014	0.0089	0.0026

Table 1. Bit error rates for proposed interference cancellation

Size, mm	Thresholding		
	Red	Green	Blue
15 x 15	0	0.0091	0.5505
20 x 20	0.0011	0.0142	0.4971
30 x 30	0.0005	0.0239	0.5200

Table 2. Bit error rates for proposed adaptive thresholding

4 Conclusion

The framework proposed in this paper, provides an effective method for extending monochrome barcodes to color. Our color QR code constructions offer three times the data rates of their monochrome counterparts with low bit-error rates that are readily handled by the error correction coding options available in the QR code.

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