DualCodes: Backward Compatible Multi-Layer 2D-Barcodes

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Abstract. Matrix codes enable a coupling between virtual and physical worlds for ubiquitous computing applications. With this paper, we propose a technique, which can be used to increase the amount of information contained in a matrix barcode in a backward compatible way. This enables applications to fully utilize the wide spread of QR Codes or Data Matrix Codes for service discovery or basic service, while being able to transmit much more information during one scan for advanced applications. We present the approach, explain difficulties in decoding typical camera images, a simulatory evaluation of decoding performance, and application examples.

Key words: Matrix code, Two-Dimensional barcode, Pervasive systems, Ubiquitous computing

1 Introduction

Matrix barcodes play an important role in ubiquitous computing applications due to various reasons: Matrix codes enable a deep integration of physical and virtual worlds without advanced infrastructure components for localization. Matrix codes can be printed, can be shown on displays, can be read from larger distances as compared to RFID or NFC, and are well-known. For all major smartphone platforms, there are free high-quality barcode reading applications available. One of the most widely known matrix barcodes is the Quick Response Code (QR Code).

In 2000, the International Organization for Standardization (ISO) published a specification of the QR Code, which has been initially developed by Denso Wave in 1994 [1]. The most important invention are the finder patterns, which allow for a simple, fast, and rotation-invariant registration of QR Codes inside camera images. Meanwhile, the QR Code was widely adopted. In June 2011, for example, 14 Million American users of mobile camera phones scanned QR Codes. These are 6.2% of the mobile audience [2]. A Japanese survey conducted in 2005 revealed that nearly 90% of the mobile users younger than 20 years have had experience with QR Codes [3].

Preprint of Mobile and Ubiquitous Systems: Computing, Networking, and Services, Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Volume 120, 2013, pp 25-36 (DOI 10.1007/978-3-642-40238-8_3)

However, QR Code readability with camera phones is limited by the effective resolution of the camera, such that decoding becomes more difficult with increasing information content. For simple Internet applications, there are URL shortening services, which can be used to increase readability of QR Codes. But for pervasive computing applications, it is important to include the complete service information inside QR Codes, because Internet access is often limited inside buildings and privacy concerns restrict a central communication given by an Internet link.

Consequently, there are many approaches, which try to increase the information capacity of a matrix code while keeping a comparable scanning performance in terms of scanning speed and robustness. One common idea is to use multiple different colors [4–8]. While this clearly increases information density as compared to black-and-white codes, it is not clear, whether common smartphone cameras have sufficient color reproduction capabilities. Another drawback of using colors is an increased complexity in normalization and the need for color printing.

Unfortunately, these approaches did not yet converge to standards nor found wide adoption. One exception might be Microsoft Tag, a limited, cloud-based color tagging system using HCCB [5, 9]. However, Microsoft Tag does not allow the dissemination of information without interacting with a cloud service. Therefore, it is not well-suited for pervasive computing applications.

With this paper, we want to bring together the wide-spread QR Code as a publicly standardized basis with an extending technique increasing information density. Therefore, we introduce the so called dual coding technique, which provides two main advantages over using classical matrix codes: First of all, a higher spatial information density can be achieved using modified scanning software without locking out classical barcode scanners from basic functionality. Second of all, hybrid applications are possible, where the service for classical scanning software is different from the service for informed readers and special applications, which make use of the second layer of information.

The next Section 2 introduces the dual coding scheme in general and defines requirements for the underlying matrix code encoding functions. Section 3 describes an enhanced decoding algorithm for dual matrix codes, which explains upcoming challenges in real world scanning situations and gives solutions to them. This Section is followed by an evaluation of the dual QR Code decoding performance with respect to perspective correction, image noise, and blur. Section 5 explains applications, which show the strengths of using a dual encoding scheme. Section 6 concludes this paper.

2 The Dual Coding Scheme

Let $\mathcal{E}_m(s)$ denote the encoding function of some matrix barcode m, which takes a string s as an argument and generates a complete matrix barcode including finder patterns. Let $\mathcal{D}_m(I)$ denote the corresponding decoding function, which takes an image I given as an intensity distribution and returns the content of the

(a) QR Code Layer 1: $\mathcal{E}_m(s)$ (b) QR Code Layer 2: $\mathcal{E}_m(t)$ (c) Dual QR Code $E_d(s,t)$ with $\alpha = 0.7$

Fig. 1. Example of the dual QR Code for $s =$ `NTKDLTMMBYAXOGSZEMIHKHTUM` and $t =$ `DHEVRZOTMRLNXIELEBJUSNDYM`

matrix barcode, which is allowed to be contained somewhere inside the possibly noisy image. There is no assumption made about possible perspective distortion, noise, and blur. Consequently, the decoding might fail returning an empty string.

A matrix encoding function $\mathcal{E}_m$ is called *DC-compatible*, if it has the following properties:

– It is *left-unique*: For two equal strings $s = t$, the encoding is also equal: $\mathcal{E}(s) = \mathcal{E}(t)$. Note, that typically left-uniquess is part of the mathematical definition of a function. But there are code systems where the encoding is not left-unique such that two different codewords have the same preimage under the encoding relation.
– The functional properties (i.e., finder patterns for registration, version codes) are kept intact under addition and scalar multiplication of images.

An example for a DC-compatible encoding function is given by the widely adopted QR Code [1,10], when the version, redundancy level, encoding and block size are chosen the same and the string argument is limited to strings of a fixed length.

The encoding function $\mathcal{E}_d(s,t)$ of dual codes is given as a linear interpolation of two DC-compatible encoding functions applied to the arguments s and t.

$$\mathcal{E}_d(s,t) = \alpha\mathcal{E}_m(s) + (1-\alpha)\mathcal{E}_m(t) \tag{1}$$

When choosing α significantly larger than 0.5, such that the first code is sufficiently stronger than the second code, compatibility implies, that the result can be decoded by the matrix code decoder:

$$\mathcal{D}_m(\mathcal{E}_d(s,t)) = s, \text{ if } \alpha \text{ large enough.}$$

This fact can be used in two ways: First of all, the dual code can be decoded by any decoder software, which can handle noise. In this way, the first information layer s in the dual code $\mathcal{E}_d(s,t)$ can be used compatibly with the basic versions of the matrix code. The second use enables decoding of the second layer of

(a) Data-Matrix Layer 1: $\mathcal{E}_m(s)$

(b) Data-Matrix Layer 2: $\mathcal{E}_m(t)$

(c) Dual Data-Matrix Code $E_d(s,t)$ with $\alpha = 0.7$

Fig. 2. Example of the dual Data-Matrix Code for $s =$ `NTKDLTMMBYAXOGSZEMIHKHTUM` and $t =$ `DHEVRZOTMRLNXIELEBJUSNDYM`

information. This can be achieved by encoding the decoded result again leading to a noiseless coding of the first information layer and removing this layer. Let I be the intensity distribution of a dual code. Then the following three-step algorithm decodes both information layers:

$$
\begin{aligned}
s &= \mathcal{D}_m(I) \\
I_2 &= \frac{1}{1-\alpha}\Big(I - \alpha\mathcal{E}_m(s)\Big) \\
t &= \mathcal{D}_m(I_2)
\end{aligned}
$$

This coding scheme has been implemented in a simulation environment for the case of QR Codes generated by the open source software qrencode [11] and decoding provided by ZXing barcode scanning software [12]. Without any image noise and disturbances, the ZXing QR code scanning software was able to decode the stronger part s for $0.67 \leq \alpha$ and the weaker part t for $0.67 \leq \alpha \leq 1-\epsilon$, where ϵ is a small positive value large enough, such that $I - \alpha E_m(s)$ is non-zero for non-zero pixels in $E_m(t)$. It might seem a bit odd, that there is a lower bound on α, but no (real) upper bound. But as we are working in a perfect environment without noise or amplitude degradation, a successful decoding of the stronger code leads to a 100% correct reconstruction of the weaker code, i.e. I_2 is actually identical to $\mathcal{E}_m(t)$, as long as *alpha* is strictly smaller than 1. An example with two random strings of length 25 is given in Figure 1.

Basically, this coding scheme allows for embedding a second layer of information keeping the first layer of information intact and decodable by software, which is not informed about the existence of the second layer. Furthermore, a given amount of information (s concatenated with t) can be transmitted with less spatial resolution. On the other hand, the image intensity has to be measured in more detail. While the basic QR Code is a binary code, the DQR Code contains four levels of intensity, namely $0, \alpha, 1-\alpha$, and 1 which have to be dis-

(a) Layer 1: $\mathcal{E}_m(s_1, s_2, s_3)$ (b) Layer 2: $\mathcal{E}_m(t_1, t_2, t_3)$ (c) Dual Code $E_d(s_i, t_i)$ with $\alpha = 0.7$

Fig. 3. Example of the dual Color Superposition Code for six random strings of length 25 assigned to the six color components of two independet RGB images

tinguishable. In summary, the dual coding scheme allows for a flexible payoff between spatial resolution and color space resolution.

The same coding scheme is also applicable to the well-known Data-Matrix Code [13]. Figure 2(c) depicts an example. The stronger symbol also decoded correctly for $\alpha \geq 0.67$. The reason for this equal value is the binary nature of the code and the fact, that the threshold settings in the local histogram binarizer giving the first common stage of decoding are the same. The weaker code could then again be reconstructed for $0.67 \leq \alpha \leq 1 - \epsilon$. Even a superposition code in the color domain (compare [7, 14, 15]) is suitable for this framework.

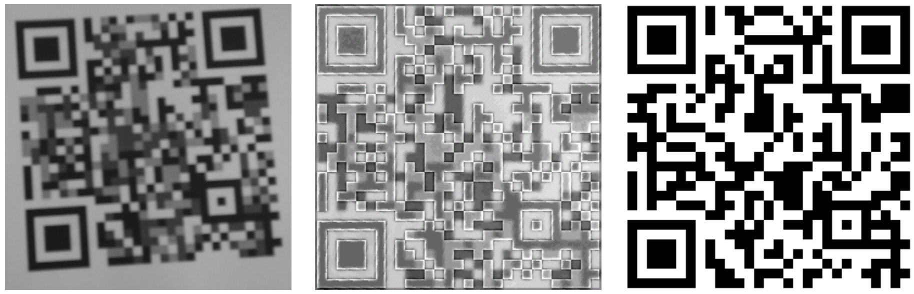
For a very simple color coding scheme, where three independent QR Codes are put into the three color components of an RGB image, the framework works well. See Figure 3 for an example of such a code. However, for real world applications one should keep in mind, that the detecting camera has to be able to correctly distinguish all three color channels in high quality making decoding under changing light conditions much harder.

In the following section, we explain in more detail, how this theoretical framework was applied for the case of the Quick Response matrix code. The dual version of this code, encoded as above, is called DQR Code.

3 DQR Codes in Real-World Scanning Situations

Figure 4(a) shows a typical smartphone camera image containing a DQR Code. The first step in decoding is the localization of the three position patterns inside the picture. This is classically done using a scanline algorithm searching for the characteristic 1-1-3-1-1 pattern in a binarized version of the camera image. Afterwards, the smaller alignment patterns are localized at the expected positions. This results in at least four locations inside the image.

These define the perspective transformation of the code in the camera image, which is used to reproject the code to known dimension and orientation. Now,



(a) Camera image (b) Reprojected and combined image $\mathrm{Norm}(I - \alpha J)$ (c) Binarized second layer

Fig. 4. Real-world scanning situation and artefacts

this code I can be decoded as usual, as we have taken care that the combined code decodes to layer 1. The result of this decoding step $s = \mathcal{D}_m(I)$ is then re-encoded to $J = \mathcal{E}_m(\mathcal{D}_m(I))$, hence correcting possible bit errors. After normalizing both codes, the reprojected code portion of the camera image and the freshly generated code for layer 1, we can substract and decode layer 2:

$$t = \mathcal{D}_m(\mathrm{Norm}(I - \alpha J))$$

In these equations Norm denotes a normalization of the resulting image with respect to intensity. This step is needed, because the second step of the algorithm, $I - \alpha\mathcal{E}_m(s)$, results in $(1-\alpha)\mathcal{E}_m(t)$ under ideal conditions and normalization is given by multiplication with $1/(1-\alpha)$ in this case. But in reality, the image I consists of the encoded data and a noise term as in

$$I = \mathcal{E}_d(s, t) + V$$

such that the normalization factor is unknown.

Due to the high noise level after substracting the re-encoded QR Code J and due to inaccuracies in the locations of the finder patterns, the image $\mathrm{Norm}(I - \alpha J)$ suffers from the following problems prohibiting a naive decoding. Figure 4(b) shows an example.

- Finder patterns can be corrupted by addition of neighbouring pixels due to numerical problems with perspective correction.
- Small high intensity edges appear between the matrix blocks, again due to inaccuracies of perspective correction, which heavily influence binarization.
- A higher bit error rate while binarizing is to be expected, as the signal energy of the second code is significantly lower as compared to the signal energy of the first code.

As a countermeasure for the first problem, one can simply correct the corrupted structural elements of the code. For the second problem, one can use a Gaussian filter centered at the known locations of the matrix blocks emphasizing their

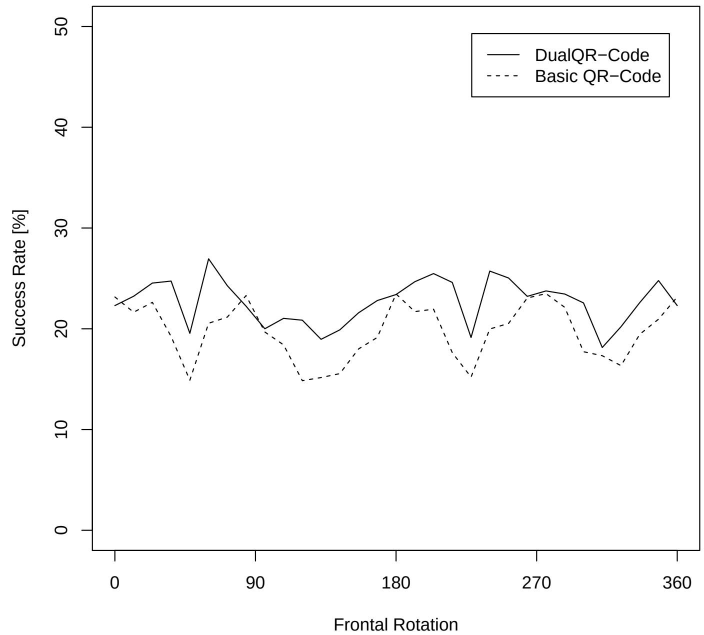
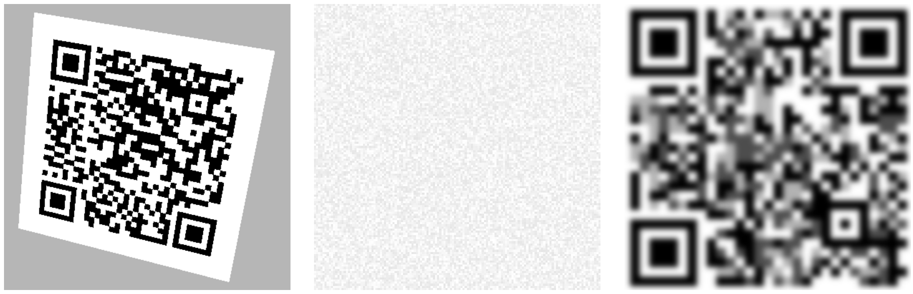


Fig. 5. Decoding performance of DQR Codes compared to classical QR Codes with respect to perspective distortion

center intensity and weakening the effects between adjacent blocks. To deal with the higher bit error rate, the redundancy level of the barcode should be chosen high enough. To further enhance the decoding performance for the second layer, it is advisable to try different binarization methods and thresholds in a loop, Figure 4(c) shows the resulting binary code for the second layer of the example image.

4 Evaluation

A first consideration with respect to evaluation of the dual coding system is the robustness concerning perspective distortion. For pervasive computing applications, it is to be expected that the barcode is scanned from different viewing angles and distances. For comparision of classical QR Codes with dual codes, we conducted a complex evaluation experiment, where the matrix code is rendered rotating around its three axis using the technique described in [16]. Figure 6(a) shows an example of a QR Code rotated around its three axis. Figure 5 depicts the results of this experiment, where the y-axis shows the decoding success rate for images rotated around the pitch axis and the yaw axis from $[\frac{-\pi}{2}, \frac{\pi}{2}]$.



(a) Three degrees of freedom rotation of a QR Code

(b) A white image containing 10% of random image noise

(c) A DQR Code containing blur with $\sigma = 0.3$ matrix blocks

Fig. 6. The effects of perspective distortion, Gaussian noise, and blur

The decoding sucess rate is defined to be the fraction of the sucessfully decoded images out of all rotated images. The x-axis gives the rotation around the rotational axis, which does not affect the spatial extensions of each matrix block. For comparision, the basic QR Code contains a string, which is twice as long as each individual string of the DQR Code, such that it contains the same amount of information. One can clearly see, that the DQR Code performs better with respect to perspective distortion as compared to the basic QR Code. This is due to the fact, that the blocks inside the basic QR Code are smaller due to the longer content.

With smartphone cameras, another source of problems is image noise. To evaluate the effect of image noise, a random image (White Gaussian Noise) was generated and used to create sequences of blendings with clean QR and DQR codes for varying noise amounts. The basic QR Code is able to deal with a noise amount of less than 48%. The dual code, of course, is more sensitive with respect to image noise, as it has to distinguish between more intensities. The message in layer 1 decodes for a noise amount of less than 33% and both layers decode successfully for a noise amount of less than 10%. This is slightly below the theoretically achievable value of 14.4% (i.e., 48% of 30%, for $\alpha = 0.7$), which is due to the fact, that image binarization is more difficult due to the artefacts coming from inaccurate projection. Nevertheless, 10% of image noise is quite a high amount of noise, as one can see in picture 6(b).

Another important effect affecting image quality is blur. For evaluation purposes, we apply a Gaussian blur filter to the matrix code image with varying standard deviation σ and radius 3σ. The block size of the source image is ten pixels and the standard deviations in the following are relative to the pixel domain and not relative to the matrix code blocks. For the DQR Code, a Gaussian blur with σ up to 2.4 pixel (i.e., 0.24 blocks) did not affect the decoding. For $\sigma \in [2.4 \ldots 4.2]$, only the stronger layer 1 was decoded sucessfully. For $\sigma > 4.2$ pixel, the system is unable to decode any of the two layers. The classic QR Code, containing the same amount of information, is decoded for $\sigma < 1.7$ pixel. The big difference is partly induced by a reduced block size of 8 pixel, which is needed, as the QR Code contains the concatenation of the strings of both layers of the dual code. Figure 6(c) shows the effect of blur applied to a DQR Code.

Furthermore, the system has been implemented for Android smartphones and been thoroughly tested in two use-cases: Scanning dual codes from paper and from screens. Both cases worked well, however accuracy problems with perspective correction before substracting a freshly generated code and a scanned code led to some interesting artefacts, which needed a Gaussian filtering step as already described in Section 3.

5 Applications

Dual matrix codes can be used to increase information density in matrix codes. But they also allow for advanced applications, where the individual layers of the dual matrix code have different functionality. In the following, we explain one application, which increases privacy for matrix code based positioning in a location based service scenario. The second application below explains, how DQR codes can be used to provide a higher security level for the adoption of matrix code technology in business environments, where some functions (e.g., adding a contact) can be limited to properly signed barcodes on informed devices, while a non-informed device can still be used with the same matrix code without this security enhancement.

5.1 Privacy-Enabled Location Based Services Using Matrix Codes for Positioning

Due to the tremendous growth of location based services, as for example forecast to grow to US10.4 billions in 2015 [17], the interest in reducing the barriers for large-scale, local provisioning of location based services is growing. However, location based services are nowaday typically provided outdoors, where GPS positioning is available. Inside buildings, however, there is no cheap positioning technology available. To solve this problem, there have been proposals to use barcode technology for location tagging. That is, to bring out different barcodes in the surroundings and to infer the position of a mobile device by scanning a barcode [18]. Unfortunately, Internet access is not available in many buildings and, from a privacy perspective, it is not a good idea to let barcodes point to Internet addresses providing location information. Because then, the time and position of each user can be independently tracked by the location based service platform. Furthermore, the presentation quality is limited by current web technology and a deep integration with smartphone content, such as contacts and calendar, is impossible.

Therefore, future location based services for navigation inside buildings should rely on mobile applications, which hold maps and navigation information on the smartphone. But then, the provisioning of location based services becomes a problem: On the one hand, the barcode could contain an Internet address, which could give hints on how to get the application. But then, location information has to be encoded into this Internet address with one severe implication: The location information is sent over the Internet and the location based service platform could collect this information. On the other hand, the distributed tags could contain only location information. But then, a user, which does not yet have the application, will have difficulties to locate and install the needed software.

With the framework of dual codes, however, one can integrate both approaches and let the stronger barcode point to an Internet address, where the user can download the application and let the weak barcode provide location information. In this way, a user, which does not yet have the application, can use any barcode reading software to locate and install the location based service application, while a user, which already has got the software, will directly get the location based service as provided by the mobile application.

For buildings, where mobile Internet access via a cellular network is problematic, the stronger code could also contain information for authenticating with a wireless local area network, which could provide information and Internet access to the user, while the second layer again contains location information which is not automatically transmitted, as common barcode readers only read the stronger part.

To summarize, with dual matrix codes it is possible to decouple location information from service and application discovery information and hence to realize privacy-friendly location based services with matrix codes.

As a side effect, depending on the information encoded in each barcode, the size of the the matrix code will be smaller than if both types of informations would have to be encoded in one layer.

5.2 Digitally Signed Matrix Codes

Scanning matrix codes, in general, raises some security risks. The reader software could be vulnerable to various attacks, which could lead to system intrusion. Furthermore, the content of the Internet address specified inside the matrix code could exploit flaws in the mobile device browser or simply trick the user to download malware [19–21]. Another risk is that users could be provided with wrong contact information inside modified barcodes enabling man-in-the-middle attacks.

For a company, the dual coding technique allows for a transparent, flexible matrix barcode authentication scheme, where smartphones are equipped with a special matrix code reader, which only allows the user to follow a QR Code, if the second layer in the dual coding scheme is a qualified digital signature over the first layer using a predefined certificate chain. These restrictions can flexibly depend on the actual content of the matrix code, such that risky operations like modifying contact information or adding WiFi credentials are impossible without a correctly signed dual matrix code, while the display of the content of the matrix code might always be allowed.

In this way, smartphones and paper documents can be easily integrated in a working environment without the risk of drive-by infection by unauthorized matrix codes.

6 Conclusion

In this paper, we have proposed a general technique, which enables the encoding of multiple information layers for most matrix codes. With this general approach, backward compatibility is combined with advanced service capabilities, such as a higher spatial information density and advanced applications using for example optional signatures. The dual encoding scheme was evaluated against the most important image distortions for smartphone cameras and a prototypical smartphone implementation based on ZXing barcode scanning library [12] was implemented. The presented dual encoding technique showed good results in simulation and practical experiments.

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