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Aesthetic QR Code Based on Modified Systematic Encoding Function

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SUMMARY Quick Response (QR) code is a two dimensional barcode widely used in many applications. A standard QR code consists of black and white square modules, and it appears randomized patterns. By modifying the modules using certain rule, it is possible to display a logo image on the QR code. Such a QR code is called an aesthetic QR code. In this paper, we change the encoding method of the Reed-Solomon (RS) code to produce an aesthetic QR code without sacrificing its error correcting capability. The proposed method randomly produces candidates of RS blocks and finds the best one during encoding. Considering an image to be displayed, we also introduce a weighting function during random selection that classifies the visually important regions in the image. We further investigate the shape of modules which represents the image and consider the trade-off between the visual quality and its readability. As a result, we can produce a beautiful aesthetic QR code, which still can be decoded by standard QR code reader.
key words: *2-dimensional code, aesthetic code, parity check matrix*

1. Introduction

QR code is a two-dimensional code consisting of black and white square modules. It is originally developed by Denso Wave [1] as an effective way for accessing digital data by forming a machine-readable format. It can carry more information than conventional barcodes and can be read very quickly by software installed in smart phones. The QR code was standardized as JIS (Japanese Industrial Standards) standard in 2004 (JIS X0510) [2] and ISO/IEC standard in 2000 (ISO/IEC 18004) [3].

A standard QR code contains only black and white square modules and its appearance has noisy looks. There are many approaches for producing aesthetic QR codes by displaying images on a QR code. For a given message and image, it is desirable to automatically generate such a QR code because manually designed barcodes are too expensive. It is also required that the aesthetic QR codes be readable by standardized decoders. The conventional approaches satisfying these requirements can be categorized into three classes.

The first class globally transforms an input image, and superimposes it on part of the QR code [4]–[6]. It modifies several modules of an original QR code within a possible error correcting capability to display a small logo image. The drawback is that it sacrifices the readability of original QR codes with small displayable size. The second class modifies the size and color of modules according to the pixel of image. Visualead [7] and LogoQ [8] keep a concentric region of modules untouched and uniformly blend the neighboring regions with pixels of an image preserving the original contrast. The third class changes the padding codewords to display an image on the QR code [9], [10]. The possible area on which the image is displayed is restricted due to the standardized structure of QR code. A free software of the QR-JAM MAKER [11] is openly available. Its main restriction is the standardized structure of Reed-Solomon (RS) code [12] employed in QR code.

Some other works studied combination of above classes and image processing techniques to effectively enhance the visual quality. Chu et al. [13] applied the halftoning technique for displaying image to produce an aesthetic QR code. Fang et al. [14] considered the sampling process and error correction to optimize the generation procedure. Zhang et al. [15] proposed two-stage approach that is a combination of module-based and pixel-based encodings. Even though these methods can enhance the visual appearance, they try to reduce the noise-like appearance at the center of image by using error correcting capability or shape of modules. The basic white/black patterns at the important region of an image are not removed in a literature.

In this paper, we develop a fourth class for generating an aesthetic QR code based on the encoding method of RS code which allows us to select the display position without sacrificing the error correcting capability. The preliminary version of such an encoding method was presented in [16]*. As the RS code belongs to a family of linear code over a finite field [12], the set of RS blocks generated by using a certain parity check matrix becomes just equal to the set of the RS blocks generated from the matrix which is calculated by column operation of the parity check matrix. Even though the correspondence between the information and RS block is different, the set of RS blocks are equal. Based on this property, the positions of information symbols in a RS block are changed in the proposed method. Since the standard QR code reader only extract first successive symbols in RS blocks, the proposed method fixes first such positions for representing data and controls the positions of the other

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*At the early stage of this study, we regarded the method as non-systematic encoding, but as explained in Sect. 2.2 it is a kind of systematic encoding by definition of error correcting code.

information symbols. As the results, the produced aesthetic QR code can be read by a standard QR code reader.

We propose two encoding methods in this paper; one is a random selection from candidates, and the other is the selection based on weights for candidates. We called them "random method" and "weighting method" in this paper. The random method randomly selects the positions of information symbols to generate RS blocks. Then, it determines the best RS block among candidates under the constraint that the Hamming distance with the original pixel values of an image becomes minimum. Based on the method, the visual appearance is improved in the weighting method, whose preliminary version was presented at IWDW2015 [17]. The weighting method is based on the following two tendencies for generic images. 1) The outer end of an image is less important than the center region. 2) The noisy region of an image is less sensitive to the modification of pixels. Based on these tendencies, we propose a weighting function to determine the positions of information symbols in the encoding method.

We also investigate the module which represents the image to be displayed. As the number of modules in a QR code is relatively small, the resolution of an image should be scaled down in order to adjust the QR code. We propose sub-modules that express each module with a matrix description to increase the resolution. Using some examples of such sub-modules, we measure the trade-off between the readability and visual quality of generated QR code.

This paper is organized as follows. In Sect. 2, the structure of QR code and the employed error correcting code are briefly reviewed. The proposed method to produce an aesthetic QR code is described in Sect. 3. In Sect. 4, the visual appearance is further enhanced by changing the module shape. In Sect. 5, we conclude this paper with some remarks.

2. Preliminaries

2.1 Overview of QR Code

The module represented by black or white pattern is the minimum component of a QR code and each module is assigned a single bit value. The size of QR code is determined by a version number from 1 to 40. The number of modules representing an encoded data in a QR code of version v is $(17 + 4v) \times (17 + 4v)$.

The QR code has function patterns which allows reader to identify the position in which an encoded data is involved. The patterns are composed of three main parts; finder pattern, alignment pattern, and timing pattern. Figure 1 shows the function patterns of QR code with version 8. The finder patterns are the three square blocks in the corners of the QR code at the top left, top right, and bottom left. They are placed irrespective of QR code version. Beside the finder patterns, white modules are placed to separate other modules. The alignment patterns are small square blocks, and their positions are defined in a table related to the horizontal and vertical coordinates of finder patterns. The timing patterns are two lines, one horizontal and one vertical, of alternating black and white modules. A dark module which is a single black module is always placed beside the bottom left finder pattern.

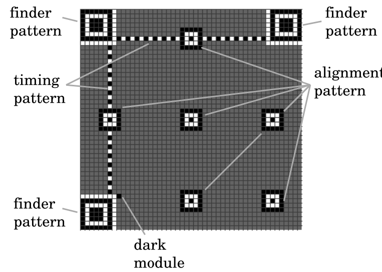


Fig. 1 Function patterns of QR code with version 8.

The data bits are placed starting at the bottom-right of the matrix and proceeding upward in a column with 2 modules wide. When the column reaches the top, the next 2-module column starts to the left of the previous column and continues downward. Whenever the current column reaches the edge of the matrix, it moves on to the next 2-module column and change direction. At the position of function patterns, the data bit is placed in the next module.

The QR code uses the RS code for error correction whose capability is classified into four levels: L, M, Q, and H in the increasing order. Each error correction level can correct symbols up to about 7%, 15%, 25% and 30% of all symbols in the QR code. Due to the characteristic of the RS code, each symbol in RS block has 8 bits, and it is arranged in neighbors of 8 modules in a QR code. Considering dirt on a QR code, the symbols of the RS block are arranged in an interleaved fashion.

Given the version number and the error correction level, the number of RS blocks and their constructions expressed by $RS(n, k, d)$ are uniquely determined in a QR code, where n, k, and d are the code length, the number of information symbols, and the minimum distance satisfying $d = n - k + 1$. For instance, 5L is composed of a single RS block of $RS(134, 108, 13)$, and 5M is composed of two RS blocks of $RS(67, 43, 12)$. The code length n is increased with the version number, while k is decreased with the error correction level.

Since each symbol of the RS block is composed of 8 bits, at most $8k$ bits (k bytes) are represented by a single RS block. If the amount of information to be encoded is less than the capacity, padding codewords are attached with the information symbols. The padding codewords have no information, so they can be changed freely. The remaining $n - k$ symbols are called parity symbols in a RS code, and its redundancy contributes on an error correcting capability. In the systematic encoding, the parity symbols are derived uniquely from the information symbols.

Considering the readability by optical camera devices, the number of black and white modules should be balanced in the QR code. There are eight mask patterns that change the bits according to their coordinates in order to make the QR code easily readable. During encoding, each element of a selected mask pattern is XORed with a current module.

2.2 Encoding of Reed-Solomon Code

In a standard QR code, the systematic encoding method of RS code is employed to generate the RS block. The systematic encoding means that the information symbols appear directly as part of the RS block. For the convenience, during decoding, the information appeares only at the first k symbols of the RS block in the QR code.

The RS code is based on the polynomial $g(x) = x^8 + x^4 + x^3 + x^2 + 1$ over finite field $GF(2^8)$, and the code is punctured through the consistent deletion of parity coordinates from each RS block. As the RS code is maximum distance separable (MDS) code, the elimination of a coordinate in a code can reduce the minimum distance of the code by 1 with each successive puncturing operation. In the QR code, the eliminated coordinate of parity check matrix is the first $255 - n$ rows out of 255. When the minimum distance is d and the root of the polynomial $g(x)$ is α, the punctured parity check matrix H is given by

$$H = \begin{bmatrix} \alpha^{0\times(n-1)} & \dots & \alpha^{0\times 0} \\ \vdots & \ddots & \vdots \\ \alpha^{(d-2)\times(n-1)} & \dots & \alpha^{(d-2)\times 0} \end{bmatrix}, \tag{1}$$

where $\alpha^{255} = 1$. Then, for any RS block $\boldsymbol{c}$, the following equation must be satisfied.

$$\boldsymbol{c}H^T = \boldsymbol{0}. \tag{2}$$

Here, we suppose that a code space contains all RS blocks generated from the matrix H. From the coding theory, two codes that differ only in the arrangement of symbols have the same probability of error, namely the same error correcting property. Specifically, the matrix H can be modified by the combination of column operations without changing the code space. It means that the RS block generated from such a modified parity check matrix is one of the RS blocks generated from the matrix H. In this case, it is possible to use the same decoder for a given RS block, but the decoded information is different. Based on such a property, the systematic encoding method prepares the following matrix $H^{(sys)}$:

$$H^{(sys)} = \left[-P^T I_{n-k} \right], \tag{3}$$

where, P is a $k \times (n-k)$ matrix, I_{n-k} is an $(n-k) \times (n-k)$ identify matrix, and T stands for a transposition. The generator matrix $G^{(sys)}$ can be easily calculated from the matrix $H^{(sys)}$.

$$G^{(sys)} = \left[I_k P \right] \tag{4}$$

By multiplying the matrix $G^{(sys)}$ with a vector of information symbols, the systematic RS block is obtained. For convenience, such an encoding function is denoted by $enc()$.

Let $\boldsymbol{\delta} = (\delta_1, \dots, \delta_k)$ be information symbols of length k, Then, the parity symbols $\boldsymbol{p} = (p_1, \dots, p_{n-k})$ is calculated from $\boldsymbol{\delta}$ using a systematic encoding function $enc()$, and the generated RS block $\boldsymbol{c}$ is represented by

$$\boldsymbol{c} = enc(\boldsymbol{\delta}) = (c_1, \dots, c_k, c_{k+1}, \dots, c_n) \tag{5}$$

$$= (\delta_1, \dots, \delta_k, p_1, \dots, p_{n-k}). \tag{6}$$

The information symbols $\boldsymbol{\delta}$ can be decoded by performing a decoder $dec()$ from a distorted RS block $\boldsymbol{c}^\star$ if the bit errors are within an error correcting capability.

3. Proposed Aesthetic QR Code

In this section, we propose two encoding methods for generating a better RS block in which binary string placed on a QR code is similar to the module patterns of logo image. The best RS block can be found by an exhaustive search among candidates. However, the number of candidates is extremely large, it is computationally difficult. Instead, the proposed method randomly and uniformly selects the candidates and checks the similarity with the module pattern, and it is called as "random method". The other method considers the local characteristics of a logo image by calculating weights in order to control the visual quality, and it is called as "weighting method".

3.1 Basic Idea

As mentioned in Sect. 2.2, the code space generated from H coincides with the code space generated from $H^{(sys)}$. It means that for a given $\boldsymbol{\delta}$, the RS block generated from $H^{(sys)}$ is one of the RS blocks of H. Therefore, the code space is same, but the assignment from information symbols is different if $H^{(sys)}$ is modified from H by using column operations. Even though the parity check matrix is different, the encoding function based on the matrix generates a certain systematic RS block. It implies that the information symbols appear not at the first k symbols of the RS block, but at certain positions of the RS block. Such a systematic encoding function can be designed by carefully selecting the column operations to the parity check matrix.

Let C be the group of all RS blocks generated by $enc()$, namely, $\forall \boldsymbol{c} \in C$. Then, the RS blocks $\boldsymbol{c}'$ encoded by a certain systematic encoding method satisfies $\forall \boldsymbol{c}' \in C$. Thus, we can obtain certain information symbols from $dec(\boldsymbol{c}')$. If no error occurrs, then the first k symbols of the RS block $\boldsymbol{c}'$ is decoded as information symbols. For a given index $\boldsymbol{\theta} = (\theta_1, \theta_2, \dots, \theta_k)$, the k symbols of the RS block $\boldsymbol{c}'$ is represented by

$$c'_{\theta_i} = \delta_i,\ (1 \le i \le k), \tag{7}$$

where $1 \le \theta_i \le n$ and $\theta_i \ne \theta_j$ for $i \ne j$. The other $n-k$ symbols are calculated according to these k symbols using the employed systematic encoding function $enc_{\boldsymbol{\theta}}()$.

Suppose that the first $\hat{k}$ ($< k$) symbols are used to represent a data to be encoded and the remain $k - \hat{k}$ symbols are regarded as padding codewords. In such a case, it is possible to use the following index.

$$\boldsymbol{\theta}_{\hat{k}} = (1, 2, \ldots, \hat{k}, \theta_{\hat{k}+1}, \ldots, \theta_k) \tag{8}$$

It means that there are $C(n-\hat{k}, k-\hat{k})$ candidates for the index $\boldsymbol{\theta}_{\hat{k}}$, where $C(a, b)$ stands for the number of b-combinations from a given set of a elements. In short, we can freely select the positions for padding codewords within the range $[\hat{k}+1, n]$ at the RS block.

3.2 Random Method

When the amount of encoding data is small, the designable area becomes large in the method. If a QR code has m RS blocks whose information symbols are k_t, $(1 \leq t \leq m)$ bytes and the data to be encoded is σ bytes, then the size of designable area is $(\sum_{t=1}^{m} k_t) - \sigma$ bytes.

Without loss of generality, the data to be encoded is composed of σ bytes and it is partitioned into m segment of length $\hat{k}_t$, $(1 \leq t \leq m)$, namely $\sum_{t=1}^{m} \hat{k}_t = \sigma$. For each segment, the RS block $\boldsymbol{c}'_t$ is calculated by the systematic encoding function $enc_{\theta_{\hat{k}_t}}$.

First, each pixel of an image is regarded as a module of ideal aesthetic QR code except for the function patterns. The pixel values are classified into black/white module at the encoding, and the binarized pixels are produced. The binarized pixels may not coincide with the binary represention of RS blocks. Allowing some errors, we generate several RS blocks by changing $\boldsymbol{\theta}_{\hat{k}_t}$ and choose the best one whose Hamming distance is minimum. The procedure to make aesthetic QR codes is described as follows.

Step 1 Assign pixels of an image to modules of a QR code, and binarize the modules with the threshold determined by the average of all RGB values.
Step 2 Operate a predetermined masking pattern to the binary matrix, and replace σ symbols of the masked image with information symbols, which are never changed in the following steps.
Step 3 Partition the masked image into m sequences which are corresponding to the RS blocks placed on the QR code in an interleaved order. We denote the m sequences by $\boldsymbol{\eta}_t$, $(1 \leq t \leq m)$.
Step 4 For $1 \leq t \leq m$, find the best RS block $\dot{\boldsymbol{c}}'_t$, whose Hamming distance from $\boldsymbol{\eta}_t$ becomes minimum, by changing the index $\boldsymbol{\theta}_{\hat{k}_t}$.
Step 5 Replace the best RS block $\dot{\boldsymbol{c}}'_t$ with $\boldsymbol{\eta}_t$ for $1 \leq t \leq m$.
Step 6 Operate the predetermined masking pattern again to cancel the masking operation at step2.

There are $C(n-\hat{k}_t, k_t-\hat{k}_t)$ candidates for the index $\boldsymbol{\theta}_{\hat{k}_t}$ for $(1 \leq t \leq m)$. It is computationally difficult to check all candidates for the search in Step 4. In the above procedure, the index $\boldsymbol{\theta}_{\hat{k}_t}$ are randomly and uniformly selected from all possible candidates, and the trial is bounded to N times. Among N candidates of QR codes, we select the best one which has the minimum number of modules different from the pixel values of logo image to be displayed.

3.3 Color Translation

According to the standardized format of QR code, each module is basically represented by black and white. Nevertheless, it is possible to use color for modules because of the following reason. When a QR code is taken by a certain camera device, the brightness of each module is first calculated in the decoding algorithm, and then, the color space is translated into luminance component. As the translation algorithm is not defined in the specification of QR code decoder, there may be some methods to determine the black and white. In the proposed method, we heuristically examine the decodability of color space by using some smart phones and develop the following color translation procedure at the production of aesthetic QR code.

Suppose that an image is square size with $L \times L$ pixels and each pixel is represented by RGB color components. Using a certain conversion algorithm equipped at a QR code reader, a binary matrix $B_{i,j}$, $(1 \leq i, j \leq 17 + 4v)$ is calculated from the input image for the given version v of QR code. In our method, the following algorithm is used as the conversion.

Step 1 The scale of the input image is changed to be the same size of the given version v of QR code.
Step 2 The RGB color components are translated into YUV color components, and the luminance (Y) components $Y_{i,j}$, $(1 \leq i, j \leq 17 + 4v)$ are obtained.
Step 3 The average $\bar{Y}$ of the values at its center square, which size is the quarter of the original image size, is calculated.

$$\bar{Y} = \frac{4}{L^2} \sum_{i=\frac{L}{4}}^{\frac{3L}{4}} \sum_{j=\frac{L}{4}}^{\frac{3L}{4}} Y_{i,j} \tag{9}$$

Step 4 The binary matrix $B_{i,j}$ is determined by the following rule:

$$B_{i,j} = \begin{cases} 1 & \text{if } Y_{i,j} > \bar{Y} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

Although the binarization of the reduced-size image is slightly varied according to the resizing algorithm, the impact on the produced aesthetic QR code is small because of the low resolution. In case of scaling-up, the visual quality is strongly affected by the resizing alrogithm. In practical, however, an input image is usually larger than a QR code.

Notice that the binarized ideal QR code is composed of the binary matrix $B_{i,j}$ except for the function patterns. At the Step 3 in the random method, the sequences $\boldsymbol{\eta}_t$ are extracted from the binary matrix $B_{i,j}$. After the determination of RS blocks $\dot{\boldsymbol{c}}'_t$, each module of QR code is modified according to the original RGB color components in order not to change the color balance. Let $\beta_{i,j}$, $(1 \leq i, j \leq 17 + 4v)$ be the binary represented RS blocks placed on the matrix of QR code. It is noted that $\beta_{i,j}$ must satisfy the black and white function patterns at the corresponding positions. We finally generate a QR code involving a given image as follows.

If $\beta_{i,j} = 1$, then

$$Y'_{i,j} = \begin{cases} Y_{i,j} & \text{if } Y_{i,j} > \bar{Y} + \epsilon \\ \bar{Y}_{i,j} + \epsilon & \text{otherwise} \end{cases}, \tag{11}$$

otherwise,

$$Y'_{i,j} = \begin{cases} Y_{i,j} & \text{if } Y_{i,j} < \bar{Y} - \epsilon \\ \bar{Y}_{i,j} - \epsilon & \text{otherwise} \end{cases}, \tag{12}$$

where ϵ is a threshold for ensuring the readability. The RGB color components are translated from the modified luminance components $\boldsymbol{Y'}$ as well as the original U and V components, and the color QR code is finally obtained.

3.4 Weighting Method

In the random method, the index $\boldsymbol{\theta}_{\hat{k}_t}$ is randomly generated without any strategies. Considering the characteristics of an image to be displayed, we introduce a weighting function to classify perceptually important regions with the others.

It is widely recognized that noisy regions of an image are less sensitive to modification than flat regions. It is also reasonable to assume that the center region of an image is much more important than its surroundings. Based upon the characteristics, we calculate weights for modules.

After the color translation, the Laplacian filter $LF()$ is operated to the matrix $B_{i,j}$, which discrete convolution kernel is given by

$$\begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}.$$

The weight matrix $W_{i,j}$ is calculated by

$$W_{i,j} = |LF(B_{i,j})|, \tag{13}$$

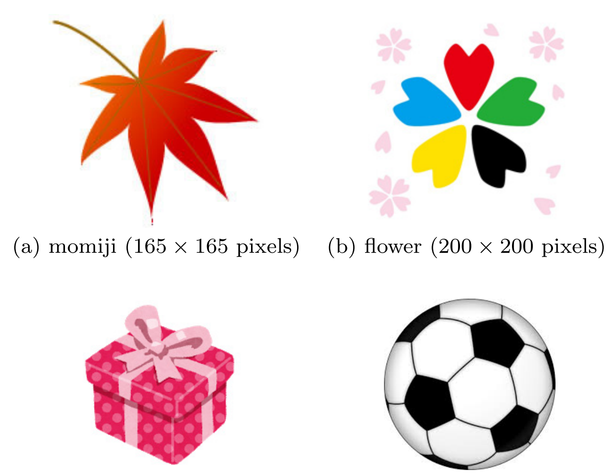
where $|a|$ returns the absolute value of a. It is noticed that $0 \leq W_{i,j} \leq 8$ because $B_{i,j} \in \{0, 1\}$. At the γ-th outer end of the matrix for $0 \leq \gamma \leq 7$, if $W_{i,j} < 8 - \gamma$, then the value is replaced as $W_{i,j} = 8 - \gamma$.

The coordinate of the matrix $W_{i,j}$ is corresponding to that of QR code. As the symbols of t-th RS block $\boldsymbol{\eta}_t$ are placed on the matrix of QR code in an interleaved order, the symbols of the weight sequence $\boldsymbol{w}_t$ is also placed on the matrix $W_{i,j}$. Namely, $\boldsymbol{w}_t$ is selected from the matrix $W_{i,j}$ in the same rule as the placement of RS block in the matrix of QR code. Remember that the symbols of RS block employed in a QR code are not binary, and represented by 8 bits. In addition, 8 modules are placed on a certain neighboring modules which positions depend on the version v. Considering such neighboring positions and their values $\boldsymbol{w}_t$, the index $\boldsymbol{\theta}_{\hat{k}_t}$ is determined to mainly select flat regions at the center of QR code for the assignment of as many as possible information symbols. It is worth-mentioning that the modules at noisy regions and the outer end of the QR code tend to be the parity symbols of RS block, and their values may differ from $\boldsymbol{\eta}_t$. By changing the index $\boldsymbol{\theta}_{\hat{k}_t}$ under the constraint of such a rule, the best RS blocks $\boldsymbol{\dot{c}}'_t$ are selected under the measurement of Hamming distance.

Among k_t information symbols in t-th RS block, the first $\hat{k}_t$ symbols are fixed to represent data and the remain $k_t - \hat{k}_t$ symbols are assumed to be padding codewords. The weight sequence indicates the priority for the selection of $k_t - \hat{k}_t$ symbols from $n - k_t$ symbols. If we choose $k_t - \hat{k}_t$ symbols which have highest $k_t - \hat{k}_t$ weights in $\boldsymbol{w}_t$, the corresponding RS block can be calculated. However, in such a case, the Hamming distance is not always small. In order to find the best RS block which has minimum Hamming distance among some candidates, we choose symbols which have highest $k_t - \hat{k}_t + \alpha$ weights, where $\alpha = 1, 2, \cdots$. By increasing α, the number of candidates is exponentially increased. For a given number N, α is adjusted in the proposed method. For example, when the version of QR code is 5L, $k = 108$ and $n = 134$. In case of $\hat{k} = 50$, the number of candidates is $C(59, 58) = C(59, 1) = 59$ if $\alpha = 1$, and it is $C(60, 58) = C(60, 2) = 1770$ if $\alpha = 2$. When $N = 500$, we determine $\alpha = 2$, and generate 500 candidates by randomly choosing $k_t - \hat{k}_t = 58$ symbols among 60 symbols which have highest 60 weights. Finally we determine the best RS block among 500 candidates.

3.5 Numerical Evaluation

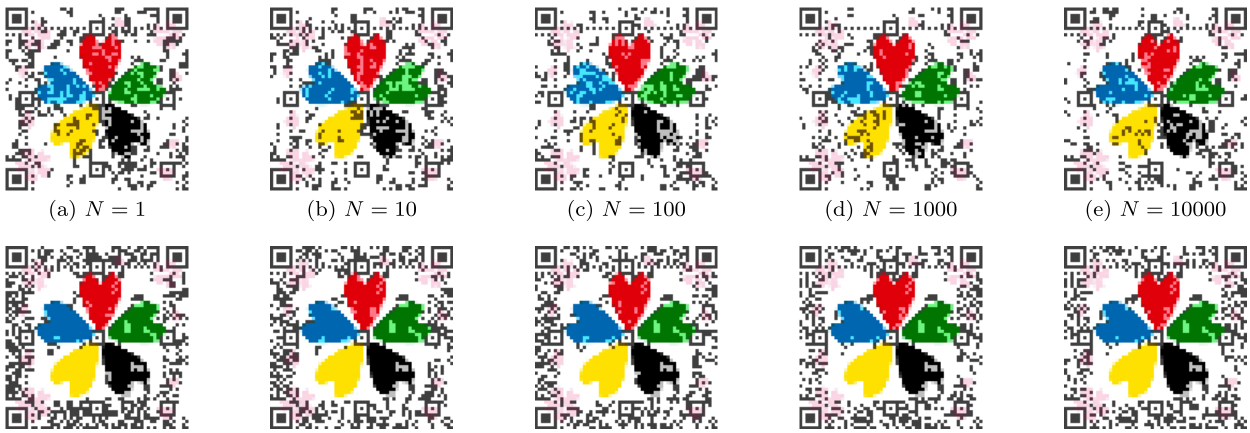
In order to evaluate the performance, we implement two proposed methods and an original method for generating RS block using a same color translation algorithm. Here, the original method changes the padding codewords to display an image on the QR code such as QR-JAM and [9], [10]. For convenience, the method explained in Sect. 3.2 is called "Prop.I" and the method in Sect. 3.4 is called "Prop.II". We use four RGB color images of different size, which are shown in Fig. 2. We use the OpenCV library [18] for resizing an input image. The encoding data is the URL: `http://www.okayama-u.ac.jp`, which is represented by



(a) momiji (165 × 165 pixels) (b) flower (200 × 200 pixels)

(c) present (180 × 180 pixels) (d) soccer (225 × 225 pixels)

Fig. 2 Original images for displaying on a QR code.



(a) $N = 1$ (b) $N = 10$ (c) $N = 100$ (d) $N = 1000$ (e) $N = 10000$

(f) $N = 1$ (g) $N = 10$ (h) $N = 100$ (i) $N = 1000$ (j) $N = 10000$

Fig. 3 Comparison of the visual appearance of aesthetic QR codes when the version is 10M, where (a)–(e) are produced by the Prop.I method and (f)–(j) are by the Prop.II method.

Table 1 Number of different modules when version is 10L.

image	method	1	10	100	1000	10000
momiji	original	280	—	—	—	—
	Prop.I	276	248	230	210	196
	Prop.II	260	232	222	218	212
flower	original	293	—	—	—	—
	Prop.I	295	243	227	215	199
	Prop.II	293	269	231	219	207
present	original	287	—	—	—	—
	Prop.I	298	254	236	206	200
	Prop.II	287	251	241	223	223
soccer	original	297	—	—	—	—
	Prop.I	296	240	230	214	200
	Prop.II	298	255	245	243	243

Table 2 Number of different modules when version is 10M.

image	method	1	10	100	1000	10000
momiji	original	523	—	—	—	—
	Prop.I	538	450	438	402	378
	Prop.II	529	473	431	425	417
flower	original	515	—	—	—	—
	Prop.I	520	476	430	400	378
	Prop.II	541	469	443	423	421
present	original	515	—	—	—	—
	Prop.I	505	457	431	403	383
	Prop.II	501	475	449	447	445
soccer	original	509	—	—	—	—
	Prop.I	518	470	426	404	386
	Prop.II	523	478	433	427	427

26 bytes. The QR code of version 10 composed of 57×57 modules, and the maximum number of information symbols for level L and M is 274 and 216 bytes, respectively. The threshold for the conversion algorithm is fixed by $\epsilon = 64$.

When an encoding method outputs an aesthetic QR code, the Hamming distance between the QR code and the ideal one is measured. Since the arrangement of symbols is fixed in the original method, the output is uniquely determined, namely, the method is deterministic. On the other hand, the proposed methods can change the arrangement by selecting the index $\boldsymbol{\theta}_{\hat{k}_t}$. Thus, we produce N candidates and select the best one with minimum Hamming distance. Tables 1 and 2 show the number of different modules when the version of QR code is 10. It is observed that the Hamming distance of Prop.II converges much faster than that of Prop.I. It is because the Prop.I selects $\boldsymbol{\theta}_{\hat{k}_t}$ at random while the Prop.II considers the characteristics of an image to be displayed for the selection. Therefore, the number of candidates for the Prop.II is smaller than that of the Prop.I. In the measurements of Hamming distance, the Prop.I seems better under a same number N of candidate RS blocks. It is worth-mentioning that it is possible to make the proposed methods deterministic by setting $N = 1$.

Figure 3 shows the visual appearance of generated QR codes when the version is 10M. The perceptual quality is slightly improved with the increase of N in the Prop.I method, while there is no clear changes in the Prop.II method. As the Prop.II method keeps perceptually important regions unchanged introducing a weight matrix $W_{i,j}$, the modules which are different from the original color appears mainly at the outer edge and noisy regions. Even though the Prop.I method is better than the Prop.II in terms of the measurement of Hamming distance, the visual appearance of the Prop.II is better as observed from these figures.

Figure 4 shows the generated QR codes of version 10 with error correction level L and M. As the encoding data is 26 bytes, the number of padding codewords is 248 and 190 bytes, respectively for level L and M. As a comparison, we show in Fig. 4 that the aesthetic QR codes generated by the original method as well as the proposed methods. In this case, it is possible to display an image at the center of QR code for the original method. However, the left side of the QR code appears as random patterns because they are determined by the RS encoding function. It is observed from the figure that the improvement of the visual quality becomes much remarkable for Prop.II method when the error correcting level is increased.

The amount of data to be encoded can be varied at most to the actual capacity of a given version of QR code. If $\hat{k} = k$, then there is only one candidate in the proposed method because $C(n-k, 0) = 1$. In such a case, what we can

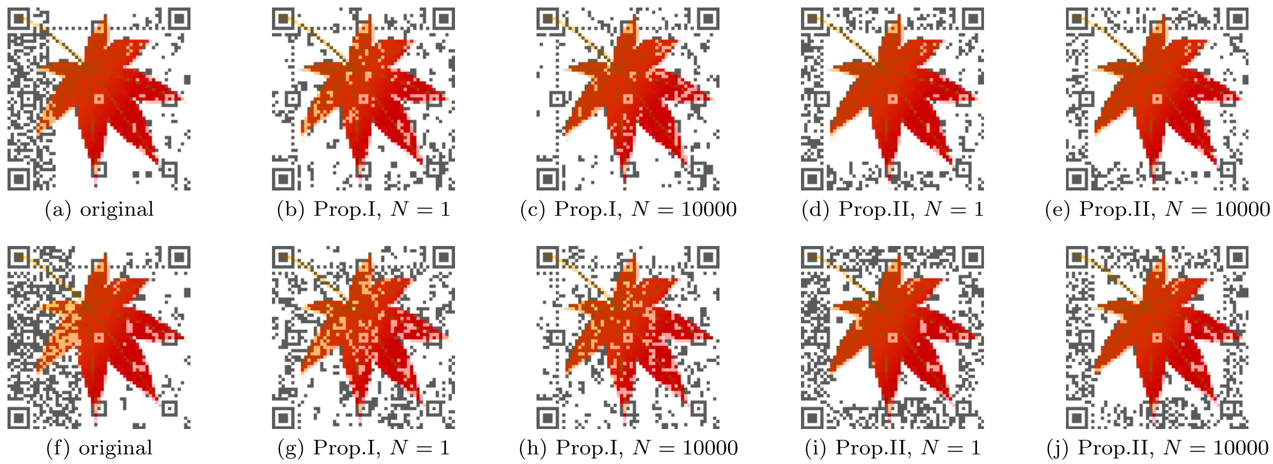


Fig. 4 Comparison of the visual appearance of aesthetic QR codes, where (a)–(e) are version 10L and (f)–(j) are version 10M.

do is the modification of module shape as well as the color according to a logo image, such a method is equivalent to the conventional methods like Visualead [7], [8].

4. Enrichment of Visual Quality

Although the visual quality is improved by the introduction of weight matrix at the encoding of RS block, the low resolution of the displayed image still reduces its benefit. The reason is due to use of one pixel for representing one module. The resolution of the displayed logo image is $(17 + 4v) \times (17 + 4v)$ pixels (e.g. only 37×37 pixels for version 5). The square shape of modules also degrades the visual appearance.

One simple method to increase the resolution is to use higher version of QR code. However, higher the version of QR code becomes, the more difficult it is to read by an optical device as the module size becomes small under a constant size of QR code. In addition, most modules become padding codewords wasting a space.

Our idea is to assign 3×3 sub-modules for each module except for the finder pattern modules placed at corners of QR code. The QR code reader estimates the module size from the finder pattern, the module shape is not modified. It is possible to only change the center of 3×3 sub-modules if necessary to generate the aesthetic QR code because most of QR code readers check the center region of module to determine black/white. However, depending on the performance of optical device, the readability must be degraded. On the other hand, if the luminance values of 3×3 sub-modules are uniformly represented by the luminance value of the module $Y_{i,j}$ and are modified by using Eqs. (11) and (12), the visual quality is still low. Considering the characteristics of popular QR code readers, we examine some types of sub-module representation method.

Suppose that the luminance values of sub-modules are respectively derived from a given logo image, and the Eqs. (11) and (12) are applied respectively for each sub-module to generate an aesthetic QR code. In such a case, the resolution of the obtained QR code is improved. For convenience, such an operation is denoted by M_1. For ensuring the readability, however, ϵ is uniformly added to these sub-modules. In case of $\beta_{i,j} = B_{i,j}$, the original luminance value $Y_{i,j}$ basically judges correct value by itself. Therefore, the value of ϵ can be decreased without seriously degrading the readabiliy. As the center sub-module is important for most readers to determine black/white, ϵ is introduced only for such a sub-module in the operation M_2. These operations M_1 and M_2 can be represented by the following matrices.

$$M_1 = \left\{ \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \right\}$$

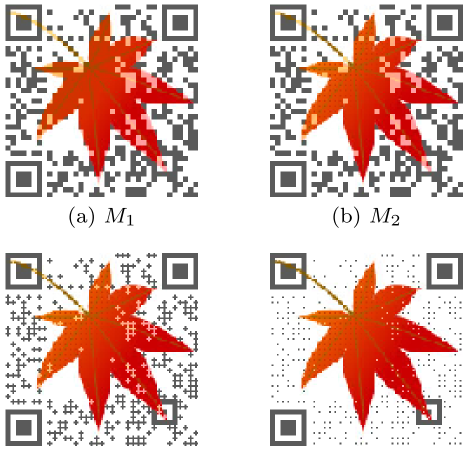
$$M_2 = \left\{ \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \right\}$$

The left matrix is used for the modules satisfying $B_{i,j} = \beta_{i,j}$, where "1" stands for the sub-module that is modified according to Eq. (11) and Eq. (12), and "0" is the sub-module that uses the original luminance value $Y_{i,j}$. The right matrix is the modules that become $B_{i,j} \neq \beta_{i,j}$.

In case of $\beta_{i,j} \neq B_{i,j}$, it is also possible change the strategy for performing Eq. (11) and Eq. (12) to sub-modules. As mentioned above, the center sub-module is the most important one among 9 sub-modules. Considering the symmetric structure, the following methods M_3 and M_4 can be good candidates.

$$M_3 = \left\{ \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 0 \end{bmatrix} \right\}$$

$$M_4 = \left\{ \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \right\}$$



(a) M_1 (b) M_2 (c) M_3 (d) M_4

Fig. 5 Hi-resolution of QR code of version 5 with error correction level M.

5. Experiments

For the Prop.II method, we change the module shapes as specified by the matrices M_1 to M_4. The version of QR code is $v = 5$, and the same encoding data in Sect. 3.5 is encoded. The threshold is $\epsilon = 64$ and the number of candidates is $N = 500$.

5.1 Visual Appearance

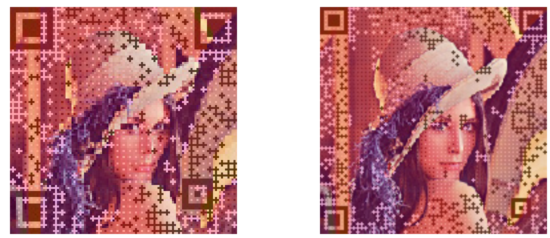
Figure 5 shows the generated QR code using four module types, where the version of QR code is 5 and error correction level is M. It is remarkable that only one center sub-module is modified for module types M_2, M_3, and M_4 if $B_{i,j} = \beta_{i,j}$. The modules satisfying $B_{i,j} = \beta_{i,j}$ are mainly flat regions, which are selected as information symbols of RS blocks in order not to be modified by the Prop.II method. Thus, these module types manage to preserve the original pixel values at flat regions as many as possible. As the result, the visual appearance of the displayed image becomes very close to the original image.

In the experiment, it is extremely difficult to read the data for the M_4 method. The readability of type M_3 is not seriously decreased from that of M_1 though its visual quality is much better as observed from Fig. 5 (c). Figure 6 show the results of other images. In some cases, a QR code reader takes more time to read the data with error correction level at L. The main reason is the noise at the optical device. When higher error correction level is employed, the readability can be improved, but it also increases the number of different modules in a QR code.

It is also possible to display a portrait image on QR codes. For instance, the "lena" image of 512×512 pixels with 24-bit color image is used in Fig. 7. As the resolution of the original image is higher than the QR code, some blocking effects appeares in case of version 5. With the increase of the version, the visual appearance can be improved.

(a) (b) (c)

Fig. 6 Examples of generated QR code using module type M_3, where the version is 5 and the error correction level is M.



(a) 5M (b) 10M

Fig. 7 Examples of generated QR code using module type M_3, where the version is 5 and the error correction level is M.

The purpose of the sub-module in [13] is basically different from the proposed method. In [13], an input image is represented by black/white sub-modules while our method use multi-level values for sub-modules to keep the original color and the quality of image. The readability is assured by keeping the center sub-module unchanged from the input image in [13]. It makes it possible to select types of 3×3 sub-modules to represent a certain gray-scaled pixel value. On the other hand, our method assures the readability by controlling the color of four neighboring sub-modules in type M_3. Due to the multi-level values for sub-modules, the visual quality of the proposed method is better than [13]. In addition, the proposed method can keep the RGB color values while [13] uses only black/white values.

5.2 Readability

These QR codes are printed out to EPSON's super fine paper using the EPSON ink jet printer PM-A900 without tuning the printing quality. The printed QR codes are 3.4×3.4[cm] and the threshold is $\epsilon = 64$. Under a fluorescent lighted environment, each QR code is read using free Apple Store app and Google play applications such as [19] and [20]. We use 9 images and try to read the printed QR codes within 5 seconds. The success probabilities for some smart phones are enumerated in Table 3.

Generally, the optical device is sensitive to external noise including LCD display's performance, scaling factor, brightness, printing quality and so on. The readability can be improved by increasing the threshold ϵ and the module shape, the scale of displayed/printed size. Such parameters should be adjusted considering the applications of aesthetic QR code if each module is not represented by black/white square. In our experiments, when $\epsilon \leq 32$, the aesthetic QR

Table 3 Test of readability from printed QR codes.

device (software)	success probability [%]	
	L	M
iphone 6 [19]	100	100
iphone 6 [20]	93.7	99.6
iphone 5s	73.9	85.6
Xperia Z3	98.3	98.3
GALAXY S5	100	100

code cannot be read by iphone 6 [19], but it depends on the optical device and the environmental condition. In practical, ϵ should be in the range, $64 \leq \epsilon \leq 128$.

6. Concluding Remarks

In this paper, we investigate the aesthetic QR code by displaying a color image. It is possible to change the positions of information symbols in RS block while keeping the decodability of standard RS decoder. If the first information symbols are fixed as the data to be encoded in a QR code, the other symbols can be freely selected as the rest of information symbols of RS block. Based on such a characteristic of RS code, we propose a modified systematic encoding method to produce aesthetic QR code. Among several candidates of such QR code, the proposed method selects the best one. Even though the visual quality can be improved with the increase of the candidates, the random selection of candidates are not suitable.

Based on the following two characteristics on logo images, we proposed a weighting function to control the symbols of RS block at the flat and center regions of an image. It based on the fact that the outer end of an image is less important than its center region, and the changes at noisy region are less sensitive than the flat region. For the improvement of the image resolution, we also proposed some module types and investigated the readability as well as the visual quality.

In order to increase the resolution of displayed image on a QR code, the module should be represented by more than 1 pixel. In the proposed method, each module is represented by 3×3 pixels, but it can be increased. If the number of sub-modules increases, the visual quality can be improved. The appearance can be further improved by considering the characteristic of image by adaptively selecting the threshold ϵ for each sub-module.

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