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Progressive transmission of color-mapped images

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Abstract. *Coded as conventional color-map addresses, a color-mapped image can be decoded only when a full color map address is available. We present the first known scheme that adds progression capability in spatial resolution as well as color resolution, enabling more flexible progression of color-mapped images. During coding, approximate pixel colors are keyed with truncated versions of the original color-map addresses. Subsequently, the coded image is transmitted by interleaving the per pixel address bit order for color resolution refinement, and a spatial pixel order for spatial resolution refinement. The interleaving is subject to user control through spatial-color progression rate control (SCPRC), a novel means for biasing the progression to accelerate either spatial resolution or color resolution for more informative early views of the image being transmitted.* © 2005 SPIE and IS&T.

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1 Introduction

Color quantization is a straightforward but effective approach for compressing a color image. For instance, coding a 24-bit color image using an 8-bit color map gives an immediate coding gain of 3. Further, the resulting color-mapped image can be easily decoded with simple table look-up operations. Unlike other spatial and transform image coding methods, which are often compute-intensive, decoding a color-mapped image involves no arithmetic computation at all.

In applications where bandwidth is critical, such as those in a wireless environment, sizable images are often transmitted progressively to enable early visual inspection. This is especially important when searching through many images so that images deemed not desirable after initial inspection can be aborted for transmission to make way for others. However, while progressive transmissions for spatial and transform images are very well studied,[1–5] a good scheme for color-mapped images is lacking. Interlaced display, as enabled in graphics interchange format[6] (GIF) in its GIF89a standard,[7] is perhaps the only commonly known one. In this paper, we report our design of a progressive transmission scheme for color-mapped images. Our goal is twofold. First, we preserve the important advantage of simple decoding, which is desirable especially for lean receivers such as personal digital assistants (PDAs) and mobile phones. Second, we strive for flexibility in the relative progression rates of spatial and color resolutions. Such flexibility should enable users to make effective use of bandwidth for early viewing. For instance, one may want better spatial resolution to begin with when viewing a road map, but better color resolution in the case of a scenic photo.

There are two major issues, namely, color quantization and bit transmission sequencing.

When progression is flexible in the way we perceive, the receiving end must render an approximate image from partial information in spatial resolution as well as color resolution. For a color-mapped image, color information of a pixel is keyed by a color-map address. Keying also an approximate color to a partial truncated address is therefore essential. In our scheme, intermediate color values (ICVs), which approximate the same final color value (FCV) of a full address, are keyed to its truncated versions. The color map, which consists of FCVs only, is augmented for the ICVs, and the unstructured linear colormap becomes a color-map binary tree (CBT), which carries ICVs in its nonleaf nodes and FCVs in its leaf nodes.

There are two ways to obtain a CBT. First, if the color map has already been given, its entries can be progressively merged in a bottom-up manner until two remain (which carry two colors to render an approximate image of 1-bit color resolution). Riskin *et al.*[8] uses this approach to reorder a vector quantization codebook into a binary tree to enable progressive transmission of vector quantization (VQ)-coded images. Second, the CBT can be constructed top-down by conducting color quantization in stages. This involves splitting and grouping pixel samples in the color space recursively. While the bottom-up approach is straightforward and does not interfere with the color quantization like the top-down approach, the visual quality would suffer much as merging the color map alone pays no attention to the original image's color value distribution. The superior top-down approach mandates adaptation of the color quantization process, for which we find the sequential scalar quantization (SSQ) of Balasubramanian *et al.*[9] suitable. Details of this approach are given in Sec. 2.

The other major issue is bit transmission sequencing. The coded image comprises the CBT (which is twice the size of the conventional color map but still tiny compared with the image data) and a set of spatially indexed CBT address values. Naturally, a CBT address value is transmitted 1 bit after another, beginning with its most significant bit. Such per bit transmissions of all CBT address values should be interleaved, as well as sequenced according to

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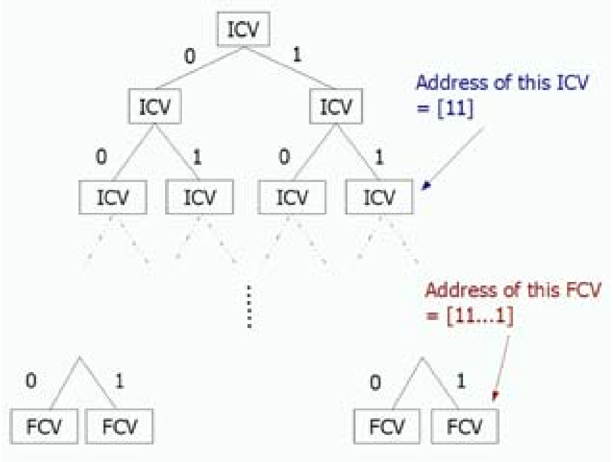

Fig. 1 CBT.

their spatial locations. There is also a natural way to sequence the spatial locations, whose goal is a smooth progression in spatial resolution. (It would be the sequence with which the bits of a 1-bit color-mapped image are transmitted for smooth progression.)

Therefore, bit transmission sequencing is a serialization of the image's CBT address values such that both natural orders are obeyed, and the way they interleave determines the relative progression rates of spatial and color resolutions. We describe our flexible spatial-color progression rate control (SCPRC) scheme in Sec. 3, which incorporates a sequencing scheme by Lloyd-Williams.[10]

We evaluate our scheme by comparing it with set partitioning in hierarchical tree[5] (SPIHT), a state-of-the-art transform coding method for progressive transmission. Results are presented in Secs. 4 and 5, before we conclude the paper in the final section.

2 Color Quantization

In progressive transmission, every newcoming bit should carry additional information useful for improving the displayed view. In our scheme, receiving and appending an extra bit means further resolving a truncated address value into two distinct colors. This hierarchical relationship between the coarser and the finer colors implies a binary tree organization, which we call a CBT. The CBT is constructed in a top-down manner during color quantization, and serves as a decision tree when coding image pixels afterwards.

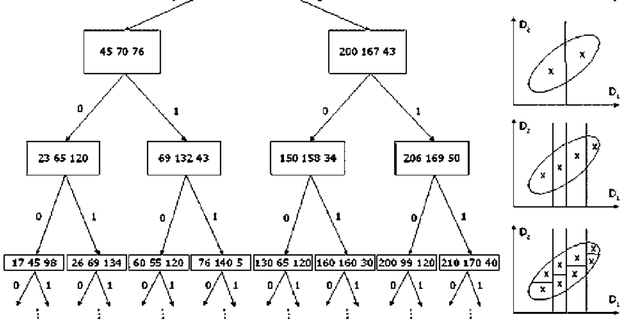

Fig. 2 CBT and the associated color space partitioning diagram (symbol x refers to the mean color in the region).

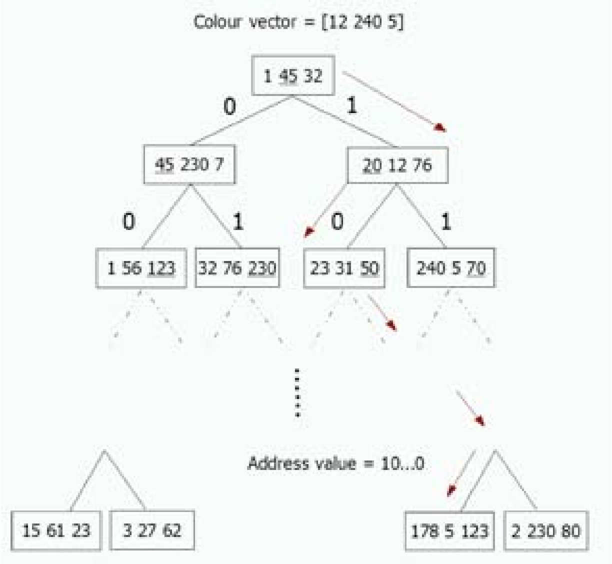

Fig. 3 CBT as a binary decision tree in encoding (the underlined is the ICV component for thresholding; note that entries in the same layer use the same thresholding dimension).

2.1 *Colormap Binary Tree*

Figure 1 shows the structure of a typical balanced CBT. Each level of the CBT comprises ICVs addressed by colormap addresses truncated to the same length. Leaf nodes at the bottom level contain FCVs, which make up a conventional color map. A good CBT is such that the ICV of each

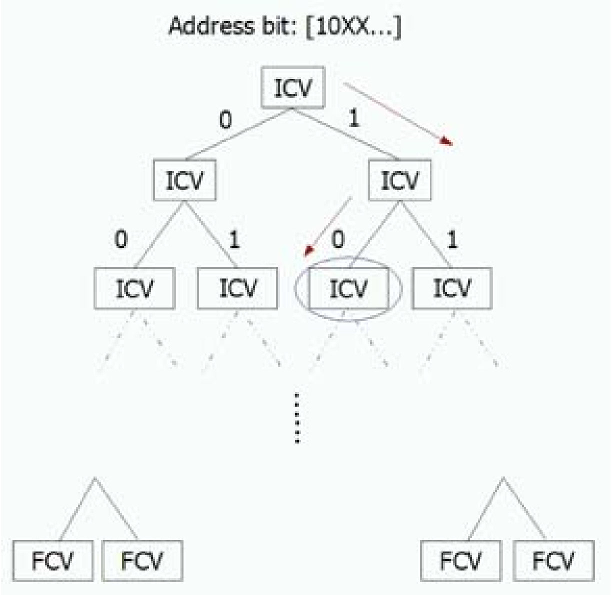

Fig. 4 Decoding with CBT (X refers to bits not yet received).

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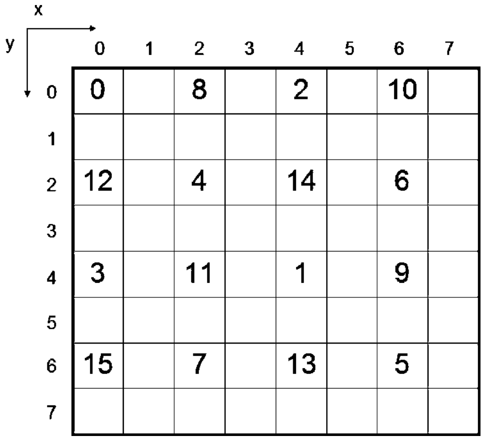


y \ x	0	1	2	3	4	5	6	7
0	0		8		2		10	
1								
2	12		4		14		6	
3								
4	3		11		1		9	
5								
6	15		7		13		5	
7								

Fig. 5 Pixels with the first 16 LWA sequence numbers in an 8×8 image.

nonleaf node well approximates the original image's pixels eventually displayed with the FCVs of the leaf nodes beneath it.

As mentioned, a bottom-up approach that averages color values is not good enough. A top-down approach that takes the original image's pixel value distribution into account is needed.

2.2 *Bitwise SSQ*

The SSQ of Balasubramanian *et al.*[9] is essentially[11] tree-structure VQ in a 3-D color space. When a perceptual color space is being used, the dimensions are perceptually meaningful color components and it suffices to quantize the scalar color components separately. Balasubramanian *et al.* further suggest that the scalar quantization may be done sequentially. It is therefore also a special instance of product quantization.[12] As a result, SSQ is computationally very efficient and they show that image fidelity suffers little as long as the color map is not too small.

As SSQ proceeds and the CBT is constructed from the top down, pixel samples in the color space are recursively split into clusters, whose mean colors become ICVs and FCVs on the corresponding CBT nodes. Figure 2 shows a part of CBT having quantization dimension D_1 in the first step and D_2 in the second step. The associated color space partitioning in each stage is a Voronoi diagram, which is like a 3-D Mondrian pattern in the color space, with the color values being centroids of the Voronoi diagram.

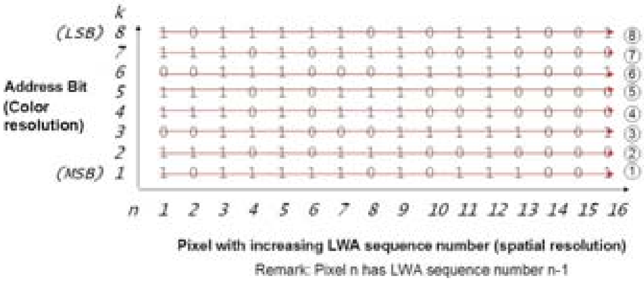


Fig. 7 AS sequence ($K=8, N=16$).

Balasubramanian *et al.* choose to use the YC_bC_r color model, and point out that the order with which the three color components are quantized, as well as the bit allocation among them, requires careful design. Obviously, the more bits a component is given, the better is its quality. Also, the earlier a component is quantized, the more are the pixel samples being clustered so that the color values, especially the ICVs, approximate the original image's pixel values better.

The human visual system is known to be more sensitive to the luminance component than the two chrominance components, which are comparable in sensitivity. Also, when one chrominance component has been refined, the other chrominance component should follow as soon as possible to reduce intermediate chrominance distortion. Based on these two heuristics, two quantization orders for typical 8-bit color maps (with 256 FCVs) are determined, namely, $(Y,Y,Y,C_b,C_r,Y,C_b,C_r)$ and $(Y,Y,Y,C_r,C_b,Y,C_r,C_b)$.

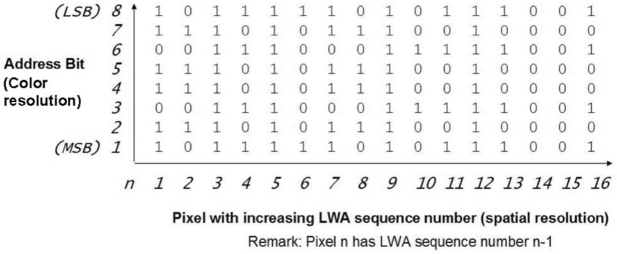
2.3 *Codec*

2.3.1 *Encoding*

An image may have already been encoded after CBT construction by SSQ if all image pixels are sampled for color quantization. Otherwise, pixels may be explicitly quantized and keyed with a color-map address assigned by sequential thresholding using the CBT as a decision tree (Fig. 3). This is equivalent to nearest neighbor assignment in the Voronoi diagram in the color space.

2.3.2 *Decoding*

Decoding for each pixel is done by traversing down the CBT (Fig. 4). As the receiving end receives and appends a new bit to a partial color-map address, the current ICV of



k \ n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
(LSB) 8	1	0	1	1	1	1	1	0	1	0	1	1	1	0	0	1
7	1	1	1	0	1	0	1	1	1	0	0	1	0	0	0	0
6	0	0	1	1	1	0	0	0	1	1	1	1	1	0	0	1
5	1	1	1	0	1	0	1	1	1	0	0	1	0	0	0	0
4	1	1	1	0	1	0	1	1	1	0	0	1	0	0	0	0
3	0	0	1	1	1	0	0	0	1	1	1	1	1	0	0	1
2	1	1	1	0	1	0	1	1	1	0	0	1	0	0	0	0
(MSB) 1	1	0	1	1	1	1	1	0	1	0	1	1	1	0	0	1

Fig. 6 Binary array model of a color-mapped image.

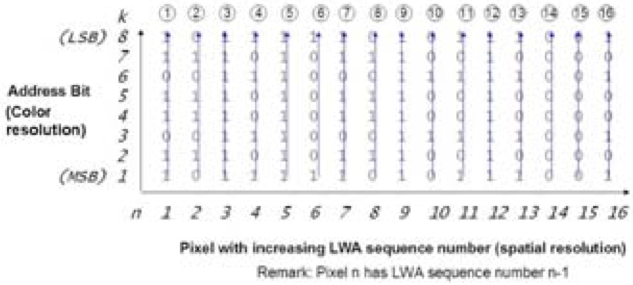


Fig. 8 AC sequence ($K=8, N=16$).

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Fig. 9 Test images in 256×256, 24-bit: (from left to right) “Map,” “Goldhill,” “Watch,” and “Zelda.”

the pixel concerned is updated with the new color value of the child node addressed by the new bit, until the FCV is obtained when the full color-map address has arrived.

3 Bit Transmission Sequencing

During the course of transmission, the receiving end has partial color-map addresses of all pixels of different lengths in general. How the spatial distribution of such lengths evolves is an important consideration. Ideally, it should always be as even as possible to avoid visual artifacts due to uneven spatial resolutions. In the extreme case with an image coded in 1-bit color-map addresses, the transmission becomes simply a sequencing of the pixel’s spatial locations. However, as we desire to vary the relative progression rates of the spatial and color resolutions, the pixel sequencing is often preempted for transmitting more bits for some pixels at the expense of others, especially when increase in color resolution is more important temporarily.

We first describe next Lloyd-Williams (LWA) pixel sequencing,[10] which we choose as the basis of our bit transmission sequencing.

3.1 *LWA Pixel Sequencing*

LWA propose a method in which sequence numbers of a square image are obtained by a simple bitwise exclusive-or (XOR) operation followed by bit interleaving. In particular, for the pixel with x coordinate $X = X_a X_{a-1} \ldots X_0$ (binary form) and y coordinate $Y = Y_a Y_{a-1} \ldots Y_0$, its sequence number is given by $Z_0 Y_0 Z_1 Y_1 \ldots Z_a Y_a$, where $Z = X \oplus Y$. Figure 5 depicts an example for an 8×8 image. To recover the coordinates of a pixel. Its sequence number is split for Y and Z and $X = Z \oplus Y$.

Such a sequencing scheme is also readily extensible to nonsquare images by zero padding before assigning LWA sequence number as usual. While the sequence numbers of valid image pixels are no longer consecutive, dummy pixels are *a priori* known to the client and passed over with little or no cost to accuracy and decoding performance.

3.2 *SCPRC*

If we order the color-map addresses, each has its most significant bit (MSB) at the bottom and K’th MSB, i.e., least significant bit (LSB) at the top (K is the full address length of the pixels), by their LWA sequence numbers (from 0 on the leftmost to $N-1$ on the rightmost where $N = L^2$ is the total number of pixels in an $L \times L$ image), we have a binary array model of the color-mapped image, as shown in Fig. 6. When the array is transmitted row by row from bottom to top, it implies accelerated increase in spatial resolution, at the expense of color resolution (Fig. 7). When transmitted column by column from left to right, it implies accelerated increase in color resolution, at the expense of spatial resolution (Fig. 8).

SCPRC can be achieved simply by choosing either sequence to send the entire image. From the test images (Fig. 9) Figs. 10–13 show early views generated by the resulting accelerated spatial (AS) and accelerated color (AC) sequences, respectively. In the AS sequence, outlines of im-

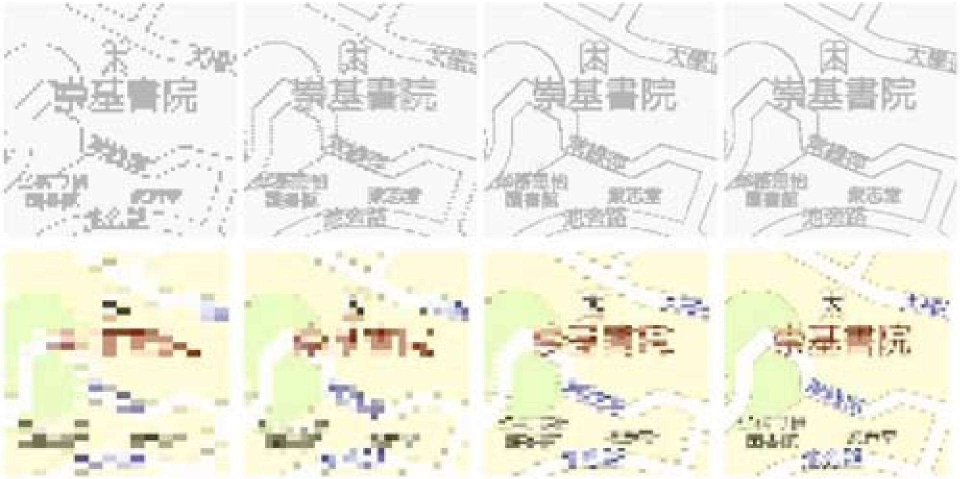

Fig. 10 “Map” under AS sequence (first row) and AC sequence (second row). Bit transmitted (from left to right): 0.78, 1.56, 3.12, and 6.25% of the color-mapped image size (256×256, 8-bit color map).

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Fig. 11 "Goldhill" under AS sequence (first row) and AC sequence (second row). Bit transmitted (from left to right): 0.78, 1.56, 3.12, and 6.25% of the color-mapped image size (256×256, 8-bit color map).

age content appear fast and early as expected, but the visual quality tends to stall early also, indicating small marginal gain from further increase in spatial resolution beyond an upper threshold. The AC sequence shows a still slower increase in spatial resolution, accompanied by original color samples right from the start. Stalling in visual quality happens much later. For an 8-bit color-mapped image, for instance, the same upper threshold in spatial resolution is reached eight times later.

In principle, there is decreasing marginal gain in visual quality for both spatial and color resolutions. It is therefore preferable to send a good combination of spatial and color details, especially when subjected to a tight bit budget at the onset of transmission, for good early views. Their relative proportions should depend on both the image content and the viewing objective. Reading texts or identifying objects by outlines would appreciate more from spatial resolution increase, while selecting or recalling images would depend on the image features or signatures being used, and the extent of color and spatial details they require.

Subsequently, we formulate our general SCPRC scheme as a two-stage process, namely, using AS to send the first k bits of pixel addresses of the first $n=l^2$ pixels (l being the corresponding vertical and horizontal resolution) under LWA sequencing, before using AC to send the rest (Fig. 14). AS is used in the first stage for its fast early views of linear features, but only up to a $k\times n$ view that corresponds to upper thresholds beyond which marginal gain in visual quality is small. Switching to AC in the subsequent stage effects a sustained and steady gain in visual quality as the n pixels rendered with approximate colors (ICVs) are augmented to their FCVs. The resulting viewing experience typically begins with fast rendering of a pale or monochromatic view of a good spatial resolution, followed by increasing sharpening of color, and finally becoming like conventional progressive transmission as the rest of the image is sent by the AC sequence.

Figure 15 shows the complete system architecture for progressive transmission of color-mapped images.

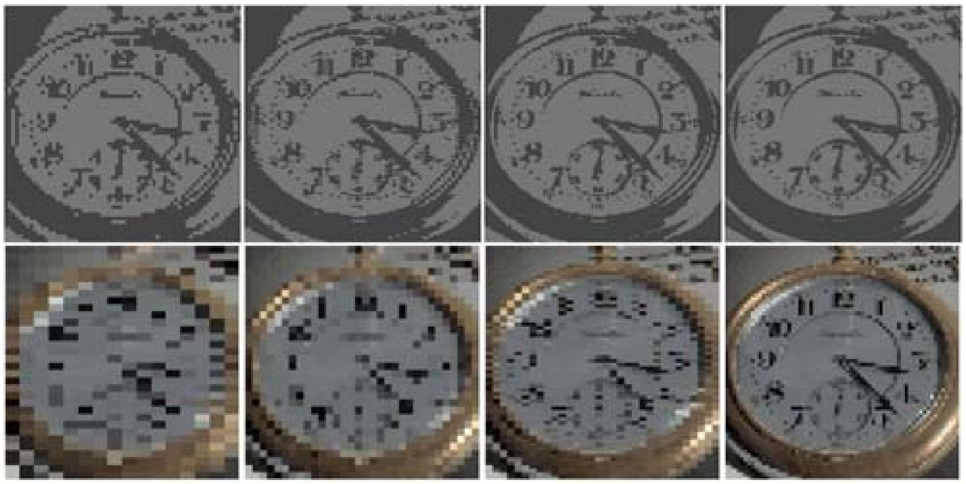

Fig. 12 "Watch" under AS sequence (first row) and AC sequence (second row). Bit transmitted (from left to right): 0.78, 1.56, 3.12, and 6.25% of the color-mapped image size (256×256, 8-bit color map).

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Fig. 13 "Zelda" under AS sequence (first row) and AC sequence (second row). Bit transmitted (from left to right): 0.78, 1.56, 3.12, and 6.25% of the color-mapped image size (256$\times$256, 8-bit color map).

4 Early View Quality Evaluation

Progressive transmission features an animated sequence of continuously improving views, which may be hard to evaluate in their entirety. However, the early views are more critical for at least two good reasons. First, human users depend on them to determine whether or not transmission should be continued. Second, latter views always converge in visual qualities to those of the source image and depend less on the particular progressive transmission scheme being used.

We evaluate our scheme by comparing early views of the four test images, namely, "Map," "Goldhill," "Watch," and "Zelda" with those generated by SPIHT, a state-of-the-art progressive transmission scheme based on the wavelet transform. Early views of bit budgets 0.78, 1.56, 3.12, and 6.25% of the color-mapped image size ($256\times256, 8$ bits) are generated for a range of SCPRC settings between the AS and AC extremes and compared with those from SPIHT of the same bit budget (Fig. 16–19). Here, the SPIHT bitstreams are truncated so that after SPIHT is done, the resulting images have the same file size as the corresponding color-mapped images.

In a psychophysical experiment, images under the same bit budget but from different progression schemes were presented together, and the subject was asked to pick the best and the second best ones, each time based on a specific criteria. For the "Watch" image, the two specific criteria were the clarity of the watch face digits, and amount of information to decide if the shot was made indoor or outdoor. We identify the first criterion as "spatial-oriented" because images with higher spatial resolution tend to perform better in this case. The second criterion is classified as "color-oriented," because images with intermediate colors closer to the original intuitively yield higher ratings in the task. The experiment was conducted with 22 human subjects, and the tallies for the "Watch" image under bit budgets 0.78, 1.56, 3.12, and 6.25% are shown in Tables 1–4.

SPIHT is immediately comparable with the SCPRC setting ($l=32, k=8$), which is equivalent to an AC sequence, since both schemes progress in spatial resolution only. As expected, SPIHT displays superior visual quality. This is revealed from consistently higher ratings of SPIHT intermediates over SCPRC AC counterparts under the color-oriented criterion.

Some other SCPRC settings, the one with ($l=91, k=1$)

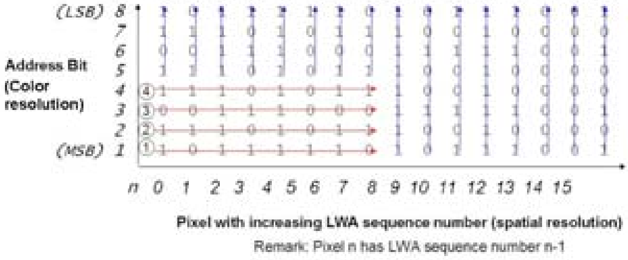

Fig. 14 Applying AS sequence to send the first *k* bits of the colormap addresses up to *n* pixels and then AC sequence for the rest (here $K=8$, $k=4$, $N=16$, $n=8$).

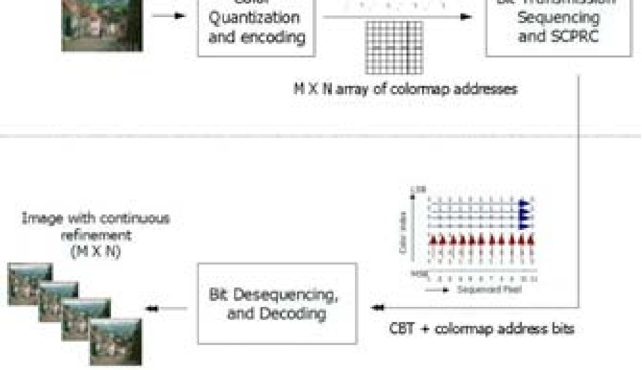

Fig. 15 Overview of progressive transmission of color-mapped image.

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Fig. 16 "Map" under SPIHT (first row) and SCPRC with $[l,k]$ being [91,1] (second row); [64,2] (third row); [45,4] (fourth row); and [32,8] (fifth row). Bit transmitted (from left to right): 0.78, 1.56, 3.12, and 6.25% of the total bitstream size (SPIHT) or color-mapped image size (256×256, 8-bit color map) (SCPRC).

in particular which is identical to the AS sequence up to 1.56% bit budget, give superior spatial details. Some subjects rated intermediate images under these settings better than the SPIHT counterparts at small bit budgets.

The early views show up rather differently under different SCPRC settings. This demonstrates meaningful flexibility of the scheme. While the choice of setting depends on the image, viewing objective, and viewing conditions, the range of visual qualities overlaps with those of SPIHT to a good extent. As shown in the psychophysical experiment, if the task is spatially oriented, a setting with large l is preferred. Our scheme enables flexible adjustment on spatial-color progression rate to color-mapped images. If linear features are important, settings close to the AS sequence would be superior to SPIHT which, typical of transform coding, often blurs linear features in early views as high-frequency components are withheld at the onset of transmission.

5 Discussion

The two important advantages of our scheme are simple decoding and flexibility in early view progression via SCPRC. SPIHT generates very good early views consistently, but lean clients such as PDAs and mobile phones may not have the computation resources required to decode a SPIHT bitstream in a timely manner, especially when it is delivered over limited bandwidth. In contrast, decoding a SCPRC sequence involves CBT look-up and LWA decoding by logical XOR operations only. As shown in the pre-

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Fig. 17 "Goldhill" under SPIHT (first row) and SCPRC with $[l,k]$ being [91,1] (second row); [64,2] (third row); [45,4] (fourth row); and [32,8] (fifth row). Bit transmitted (from left to right): 0.78, 1.56, 3.12, and 6.25% of the total bitstream size (SPIHT) or color-mapped image size (256 × 256, 8-bit color map) (SCPRC).

Table 1 Tally on the best and second best intermediate images rated by 22 subjects for bit transmitted: 0.78% of the total bitstream size (SPIHT) or color-mapped image size (256 × 256, 8-bit color map) (SCPRC).

Criterion	Ranking	SPIHT	SCPRC (91,1)	SCPRC (64,2)	SCPRC (45,4)	SCPRC (32,8)
Spatially oriented	Best	0	8	14	0	0
Spatially oriented	Second best	1	13	7	1	0
Color oriented	Best	17	0	3	1	1
Color oriented	Second best	3	3	1	2	13

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Fig. 18 "Watch" under SPIHT (first row) and SCPRC with $[l,k]$ being [91,1] (second row); [64,2] (third row); [45,4] (fourth row); and [32,8] (fifth row). Bit transmitted (from left to right): 0.78, 1.56, 3.12, and 6.25% of the total bitstream size (SPIHT) or color-mapped image size (256×256, 8-bit color map) (SCPRC).

Table 2 Tally on the best and second best intermediate images rated by 22 subjects for bit transmitted: 1.56% of the total bitstream size (SPIHT) or color-mapped image size (256×256, 8-bit color map) (SCPRC).

Criterion	Ranking	SPIHT	SCPRC (91,1)	SCPRC (64,2)	SCPRC (45,4)	SCPRC (32,8)
Spatially oriented	Best	2	12	8	0	0
Spatially oriented	Second best	7	6	9	0	0
Color oriented	Best	14	3	2	3	0
Color oriented	Second best	5	3	6	2	6

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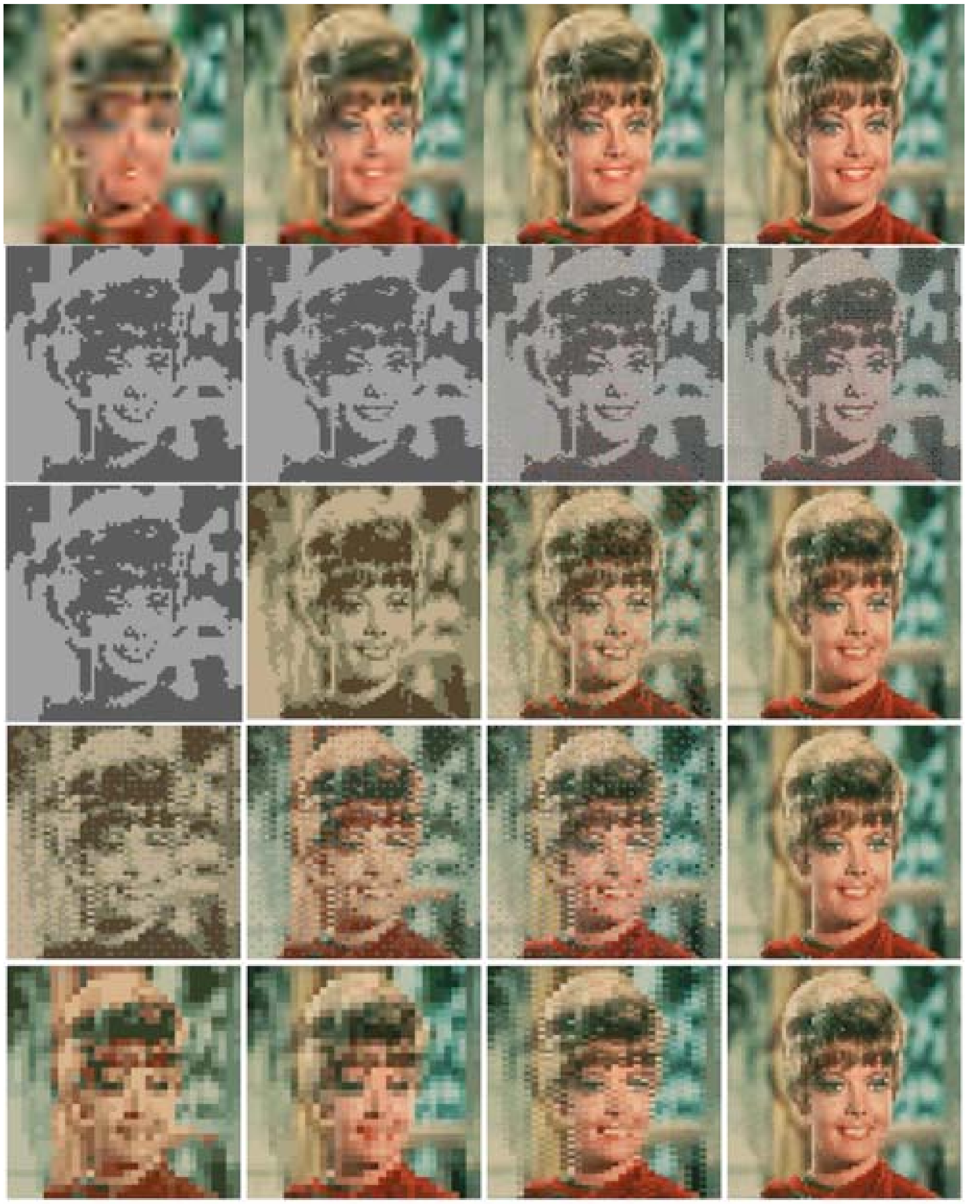

Fig. 19 “Zelda” under SPIHT (first row) and SCPRC with $[l,k]$ being [91,1] (second row); [64,2] (third row); [45,4] (fourth row); and [32,8] (fifth row). Bit transmitted (from left to right): 0.78, 1.56, 3.12, and 6.25% of the total bitstream size (SPIHT) or color-mapped image size (256×256, 8-bit color map) (SCPRC).

Table 3 Tally on the best and second best intermediate images rated by 22 subjects for bit transmitted: 3.12% of the total bitstream size (SPIHT) or color-mapped image size (256×256, 8-bit color map) (SCPRC).

Criterion	Ranking	SPIHT	SCPRC (91,1)	SCPRC (64,2)	SCPRC (45,4)	SCPRC (32,8)
Spatially oriented	Best	14	7	1	0	0
Spatially oriented	Second best	7	6	9	0	0
Color oriented	Best	19	1	2	0	0
Color oriented	Second best	2	3	15	1	1

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Table 4 Tally on the best and second best intermediate images rated by 22 subjects for bit transmitted: 6.25% of the total bitstream size (SPIHT) or color-mapped image size (256×256, 8-bit color map) (SCPRC).

Criterion	Ranking	SPIHT	SCPRC (91,1)	SCPRC (64,2)	SCPRC (45,4)	SCPRC (32,8)
Spatially oriented	Best	22	0	0	0	0
Spatially oriented	Second best	0	6	4	6	6
Color oriented	Best	18	1	1	2	0
Color oriented	Second best	3	4	3	5	6

vious section, visual qualities of early views from our scheme are very reasonable. With SCPRC settings suitably chosen for an image, the early view sequence can be as informative as that from SPIHT, especially when SCPRC may be tuned for better display of linear features. In the case of an image database, the choice of SCPRC settings for an image is best made when it is first added, by examining static iconic views of the same bit budget under different $[l,k]$ settings and choosing the one deemed most informative.

Lean clients may also have limited display resources for which color-mapping produces just as good color ranges as direct mode display, which SPIHT assumes. Furthermore, as image capture becomes popular among portable devices that are often lean in both computation and display resources, images may be captured, shared, and displayed among devices over a peer-to-peer network without passing through any resourceful servers. An end-to-end color-mapped image communications system may be a competitive alternative to one beginning with conventional compression coding that ends up with a color-mapped display device. Computation-efficient color-mapped image encodings such as SSQ or our bitwise version would also be more appropriate.

6 Conclusion

Progressive refinement is a very useful principle when intermediate results are worth knowing, especially when the complete transmission of images takes significant time. Invariably, it is the pixel values that are being progressively refined during transmission. Our work extends the principle to refining color-map addresses of the pixels instead by means of a balanced CBT that carries the original color map of fixed-length FCVs in the leaf nodes as well as their truncated versions as ICVs in all nonleaf nodes.

Flexibility in progression is also provided by means of SCPRC, with which the progressive transmission may be biased to accelerate the refinement in either spatial resolution or color resolution for more informative early views of the image concerned. This is a novel function not found in conventional schemes. SCPRC generates a variety of early view sequences for our test images, which indicates that the flexibility is meaningful and useful. While some transform-based image coding schemes like JPEG2000 (Ref. 13) have enabled such progression flexibility, our paper presents the first packaged solution that offers the same capability for color-mapped images. Featuring CBT structure, computation-efficient bitwise SSQ as the quantization scheme and SCPRC as the bit transmission sequencing approach, our scheme realizes flexible and controllable progressive transmission of color-mapped images especially suited for lean client devices.

We expect this simple and flexible scheme for progressive transmission of color-mapped images to be of good practical use, especially in situations where bandwidth, computation, and display resources are too restricted for conventional spatially or transform-based methods such as SPIHT and JPEG2000. For further work, it should be interesting to consider progressive transmission with unbalanced CBT or variable-length FCVs for better coding efficiency. How SCPRC can be extended to incorporate other dimensions of resolution, such as time in the case of digital video, is also interesting.

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