Wide Gamut Multi-Primary Display for HDTV

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Abstract

Wide gamut display technologies using light sources with a narrow spectral radiance or applying multi-primary techniques have been introduced by several authors in forms of laboratory based models and high-end applications. To bring these technologies into the consumer field, our latest investigation resulted in a rear projection type multi primary display (MPD) for HDTV. The MPD has been realized by a modification of our previous three channel DLP™ projection TV system. Thereby the full spectral energy of the UHP™ projection lamp is sequentially separated into five primary spectrums through a rotating color wheel.

The main focus of this paper is to describe a gamut mapping method that allows using a full range of color gamut of MPD for a given limited color gamut of TV signal. This approach is to display an image in such a way that the limited color saturations of the current TV signal are adaptively enhanced for every observer. Through the color gamut mapping, the picture quality of MPD is significantly improved in comparison with a conventional display system.

Introduction

Historically, the color gamut of TV standard (ITU R. BT. 709) covers approximately 76% of all reflected colors of natural objects.[1] Therefore, some highly saturated colors can't be reproduced on such display systems. In other words, all colors of outside the Rec. 709 color gamut can be clipped on the boundary of the Rec. 709 gamut by signal processing in conventional camera systems, or by an appropriate gamut mapping algorithm even in more sophisticated cameras. Hence, we can only see similar colors within the display color gamut instead of very highly saturated colors. It may finally result in a de-saturation of those colors.

Furthermore, we can see statistically much more artificial colors with higher saturation, such as colors of pigment, paints, clothing materials and monochromatic illuminant colors of LED and Laser in our modern life. Because of the increased population of such highly saturated colors, a wide gamut imaging system will be needed.

For this aspect, the International Telecommunication Union (ITU) and International Electro-Technical Committee (IEC) already published the wide gamut signal definitions of ITU-R.BT.1361 and extended scRGB.[13,14]

In recent imaging technology, several authors introduced the multispectral imaging system to capture and reproduce the wide range of colors. Especially in the display field, wide gamut displays using pure color light sources with narrow spectral radiance, such as RGB-laser[8,9] and high power LEDs,[10] or applying multi-primary techniques have been introduced.[2-7] Among these, the multi-primary display technique can be easily realized for a projection type display system with minimum cost.

For an application of this technology, our latest investigation resulted in a five primary MPD. Thereby, the proto type MPD has been realized by a color wheel modification of our previous RGB DLP™ projection TV with 50/60" screen size. To get the primary colors, the full spectral energy of a 120W UHP™ projection lamp is sequentially separated into five primary spectrums through a rotating color wheel with five interference filter segments. Fig.1 shows the relative spectral irradiances of the primary colors, and their chromaticity coordinates on CIE-UCS color chart showed in Fig. 2a in comparison with the gamut of Rec. 709 (sRGB).

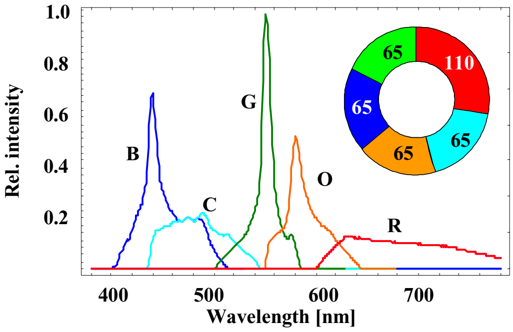
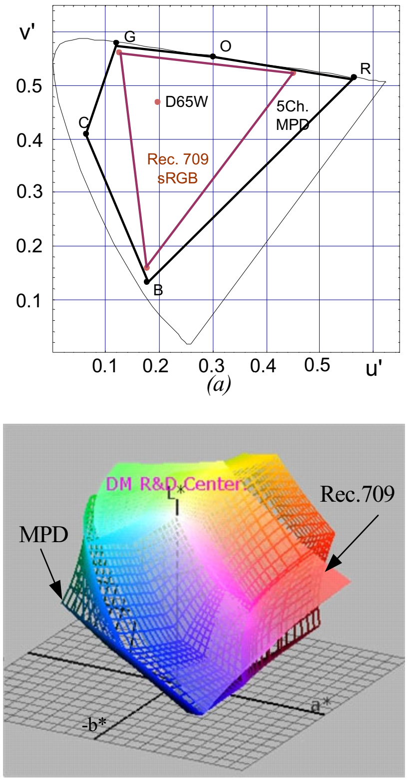


Figure 1. Relative spectral irradiances of primary colors and the color wheel configuration (the inside numbers indicate the occupation angle of each filter segment)

The color gamut volume of the MPD is approximately 1.5 times larger than Rec. 709 based on CIE-L*a*b* color space (Fig.2b). It will be explained more precisely in the following chapter. Hence, the multi primary HDTV system is able to reproduce not only the limited colors by Rec. 709 but also some parts of extended colors.

Even though the wide gamut signal has been defined, there are yet no available wide gamut signals or video streams in broadcasting network.

To utilize the full range of color gamut of MPD for the given Rec. 709 signal, a gamut matching method has been developed and applied between two gamuts.



(a)

(b)

Figure 2. (a) primary color coordinates on CIE-u'v' color chart, (b) perspective view of the MPD gamut in CIELAB$_{76}$ *color space in comparison with the Rec.709 (sRGB) gamut*

The following chapters handle further detailed issues of the color gamuts, a colorimetric image reproduction using an inverse display model, a concept of gamut mapping algorithms, and an implementation in hardware for the real time processing. In addition, an image quality of the MPD will be also discussed in the last chapter.

Display Model and Color Gamut

The realized MPD system has five primary colors of Red, Green, Blue and additional Cyan and Orange color primaries which are optimally chosen for the given spectral characteristics of the UHP lamp, for a transmittance characteristic of additional projection optics and for the D65 display white.

Because of the linear characteristic of DMD™ (digital mirror device) and faithful digital electronic circuits, the conventional additive display model suits very well for the MPD system. With a negligible black offset the forward model can be described as:

$$F = M.C,$$

with the tristimulus color vector F=(X, Y, Z) and linear display control vector C=(C1,C2,C3,C4,C5). (1)

Thereby, the 3x5 conversion matrix is obtained from the measurement of the 5 primary colors using an accurate spectrophotometer (Minolta CS1000).

With the model equation, the gamut volume of MPD can be calculated for given control vectors on the gamut boundary and converted these values into CIELAB$_{76}$ uniform color space. In that uniform space, we calculated and compared volume sizes of the three different color gamuts of Rec. 709, MPD and an optimal color space according to the computing method of Hill.[12] Hereby, the optimal color space represents all human visible colors.

For this calculation, we took unit spheres with diameter of ΔEab=1 and completely filled up each color gamut with those spheres. Then, we counted all the spheres inside the gamut volume. The total number of spheres is shown in Table 1. It reflects the total distinguishable colors for human eye based on CIELAB97 color space. As shown in the table, the MPD has about 1.5 times more than Rec. 709(CRT) gamut and covers approximately 51% of the optimal color space.

Table 1. Distinguishable Colors

	Rec. 709 (CRT)	5 ch. MPD	Optimal color space
Colors [Million]	1.16	2.7	3.24
Relative ratio [%]	36	51	100

Even though MPD has larger volume of the color gamut than Rec. 709, in some color regions Rec. 709 has larger chroma as shown in Fig. 2b. Because, in MPD, the common reference white is composed of the five primary colors instead of three primaries, the luminance level of each RGB primaries of MPD is normally lower than the three-channel system (Rec.709).

Inverse Display Model

Because of the non-square matrix M of Eq. (1), the matrix inversion is not unique for the CIE-XYZ tristimulus reproduction due to the violation of the physical constraint of the control vector. To overcome this problem, several methods have been published.[2,4-6] What we utilized is the modified matrix switching of Ajito.[5] In this method, the MPD gamut splits into a certain number of pyramids. Then, the control vector is calculated by solving the linear equations for given XYZ triple within a belonging pyramid. A pyramid needs to be selected also in which a given tristimulus vector is included. To find this belonging pyramid, the two-dimensional xy-LUT with corresponding pyramid numbers for input chromaticity values has been used. Normally, this method needs large amount of LUT-memories for the proper searching of belonging pyramids on the boundaries of adjacent pyramids, typically over 1Kx1K address range.

Our modified method tries to remove such additional LUT. Instead, we applied a parallel processing for candidate pyramids and an appropriate algorithm decides a possible solution by checking the constraint conditions afterwards.

Figure 3a shows an example of a color gamut with four primaries (P=4) in XYZ color space. The color gamut can be then split into P(P-2) pyramids without overlapping. The pyramid has 5 vertices including one common vertex as the black point of the gamut.

To get all the vertex information of the pyramids, a simple graphical analysis of the gamut surface has been developed as shown in Fig. 3d. This assumption is only valid if all the primary colors are located on a surface of the color gamut. Normally, all vertices on the gamut surface have the extreme control values of zero or one in normalized control value form, as indicated in circle node (Fig. 3d).

Now, we can construct the diagram from black point “0000” to white “1111” with an incremental setting of channel control values, as shown in Fig. 3d. For example, the first step is to assign P1-P4 primary colors (nodes 1000, 0100, 0010, 0001) in counterclockwise direction as shown in Fig. 3e. In the second step, other surface vertices (1100, 0110, and so on) are constructed from the two neighboring vertices of the nodes from the first step. In this manner, the diagram should be completed until the white point is assigned as (1111). From this diagram of gamut surface, we get the generalized information that the MPD with P primaries has P*(P-1)+2 number of surface vertices and P(P-2) pyramids.

As proposed by Ajito, the computation of a control vector for given F=(X,Y,Z) tristimulus values is a solution to the following linear equation (see Fig. 3b):

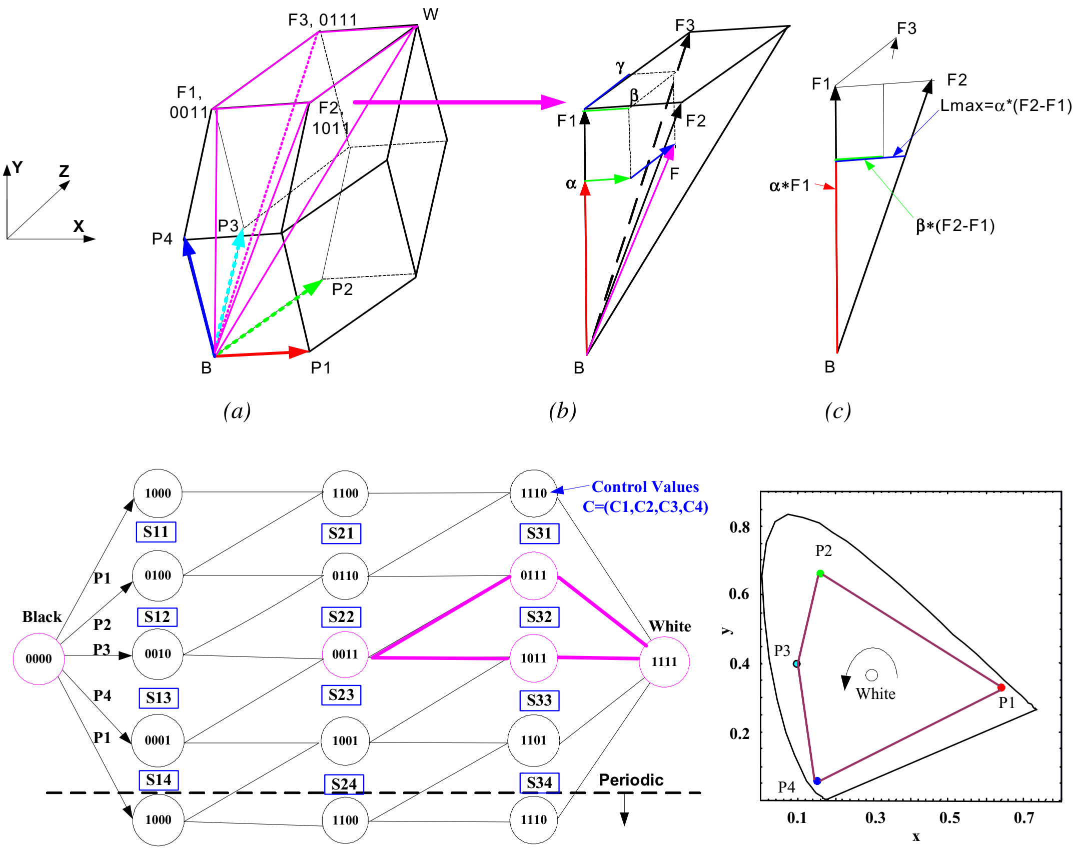
$$F=\alpha*F1+\beta*(F2-F1)+\gamma*(F3-F1) \qquad (2)$$

where Fi: tristimulus vectors for the control values C in circle nodes (Fig.3d).

The scale factors α, β, γ are the final control values for an input color vector F. First, its range has to fulfill the physical constraint condition $0\leq(\alpha, \beta, \gamma)\leq 1$.

To assign the solved (α, β, γ) to the channel control values C=(C1, C2, C3, C4), we applied the exclusive-OR bit-operation between the control values of vertices of a selected pyramid. For example, the pyramid with the base plane of S32 and black point in Fig.3d (as indicated in magenta) delivers three vertex control vectors of C_{F1}=(0011), C_{F2}=(1,0,1,1) and C_{F3}=(0,1,1,1). Through the bit-operation between C_{F1} and C_B=(0,0,0,0), the value (0,0,1,1) is delivered for α. Multiplying α with the result, we get the temporal result (0,0,α,α). The same procedure should be applied for β (between C_{F1} and C_{F2}) and γ (between C_{F1} and C_{F3}), Then the final control vector C=(β, γ, α, α) is obtained for this case.

The remaining process is to find the appropriate pyramid for a given XYZ input. To do this, a parallel process for the candidate pyramids has been developed instead of the chromaticity LUT. In this process, the information about the candidate pyramids is obtained from the 3D-LUT in Fig. 6 or the adequate analysis of input signal range. It will be more discussed in the chapter “Implementation”.



(a) (b) (c)

(d) (e)

Figure 3. (a) Color gamut in XYZ space, (b) vector addition within the pyramid, (c) illustration for constraint check, (d) graphical gamut surface analysis, (e) chromaticity diagram for an example display with 4 primaries

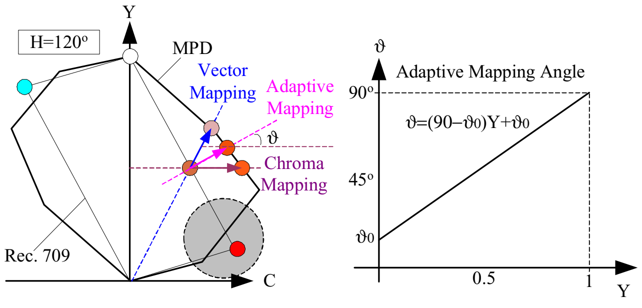
Even if the physical constraint $0 \le (\alpha, \beta, \gamma) \le 1$ has been satisfied, more than one solution can be delivered during the parallel processing for the given candidate pyramids. To obtain the best solution, or to ensure the contourless image rendering, the continuity of control values for given continuous tristimulus values is required. To meet this goal, additional conditions should be necessary. The required condition was taken from a trigonometrical proportionality term as shown in Fig. 3c.

For the triangle (B, F1, F2), we can formulate the proportionality equation as $F1/(F2-F1) \doteq \alpha * F1/Lmax$. The existence of the component vector β*(F2-F1) within the pyramid will be satisfied, if β*(F2-F1) is smaller than Lmax. It results in the additional conditions of $\alpha \ge \beta$, and $\alpha \ge \gamma$ for the other γ*(F3-F1) component vector. With these conditions, we always get a single solution for any given vector F.

Gamut Matching

To utilize the full range of the MPD color gamut for the input Rec. 709 signal, two kinds of gamut matching methods have been developed.

The first method is gamut mapping in an intensity-linear color space. This mapping strategy has an advantage in a relative simpler hardware implementation.



(a) *(b)*

Figure 4 (a) Gamut comparison in YWV space and mapping concepts, (b) mapping angle in function of luminance level

In contrast, a second mapping method carries out in a uniform color space. This is a common concept in color science and generally delivers a better result. However, it is very time costly due to complex transformation and determination of gamut boundaries. For real time processing, it often needs a large amount of memory. Therefore, our study has investigated both methods.

For the first method, we transformed the XYZ color gamut in YWV color space with the linear conversion matrix *N={{0, 1, 0}, {-0.53, -0.687, 0.643}, {1.82, -1.48, -0.23}}*. Because of the similar construction of YWV with YCbCr space, we regard it as a *linear* YCbCr space.

Figure 4 shows the gamut of the Rec. 709 in comparison with the gamut of the MPD for the constant hue and shows the concept of the gamut mapping in that space.

As shown in the figure, MPD has generally more volume of gamut than the Rec. 709 space. However, RGB primary colors of Rec. 709 have higher luminance than the colors of MPD with the same chromaticity due to the reasons mentioned above. Therefore, the gamut mapping in such color regions needs more efforts.

The simplest way of gamut matching will be chroma matching at a constant lightness and hue, as shown in Fig. 4a (brown line). In most cases, this chroma mapping operates quite well. However, in gamut compression case, the method has a de-saturation effect in the color region of RGB primary colors of Rec. 709, and this degradation in red color may be perceptually worse than in other primary colors.

Instead of chroma matching, an alternative vector mapping (as plotted as blue line) can be applied to reduce the de-saturation effect. It changes magnitudes of the color vectors at the same chromaticity coordinates. However, this method has also another problem in a large transition of luminance levels in near of the cross point of two gamut boundaries (marked as gray circle in Fig. 4a). It may cause a contouring problem at the image rendering level.

More sophisticated, adaptive vector-chroma mapping was applied (as marked in magenta). Thereby, the mapping angle ϑ can be varied as a function of the luminance as shown in Fig. 4b, so that the above-mentioned de-saturation and the contour problem will be effectively minimized.

The relative simpler implementation of gamut mapping in intensity-linear color space (YWV) sometimes needs a careful optimization process. Hence, further investigation was done in a uniform color space.

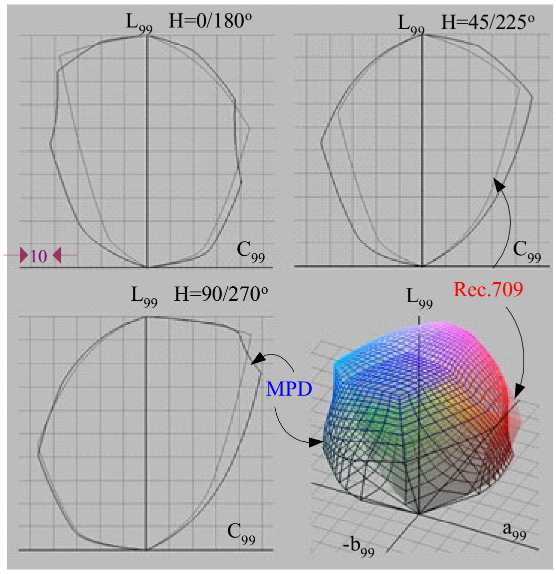


*Figure 5. Gamut comparison in uniform DIN99d color space: L*C* cuts for variety hues, thin line indicates Rec. 709 and thick line indicates MPD gamut boundaries and perspective view of 3D gamut (frame for MPD, volume for Rec. 709 gamut)*

Recently, many of uniform color spaces are available. Fig. 5 shows the gamut comparison in a uniform color space based on DIN99d color difference formula.[15] In the following, such color space will be referred to as being the LAB99d space. The chosen LAB99d was constructed by mainly two modifications in regard to CIELAB76: the logarithmic transformation of lightness and the logarithmic chroma compression in radial direction with reduced blue-yellow weighting. Consequently, the uniformity of color difference was quite improved over the whole gamut.

In such improved uniform color space, we could apply the same adaptive vector-chroma mapping much more effectively and conveniently. Therefore, it delivers a better natural image reproduction than YWV space and requires shorter optimizing process.

Implementation

The signal transformation into LAB99d color space and the determination of the gamut boundaries are very complex and computing intensive. Therefore, for real time processing, the gamut mapping had been applied for the 32x32x32 equidistant linear RGBL signals of Rec. 709. The corresponding XYZ values were calculated by using of a mathematical program on PC and implemented as a color transformation table, as shown as 3D-LUT in Fig. 6.

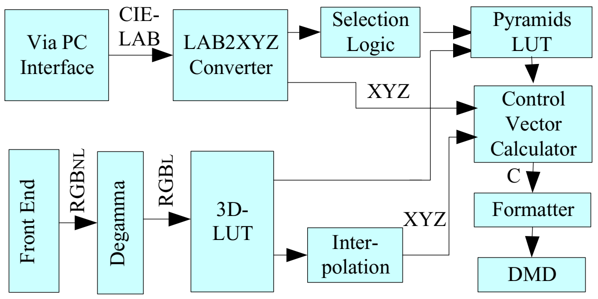


Figure 6 Simplified signal flow in FPGA

Additionally, a belonging pyramid number to every XYZ value of LUT can be also assigned in LUT for the parallel process of the next stage. Besides, the 3D-LUT data can be final control values instead of tristimulus values. However, in order to share the parallel processing block with the CIELAB interface it was purposely separated.

The next interpolation block then tries to compute the intermediate XYZ values by the conventional tetrahedral interpolation and the interpolated values are delivered to the control vector calculator.

At the same time, we obtain the additional pyramid numbers for four tristimulus vectors from the LUT, as the required 4 vertices for the tetrahedral interpolation. With these pyramid numbers, the following parallel process can get all the required pyramid information (such as F1-F3 and belonging control vectors) from the pyramids-LUT.

After the parallel process, the successive checking of the constraint conditions $(0\le (\alpha, \beta, .\gamma) \le 1,\ \alpha \ge \beta$ and $\alpha \ge \gamma)$ for four results is followed. Then, the final control values are available for a formatter, in which the linear control values are specially prepared for the control of DMD^{TM} (Digital Micro-mirror Device).

Contrary to the gamut matching method, we also implemented CIELAB76 signal interface in order to test the rendering of wide gamut images. It was realized by using of the conventional TV RGB interface for PC mode instead, so wide gamut images in CIELAB76 format can be also reproduced. It allows the colorimetric XYZ reproduction on the MPD without any additional processing on FPGA board. A necessary gamut mapping of not-reproducible colors, which lie outside the MPD color gamut, is done by an external program on PC before putting the signal into the interface. Via LAB2XYZ converter, we obtain the corresponding XYZ values. For this tristimulus signal, a selection logic block in Fig. 6 provides candidate pyramid numbers to the control vector calculator. The processing after this stage is common.

In the end, the FPGA board allows two kinds of image reproductions for the wide gamut signal in CIELAB via conventional PC-RGB interface (8x3Bits resolution) and for the limited color gamut of Rec. 709 with the gamut-matching algorithm for HDTV application. The display allows reproduction of the progressive video stream with the pixel resolution of up to 1280x720 at the contrast ratio of 1000:1 and the white luminance of about 400 cd/m^2.

Image Reproduction Experiments

In previous chapter, we discussed about the computing of control values for given tristimulus values. After the color patch measurement, the color reproduction error recorded in the average of $\Delta Eab=2.35$ and maximum $\Delta Eab=5.8$ for the measurements of 243(3x3x3x3x3) color patches, of which XYZ values are computed from the all combinations of linear control values with (32, 128, 255) levels for each channel. It assures of an accurate colorimetric reproduction on the MPD screen.

For a test of real life images, a couple of wide gamut images with natural and artificial objects had been captured by the commercially available multi-spectral camera system of Color Aixpert in Germany.[16] Their spectral data were calculated into the XYZ values for a D65 simulator lamp of the viewing booth (Minolta GTI Color Matcher) and the reproduced images on the screen were compared with the originals in the viewing booth. Within the reproducible colors, the MPD provides much more vibrant colors than the conventional CRT display and therefore more color details are provided.

Other approach of this paper was to develop the gamut matching method to use the full range of color gamut of MPD for given signal with limited color gamut. To decide the availability of the matching algorithms on the consumer TV, in aspect of the color saturation enhancement for the wide gamut MPD until the establishment of the future wide gamut broadcasting signals, the two kinds of mapping algorithms have been applied to the Rec. 709 video pictures. Generally, the gamut matching in LAB99d shows a better result than in YWV space. The careful optimization of the mapping parameters in YWV space can also indicate almost the same reproduction result as LAB99d.

The mapping in YWV needs however more developing time on one hand, but it allows the real time processing with relative small amount of hardware resources on the other hand. Contrary to that, the optimizing process of the mapping in LAB99d is much more robust due to the uniform color space. The choice of the mapping algorithms is mainly dependent upon its applications.

A visual impact of the reproduced images varies by the adjusting of the adaptive mapping angle ϑ in Fig.4d. If the mapping line assigned near the vector mapping line, then the reproduced images are more natural. On the other hand, if the mapping line assigned as the near chroma mapping line (especially in case of the stretching) more vibrant images are reproduced.

Finally, the relative increasing of lightness and chroma by the gamut mapping makes the increasing of perceptual saturation (Helmholtz-Kohlrausch effect) in comparison to the conventional systems. It results in an improved color contrast, sharpness and therefore increases the picture quality, respectively.

Conclusion and Outlook

The focus of the paper is to describe a method that allows using a full range of color gamut of MPDs for given limited color gamut signal so that the limited color saturations of conventional displays are adaptively expanded. The paper handled also further issues of the related gamut mapping concepts and its practical implementation, especially for the application of the real time processing.

Thanks to the wider color gamut and the appropriate gamut matching algorithm, the picture quality of MPD is significantly improved. The system was implemented in FPGA and it enables the moving picture reproduction up to HD format size in real time.

For better picture quality, our research is still running in an advanced gamut matching method and a new system configuration such as four-primary display and new illumination system in order to compensate the lower luminance of RGB primary colors. In this study, we could not fully emphasize an image quality in point of human perception that will be assessed further.

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Biography

Moon-Cheol Kim received his Diploma in Electrical and Telecommunication Engineering from Aachen University of Technology, Germany, in 1995. From 1995 to 2001, he was a scientific researcher in field of color science at Technical Electronics Institute of the same university and received his doctor degree. In 2001, he joined Digital Media Network R&D Center in Samsung Electronics Co. Ltd., South Korea. He is currently senior researcher in Video Lab. and working in field of color science and new display technology. He is a delegate member of Korean national body of IEC TC100/TA2 and of CIE Div. 8 in Korea (KCIE).