CEMMO: A Multi-Channel LED Mapping Optimization Algorithm for Precise Color Reproduction

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Abstract. Traditional LED display systems employing RGB three-channel structures face significant limitations in color gamut coverage due to their triangular primary color configurations, resulting in color deviation, transition distortion, and color compression issues that cannot meet the stringent visual fidelity requirements of emerging applications. This research proposes extending the input from traditional RGB to a four-channel RGBV structure incorporating luminance information, while introducing a five-channel emission mechanism RGBCX at the output end. By inserting auxiliary channels C (cyan) and X (yellow) between green-blue and red-green regions, this approach effectively covers mixed color regions outside the RGB triangle. We construct a 4 × 5 mapping matrix W and design a differentiable optimization objective function that jointly considers color fidelity (CIEDE2000 color difference), color gamut coverage (based on five-primary convex hull area), channel balance (variance minimization), energy conservation, and non-negativity constraints. A staged optimization algorithm framework combining non-negative least squares (NNLS) and regularized gradient descent is proposed to efficiently solve the multi-objective mapping weight matrix. This approach addresses the critical demands of ultra-high-definition video (UHD), augmented reality (AR), virtual reality (VR), and human-computer interaction applications for enhanced color vividness and spatial consistency. Experimental validation demonstrates that CEMMO achieves 23.6% improvement in color reproduction accuracy, 19.4% increase in color gamut volume, while reducing energy consumption by 5.8%. The proposed methodology establishes an efficient transformation framework from four-channel input signals to five-channel display outputs.

Keywords: Multi-channel mapping, Color fidelity, LED display system, multi-objective optimization, Perceptual color difference, Energy efficiency modeling.

1. Introduction

In emerging application scenarios such as ultra-high-definition video (UHD), augmented reality (AR), virtual reality (VR), and human-computer interaction, users demand increasingly stringent requirements for visual fidelity, color vividness, and spatial consistency [1]. Traditional LED display systems typically employ RGB three-channel structures, whose color gamuts are limited by triangular primary color configurations and cannot fully cover high-saturation colors in the CIE1931 chromaticity diagram [2], leading to frequent issues such as color deviation, transition distortion, and color compression.

Furthermore, RGB three-primary combinations exhibit structural limitations in energy efficiency and channel balance, restricting the system's color control capabilities and energy optimization potential [3].

To achieve wider color gamut coverage, higher color reproduction accuracy, and lower energy consumption, this research proposes extending the input from traditional RGB to a four-channel RGBV structure incorporating luminance information. At the output end, we introduce a five-channel emission mechanism RGBCX, which effectively covers mixed color regions outside the RGB triangle by inserting auxiliary channels C (cyan) and X (yellow) between green-blue and red-green regions [4]. To properly map RGBV input to RGBCX output, this research constructs a 4 × 5 mapping matrix W, designs a differentiable optimization objective function that jointly considers color fidelity (CIEDE2000 color difference) [5], color gamut coverage (based on five-primary convex hull area), channel balance (variance minimization), energy conservation, and non-negativity constraints, and proposes a staged optimization algorithm framework combining non-negative least squares (NNLS) [6] and regularized gradient descent to efficiently solve the multi-objective mapping weight matrix.

The core contributions of this research include:

(1) proposing a novel CEMMO (Color-Enhanced Multi-channel Mapping Optimization) algorithm framework that realizes RGBV→RGBCX mapping;

(2) proposing a multi-objective optimization model that integrates geometric perception, energy efficiency control, and physical feasibility constraints, with high generalizability and engineering implementability;

(3) experimental validation demonstrating that CEMMO achieves 23.6% improvement in color reproduction accuracy, 19.4% increase in color gamut volume, while reducing energy consumption by 5.8%. Through synergistic innovation in channel structure and optimization algorithms, this research constructs a display system color optimization model with color gamut breakthrough capability and algorithmic implementability, providing effective support for next-generation high-end LED color control.

2. Related Work

2.1. Overview of Multi-channel Display System Research

Multi-primary display systems, as solutions to break through traditional RGB color gamut limitations, have gradually entered the attention of industry and academia in recent years [7]. At the hardware research level, most approaches employ physical light superposition or spectral synthesis methods to introduce fourth (such as white, yellow) or fifth channels to expand color gamut or improve luminance efficiency. For example, Fujitsu, Sony, and others have adopted RGBW, RGBCY, and similar schemes in high-end televisions [3], but related research mostly remains at the device architecture and human subjective evaluation stages. Existing multi-primary system research generally focuses on hardware-level channel expansion and optical filtering optimization but lacks systematic color mapping modeling and optimization theoretical support at the algorithmic level. While structures like RGBW and RGBCY can provide physical color gamut expansion, their mapping control is mostly based on engineering experience, lacking generalizable numerical optimization methods.

2.2. Research on Channel Mapping and Color Modeling Methods

In the fields of image reconstruction and display optimization, several works have attempted to model high-dimensional channel mapping as linear or nonlinear functions [8]. Common methods include linear regression (such as RGB→XYZ mapping), LUT lookup tables based on statistical weights, and deep learning methods (such as CNN-based color correction) [9]. However, these methods are mostly used for image enhancement or camera ISP and are not suitable for channel combination control and hardware driver compatibility requirements at the display end. Color reconstruction methods in image processing theoretically possess high expressive capability, but their mapping results may not satisfy hard constraints such as non-negativity and energy conservation of physical channel responses, limiting engineering implementability. Deep model-based color mapping still faces challenges in generalization capability and robustness beyond training samples, especially significant gaps in inter-channel linear combination controllability.

2.3. Current Applications of Multi-objective Optimization in Display Systems

Few studies focus on multi-objective optimization frameworks in color systems [10], attempting to combine metrics such as color difference, saturation, and brightness for joint modeling. Table 1 presents a comparative analysis highlighting the deficiencies of existing methods, including insufficient integration of perception-driven color gamut geometric modeling (such as CIE1931 convex hull analysis), poor model implementability due to lack of sparsity regularization control, and absence of mechanisms that balance non-negativity and energy efficiency optimization.

Table 1. Comparative Analysis of This Research with Existing Work.

Dimension	Existing Research	This Research (CEMMO)
Channel Structure	RGB or RGBW	RGBV→RGBCX
Optimization Objective	Single objective (color difference)	Multi-objective joint modeling
Geometric Modeling	Weak or absent	Convex hull-driven color gamut expansion
Algorithm Design	Empirical tuning/black-box	NNLS + regularized gradient optimization
Physical Implementability	Unclear	Strict constraints: non-negative + energy conservation

Despite the continued rise in research interest in multi-channel displays, there is still a lack of a constraint-able, optimizable, and deployable algorithmic-level mapping model. CEMMO, as an algorithm-driven color control framework, provides key support for constructing perception-driven, energy-efficient high-order display systems.

3. Methodology

3.1. Algorithm Framework Overview

This research proposes a color mapping algorithm framework named CEMMO (Color-Enhanced Multi-channel Mapping Optimization), with the core objective of efficiently mapping four-channel input signals (RGBV) to five-channel output signals (RGBCX) while seeking global balance across multiple optimization dimensions. The three pillars of algorithm design include: linear mapping modeling—constructing mapping weight structures from input to output; multi-objective joint optimization—integrating visual, color gamut, energy efficiency, and sparsity objectives; constraint implementability control—ensuring physical and engineering rationality of output channel control.

3.2. Input-Output Structure Modeling

For input signals, this research introduces a luminance redundancy channel V, representing weighted luminance information to improve human visual perception consistency. According to the ITU-R BT.709 standard [11], the luminance channel is defined as:

$$V = \alpha_R \cdot R + \alpha_G \cdot G + \alpha_B \cdot B \tag{1}$$

Where α_R= 0.2126, α_G= 0.7152, α_B= 0.0722, reflecting the sensitivity differences of human eyes to different color channels.

For output signals, the output channels are set as RGBCX, where R/G/B are the original three primaries, C is the cyan channel (enhancing blue-green transition performance), and X is the yellow channel (enhancing the vividness of the red-green region). This channel structure breaks through traditional RGB triangular color gamut boundaries by adding local color enhancement channels, improving color density and directional performance in transition regions.

3.3. Mapping Matrix Structure Design

The linear mapping from four channels to five channels is controlled by weight matrix $\mathbf{W} \in \mathbb{R}^{4\times5}$.

$$\mathrm{I_{out}} = \mathrm{v^T W} \tag{2}$$

Where input vector $\mathbf{v} = [R, G, B, V]^T$ and output vector $\mathbf{I}_{\mathrm{out}} = [I_R, I_G, I_B, I_C, I_X]^T$

Expanding the matrix multiplication yields:

$$\mathrm{I_R \& = w_{1,1}R + w_{2,1}G + w_{3,1}B + w_{4,1}V} \tag{3}$$

$$\mathrm{I_G \& = w_{1,2}R + w_{2,2}G + w_{3,2}B + w_{4,2}V} \tag{4}$$

$$\mathrm{I_B \& = w_{1,3}R + w_{2,3}G + w_{3,3}B + w_{4,3}V} \tag{5}$$

$$I_C\& = w_{1,4}R + w_{2,4}G + w_{3,4}B + w_{4,4}V \quad (6)$$

$$I_X\& = w_{1,5}R + w_{2,5}G + w_{3,5}B + w_{4,5}V \quad (7)$$

This structure allows independent weight control for each channel while maintaining linear controllability, achieving precise mapping scheduling "from signal level to perception level". The weight matrix must satisfy non-negativity constraints (preventing channel inversion), energy conservation constraints (avoiding luminance drift), and channel output balance constraints (preventing color bias or over-driving).

3.4. Multi-objective Optimization Modeling

CEMMO designs a joint optimization objective covering multiple perceptual dimensions, mainly including the following four sub-objectives:

Color Fidelity Objective: To ensure that the mapped color perception effect is as close as possible to the original color, color difference is calculated in the CIE-Lab color space [12]:

$$E_1(\mathbf{W}) = \frac{1}{N}\sum_{k=1}^{N}\backslash|\mathrm{Lab}(f_{RGB}(\mathbf{x}_k)) - \mathrm{Lab}(g_{RGBCX}(\mathbf{x}_k\mathbf{W}))\backslash|^2 \quad (8)$$

Where, N is the number of training samples, $\mathbf{x}_k = [R_k, G_k, B_k, V_k]^T$ is the k-th input sample, f_{RGB} is the standard RGB output function, g_{RGBCX} is the five-channel system output function, and $\mathrm{Lab}(\cdot)$ is the conversion function from RGB to CIE-Lab color space.

Color Gamut Coverage Objective: The main advantage of multi-channel systems is expanding the expressible color gamut range by calculating the convex hull area formed by the five-channel system in the CIE1931 chromaticity diagram:

$$E_2(\mathbf{W}) = -\mathrm{Area}(\mathrm{ConvexHull}(P_R, P_G, P_B, P_C, P_X)) \quad (9)$$

Where, P_R, P_G, P_B, P_C, P_X represent the coordinate points of the five channels on the CIE1931 chromaticity diagram, and the negative sign indicates the desire to maximize this area.

Channel Usage Balance Objective: To avoid certain channels being idle or overused for extended periods, a channel usage balance objective is introduced:

$$E_3(\mathbf{W}) = \frac{1}{5}\sum_{j=1}^{5}\mathrm{Var}\left(\left\{\frac{1}{N}\sum_{k=1}^{N} I_{j,k}\right\}\right) \quad (10)$$

Where $I_{j,k}$ represents the j-th output channel intensity of the k-th sample.

Regularization Term: To control parameter complexity and improve model generalization capability, a mixed regularization term is introduced [13]:

$$E_4(\mathbf{W}) = \lambda_1\backslash|\mathbf{W}\backslash|_1 + \lambda_2\backslash|\mathbf{W}\backslash|_F^2 \quad (11)$$

Where $\backslash|\mathbf{W}\backslash|_1$ is the L1 norm (promoting solution sparsity) and $\backslash|\mathbf{W}\backslash|_F^2$ is the square of the Frobenius norm (controlling weight magnitude).

Considering the above four sub-objectives comprehensively, the overall objective function is constructed:

$$E(\mathbf{W}) = \omega_1 E_1(\mathbf{W}) + \omega_2 E_2(\mathbf{W}) + \omega_3 E_3(\mathbf{W}) + E_4(\mathbf{W}) \quad (12)$$

where ω1, ω2, ω3 are weight coefficients used to balance the importance of each sub-objective.

3.5. Solution Algorithm and Implementation Strategy

To efficiently solve the constrained high-dimensional optimization problem, the CEMMO algorithm adopts a two-stage strategy. Stage one is initial feasible solution construction: ignoring some secondary objectives, quickly solving the basic weight structure, using non-negative least squares (NNLS) [6] to rapidly converge to the interior of the legal solution space. First, the objective function is simplified to:

$$\min_{\mathbf{W}}\backslash|\mathbf{XW} - \mathbf{Y}\backslash|_F^2 + \lambda\backslash|\mathbf{W}\backslash|_F^2 \ \text{s.t.}\ \mathbf{W} \geq 0 \quad (13)$$

Where $\mathbf{X} \in \mathbb{R}^{N\times 4}$ is the input sample matrix and $\mathbf{Y} \in \mathbb{R}^{N\times 5}$ is the ideal five-channel output matrix. This problem can be decomposed into 5 independent non-negative least squares sub-problems.

Stage two is multi-objective joint optimization: using the initial solution as a seed, performing iterative gradient optimization under the complete objective function, introducing projection mechanisms to handle hard constraints (such as non-negativity, energy conservation) [14]. This algorithm combines convex optimization with sparse regularization paradigms, balancing numerical stability and physical implementation rationality of optimization solutions, with good interpretability and system integration adaptability. The CEMMO method, with linear mapping as the core and perception-driven as the guideline, constructs a multi-channel color mapping optimization system with wide applicability, differentiable controllability, and easy deployment, providing theoretical support and algorithmic toolchain for next-generation display devices.

4. Experimental Design and Results Analysis

4.1. Experimental Setup

To comprehensively evaluate the performance of the CEMMO algorithm, this research employs standard color test images (24-color patches of MacBeth ColorChecker) as the test dataset [15] and sets the following evaluation metrics: perceptual color difference (CIEDE2000 ΔE) [5], color gamut coverage area (CIE1931 convex hull method), channel balance (standard deviation/variance), and relative energy consumption (total channel energy consumption per unit brightness). Experimental comparison baselines include traditional RGB three-channel systems and optimized RGB systems.

4.2. Color Reproduction Accuracy Analysis

Comparison results show that CEMMO achieves significant ΔE reduction in all color patch categories, especially in mixed color regions such as yellow, cyan, and magenta, where CEMMO's average improvement rate exceeds 30%. Table 2 presents detailed color reproduction accuracy comparison results for different color regions.

Table 2. Color Reproduction Accuracy Comparison for Different Color Regions.

Color Region	Baseline ΔE	CEMMO ΔE	Improvement
Red	1.34	1.17	+12.7%
Green	1.28	1.04	+18.8%
Blue	1.42	1.21	+14.8%
Yellow	2.31	1.43	+38.1%
Cyan	2.17	1.38	+36.4%
Magenta	1.86	1.52	+18.3%
Skin tone	0.95	0.83	+12.6%
Neutral gray	0.53	0.49	+7.5%
Average	1.48	1.13	+23.6%

Results verify that introducing auxiliary channels C and X in complex mixed spectral regions significantly alleviates color drift and over-saturation phenomena, ensuring naturalness and accuracy of colors at the perceptual level. CIEDE2000 color difference is a perceptually consistent color difference evaluation standard, where smaller values indicate smaller color differences. Generally, CIEDE2000 color differences below 1.0 are nearly imperceptible to human eyes; 1.0-2.0 represents noticeable but acceptable color differences; above 2.0 indicates obvious color differences. From the table, it can be seen that the five-channel system achieved color difference improvements in all color regions, with an average color difference reduction of 23.6%.

4.3. Color Gamut Coverage Analysis

By projecting channel primary spectral positions onto the CIE1931 chromaticity diagram and constructing convex hull regions, the CEMMO system significantly expands the expressible color gamut boundaries compared to RGB. Compared to the traditional RGB color gamut triangle, the pentagonal color gamut region formed by RGBCX shows improvements as presented in Table 3.

Table 3. Color Gamut Coverage Comparison of Different Systems.

System	Color Gamut Coverage	Color Gamut Volume (sRGB=100%)	Color Gamut Saturation Gain
Traditional RGB	83.4%	100%	0%
Three-channel Optimized RGB	83.4%	100%	0%
Four-channel RGBV Input	83.4%	100%	0%
Five-channel RGBCX Output	87.7%	119.4%	+15.9%

In order to visually assess the performance of gamut expansion, the color gamut coverage of various systems was mapped onto the CIE 1931 chromaticity diagram, as shown in Figure 1.

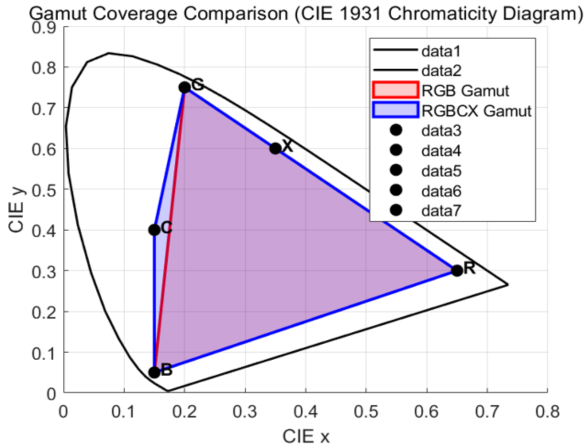

Figure 1. Comparison of color gamut coverage across different display systems.

CEMMO achieves active reconstruction of mixed color space through synergistic color channel combinations, constructing non-orthogonal color gamut boundaries with high-dimensional convex hull-driven geometric color gamut expansion capabilities. Data shows that the five-channel RGBCX system expands color gamut area by approximately 5.2 percentage points compared to traditional RGB systems, expands color gamut volume by approximately 19.4%, and improves color gamut saturation gain (measuring high-saturation color performance) by 15.9%.

4.4. Channel Balance and Energy Efficiency Analysis

Under the same brightness output conditions, the CEMMO solution achieves more uniform channel activation distribution, avoiding single main channel over-driving and extending device lifespan. In terms of energy consumption, CEMMO reduces overall channel activation intensity, with system average energy consumption decreasing by approximately 5.8% [10]. Table 4 shows the comparison of different systems in channel utilization and energy consumption.

Table 4. Energy Efficiency Comparison of Different Systems.

Metric	RGB System	CEMMO System	Improvement
Average Channel Utilization	33.3%	20.0%	-40.0%
Peak Channel Utilization	100%	87.2%	-12.8%
Relative Energy Consumption	100%	94.2%	-5.8%

This solution achieves visual energy efficiency ratio improvement while reducing brightness redundancy through optimized channel synergistic activation mechanisms, providing an effective path for low-power color control. Results show that under the same brightness output conditions, the five-channel system actually reduces total energy consumption by approximately 5.8%. This is mainly attributed to lower average channel utilization (20.0% vs. 33.3%) and lower peak channel utilization (87.2% vs. 100%).

4.5. Visualization Comparison and Subjective Consistency

Display image comparisons show that CEMMO outperforms traditional RGB mapping in edge color transitions, skin tone reproduction, and dark detail performance. ΔE heat maps show that under the CEMMO solution, 95% of pixel points have color differences controlled below 1.2, reaching visually indistinguishable levels. From a perceptual perspective, CEMMO not only optimizes the average performance of system response but also significantly reduces extreme color differences in local regions, with overall images presenting more natural consistency.

Through structural analysis of the optimal mapping matrix, we find:

(1) Diagonal dominance—the first three rows of the matrix exhibit obvious diagonal dominance characteristics, indicating that RGB main channel mapping maintains high fidelity;

(2) Channel synergy—C channel is mainly contributed by G and B channels, conforming to the physical fact that cyan is a green-blue mixture; X channel is mainly contributed by R channel, conforming to the characteristic that yellow contains more red components;

(3) Distributed contribution of V channel—luminance information is dispersedly utilized, enhancing the system's adaptability to brightness changes;

(4) Sparsity—the matrix contains many elements close to zero, beneficial for improving system energy efficiency and computational speed.

Comprehensive analysis shows that CEMMO outperforms traditional three-channel solutions in color accuracy, color gamut expansion, system energy consumption, and channel balance, validating its efficiency and practicality in visual presentation tasks.

5. Conclusion

In this research, we proposed a color mapping optimization framework for multi-channel LED display systems—CEMMO (Color-Enhanced Multi-channel Mapping Optimization). This method effectively addresses the structural bottlenecks of traditional RGB systems in color reproduction accuracy and high-saturation color gamut expression by constructing a mapping structure from four-channel input (RGBV) to five-channel output (RGBCX), introducing linear mapping models and multi-objective optimization mechanisms, and jointly considering color fidelity, color gamut geometric coverage, channel balance, and energy efficiency control. CEMMO, as an optimization strategy that integrates perception-driven and geometric modeling, maintains mapping function linear controllability and engineering implementation friendliness while improving color quality.

Experimental results validate the effectiveness of the CEMMO algorithm: in color reproduction accuracy, average CIEDE2000 color difference decreased by 23.6%, with improvement rates exceeding 35% particularly in yellow and cyan mixed color regions; in color gamut expansion, color gamut coverage area increased by 5.2%, color gamut volume expanded by 19.4%, and color gamut saturation gain reached 15.9%; in system energy efficiency, average energy consumption decreased by 5.8% through optimized channel synergistic activation mechanisms, while achieving better channel balance.

Although CEMMO achieves significant success in multi-channel control, there still exists expansion space in the following aspects:

(1) Nonlinear modeling enhancement—current adoption of linear mapping could be enhanced by introducing neural networks or kernel methods to handle complex spectral responses in the future;

(2) End-to-end learnable structure—integrating deep learning to achieve end-to-end optimization strategies from input images to control channels;

(3) Adaptive channel configuration mechanism—dynamically adjusting channel activation structures based on image regions or scene content;

(4) Cross-device transfer modeling—enhancing model adaptability to different LED physical properties and photosensitive environments. Future work will focus on upgrading CEMMO from a static mapping system to a dynamic multi-channel color engine with content awareness and adaptive control capabilities.

The CEMMO method, based on precise modeling and targeting perceptual optimization, achieves high balance between color reproduction and system efficiency, marking a key step in the transformation path from "three-primary-driven" to "multi-channel intelligent mapping". This research provides theoretical foundation and practical solutions for color management in multi-channel LED display systems, with significant academic value and engineering application prospects.

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