

Color Crosstalk and Gamma Distortion in Space-Time-Color Screen-to-Camera Communications

Leandro R. Ximenes and Miguel S. Pinheiro

Abstract—Screen-to-camera (S2C) communication is a promising solution for low-cost optical wireless links using commercial displays and cameras. However, hardware non-idealities, such as color crosstalk and gamma nonlinearity, are present in practical screen-camera systems and remain poorly investigated in terms of link performance. This paper incorporates these impairments into a third-order parallel factor (PARAFAC)-based model for multi-color S2C links. Color crosstalk appears as a multiplicative matrix affecting one decomposition factor, while gamma distortion acts nonlinearly on the other factors. Simulations show that crosstalk causes an SNR penalty, gamma alters SER decay, and their combined effect limits high-SNR performance.

Keywords—Screen-to-Camera Communication, Color Crosstalk, Gamma Nonlinearity

I. INTRODUCTION

As the demand for high-speed and interference-free wireless connectivity accelerates towards the 6G era, optical wireless communications have emerged as a pivotal technology to complement crowded radio-frequency (RF) spectra [1]. Within this domain, optical camera communication (OCC) has gained significant traction due to its ability to leverage ubiquitous image sensors as receivers [2]. By embedding data into visible light sources, OCC provides a low-cost, secure, and easily deployable framework for pervasive connectivity in indoor environments and Internet of Things (IoT) ecosystems, forming a critical component of next-generation wireless networks [3], [4].

A highly promising yet underexplored branch of OCC is screen-to-camera (S2C) communication [5]. Unlike traditional visible light communication (VLC) systems that require dedicated LED infrastructure, S2C utilizes existing commercial digital displays (such as monitors, smartphones, and digital signage) as transmitters. This ubiquitous infrastructure paradigm enables screens to function as dual-purpose devices, simultaneously displaying multimedia content for human viewers and transmitting high-rate data to mobile camera receivers [6]. Consequently, S2C offers unparalleled deployment flexibility without the need for additional hardware installation.

Leandro R. Ximenes, Faculdade de Tecnologia (FT), Universidade Estadual de Campinas (UNICAMP), Limeira-SP, e-mail: ronchini@unicamp.br; Miguel S. Pinheiro, Faculdade de Tecnologia (FT), Universidade Estadual de Campinas (UNICAMP), Limeira-SP, e-mail: m239209@dac.unicamp.br. This study was financed, in part, by the São Paulo Research Foundation (FAPESP), Brasil, Process Number #2025/28270-9, by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, and by the Programa de Pós-Graduação em Tecnologia (PPGT/FT/UNICAMP).

Despite its immense potential, practical S2C links suffer from severe physical and hardware non-idealities that compromise data recovery. While optical blurring is a well-documented impairment extensively addressed in the literature [5], [7], other phenomena pose critical bottlenecks, especially in multi-color systems. Color crosstalk, or the spectral leakage between adjacent color bands, is a known adversity in standard VLC systems that drastically reduces channel orthogonality [8], [9]. Furthermore, commercial displays inherently apply gamma correction, a non-linear amplitude distortion engineered exclusively to enhance human visual perception. This correction severely distorts the linear mapping of pixel intensities, fundamentally degrading data communication tasks.

To overcome limitations regarding data rates and perceptual flickering in S2C links, different tensor-based schemes have been proposed [5], [10], [11]. The most recent one, the Screen-to-Camera Color-Hopping Space-Time (S2C-CHST) scheme [11], is a pioneering framework that proposes a multidimensional tensor modeling for S2C systems using color-shift keying (CSK) modulation. This unique architecture provides robust space-time-color diversity and enables flicker-free, high-order color modulation in tensor-based S2C, a domain previously restricted to grayscale intensity modulations.

Therefore, the objective of this paper is to analyze and quantify the combined impacts of gamma correction and color crosstalk within the tensor-based S2C-CHST framework. The main contributions of this work include: 1) incorporating color crosstalk and display gamma nonlinearity into a unified tensor-based S2C-CHST framework; 2) proposing Proposition 1 as a novel theoretical formulation to resolve scaling ambiguities in the gamma domain; and 3) evaluating system SER performance under combined hardware impairments compared to state-of-the-art benchmark schemes.

II. SYSTEM MODEL

We consider the unified framework of the S2C-CHST scheme [11]. Within this framework, the screen transmitter is equipped with L_T LEDs of K_T color channels, and the camera receiver has L_R photodiodes (PDs) of K_R color channels (e.g., $K_R = 3$ for red-green-blue sensors). Data transmission occurs across P permutation blocks, F video frames, and N symbol periods per LED. The received signal is collected into a third-order tensor $\mathcal{Y} \in \mathbb{R}^{K_R \times P \times L_R \times F \times N}$. Without loss of generality, each receive pixel is associated with a single PD, while each transmit pixel is associated with one of the L_T screen LEDs.

Then, under linear space-invariant conditions, the system can be expressed through the following matrix model

$$\mathbf{Y} = \mathbf{H} (\mathbf{I}_{L_T} \otimes \mathbf{M}) (\mathbf{S} \diamond \mathbf{X})^T, \quad (1)$$

where $\otimes$ denotes the Kronecker product, $\diamond$ denotes the Khatri–Rao product, $\mathbf{H}$ is the diagonal channel matrix between screen and camera, $\mathbf{S}$ is the symbol matrix associated with the stream of N symbols per LED, and $\mathbf{X}$ represents the block of transmitted video content of F frames. In (1), $\mathbf{M}$ represents a permutation block matrix, not evaluated in this paper – see [11], [12] for more details. In addition, all matrices have real-valued entries, as they deal with pixel intensities or intensity-modulated signals.

The model admits a third-order parallel factor (PARAFAC) decomposition given by

$$\mathcal{Y} = \mathcal{I}_{K_T L_T} \times_1 \mathbf{H} (\mathbf{I}_{L_T} \otimes \mathbf{M}) \times_2 \mathbf{S} \times_3 \mathbf{X}, \quad (2)$$

where $\times_n$ is the mode- n product [13], and $\mathcal{I}_{K_T L_T}$ is a third-order identity tensor, with K_T being the number of screen LED colors (typically $K_T = K_R$).

This compact formulation preserves the multilinear structure of the problem and allows the use of tensor factorization techniques for joint channel, symbol, and video estimation.

However, practical S2C systems are affected by several hardware impairments introduced by both the display and camera devices. Among the most relevant impairments are spectral coupling between color channels (e.g., color crosstalk) and nonlinear intensity distortions. In the following sections, these effects are progressively incorporated into (2).

III. COLOR CROSSTALK IN THE EFFECTIVE CHANNEL

In practical screen-to-camera systems, neither the transmitter LEDs nor the receiver color filters exhibit ideally narrowband spectral responses. As a result, the transmitted color components are not perfectly separated at the receiver due to spectral overlap between the display primaries and the camera color filters [8]. This effect, known as color crosstalk, introduces coupling among color channels and affects CSK-based transmission.

To account for this effect, we define a color crosstalk matrix $\mathbf{C}_T \in \mathbb{R}^{K_T \times K_T}$ acting on the transmit color components as

$$\mathbf{C}_T = \begin{bmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,K_T} \\ c_{2,1} & c_{2,2} & \cdots & c_{2,K_T} \\ \vdots & \vdots & \ddots & \vdots \\ c_{K_T,1} & c_{K_T,2} & \cdots & c_{K_T,K_T} \end{bmatrix}, \quad (3)$$

where $c_{i,j}$ represents the contribution of the transmitted color component j to the received color i , with $i, j = 1, \dots, K_T$.

Since the S2C-CHST scheme expands the signal across P permutation blocks and L_T LEDs, the crosstalk must be applied independently to each of these blocks. Therefore, the original channel term in (1) is replaced by the following effective channel

$$\mathbf{H}_e = \mathbf{H} (\mathbf{I}_{P L_T} \otimes \mathbf{C}_T) (\mathbf{I}_{L_T} \otimes \mathbf{M}). \quad (4)$$

In the particular case of absence of symbol permutation ($P = 1$), then $\mathbf{M} = \mathbf{I}_{K_T}$, and (4) reduces to

$$\mathbf{H}_e = \mathbf{H} (\mathbf{I}_{L_T} \otimes \mathbf{C}_T), \quad (5)$$

and $\mathbf{H}_e$ is a diagonal matrix (i.e., without color crosstalk) if and only if $\mathbf{C}_T$ is also diagonal.

This simplified expression shows that color crosstalk can be modeled as a multiplicative matrix embedded in the effective channel. Therefore, it represents an aggregate spectral mixing effect that may arise from the display color primaries, the camera color filters, or both. The separation between $\mathbf{H}$ and $\mathbf{C}_T$ is adopted to distinguish geometric propagation effects from color-domain coupling, which is treated independently of the link geometry.

For the conventional RGB case, $K_T = 3$, and $\mathbf{C}_T$ reduces to

$$\mathbf{C}_T = \begin{bmatrix} c_{R,R} & c_{R,G} & c_{R,B} \\ c_{G,R} & c_{G,G} & c_{G,B} \\ c_{B,R} & c_{B,G} & c_{B,B} \end{bmatrix}, \quad (6)$$

where, for example, $c_{R,G}$ represents the leakage of the transmitted green component into the received red component.

A commonly adopted parametric model for RGB color crosstalk is given by

$$\mathbf{C}_T = \begin{bmatrix} 1 - \varepsilon & \varepsilon & 0 \\ \varepsilon & 1 - 2\varepsilon & \varepsilon \\ 0 & \varepsilon & 1 - \varepsilon \end{bmatrix}, \quad (7)$$

where $\varepsilon \in [0, 0.5]$ controls the level of spectral leakage between adjacent color channels [8], [9], [14]. In this model, the main diagonal represents the desired signal contribution, while the off-diagonal terms capture inter-channel interference. This structure reflects a practical scenario in which crosstalk is stronger between spectrally adjacent components (e.g., red–green and green–blue), while non-adjacent leakage (red–blue) is negligible.

Although color crosstalk modifies the effective channel response, the system model remains linear with respect to the tensor factors. While (7) captures dominant adjacent spectral leakage, commercial devices may exhibit asymmetric crosstalk due to manufacturing tolerances and wavelength-dependent sensor responsivities. Nevertheless, (7) provides a tractable realistic model for performance evaluation. Practical S2C systems are also affected by nonlinear distortions introduced by display and camera processing stages, as discussed next.

IV. GAMMA NONLINEARITY

The optical signal emitted by the display may undergo nonlinear intensity transformations due to the display electro-optical response [15]. Although this nonlinear response is intentionally introduced to improve perceptual brightness rendering, it produces a nonlinear mapping between the input digital color levels and the emitted optical intensities. This effect, commonly referred to as gamma nonlinearity, is modeled here as an equivalent nonlinear distortion applied before propagation through the optical channel.

Let $\Gamma(\cdot)$ denote an element-wise nonlinear mapping. Since the transmitted (encoded) signal in (1) is given by $(\mathbf{S} \diamond \mathbf{X})$, the gamma distortion acts on this term as

$$\Gamma(\mathbf{S} \diamond \mathbf{X}) = (\mathbf{S} \diamond \mathbf{X})^{\circ\gamma}, \quad (8)$$

where $(\cdot)^{\circ\gamma}$ denotes element-wise exponentiation with exponent $\gamma > 0$. The particular case $\gamma = 1$ corresponds to the linear model without gamma distortion, whereas commercial display systems commonly exhibit nonlinear gamma responses with typical values around $\gamma \in [2.2, 2.4]$ [15]. While standard color spaces (such as sRGB [15]) define a piecewise function with a linear segment near zero, the pure power-law model in (8) is widely adopted as a close analytical approximation.

Therefore, the input-output relation in (1) becomes

$$\mathbf{Y} = \mathbf{H}_e (\Gamma(\mathbf{S} \diamond \mathbf{X}))^T \quad (9)$$

$$= \mathbf{H}_e ((\mathbf{S} \diamond \mathbf{X})^{\circ\gamma})^T, \quad (10)$$

where $\mathbf{H}_e$ is defined in (4).

It is important to note that this operation breaks the strict multilinearity of the PARAFAC model in (2), since the nonlinearity falls on factors $\mathbf{S}$ and $\mathbf{X}$.

However, despite the loss of multilinearity in the original domain, it is still possible to derive an equivalent multilinear representation in the transformed domain. To show this, let $\mathbf{s}_k$ and $\mathbf{x}_k$ denote the k -th columns of $\mathbf{S}$ and $\mathbf{X}$, respectively. Then, by definition of the Khatri-Rao product,

$$\mathbf{S} \diamond \mathbf{X} = [\mathbf{s}_1 \otimes \mathbf{x}_1 \quad \cdots \quad \mathbf{s}_{K_T L_T} \otimes \mathbf{x}_{K_T L_T}]. \quad (11)$$

Applying the element-wise gamma operation gives

$$(\mathbf{S} \diamond \mathbf{X})^{\circ\gamma} = [(\mathbf{s}_1 \otimes \mathbf{x}_1)^{\circ\gamma} \quad \cdots \quad (\mathbf{s}_{K_T L_T} \otimes \mathbf{x}_{K_T L_T})^{\circ\gamma}]. \quad (12)$$

Since the Kronecker product is formed by products between elements of $\mathbf{s}_k$ and $\mathbf{x}_k$, we have

$$(\mathbf{s}_k \otimes \mathbf{x}_k)^{\circ\gamma} = \mathbf{s}_k^{\circ\gamma} \otimes \mathbf{x}_k^{\circ\gamma}, \quad (13)$$

because $(ab)^\gamma = a^\gamma b^\gamma$ for nonnegative a and b . The nonnegative condition is satisfied because both $\mathbf{S}$ and $\mathbf{X}$ have only positive real-valued entries.

Therefore,

$$(\mathbf{S} \diamond \mathbf{X})^{\circ\gamma} = \mathbf{S}^{\circ\gamma} \diamond \mathbf{X}^{\circ\gamma}. \quad (14)$$

Consequently, the gamma-distorted input-output relation can be rewritten as

$$\mathbf{Y} = \mathbf{H}_e (\mathbf{S}^{\circ\gamma} \diamond \mathbf{X}^{\circ\gamma})^T. \quad (15)$$

Accordingly, the equivalent tensor representation in the gamma domain becomes

$$\mathcal{Y} = \mathcal{I}_{K_T L_T} \times_1 \mathbf{H}_e \times_2 \mathbf{S}^{\circ\gamma} \times_3 \mathbf{X}^{\circ\gamma}, \quad (16)$$

which allows the use of the PARAFAC decomposition in the transformed domain despite the nonlinear distortion.

In addition, assuming perfect knowledge of $\mathbf{H}_e$, the PARAFAC model in (16) does not present permutation ambiguity [16]. Therefore, only column-wise scaling ambiguities remain between $\mathbf{S}^{\circ\gamma}$ and $\mathbf{X}^{\circ\gamma}$, i.e.,

$$\hat{\mathbf{S}}^{\circ\gamma} = \mathbf{S}^{\circ\gamma} \Delta_\gamma, \quad (17)$$

$$\hat{\mathbf{X}}^{\circ\gamma} = \mathbf{X}^{\circ\gamma} \Delta_\gamma^{-1}, \quad (18)$$

where Δ_γ is a nonsingular diagonal matrix.

As a novel theoretical contribution of this work, the following proposition formalizes the resolution of these scaling ambiguities by the receiver:

Proposition 1: Assume that $\mathbf{H}_e$ is known at the receiver. In this case, the estimated factors $\hat{\mathbf{S}}$ and $\hat{\mathbf{X}}$ are determined up to diagonal scaling ambiguities, according to

$$\hat{\mathbf{S}} = \mathbf{S} \Delta_S, \quad (19)$$

$$\hat{\mathbf{X}} = \mathbf{X} \Delta_S^{-1}, \quad (20)$$

where Δ_S is a nonsingular diagonal matrix. Assume also that γ is known and that the first row of $\mathbf{S}$ is fixed as a reference row with all entries equal to one, i.e.,

$$\mathbf{S}_{1,\cdot} = \mathbf{1}_{1 \times K_T L_T}. \quad (21)$$

Under these assumptions, the scaling ambiguity associated with $\mathbf{S}$ and $\mathbf{X}$ can be uniquely identified from the first row of $\hat{\mathbf{S}}^{\circ\gamma}$ and removed by applying

$$\Delta_S^{-1} = [\text{diag}(\hat{\mathbf{S}}_{1,\cdot}^{\circ\gamma})]^{-1/\gamma}. \quad (22)$$

Proof: From $\hat{\mathbf{S}} = \mathbf{S} \Delta_S$, and since Δ_S is diagonal, each column of $\mathbf{S}$ is scaled by one scalar factor. Therefore, applying the element-wise gamma transformation gives

$$\hat{\mathbf{S}}^{\circ\gamma} = (\hat{\mathbf{S}})^{\circ\gamma} = \mathbf{S}^{\circ\gamma} (\Delta_S)^{\circ\gamma}. \quad (23)$$

Comparing (23) with the ambiguity term in (17), we obtain

$$\Delta_\gamma = \Delta_S^{\circ\gamma}. \quad (24)$$

Therefore,

$$\Delta_S = \Delta_\gamma^{1/\gamma}. \quad (25)$$

Using the reference row in (21), the corresponding row of $\hat{\mathbf{S}}^{\circ\gamma}$ contains only the diagonal scaling factors, namely

$$\hat{\mathbf{S}}_{1,\cdot}^{\circ\gamma} = \mathbf{1}_{1 \times K_T L_T} \Delta_\gamma, \quad (26)$$

Hence, the diagonal matrix Δ_γ is directly obtained from this row as

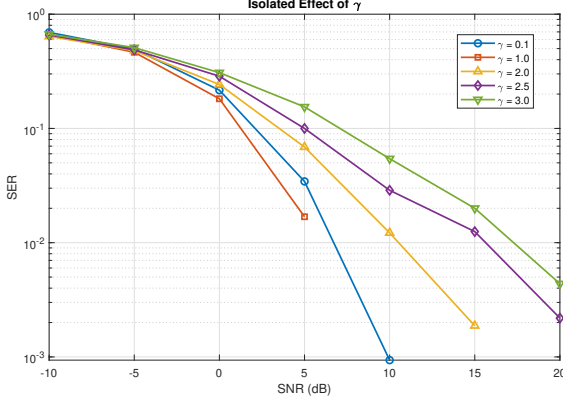
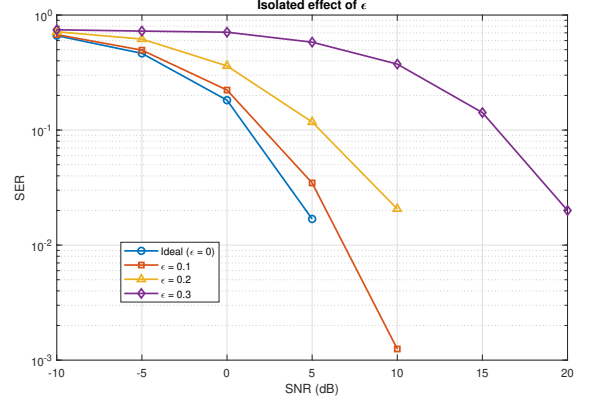
$$\Delta_\gamma = \text{diag}(\hat{\mathbf{S}}_{1,\cdot}^{\circ\gamma}). \quad (27)$$

Finally, from (25), the scaling ambiguity associated with $\mathbf{S}$ is compensated by applying (22). ■

V. PERFORMANCE EVALUATION

This section evaluates the S2C-CHST system proposed in [11] under the effects of display gamma distortion and color crosstalk, both modeled in this paper.

The system parameters are set as follows: $P = 1$ (i.e., absence of symbol permutation in the CHST scheme), $N = 10$ transmitted symbols per LED, $L_R = 16$ PD arrays and $L_T = 16$ LED arrays operating with RGB colors ($K_R = K_T = 3$), and 4-CSK modulation. The performance is assessed through MATLAB-based Monte Carlo simulations with 100 independent realizations, where each realization corresponds to one transmitted video block with synthetically generated


 Fig. 1. Isolated effect of γ correction on the S2C-CHST system performance.

 Fig. 2. Isolated effect of color crosstalk (ϵ) on the SER performance.

video data, resulting in a total of $NL_T = 160$ transmitted symbols per realization.

The channel matrix $\mathbf{H}$ was assumed to be ideal, i.e., $\mathbf{H} = \mathbf{I}$, in order to isolate the effects of gamma distortion and color crosstalk. Symbol detection was performed using the AO-KRF algorithm proposed in [11], with ambiguity removal according to Proposition 1. The transmitted video content was synthetically generated, with RGB pixel intensities independently drawn from a uniform distribution over $[0, 1]$.

As $\mathbf{Y}$ is the noise-free received signal, the noisy observation is given by $\tilde{\mathbf{Y}} = \mathbf{Y} + \mathbf{N}$, where $\mathbf{N} \sim \mathcal{N}(0, \sigma_n^2 \mathbf{I})$ denotes additive white Gaussian noise (AWGN), and $\mathbf{I}$ is the identity matrix. Thus, the signal-to-noise ratio (SNR) is defined as

$$\text{SNR}_{\text{dB}} \triangleq 10 \log_{10} \left(\frac{\|\mathbf{Y}\|_F^2}{F N K_R P L_R \sigma_n^2} \right), \quad (28)$$

where $\|\cdot\|_F^2$ denotes the Frobenius norm.

The simulations evaluate the Symbol Error Rate (SER) by sweeping the SNR from -10 dB to 20 dB, testing varying numbers of video frames ($F \in \{5, 10\}$), gamma correction values ($\gamma \in \{0.1, 1.0, 2.0, 2.5, 3.0\}$), and crosstalk factors ($\epsilon \in \{0, 0.1, 0.2, 0.3\}$).

For the analysis of gamma in Fig. 1, no color crosstalk is considered, i.e., $\epsilon = 0$, while the gamma exponent γ is varied. The ideal configuration without distortion ($\gamma = 1.0$) achieves the lowest SER. In contrast, deviations from this ideal state (e.g., $\gamma = 0.1$ or $\gamma > 1$) progressively degrade signal recovery. This behavior was intuitively expected, since gamma distortion introduces an amplitude nonlinearity that modifies the relative distances among transmitted symbols, thereby impairing symbol decision.

Next, with the gamma response kept linear ($\gamma = 1.0$), Fig. 2 shows the isolated effect of color crosstalk. As ϵ increases from 0 to 0.3 , the off-diagonal entries of $\mathbf{C}_T$ in (7) become more pronounced, which worsens the conditioning of the effective channel matrix $\mathbf{H}_e$ and affects the orthogonality among its color subchannels. Notably, for this set of simulations, this impairment mainly produces a rightward shift in the SER curves, indicating that a higher SNR is required to maintain a target SER performance.

Finally, to understand the interaction between both impairments, Fig. 3 compares the ideal scenario ($\gamma = 1.0, \epsilon = 0$), the

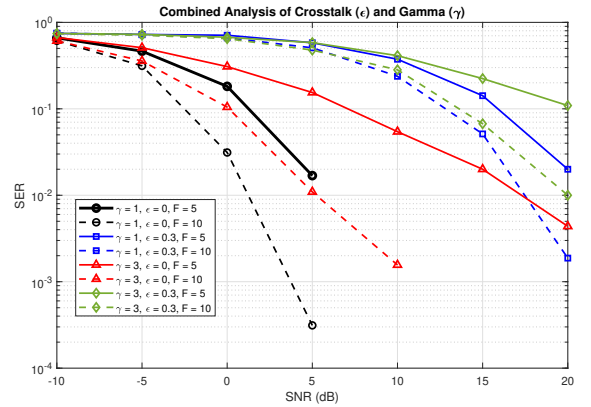


Fig. 3. Combined analysis of color crosstalk and gamma correction.

severe isolated cases ($\gamma = 3.0$ or $\epsilon = 0.3$), and the combined worst-case scenario ($\gamma = 3.0, \epsilon = 0.3$). Across all evaluated conditions, increasing the number of video frames from $F = 5$ to $F = 10$ consistently improves the SER by providing greater temporal diversity.

An isolated analysis reveals distinct degradation mechanisms. Color crosstalk primarily affects the system's SNR gain, observed as a severe rightward shift of the curves. While color mixing inherently reduces the color diversity order, the dominant effect remains the substantial SNR penalty required to overcome spectral overlap. Conversely, gamma correction fundamentally alters the SER decay rate. As depicted by the curves for $\gamma = 3.0$, the non-linearity flattens the slope of the error curve in relation to the SNR.

Consequently, the criticality of these impairments depends heavily on the operational regime. In low-SNR environments (e.g., long-distance optical links), color crosstalk might act as an important bottleneck. However, in high-SNR regimes typical of standard short-range S2C communications, although isolated crosstalk remains severe, it is the combined effect of both crosstalk and the non-linearity dictated by the γ parameter that becomes the dominant limiting factor. Because this combined distortion severely degrades the rate of error decay, it restricts the system's ability to efficiently reach low error floors at higher transmission powers.

Figure 4 compares the SER performance of the S2C-

CHST scheme using 4-CSK modulation with the benchmark scheme of Kim et al. [17] using 4-level pulse amplitude modulation (4-PAM) under different values of γ . The results show that gamma nonlinearity degrades the performance of both schemes, as expected. However, the proposed S2C-CHST scheme achieves lower SER for most evaluated SNR values. This behavior indicates that its space-time-color structure provides additional robustness against nonlinear intensity distortions when compared with a conventional amplitude-based modulation scheme.

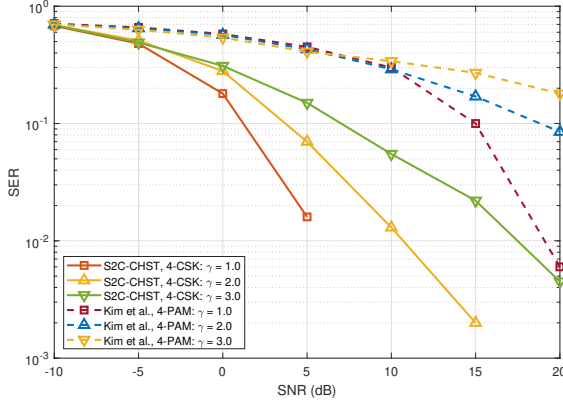


Fig. 4. SER comparison between the S2C-CHST scheme and Kim et al. [17] with 4-PAM modulation under different gamma nonlinearity levels.

Figure 5 now compares the SER performance of the S2C-CHST scheme with the scheme of Dong et al. [8] under different ϵ and the same CSK modulation. For all evaluated values of ϵ , the proposed S2C-CHST approach achieves lower SER than the benchmark, especially visible in the moderate-to-high SNR region. This improvement is attributed to the additional (time-color) diversity provided by S2C-CHST.

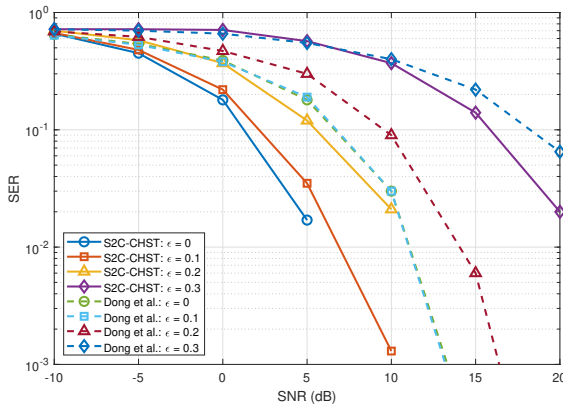


Fig. 5. SER comparison between the proposed S2C-CHST scheme and the benchmark scheme of Dong et al. [8] under different color crosstalk levels.

VI. CONCLUSIONS

This work investigated the impact of color crosstalk and gamma nonlinearity on tensor-based S2C-CHST communications. Color crosstalk was embedded into the effective channel as a multiplicative matrix, while gamma distortion was shown to preserve a multilinear structure in the transformed domain,

enabling the continued use of PARAFAC-based estimation. A closed-form procedure for resolving the resulting scaling ambiguities was derived and formalized in Proposition 1.

Simulation results revealed distinct degradation mechanisms: crosstalk primarily incurs an SNR penalty, whereas gamma nonlinearity reduces the effective diversity gain by flattening the SER decay slope. In high-SNR regimes, their combined effect emerges as the dominant bottleneck, underscoring the need for joint compensation strategies. Furthermore, S2C-CHST consistently outperformed state-of-the-art benchmarks under both impairments, confirming that its space-time-color diversity structure provides inherent robustness for practical screen-to-camera deployments. Validating the proposed framework on a real-world testbed with commercial displays and mobile cameras under spatial alignment and rolling shutter effects remains an important topic for future research.

REFERENCES

- [1] Z. Zhang et al., "6G wireless networks: Vision, requirements, architecture, and key technologies," *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 28–41, Sep. 2019.
- [2] N. Saeed et al., "Optical camera communications: Survey, use cases, challenges, and future trends," *Phys. Commun.*, vol. 37, Art. no. 100900, 2019.
- [3] A. Liu et al., "Design guidelines for optical camera communication systems: A tutorial," *IEEE Photon. J.*, vol. 16, no. 4, Art. no. 7303025, Aug. 2024.
- [4] *IEEE Standard for Local and Metropolitan Area Networks – Part 15.7: Short-Range Optical Wireless Communications Amendment 1: Higher Rate, Longer Range Optical Camera Communication (OCC)*, IEEE Std 802.15.7a-2024, Feb. 2025.
- [5] L. R. Ximenes and M. F. Alves, "Tensor-based screen-to-camera communications," *IEEE Commun. Lett.*, vol. 27, no. 10, pp. 2787–2791, Oct. 2023.
- [6] T. Nguyen et al., "Technical issues on IEEE 802.15.7m image sensor communication standardization," *IEEE Commun. Mag.*, vol. 56, no. 2, pp. 213–218, Feb. 2018.
- [7] A. Liu, W. Shi, M. Ouyang, and W. Liu, "Characterization of optical camera communication based on a comprehensive system model," *J. Lightw. Technol.*, vol. 40, no. 18, pp. 6087–6100, Sep. 2022.
- [8] J.-M. Dong, Y.-J. Zhu, and Z.-G. Sun, "Adaptive multi-color shift keying constellation design for visible light communications considering lighting requirement," *Opt. Commun.*, vol. 430, pp. 293–298, 2019.
- [9] Y. Zuo and J. Zhang, "Energy-efficient optimization design for the multi-color LED based visible light communication systems under illumination constraints," *Appl. Sci.*, vol. 9, no. 1, Art. no. 1, 2019.
- [10] L. R. Ximenes, B. A. Laredo, and R. Arthur, "Integrated data detection and video restoration for optical camera communications," *Digit. Signal Process.*, vol. 141, Art. no. 104192, 2023.
- [11] L. R. Ximenes, I. S. C. Rodrigues, and M. S. Pinheiro, "Space-time-color scheme for screen-to-camera communications," *IEEE Commun. Lett.*, vol. 30, pp. 507–511, 2026.
- [12] I. S. C. Rodrigues et al., "Color-selective channel modeling for visible light communication (VLC)," *IEEE Access*, vol. 13, pp. 134758–134771, 2025.
- [13] T. G. Kolda and B. W. Bader, "Tensor decompositions and applications," *SIAM Rev.*, vol. 51, no. 3, pp. 455–500, 2009.
- [14] Q. Gao, C. Gong, and Z. Xu, "Joint transceiver and offset design for visible light communications with input-dependent shot noise," *IEEE Trans. Wireless Commun.*, vol. 16, no. 5, pp. 2736–2747, May 2017.
- [15] International Electrotechnical Commission, *IEC 61966-2-1: Multimedia Systems and Equipment – Colour Measurement and Management – Part 2-1: Default RGB Colour Space – sRGB*, IEC 61966-2-1, 1999.
- [16] N. D. Sidiropoulos, L. De Lathauwer, X. Fu, K. Huang, E. E. Papalexakis, and C. Faloutsos, "Tensor decomposition for signal processing and machine learning," *IEEE Trans. Signal Process.*, vol. 65, no. 13, pp. 3551–3582, Jul. 2017.
- [17] S.-J. Kim, J.-W. Lee, D.-H. Kwon, and S.-K. Han, "Gamma function based signal compensation for transmission distance tolerant multilevel modulation in optical camera communication," *IEEE Photon. J.*, vol. 10, no. 5, pp. 1–7, Oct. 2018.