Metameric Modulation for Diffuse Visible Light Communications with Constant Ambient Lighting*

Pankil M. Butala, Jimmy C. Chau, Thomas D. C. Little
Department of Electrical and Computer Engineering
Boston University, Boston, Massachusetts
{*pbutala, jchau, tdcl*}@*bu.edu*

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Abstract–Advances in solid-state lighting are renewing interest in the adoption of the visible spectrum for optical wireless communications. Under the luminaire-as-transmitter model, wireless communication is achieved by modulating LED(s) that must simultaneously meet the illumination mission. Illumination requirements include maintaining energy efficiency, constant color and intensity control whereas communications requirements are speed and BER goals. In this paper we explore the perceptual qualities of visible light from LED luminaires to render color. We then propose a novel modulation scheme for visible light communications which can maintain constant perceived ambient lighting. By using D>3 LEDs, multiple lighting states that are indistinguishable to humans but are distinguishable to an electronic receiver can be achieved. Changes between these states are detected as intensity modulation in different wavelength bands.

Keywords–Visbile Light Communications (VLC), Color Shift Keying (CSK), IEEE 802.15.7, Optical Wireless Communications, CIE1931, tristimulus.

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1 Introduction

Over the past few years the quantity and use of mobile devices has dramatically increased, thus increasing the demand for ubiquitous access to wireless data. According to most estimates [1], advancements in radio frequency (RF) data transmission capacities will not keep up with this growth in demand. Thus there is a need to develop hybrid networks which can reduce the load on traditional wireless networks.

The visible spectrum is virtually untapped for wireless communications. Advancements in light emitting diode (LED) technology are making it commercially feasible to achieve wireless communication at high data rates with these devices. For indoor spaces, especially in restricted areas such as aircraft and hospitals, VLC is a promising modality for wireless data access with desirable characteristics.

A number of recent prototypes have been developed to demonstrate VLC [2–6]. These systems primarily focus on maximizing data rate and minimizing bit error rate (BER). For lighting applications, VLC-enabled luminaires must also be optimized for color stability and control, energy efficiency and human factors. Luminaires can be created with phosphor-converted white LEDs or with multiple LEDs that combine monochromatic light to produce white light. The latter technique can produce both a range of colors and color temperatures by varying the amounts of each constituent color. This controllability is desirable in lighting systems because it enables better matching of the lighting state to the human factors. This ability is also the basis for our proposed modulation scheme for VLC. Color Shift Keying (CSK) [7] also uses multispectral sources, however, we show that CSK has deficiencies with respect to color rendering that can create undesirable color and intensity fluctuations.

In this paper, we propose a new modulation technique for VLC that is optimized for lighting control and color rendering.

2 Human Eye And Color Perception

The human eye is a sensory organ that enables humans to perceive electromagnetic radiation in a subset of the optical spectrum. Figure 1 [8] shows the typical photopic relative luminous efficiency function of our visual system under moderate to higher levels of illumination. The retina in the eye contains sensory receptors called rods and cones. A normal human eye has three kinds of cones - short (S), medium (M) and long (L) based on the relative wavelengths that induce the peak response. Photons at different wavelengths are absorbed differently by the rods and the three sets of cones. Figure 2 [9] shows the normalized absorbance of photons by rods and cones over a range of wavelengths. The peak responses of the cones are 420nm, 534nm and 564nm while that of the rods is 498nm. Cones are responsible for color vision. Let $S_i(\lambda)$ denote their spectral responses to stimulus over a range of wavelengths. Optical stimulus with a spectral power distribution (SPD) $C(\lambda)$ will induce optical sensation α_S, α_M and α_L within the cones as described in (1).

$$\alpha_i = \int_0^\infty C(\lambda) S_i(\lambda) d\lambda \tag{1}$$

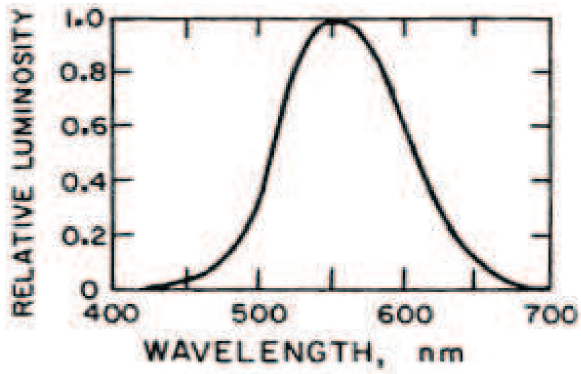

Figure 1: Typical Photopic Relative Luminous Efficiency Function. Ref. [8]

3 Proposed Metameric Modulation (MM)

Grassmann's laws [10] of color matching develop the theory behind the psychovisual color space spanned by cones in the human eye, henceforth called the visual color space (VCS). This space is a subspace of the infinite dimensional universal color space (UCS), which contains all possible SPDs. This observation leads to another interpretation of (1) - the point $[\alpha_S, \alpha_M, \alpha_L]$ is a projection of a given SPD $C(\lambda)$ onto the VCS. Thus it is possible for multiple different SPDs to project onto the same point within the VCS and produce the same sensations, $[\alpha_S, \alpha_M, \alpha_L]$, in the human eye. These SPDs are sensed as the same color by the human eye and are called metamerically equivalent.

Light from three independent primary light sources can be mixed in varying amounts to generate arbitrary colors. We call this resulting color space the primary color space (PCS). The projection of the PCS onto the VCS is called the color gamut of the primaries.

The purpose of metameric modulation is to encode data in the visible spectrum while maintaining a constant ambient lighting state. To achieve this, at the transmitter, we use multiple primary sets each capable of generating its own color gamut. If we have D sources and each primary set is rendered with 3 primary elements, there are $\binom{D}{3}$ possible primary sets. As the number of primary sets increases, the intersection of their color gamuts quickly approaches an empty set. However we select only N of the possible primary sets so that the intersection of their color gamuts contain all of the desired lighting states. Figure 3 shows an example for $D = 4$ and $N = 2$. The two sets of primaries, $[Blue, Cyan, Red]$ and $[Blue, Green, Red]$ have a significant overlap in their color gamuts. In this case they are capable of generating a set point with two different metameric SPDs.

MM requires detection and discrimination of multiple wavelengths at the receiver. The necessary photodiodes must be designed such that when different primaries are activated to generate a desired ambient color, the receiver can detect which primary set is active while the lighting state appears the same to the human eye. The following derivation details how this can be achieved.

Initially consider three independent light sources that form one set of primaries. Let each $L_k(\lambda)$ be the normalized emission spectra of the k^{th} of the three sources such that (2) holds.

$$\int_0^\infty L_k(\lambda) d\lambda = 1 \tag{2}$$

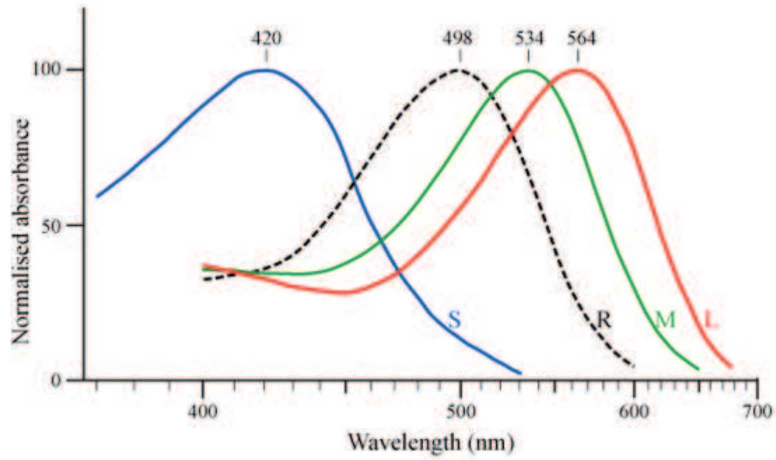

Figure 2: Normalized Absorbance of Photons by Rods and Cones. Ref. [9]

Let α_i^k (3) be the spectral response induced by the k^{th} primary on the i^{th} class of cones.

$$\alpha_i^k = \int_0^\infty L_k(\lambda) S_i(\lambda) d\lambda \tag{3}$$

Let $C(\lambda)$ be the SPD of the ambient color that we wish to maintain. Let each β_k be the amount of the corresponding $L_k(\lambda)$ needed to metamerically match $C(\lambda)$. Let $\alpha_i^{'}$ (4) be the aggregate response evoked by the primaries on the i^{th} class of cones. Grassmann's laws of color matching uphold the linearity property of color addition over a wide range of luminances. Our typical ambient illuminance levels lie well within this range of luminances.

$$\alpha_i^{'} = \sum_{k=1}^{3} \beta_k \alpha_i^k \tag{4}$$

The primaries must collectively evoke the same spectral responses in the human eye to match the color that is sensed due to $C(\lambda)$. Equating α_i in (1) with $\alpha_i^{'}$ in (4) $\forall i$ leads to the color matching equation (5). Solving for β_k gives the relative amount of each primary that is needed to achieve a metamerical match with $C(\lambda)$.

$$\sum_{k=1}^{3} \beta_k \int_0^\infty L_k(\lambda) S_i(\lambda) d\lambda = \int_0^\infty C(\lambda) S_i(\lambda) d\lambda \tag{5}$$

Let $W(\lambda)$ be the SPD of the reference white against which the LEDs are calibrated. Let w_k be the amount of $L_k(\lambda)$ needed to metamerically match $W(\lambda)$. Each tristimulus value, t_k, of each primary is defined in (6). Varying t_k for each primary changes the relative amount of the light output from each source that is mixed and thus changes color.

$$t_k = \beta_k / w_k \tag{6}$$

Now consider the case where we have N sets of primaries each with K (typically $K = 3$) sources. Let the individual emission spectra of the k^{th} source from the n^{th} set of primaries be

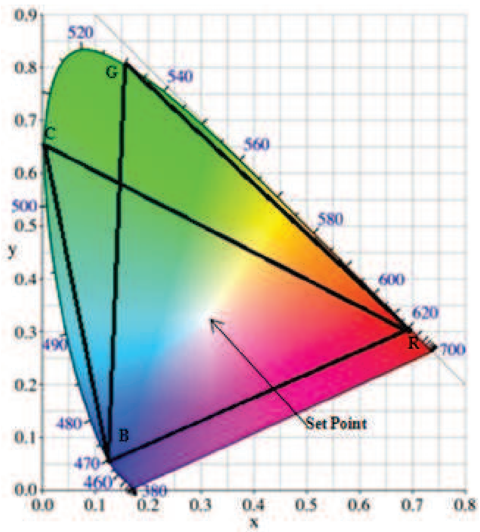

Figure 3: Example gamuts for metameric modulation with $N = 2$, $D = 4$ - B:Blue, C:Cyan, G:Green, R:Red overlayed on the CIE-XYZ chromaticity diagram

$L_k^n(\lambda)$. Now, let us assume we have P photodiodes selected as mentioned above. Let the photodiode spectral responses be $S_p^{'}(\lambda)$. When light from all sources of the n^{th} set of primaries is incident on the p^{th} photodiode, its current output, I_p^n, is given by (7).

$$I_p^n = \sum_{k=1}^{3} \beta_k \int_0^\infty L_k^n(\lambda) S_p^{'}(\lambda) d\lambda \tag{7}$$

For a given color, the response matrix R_g is given by (8). It is possible to design a system where every column of matrix R_g would be distinct. This system design is beyond the scope of this paper. By comparing the output of the photodiodes with the columns of R_g, the system can then detect which set of primaries is currently active.

$$R_g = \begin{pmatrix} I_1^1 & \cdots & I_1^N \\ \vdots & \ddots & \vdots \\ I_P^1 & \cdots & I_P^N \end{pmatrix} \tag{8}$$

The desired ambient lighting state can be specified by a point in the standard CIE-XYZ coordinate system for standard observer. For this given set point, the constellation diagram should be a set of unique points in the RCS which corresponds to the set point for each primary set. Table 1 shows

Primary Set Index	Symbol
1	00
2	01
3	10
4	11

Table 1: Metameric Channel Symbol Assignment

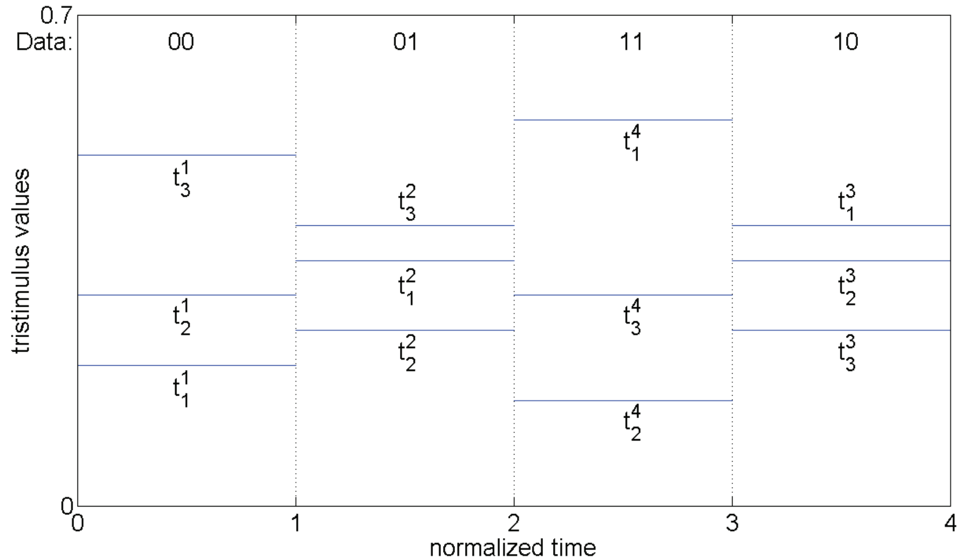

Figure 4: MM example timing diagram

symbol assignment for $N = 4$. Well known color space transforms can then be applied to specify the desired color within the N individual coordinate systems for each individual primary set. Let t_k^n be the tristimulus value of the k^{th} primary of the n^{th} primary set. These primary sets can now generate distinct but metamerically equivalent SPDs. Switching between the different primary sets generates the data stream.

Figure 4 illustrates MM using these primary sets to transmit a part of a data stream (00011110_2). This is accomplished by switching primaries in the order 1-2-4-3. This order can then be detected by analyzing the photodiode outputs and data can be decoded. The embedded MM modulation is invisible to humans due to metamerism.

4 Conclusion

In this paper we propose a new modulation scheme called Metameric Modulation for achieving constant color control in optical wireless communication using luminaires. This technique attempts to optimize color rendering for illumination while achieving wireless communication function.

MM offers several advantages over CSK. MM can achieve energy efficiency over CSK. In MM, to generate a set point, we can easily leverage MacAdams ellipses [11] to generate a color at a lower energy consumption point inside each ellipse. Such a technique cannot be applied to CSK because the average then would differ significantly from the set point. Additionally MM always generates the true requested ambient lighting state. The CSK constellation points always generate significantly different colors. Thus MM inherently has the ability to greatly reduce color flicker and improve color rendering. Like CSK, using multiple LEDs, the bandwidth of the system can exceed the signal bandwidth of the LED and thus can be scaled depending on the desired data rate.

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