# Improved Performance of Colour Shift Keying using Voronoi Segmentation for Indoor Communication

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***Abstract*— We analyze the performance of IEEE 802.15.7 colour shift keying (CSK) modulation for indoor visible-light optical wireless communication system. In CSK, the combined intensity of the R, G, and B of a white LED is held constant while their relative intensities vary. Design of multilevel CSK constellation for high bit rate transmission is a challenging problem. In this work, Voroni segmentation is employed for coding and decoding CSK constellation and system performance is analyzed. Monte Carlo simulation shows superiority of this method over other available CSK constellation design in terms of better received SNR for a given symbol error rate.**

***Index Terms*— LED, Voronoi Diagram, CSK Constellation**

## I. Introduction

Visible light communication (VLC) with direct detection is a viable medium for short range multimedia indoor wireless communication for the next generation wireless communication systems (4G) based on different complementary access technologies. VLC operates in eye safe visible light at wavelengths of 380 –780 nm via LEDs over an unregulated and available modulation bandwidth more than 100 MHz, without electromagnetic interference (EMI) to existing radio systems; moreover, it provides room illumination. White LEDs are expected to serve in the next generation of energy efficient lamps. Enabled by recent advances in LED technology, IEEE 802.15.7 supports high-data-rate visible light communication up to 96 Mb/s by fast modulation of optical light sources [1]. The IEEE 802.15.7 physical (PHY) types III speaks for colour shift keying (CSK) modulation which overcomes two main challenges faced by the conventional intensity modulation (IM) or pulse position modulation (PPM) in terms of flicker reduction and dimming support. Although pulse position modulation (PPM) provides the unparalleled power efficiency in line of sight (LOS) links but the performance degrades severely in dispersed communication channel using LEDs. Flicker mitigation is effective in CSK as the combined light illumination of R, G and B LEDs is held constant during transmission.

Designing higher order multilevel CSK constellation from these colour chromaticity is a challenging problem. Color-shift keying systems typically have a required operating color for the transmitter and colours are mapped from the CIE chromaticity curve. Few works have been done on mapping of CSK colours. Recently CSK constellation design is investigated by Eric Monteiro, and Steve Hranilovic [2] based on interior point methods [3]. The designed constellation is equivalent to the optimal packing of several disks in an equilateral triangle. In another work, Drost and Sadler [4] has designed CSK constellation employing "billiards algorithm" to solve an equivalent disk packing problem. The disadvantage of these schemes is that the non-overlapping packed circles always leave some empty spaces in between and when a received symbol point falls within the empty spaces the receiver can't decide which symbol was transmitted. To eliminate this drawback, in this work, Voronoi segmentation of an triangle of CIE chromaticity curve has been used. Advantage of Voronoi cell is that the region of the chromaticity triangle is fully divided according to the symbol points without any gap left in the triangle and hence design is more accurate.

## II. CSK Modulation and Demodulation

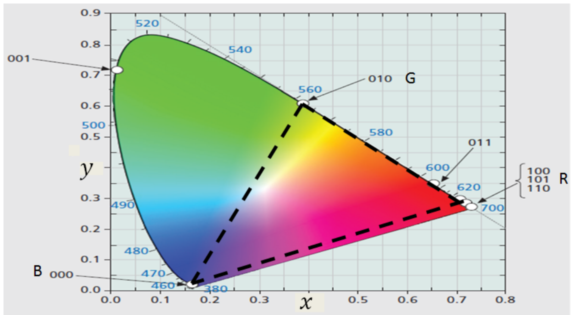


Fig.1 CIE 1931 colour space diagram [1] and constellation triangle

IEEE 802.15.7 defines seven colors bands with wavelengths (nm) defined in the periphery of the colour space as shown in Fig.1 Any three colour bands at least one from red $(x_R, y_R)$, green $(x_G, y_G)$ and blue $(x_B, y_B)$ forming a constellation triangle can be used for communication. Output white light illumination can be formed by mixing these three different colours red, green and blue. Combinations of powers of three different LEDs to form 16 different white light can be found from the IEEE 802.15-10-0724-00-0007 standard. For example, three color codes B (000) from blue region, G (010) from green region and R (101) from red region may be combined to form a CSK signal. Every point into the constellation triangle represents a CSK symbol. N –CSK symbols occupies within this triangle. These constellation points are represented by the chromaticity coordinate $(x_n, y_n)$ which are calculated as follows:

$$\begin{aligned} x_n &= (x_R L_{Rn} + x_G L_{Gn} + x_B L_{Bn})/(L_{Rn} + L_{Gn} + L_{Bn}) \\ y_n &= (y_R L_{Rn} + y_G L_{Gn} + y_B L_{Bn})/(L_{Rn} + L_{Gn} + L_{Bn}) \end{aligned} \quad (1)$$

Where $L$`s are the LED powers weighted by eye sensitivity factors which are given by [5]

$$\begin{aligned} L_{Rn} &= [\bar{x}(\lambda_R) + \bar{y}(\lambda_R) + \bar{z}(\lambda_R)]P_{Rn} \\ L_{Gn} &= [\bar{x}(\lambda_G) + \bar{y}(\lambda_G) + \bar{z}(\lambda_G)]P_{Gn} \\ L_{Bn} &= [\bar{x}(\lambda_B) + \bar{y}(\lambda_B) + \bar{z}(\lambda_B)]P_{Bn} \end{aligned} \quad (2)$$

Where $\bar{x}(.), \bar{y}(.)$ and $\bar{z}(.)$ are colors matching functions of human eye. $P_{Rn}, P_{Gn}$ and $P_{Bn}$ are respectively the R, G and B LED powers for the $n$ th constellation point. For constant illumination perceived by human eye we can use a constraint $L_{Rn} + L_{Gn} + L_{Bn}$ =1. Symbols can be decoded by detecting the powers R, G and B from three photo-detectors. From (1) and (2), $(x_n, y_n)$ corresponding to symbols can be derived.

## III. Propagation Model Using White LED Lights

In this work, we assumed that LED chip has a Lambertian radiation pattern. The LED chip is formed by 5x5 LEDs to provide sufficient illumination in the room. The equivalent discrete time baseband (X) channel (h) model under additive white Gaussian noise $n(t)$, can be given by

$$Y(t) = rX(t) * h(t) + n(t) \quad (3)$$

and the received signal power is

$$S = P_{rsig} = \int_0^T \left(\sum_{i=1}^{LEDS} h_i(t) * X(t)\right) dt \quad (4)$$

### *A. Evaluation of DC channel gain for direct and reflected light path*

Channel DC gain [6] for R, G and B LED link is given by

$$H_{R,G,B}(0) = (m+1)A_R/2\pi D_0^2 . \cos^m(\varphi_1) \; T_{R,G,B}(\lambda) G_{R,G,B}(\lambda) \cos(\alpha_1)\, rect(FOV) \quad (5)$$

Where $A_R$ is the physical area of detector, α is the angle of incidence, $D_0$ is the distance between LED and detector in meter, FOV is the Field Of View of the detector $T_{R,G,B}(\lambda)$ is the gain of an optical filter, and $G_{R,G,B}(\lambda)$ is the gain of an optical concentrator. Optical concentrator gain depends on refractive index (n) can be given by $G_{R,G,B}(\lambda) = n^2(\lambda)/\sin^2(FOV)$ . The channel DC gain of the reflected path is

$$dH_{R,G,B}{}_r^{Ref}(0) = (m+1)A_R/2\pi D_1^2 D_2^2 . \rho_{R,G,B}(\lambda)\, dA_{Wall} \cos^m \varphi_2 \; cos(\gamma)\, cos(\beta)\, T_{R,G,B}(\lambda) G_{R,G,B}(\lambda) \cos(\alpha_2)\, rect(FOV) \quad (6)$$

Here $\rho_{R,G,B}(\lambda)$ is reflectance, $\gamma$ is the incident angle, $\beta$ is reflected angle and $dA_{Wall}$ is the effective reflected area of the wall. The minimum and maximum received power all over the room for the direct light is respectively -17.43 dBm and -3.805 dBm and for the reflected light the values are -16.87 dBm to -3.745 dBm for the parameter shown in the Table-I. Received power distribution with in a room is shown in Fig. 2. The average received reflected power is 0.35 dBm higher than the directed light and VLC broadband communication is feasible with these power levels.

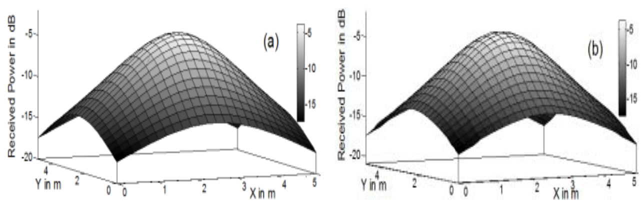


Fig. 2. Received red LED power for (a) direct light and (b) reflected light

## IV. Performance Analysis of CSK by Voronoi Method

We have analyzed here the performance of 16 CSK signal. Three color codes, namely (000), (010) and (101) have been chosen for communication. These three bands are the vertex points of a triangle which contain the chromaticity values of CSK symbols. We sectorize the whole triangular area into 16 small polygonal cells (with a single constellation inside each cell) using Voronoi diagram by employing Fortune's algorithm. The symbol points and the Voronoi diagram are shown in Fig. 3(a).

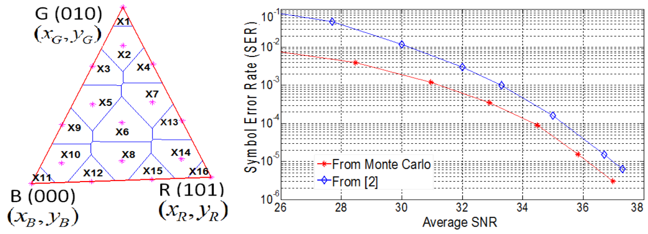


Fig. 3. (a) 16 CSK symbols and corresponding Voronoi cells (b) SER vs received signal to noise ratio

For 16-CSK modulation we place 16 constellation points within this triangle as per the IEEE standard 802.15-10-0724-00-0007. CSK modulation has been carried out using (1), (2). During reception the received power is calculated from (4) using (5) and (6). The symbol points $(x_n, y_n)$ is derived from (2) and (3). Receiver checks whether the received symbol point falls within a particular Voronoi cell and accordingly assign the fixed constellation point within that Voronoi cell as the received symbol. At the receiver if a received symbol point due to noise and ISI of the channel falls outside a Voronoi cell containing the corresponding transmitted symbol point then the receiver will not detect the symbol correctly resulting an error.

To find the symbol error rate (SER) for a particular signal-to-noise ratio we have used Monte Carlo simulation where each of the constellation points is transmitted individually 50000 times and each time checking is done whether the received symbol point has fallen within the associated Voronoi cell or not. This process is followed to all the 16 symbols and then average is taken to find the SER. Its plot with respect to the average SNR are shown by red dots in Fig. 3(b). SER corresponding to IEEE standard constellation points have been compared with [2] which are shown by blue squares in Fig. 3(b). Our method of designing constellation cells guarantees 1 dB advantage at SER $10^{-4}$ over the other method [2]. With optimization of CSK constellation points SER can be improved further.

Table-I

| | |
|---|---|
| Transmitted peak optical power | 1600 mW |
| Semi-angle at half power | 70 [deg] |
| Size of room | 5 m x 5m x 3m |
| Area of the detector | 1 $cm^2$ |
| Receiver *FOV* | 70 [deg] |

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