Merging Color Shift Keying and Complementary Pulse Position Modulation for Visible Light Illumination and Communication

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Abstract—The ever increasing need to be able to take advantage of broadband services without the need to increase the electromagnetic pollution, has led the scientific community, in recent years, to look for alternatives to the use of a radio frequency communication. From this, it stems the need of budding paradigm of visible light communications. In the context of the activities of the IEEE 802.15.7 Task Group, a new modulation format named Color Shift Keying (CSK), based on sending signals spaced in the domain of the wavelength able to both support the communication and the illumination of indoor environments has been tackled. In this paper, a transmission scheme based on the use of the CSK modulation which also makes use of a modulation format that descends from the Pulse Position Modulation (PPM) has been proposed. The aim of this contribution is also proposing the receiver architecture for that kind of transmission and then evaluate its performance in terms of Bit Error Rate (BER) of Transmission Rate by performing also comparisons with the literature. The proposed scheme is robust with respect to optical interference and presents high rate and low BER at the cost of a bit complexity increasing with respect to other approaches.

I. INTRODUCTION

The needs for wireless data capacity has been strongly increased in the last years, in fact as reported by Cisco VNI Forecast [1], the global mobile data traffic is grown by 81 percent in 2013 and it is expected that will grow at a compound annual growth rate of 61 percent from 2013 to 2018, an increasing that is due particularly to smart-phone and tablet diffusion as well as the spread of wireless modules for machine to machine communications. Moreover as long as mobile video is a significant part of the traffic, half of the total in 2013, the need for high speed data link is requested for good quality of service. These two aspects entail a crowded and overloaded wireless spectrum, an issue that can be also addressed, in indoor propagation scenarios, by Visible Light Communications (VLC), because it can exploit the unlimited and unregulated band of visible light along with the possibility to work where Radio Frequency (RF) is forbidden. In fact, VLC has not issue of interference with others RF devices and also can provide higher spatial density of communications rates than RF, through spatial reuse.

The VLC, rising as complementary technology to RF, has been driven by the development that has been reached in solid state lighting in the last decade and also by the foreseen presence of LEDs as the future luminaire infrastructure, since they are highly energy efficient compared to incandescent lighting, so we can use potentially the same infrastructure for data transmission and lighting.

Luminaries that are mainly used for VLC are either phosphor based or three-chromatic LEDs, i.e. Red-Green-Blue (RGB) LEDs. Nowadays the former ones are the most used because they are easier to design and are less expensive than RGB, though the coating of a blue LED with a yellow phosphor causes a lower luminous efficacy compared with RGB LEDs due to problems related to the degradation of the phosphor and also they have a very limited modulation bandwidth (few MHz) if a blue filter is not employed [2]. Three-chromatic LEDs instead have a more higher bandwidth per channel and they can use three channels for increasing the data throughput.

Indeed the highest data rate in the standard IEEE 802.15.7 is achieved by a multicolor LED based modulation (see [3]), via Color Shift Keying (CSK) that provides communication data rates up to 96 Mbit/s (see [4]). CSK encodes data in the instantaneous output color of the LEDs by varying the instantaneous optical power of each color band while maintaining constant the total intensity to ensure flicker-free operation and avoid dimming.

Those rates are achieved by using Variable (length) Pulse Position Modulation, while On-Off Keying (OOK) is not so performing in terms of transmission rate (see [4]).

In CSK different colors are transmitted in series, with a fast transition time among them that it is not perceived by a human eye, and also with a selection of colors that combined on the cornea provide an overall white sensation. Another way to use a modulation with combination of different colors is using the principle of metamerism. In fact it is possible to transmit continuously a perceived white color by using different triple colors that have a different spectrum representation but are metamerically equivalent.

A. Previous related works

There are just a few works in the literature addressing issues in color-mixing modulation, and there is a lack in the study of the receiver architectures.

The IEEE 802.15.7 CSK physical layer standard specifies all the possibles colors band combinations (CBC) and the relative symbols constellations design for the modulation. Although the choice of the symbols are made without considering a thorough color rendering evaluation, an optimization in the
constellation design taking into account the rendering of output colors is tackle in [5], [6].

There, two important parameters, luminous efficiency that characterizes illumination of the LEDs and color rendering index that is a measure of the capacity of a LED to produce a color comparable with an ideal light source, have been taken into account.

The first work aiming at evaluating the communication performance of the standardized CSK modulation, from a Bit Error Rate (BER) point of view, is [7]. There, the authors compare the different CBCs over an additive white Gaussian noise and over a dispersive channel. That scheme utilizes three LEDs and three photodiodes (each tuned on red green and blue) and, after an optical filtering operated at each photodiode, basing on \((x−y)\)-tabular related to CIE 1931 (see [8]), that leads to costly demodulation operations.

Last, a very interesting contribution, that inspired this work, is that proposed in [9] since it resorts to the concept of methamerism by using three LEDs and three photodiodes. That method reduces color flicker by maintaining constant perceived ambient lighting and improves color rendering. As a drawback the receiver is based on conversion (optical-to-electrical) current distance with respect to pre-stored ideal values that does not present robust performance with respect to impairments (channel and external optical disturbances). More, the transmission scheme proposed in [9] considers the presence of three LEDs and three photodiodes.

B. Goals of the work

In this contribution we consider the transmission of CSK symbols with a single photodiode receiver in place of RGB that reduces the cost of the receiver. The modulation format is inspired both by the work in [9] and Orthogonal Frequency Division Modulation (OFDM) with a slight difference since the sub-carriers are chosen in order to satisfy illumination constraints and three sub-channel per symbols are used. More, we propose a Complementary Pulse Position Modulation (CPPM) signalling that is a PPM format with the difference of carrying information only where power is not present. This is used jointly with CSK in order to improve data rate and reliability of the link. By fact, CPPM, since used in combination of CSK can be interpreted as a sort of Not-Return-to-Zero (NRZ) signalling since there is not a larger bandwidth (or lower rate) request for implementing such a CPPM. The receiver is based on a single photodiode with a bank of pass-band filters able to detect the CSK symbols while the CPPM is based on time-based matched filters.

The paper is organized as follows. After introducing in Sect.II the problem of communication and illumination, Sect.III presents the transmitter scheme by showing how to merge CSK and CCPM. The receiver architecture is detailed in Sect.IV while the performances are presented in Sect.V before giving conclusions in Sect.VI.

II. HUMAN VISION ESSENTIALS

The features at the basis of human vision are characterized by the capability of the retina, composed by sensors (cones and rods), allowing the possibility of perceiving electromagnetic radiation in a subset of the optical spectrum. A normal human eye presents three different kinds of cones that are short (S), medium (M) and long (L) based on the relative wavelengths that induce the peak response. Different wavelengths of the light are absorbed differently by the rods and the three sets of cones. In this sense it can be seen as a wavelength selective filter weighting differently the different wavelengths of light. Cones are responsible for color vision. Let us name \(S_i(\lambda)\) their spectral responses to the electromagnetic stimulus over a range of optical wavelengths \(\lambda\), where the subscript \(i\) related to the \(i\)-th class of cones (S, M and L). Optical stimulus with a spectral power distribution (SPD) \(C(\lambda)\) will induce optical sensation \(\alpha_S, \alpha_M, \alpha_L\) within the cones as follows

\[
\alpha_i = \int_0^\infty C(\lambda)S_i(\lambda)d\lambda.
\]

In this context Grassmann’s laws (see [8]) regarding color matching, proposes some theories about the psycho-visual color space spanned by cones in the human eye, named the visual color space (VCS). This observation leads to another interpretation of (1) and the point with coordinates \([\alpha_S, \alpha_M, \alpha_L]\) 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 in the human eye (known as metamERICally equivalent). Light from three independent primary light sources can be mixed in varying amounts to generate arbitrary colors. This resulting color space is the primary color space (PCS) according to [9]. The projection of the PCS onto the VCS is called the color gamut of the primaries. The purpose of metameric modulation (see [9] for further details) is to map data in the visible spectrum while maintaining a constant ambient lighting state. To achieve this, at the transmitter, multiple primary sets each capable of generating its own color gamut must be used. Metameric modulation requires detection and discrimination of multiple wavelengths at the receiver. The necessary photodiode(s) 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. Work in [9] proposes how to obtain the same color with different wavelengths. Some insights are detailed later in the paper.

III. COMPLEMENTARY PPM OVER DIFFERENT COLORS - TRANSMITTER

The transmitter is characterized by three different LEDs each able to transmit with a very specific set of wavelengths, related to Red, Green and Blue (RGB). By resorting to the Color Shift Keying (CSK) proposed in [3] with the possibility of transmitting \(M\) different symbols, each one is basically characterized by three wavelengths so the \(k\)-th CSK symbol is univocally defined by a spectrum centered on the triplet \([\lambda_k^{(1)}, \lambda_k^{(2)}, \lambda_k^{(3)}]\). Basing on this modulation, the number of bits that can be carried per symbol is \(\log_2(M)\) as for Frequency Shift Keying (FSK) modulation even if this scheme requires 3 different wavelengths (bands) so it is a bit inefficient with respect to RF FSK.
Formalizing the M-CSK signal description, it can be written as follows

\[ x_k(t) = \sum_{m=1}^{3} \beta_{m,k} g_{m,k}(t) e^{j \frac{2\pi m}{L} t}, \quad k = 1, \ldots, M. \quad (2) \]

where \( \beta_{m,k} \) refers to the power associated with the emission of \( \lambda_k^{(m)} \) related to the \( k \)-th CSK symbol that corresponds also to the \( m \)-th transmitting LED, \( v \) is the propagation speed of the light, while \( g_{m,k}(t) \) is the shaping filter related to the emission of the \( m \)-th LED on \( \lambda_k^{(m)} \) wavelength. It can be determined by observing that there is a constraint on the perceived light. In this regard, let each \( G_{m,k}(\lambda) \) be the normalized emission spectra (equivalent to the Fourier Transform of \( g_{m,k}(t) \)) related to \( m \)-th of the three sources related to the \( k \)-th CSK symbol such that the following constraint is met

\[ \int_0^{\infty} G_{m,k}(\lambda - \lambda_k^{(m)}) d\lambda = 1. \quad (3) \]

Let us define \( \alpha^m \) as the spectral response induced by the \( m \)-th primary on the \( i \)-th class of cones, defined as follows

\[ \alpha^{(i)}_{m,k} = \int_0^{\infty} G_{m,k}(\lambda - \lambda_k^{(m)}) S_i(\lambda) d\lambda. \quad (4) \]

Furthermore, \( C(\lambda) \) is the SPD of the ambient color that we wish to maintain. As previously anticipated, differently from PPM where the position of the pulse but by slot where the pulse is absent. Even if this modulation format is less power saving, since it uses \( L - 1 \) times the power spent by L-PPM, it avoids dimming/flickering since its duty cycle is given \( \delta_{dc} = (L - 1)/L \). More regarding power saving, it is not an issue in this context since LEDs must provide data and illumination services.

After introduced signal description for M-CSK and L-PPM we can define the M-CSK/L-PPM generic symbol as follows

\[ P_{nk}(t) = \sum_{m=1}^{3} \beta_{m,k} g_{m,k}(t) e^{j \frac{2\pi m}{L} t} \sum_{l=0,l\neq n}^{L-1} \Pi_{T_p}(t - l \Delta_p). \quad (10) \]

As previously anticipated, differently from PPM where the time. A possible shape for the electrical signal enabling LED transmission can be the rectangular wave formally defined as

\[ u(t) = \Pi_{T_p}(t) = \begin{cases} 1 & t < \left[ \frac{T_p}{2} \right] \\ 0.5 & t = \left[ \frac{T_p}{2} \right] \\ 0 & t > \left[ \frac{T_p}{2} \right] \end{cases}. \quad (8) \]

One drawback of PPM, if used with M-CSK and, more, in the context of illumination, is duty cycle defined as the ratio between the percentage on one period in which the signal is non zero and the signal period, and it is given by \( \delta_{dc} = 1/L \) that can give rise to flickering. The same is for the VPPM proposal in [4] where different symbols present different duty cycles. This is the reason leading to a modified version of PPM, namely, Complementary PPM (CPPM) defined as follows

\[ P_n(t) = \sum_{l=0,l\neq n}^{L-1} u(t - l \Delta_p), \quad (9) \]

thus meaning that the information is not carried out by the position of the pulse but by slot where the pulse is absent.
A. Pseudo-coding mapping

The Color Mapper and C-PPM mapper operates according to the bit stream to be sent over the channel. Practically speaking, the first \( \log_2 M \) bits are used by M-CSK while the successive \( \log_2 L \) are used by L-CPPM. Hence, on one of the the M spectral combinations L-CPPM symbols are emitted. As previously anticipated this is equivalent to transmit an M-CSK symbol of \( T_s \) length, as for CSK modulations from the literature, with a zero transition for a time length equal to \( T_s/L \) that equates \( T_p \) in (7) and (10). By representing the signal as a \( L \)-length sequence (\( L \) elements vector) the possible transmitted pseudo-codeword is of the following kind

\[
e_{u} = [1...0...1]
\]  

(11)

About the rate that can be achieved by the presented system it is given by

\[
\mathcal{R} = \frac{\log_2(LM)}{T_s}.
\]  

(12)

At a first glance it seems that the time to be spent to transmit a C-PPM is not taken into account. On the other hand, since we already anticipate that this kind of modulation does not reduce rate (or increase bandwidth) since it presents simply a hole and at the receiver we apply a sort of oversampling of the M-CSK signal giving the interpretation of C-PPM, we can conclude that increasing \( L \) will induce a technological effort and increasing receiver complexity as will be clear in the following. In figure 2 the achievable rates for different values of \( L \) and \( M \) are reported. The maximum value, by considering a bandwidth of 24Mhz (as in [4]) is achieved for 32-CSK (maximum allowed by IEEE 802.15.7) and 32-CPPM (in line with the technological possibility of sampling electrical converted signals) and equates 240Mb/s.

![Achievable rates for different values of L and M.](image)

IV. RECEIVER ARCHITECTURE

The signal received after the photodiode is given by

\[
Z(t) = \rho A_e P_{tk}(t) * h(t) + N(t) + W(t)
\]  

(13)

where \( h(t) \) is the channel impulse response taking into account the propagation, LEDs and photodiode behavior, \( * \) is the convolution operator, \( N(t) \) is shot noise due to ambient light, Poisson distributed, \( W(t) \) is the Additive White Gaussian Noise due to the electrical components in the receiver. In wireless optical, as opposed to fiber, a large amount of ambient light is collected, therefore it is appropriate to model this noise as white and Gaussian [10]. The term \( \rho \) indicates the responsivity of the photodiode (\( A/W \) and \( A_e \) is the effective receiver area (\( m^2 \)). By observing figure 3, after the photodiode, the receiver is composed by \( M \) different branches each one tuned on three different sub-bands corresponding to the CSK symbols, so the general \( k \) pass-band filter blocks bandwidths with the exception of those assigned to the \( k \)-th CSK symbol.

![Receiver Scheme for the proposed modulation.](image)

\[
y^{(k)}(t) = Z(t) * g'_{\lambda_k}(t) \quad k = 1, ..., M
\]  

(14)

where the \( g'_{\lambda_k}(t) \) is the shaping term defined as

\[
g'_{\lambda_k}(t) = \sum_{m=1}^{3} g_{m,k}(t) e^{j \frac{2\pi m t}{\lambda_k}}, \quad k = 1, ..., M.
\]  

(15)

Each \( y^{(k)}(t) \) is then processed by evaluating the energy component in the sub-interval \([T_s/L, (l+1)T_s/L]\) with \( l = 1, ..., L-1 \) due to the CPPM modulation structure in order to detect when the hole is present as follows

\[
\eta_{kl} = \int_{lT_s/L}^{(l+1)T_s/L} y^{(k)}(t) dt \quad k = 1, ..., M, \ l = 0, ..., L - 1.
\]  

(16)

A. Decision mechanism

The decision process can be performed, as reported in figure 3 according to a Hard Decision (HD) or Soft Decision (SD). Once available the \( M \cdot L \) metrics \( \eta_{kl} \) these must be compared with a threshold \( \vartheta \) in order to decide for 0 or 1. So, the hard decision metrics once operated thresholding mechanism become

\[
\eta_{kl}^{HD} = \begin{cases} 
1 & \eta_{kl} \geq \vartheta \\
0 & \eta_{kl} < \vartheta
\end{cases} \quad k = 1, ..., M, \ l = 0, ..., L - 1.
\]  

(17)

Those metrics are then gathered in \( M \) vectors composed by \( L \) elements defined as follows

\[
\eta_k^{(HD)} = [\eta_{k0}^{HD} \eta_{k1}^{HD} ... \eta_{k(L-1)}^{HD}].
\]  

(18)
So, each L-ple is compared (in the Hamming distance sense) with all the possible transmitted pseudo-codewords. So the \( M \cdot L \) decided codeword is given by

\[
\hat{c} = \arg \min_{k=1,\ldots,M, u=0 \ldots L-1} \sum_{l=1}^{L} c_u(l) \oplus \eta^{HD}(l) \tag{19}
\]

where \( \oplus \) is the exclusive OR operator. Regarding the Soft Detection the metrics in (16) are gathered in the following \( M \) vectors defined as

\[
\eta_k^{(SD)} = [\eta_{k0} \eta_{k1} \ldots \eta_{k(L-1)}] \quad k = 1,\ldots,M, \quad l = 0,\ldots,L-1.
\]

and the decision mechanism works according to the following rule

\[
\hat{c} = \arg \min_{k=1,\ldots,M, u=0 \ldots L-1} ||E \cdot c_u - \eta_k^{(SD)}||^2 \tag{21}
\]

where \( E \) is the reference expected signal level at the transmitter by considering the channel effect.

**B. Pseudo-code demapping**

The inverse operation with respect to pseudo-code mapping is the pseudo-code demapping. Once determined the indexes \( k^* \) and \( u^* \) that are the ones achieving the minimization in (19) or (21) the demapping will lead to have the first \( \log_2 M \) bits characterized by the binary representation of \( k^* \) and the successive \( \log_2 L \) bits are obtained by the binary representation of \( u^* \).

**Remark on Threshold and channel knowledge**

Both threshold \( \vartheta \) for HD in (19) and \( E \) term in (21) must be properly, and in general adaptively, set in order to take care of the effect of the channel. By fact, without taking into account the channel attenuation/distortion the error rate can be high since it is possible to have misdetection events, that is, 0 decided for 1 and vice versa. This effect can be counterbalanced by channel estimation performed on the basis of a specific training sequence transmitted with a sufficient time interval, that means, not so frequent since it induces rate loss, and not to sporadic since channel changes (i.e., due to relative positions of transmitter and receiver changed). Pilots symbols sent every second is in line with the above consideration. By performing a channel estimation using pilot symbols one for each symbol since the channel must consider different channel behavior at different wavelengths, the signal received related to the \( k \)-th CSK symbol is

\[
Z_k^{[training]}(t) = \rho A_r P_k^{[training]}(t) \ast h(t) + N(t) + W(t) \tag{22}
\]

and, since \( P_k^{[training]}(t) \) is known at the receiver, the term \( E \) can be given by

\[
E = \frac{Z(0)}{\min_{k,m} P_k^{[training]} h(0)} \tag{23}
\]

since the minimum takes care of the worst case (higher attenuation) and, consequently, due to the nature of CPPM, the threshold for HD \( \vartheta \) can be set according to

\[
\vartheta = E/2. \tag{24}
\]

**V. NUMERICAL RESULTS**

We used computer modeling to evaluate the performance of the proposed modulation scheme. The model we used is described in large part in [11]. We make a brief accounting of the model parts here also by detailing the propagation scenario.

- For the source LED, we included the overall color spectrum of the blue plus yellow “white” light as well as the low pass signal frequency response of the instantaneous power waveform that is modulated on each light component: the total white light, the blue by itself and the remaining yellow, approximating those in [2]. For optics, we assumed lensing that results in a wide (45° FWHM) intensity pattern that is common for lighting LEDs.

- The light signal encounters a realistic indoor environment with many barriers as shown in Fig. 4. The walls and surfaces are simulated as being strongly reflective across the visible light spectrum (0.8 reflectivity factor, similar to light colored or white walls). The direct LOS path and all indirect paths of light up to and including four reflections were included in all propagation scenarios, which is required for accurate approximation of the multipath impulse response [12].

- Noise sources modelled include shot noise from the LED light and from a level of sunlight in the room that is considered high, as well as thermal and amplifier noise from receiver electronics [13].

- The receiver effective area \( A_r \) includes the actual photodiode area, and accounts for angle of light incidence, and the concentrator used [13], [14]. We modelled a wide FOV hemispherical lens. The photodiode responsivity function \( r \), which in turn depends on the LED source spectrum as well as the color filter used at the receiver in the case of the blue only channel.

![Fig. 4. A model of a small cubicle office in which a VLC transmitter light bulb is deployed at the ceiling pointed down. The is shown here directly below the transmitter. In our modeling, the receiver is mobile and occupies different positions and orientations. The three representative cases are as follows: (1) ideal case is a short distance aligned case (LOS 0.1 m) (2) a long distance aligned case (LOS 2.5 m) which is dominated by the direct link but also exhibits a significant multipath tail due to reflected components, and (3) a case in which the receiver is pointed away from the transmitter resulting in a diffuse (NLOS) link that only relies on reflected signal components.](image-url)
tion of SNR and, more, we compare the achieved performance with those relative to the scheme proposed in [9] when Line Of Sight (LOS) propagation is considered and Non Line Of Sight (NLOS) is accounted for. For evaluating the performance of NLOS we consider some reflective components as those output by CandLES simulator (see [11]) correspondent to be close to te wall of the room. Performance in LOS are better than in NLOS 4-CSK scheme proposed in [9] while it is not true for the scheme here detailed. While the 4-CSK scheme considers only the different components and it is passed on the Euclidean distances of the converted currents, the proposed scheme gain since in the NLOS scenario reflections are combined as in a RAKE, thus meaning that reflection fall in the reception since in the NLOS scenario reflections are combined as in distances of the converted currents, the proposed scheme gain proposed in [9] by considering also the effect of channel state information.

VI. Conclusion

The proposed scheme is able to provide illumination without loss in terms of color perception due to metamerism, in the framework of IEEE 802.15.7. The joint use of Color Shift Keying and Complementary Pulse Position Modulation allows to gain in terms of BER and, especially, in rate, thus achieving values up to 240Mb/s. This is paid in terms of complexity both at the transmitter and the receiver even if sustainable by the current technology.

REFERENCES