Impact of VLC on Light Emission Quality of White LEDs

Wasiu O. Popoola

***Abstract*—This paper reports the effect of data modulation on the emitted light quality of phosphor converted white LEDs. The results showed that provided the expected average current driving the LEDs remains unchanged then the emitted light quality will stay the same. For a DC-balanced modulating signal, with a non-varying average value, any fluctuations in the instantaneous driving current due to data modulation do not have any significant impact on the measured light quality metrics. For visible light communication applications therefore, a DC-balanced signalling becomes a prerequisite if the expected quality of light emitted by the LEDs is to be preserved. The findings are premised on adequate thermal management for the LEDs under test.**

***Index Terms*—Light quality, modulation techniques, optical wireless communications, visible light communications, white LEDs.**

I. Introduction

The need to reduce energy consumption/CO_2 emission and the ever-increasing demand for high speed wireless communication to sustain the global socio-economic activities represent some of the daunting challenges of the modern world. Visible light communications (VLC), also termed Li-Fi, proposes the use of LEDs to address these two challenges simultaneously. Tremendous progress has been recorded in VLC research to date, leading to a number of high profile demonstrations by research groups across the globe [1]–[4]. To reduce energy consumption, LEDs are progressively being used for illumination due to their durability, energy efficiency and ability to produce aesthetically pleasing lighting. To aid in averting any impending crisis due to limited radio spectrum to meet our demand for high speed wireless communications, LEDs are being modulated to transmit data. This is achieved by combining wireless data transmission with the LED's primary purpose of illumination/display [1].

Hence, VLC has the potential to expand wireless communication coverage to areas such as hospitals, factories, secure environments and others where user preference, regulation, or the propagation environment makes radio-based wireless communication undesirable. It equally allows for new services to be developed and more efficient operation of facilities such as factories. By leveraging the existing lighting and display infrastructure for data transmission, VLC adds data capacity at little additional cost thereby increasing the economic efficiency of the network infrastructure. It is worthy of mention that the exact additional cost will depend largely on the amount of extra signal processing or conditioning required by the modulation technique of choice. Moreover, VLC could also be an extra impetus needed to accelerate the deployment of solid state lighting which in turn will lead to increased energy savings and CO_2 reduction. To further enhance the economic prospects of VLC, the IEEE 802.15.7 standard was produced in 2011; this is currently being revised.

However, all of the research emphasis to date has been on demonstrating that VLC is a formidable technology that is complementary to other means of wireless communication. The impact that VLC has on the quality of the light emitted by an LED and by extension the users' well-being has however never been addressed in open literature. To this end, this work will experimentally investigate the effect of a rapidly changing driving current, due to data modulation, on the emitted light quality of illumination LEDs.

II. Need for Light Quality Metric in VLC Evaluation

The rated energy efficiency and CO_2 reduction benefits of LEDs are only achieved if operated at the manufacturers stipulated conditions. The most critical of these conditions include the operating temperature and current. Driving LEDs with constant current is an absolute requirement when using them for display backlighting or other illumination purposes. The main reasons for this are 1) to avoid violating the absolute maximum current rating and compromising the reliability and 2) to obtain predictable and matched luminous intensity and chromaticity (i.e. light quality) from each LED. This light quality requirement has a stack health/user well-being ramification to it [5]–[7]. In addition to visual effect, light is well reported to equally have psychological and biological effects [6], [8]. Psychological effects of light impact on our: mood, feelings, motivation and emotions. The non-vision light receptor responsible for the biological effect of light is the Melanopsin and it is responsible for producing the cortisol (stress hormone) and melatonin (sleep promoting hormone that regulates alertness and sleep). The circadian rhythm that regulates the cortisol and melatonin levels is affected by all light but mostly by blue light. According to a report by the European Union on Health Effects of Artificial Light (please see: http://goo.gl/TJMnss): '*Circadian disruptions, including decrease of melatonin levels, have been suggested to play an important role in development of chronic diseases and conditions such as: cancer (breast, prostate, endometrial,*

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ovary, colo-rectal, skin and melanomas, non-Hodgkins lymphomas), cardiovascular diseases, reproduction, endometriosis, gastrointestinal and digestive problems, diabetes, obesity, depression, sleep deprivation, and cognitive impairment'. This health impact of light is well established and illumination LED manufacturers have this in mind when specifying the driving conditions for LEDs. Any deviations from this has clear implications on the user well-being.

But with VLC, data is usually added by rapidly changing the LED driving current. The result is a subtle fluctuation of the emitted light intensity. Although the fluctuation is imperceptible to the naked eye, it does represent a deviation from the typical requirement for illumination. The magnitude of the continuous variations in the driving current depends on the type and depth of modulation used. It should be noted that the chromaticity and colour rendering properties are strongly tied to the specific driving current of the LEDs. Thus any deviation in the driving current will induce perceptible changes to the radiated light quality. In fact, dimming which causes very slow changes in the average driving current of the illumination LEDs has been reported to cause considerable undesirable shift in colour (chromaticity) of LEDs emitted light [9], [10]. Dimming, either by pulse width variation or varying the continuous driving current level, also induces temperature changes [9], [10]. Moreover, findings by Cree (a leading LED manufacturer) show that the undesirable changes in LED chromaticity could greatly affect the droop effect [11] - an unsavoury decrease in LED efficiency as driving current increases.

The foregoing therefore makes it imperative to further investigate the impact of high speed data on the emitted light quality. Since the users productivity and mood is greatly influenced by the quality of lighting, the currently unknown impact of data modulation on light quality thus represents a potent hindrance to the adoption of VLC and realisation of its potential. In fact, none of the existing modulation techniques for VLC can be deemed appropriate without quantifying their impact on the light emitted by the transmitting LEDs.

It can hence be said that the realisation of VLC socio-economic potential is hinged on the following factors that have not been well studied since the focus has hitherto been on proofing that data can indeed be added unto visible LEDs. These are the ability of VLC: (i) to achieve fast, low-cost data communication using lighting LEDs without any perceptible impact on the users. (ii) to achieve (i) without any significant impact on the expected quality of the LEDs light output and/or quality of display in backlighting applications.

The first point is of particular interest to the communication industry while the second one is vitally important to the lighting/display industry. VLC has to fulfil the needs of these two industries to realise its huge socio-economic promise. The state-of-the-art VLC research, including demonstrations, has convincingly achieved the first point through the use of various electrical signalling/modulation techniques. The viability of these systems are traditionally measured using metrics such as signal-to-noise ratio (SNR), bit/symbol error rate, range, data rate, spectral efficiency, energy efficiency and so on. However, these metrics do not in any way measure, quantify

TABLE I: Light quality metrics evaluated in the light quality measurements

Light quality	Significance
Light quality is measured by the following photometric properties as stipulated by the lighting standards: 1) Correlated colour temperature: characterizes how cool or warm a light appears. 2) Colour rendering index: a measure of the fidelity of the emitted light 3) Chromaticity: shift in colour.	• Change in chromaticity could lead to efficacy degradation and increased energy consumption. • Colour shift towards blue poses health risks known as the blue light hazard including eye problems [12]. • Changes in light hue and colour could lead to undesirable shifts in intended lighting effect which might impact on human productivity, mood and physical surrounding aesthetics.

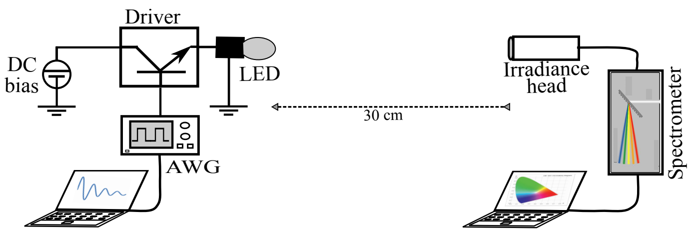


Fig. 1: An illustration of the light quality measurement experimental set-up

or reflect on their impact on light quality. But this light quality understanding is vital to satisfy the lighting/display industry requirements and regulations. It therefore becomes imperative to consider light quality when evaluating any VLC system. To quantify light quality, the following metrics will be considered in this work: correlated colour temperature (CCT), colour rendering index (CRI) and chromaticity.

Generally, variations in the driving current influences 1) the LED itself - in terms of its reliability/durability/efficiency and 2) the light output from the device. The focus in this work will be on the latter; specifically on the impact of changes in the driving current brought about by data modulation on the emitted light quality.

III. Experimental Procedure

To evaluate the impact that VLC might have on the light emitted by an LED, experiments will be carried out to quantify the impact of data modulation on the light quality metrics presented in Table I. To eliminate any background light contamination, all measurements will be carried out in a dark room with the LED under test being the only source of light. The photometric properties of light emanating from the LED will be captured and analysed with an irradiance head/spectrometer combination as illustrated in the experimental set-up of Fig. 1.

In this study, two phosphor converted high brightness illumination LEDs will be considered. These are i) OSW 4301-Cool white LED and ii) Ostar-Osram warm white LED. Adequate thermal management is ensured by adhering to the heat sink specified by the manufacturer and keeping within the rated maximum driving current for the LEDs. In terms of modulation technique, the two broad categories of pulse-based and continuous-time base band signalling technique will be considered. For the pulse-based, on-off keying (OOK) is adopted while DC biased optical orthogonal frequency division multiplexing (DCO-OFDM) is used in the continuous time category. These modulation techniques are synthesized with a computer controlled arbitrary waveform generator (AWG) as depicted in Fig. 1.

In the experiments, the 'no LiFi' baseline condition refers to the measurements taken when the LED under test is driven at a constant drive current, $I_{\rm d}$ with no data modulation. For OOK modulation, the driving current is pulsed to carry LiFi data. A randomly generated binary data (a pulse for bit 1 and no-pulse for 0) sequence is superimposed on the original mean drive current. The resulting average drive current as well as the light quality parameters are recorded and compared with the case with no LiFi. For the DCO-OFDM, a representative 4 level quadrature amplitude modulation is used throughout as the emphasis is not on high data rate in this study. During each measurement, a total of between 1100 and 1400 samples are acquired. These sample are then used to produce an empirical probability distribution function of each of the measured parameters.

IV. Results and Discussions

In this section, findings relating to each of the light quality metrics under consideration are discussed separately as follows:

A. Correlated Colour Temperature

The result of the CCT measurements as presented in Fig. 2a shows that for the cool white LED, as data is added, a decrease in the CCT is observed. This decrease is however proportional to the modulating signal amplitude/modulation index and the average driving current, $I_{\rm d}$. Using a return-to-zero OOK pulse stream with 40 % duty cycle and 2 Vpp amplitude resulted in $I_{\rm d}$ dropping from 351mA to 165mA expectedly. As a result, the CCT is observed to decrease by ~ 25 % in the process. This represents the maximum observable decrease in CCT for the cool white LED. But with non-return-zero OOK signalling of the same amplitude as the RZ-OOK, the decrease in CCT is about 20 %. However, when the modulating signal amplitude is no more than 1 Vpp and average driving currents is approximately same as with the no LiFi condition, the observable change in CCT is quite tiny at no more than 7 %.

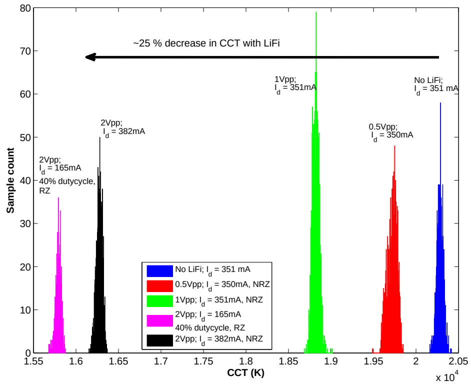
With respect to the warm white LED, the maximum observable shift in CCT with NRZ-OOK is only about 0.2 % as shown in Fig. 2b. This is with a 2 Vpp modulating signal that corresponds to a modulation index of ~ 80 %. What is observable here is a clear overlap of the CCT distributions particularly for identical $I_{\rm d}$ values. It is worth mentioning that the data is uniformly distributed with on and off having the same probability of occurence. Hence, the NRZ-OOK signal format is expected to be DC-balanced, any slight variation in the recorded mean drive current $I_{\rm d}$ can be attributed to the randomness of the data sequence.

For the OFDM modulation, two cases are considered. In both cases, an electrical OFDM signal is mixed with a fixed DC bias set at 330 mA to drive the LED. For the first case, the unipolar electrical OFDM signal is added directly to the fixed DC bias to make the signal unipolar. In the second case, the electrical OFDM is made unipolar with the addition of an offset. This offset represents an addition bias for the LED. In contrast with the extra offset case, the OFDM system with no extra offset has relatively fixed mean driving current as Fig.2c shows. Also from this figure, there exist an overlap in the distribution and no clear shift (less than 0.2 % variation) in the CCT. But when an additional DC offset is added to the OFDM signal, thereby resulting in an increase in $I_{\rm d}$ from 331 mA with no LiFi to 563 mA with a 1 Vpp modulating signal as shown Fig. 2d, a minor increase of about 1.2 % in the CCT is observed. A comparison of these histograms therefore indicates that the average drive current has greater influence on the CCT than the instantaneous drive current.

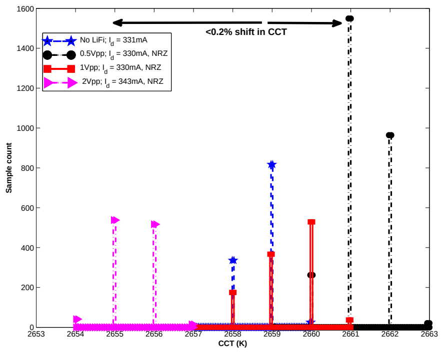
In terms of the impact of the observed shift in CCT on light quality, it is worthwhile to refer to the industry standard on the level of acceptable variations in CCT. Within the illumination industry, the ANSI standard specifies nominal CCT values and their acceptable/allowable range of variation. The amount of tolerance or variation of CCT is usually measured using the MacAdam ellipse [13]. The MacAdam scale is determined by the standard deviation of colour matching (SDCM). A variation of 1 MacAdam step (or 1 SDCM step) is not visible while 2 to 4 steps are barely visible [14]. Although a step of 5 is described as readily noticeable, to have up to 7-step SDCM variation is deemed acceptable in the ANSI standard. Figure 3 shows the allowable variations and the corresponding tolerance values for eight nominal CCT values as specified in the ANSI C78.377A standard. The quadrangles that define the eight nominal CCTs in the figure are approximately 7-step MacAdam ellipses in size. In relation to this, the warm LED used in the experiment falls into the 2700 K nominal CCT where the acceptable 7-step SDCM tolerance is $\pm$ 145 K (or 5.3 % variation). All the observed variations in Fig. 2b-d are however well within this range. It can thus be surmised that, directly modulating the driving current of a white LED to transmit a DC balanced data pattern does not result in any significant changes to the CCT of the emitted light.

B. Colour Rendering Index Results

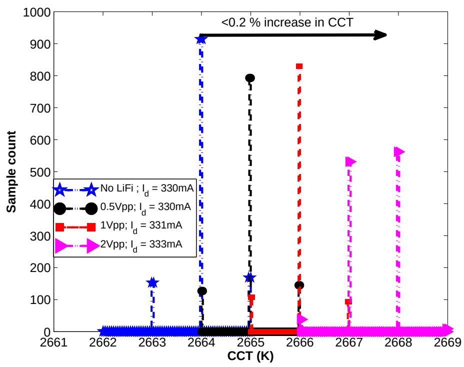
The results of Fig. 4 indicates that modulating the driving current of a phosphor convert white LED does not have any pronounced effect on the CRI of the emitted light. Specifically, using NRZ-OOK with a data signal depth of 2 Vpp only resulted in about 0.3 and about 0.45 point drop in the CRI of the cool and warm white LED respectively. With OFDM modulation, there exists a slightly broader spread of the CRI values with data modulation but there is no evidence of a clear shift in the mean values. With 2 Vpp data depth, the shift in the mean CRI values is less than 0.1 point when compared with no LiFi case as Fig. 4c shows. Furthermore, increasing the mean



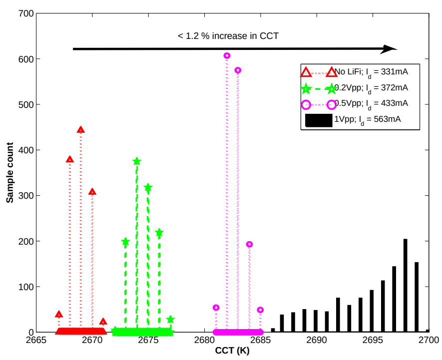
(a) CCT of OOK modulated cool white LED



(b) CCT of OOK modulated warm white LED



(c) CCT of OFDM modulated warm white LED



(d) CCT of OFDM modulated warm white LED with additional DC offset

Fig. 2: Correlated colour temperature results for both cool and warm white LED using OOK and DCO-OFDM modulation techniques

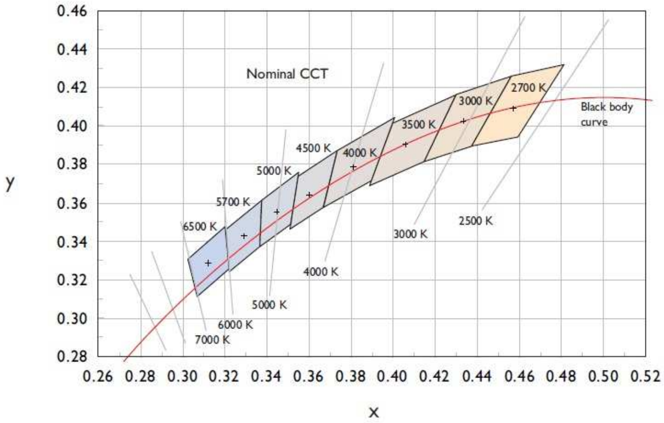


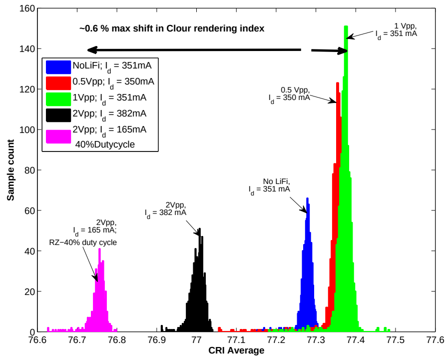
Fig. 3: Allowable variations in the eight nominal CCT values as specified in the ANSI C78.377A standard [14].

driving current I_{d} (with OFDM modulation) by over 200 mA with additional bias as seen in Fig. 4d, only resulted in less than 0.2 point shift in the mean CRI values. By all account, this is insignificant and thus negligible. In fact, according to the US Department of Energy guideline on LED lighting [15], a less than 5 points difference in CRI is considered insignificant and an LED lamp with say 80 CRI is same as one with 76 or 84.

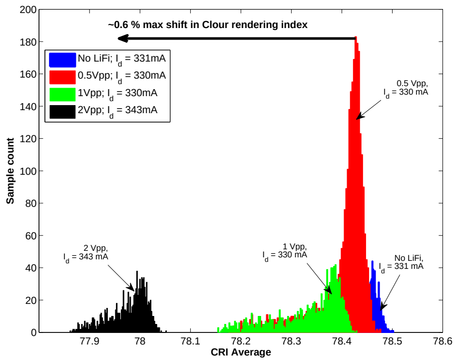
C. Chromaticity

To illustrate the effect of data addition on chromaticy, we present the plots of the chromaticity x and y coordinates in Fig. 5. It is observed here that for a similar average current I_{d}, the chromaticity values are quite similar. Any observable shift in chromaticity is brought about by a corresponding shift in I_{d}. For example in Fig. 5b modulating the LED with a random data sequence using 2Vpp NRZ-OOK data resulted in a slight increase in I_{d} by 12 mA compared with no LiFi case and consequently a slight drop in the chromaticity x and y coordinates for the warm white LED. For the cool white LED of Fig. 5a, a 31 mA increase in the average driving current due to the addition of 2 Vpp NRZ-OOK data stream resulted in a slight increase in the chromaticity x and y coordinates. Similarly with OFDM, the addition of additional bias to increase the average driving current I_{d} resulted in a clear shift in the chromaticity coordinates as can be seen in Fig. 5d. But when I_{d} remains roughly the same as is the case in Fig. 5c the chromaticity values broadens and overlap but no clear shift is observed.

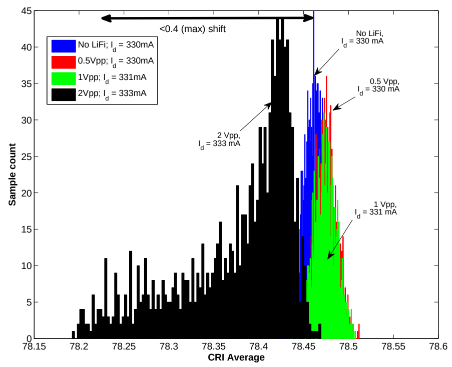
To bring these results into perspective, in Fig. 6 we show on a CIE chromaticity plot, the chromaticity with and without LiFi. We have used the OOK modulation that resulted in the most shift here. It can be seen that for both the warm and cool LED under consideration the emitted light is still white. It is also worthy of note that LEDs are usually not characterised with a single chromaticity value. The chromaticity is typically given as a range of values. The observed chromaticity coordinates with and without LiFi are well within the acceptable range specified by the manufacturer for the particular LEDs



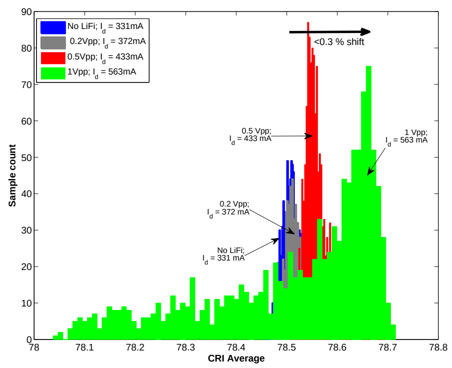
(a) CRI for OOK modulated cool white LED



(b) CRI for OOK modulated warm white LED

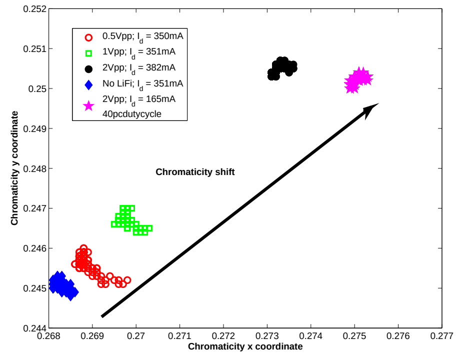


(c) CRI of OFDM modulated warm white LED

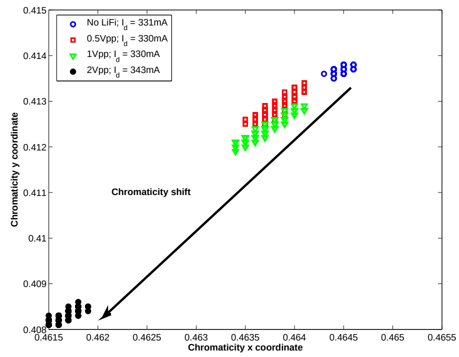


(d) CRI of OFDM modulated warm White LED with additional DC offset

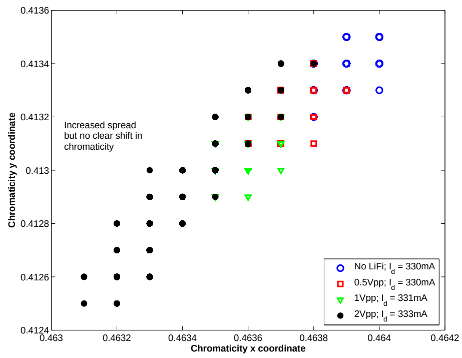
Fig. 4: Colour rendering index results for both Cool and warm white LED using OOK and OFDM modulation techniques



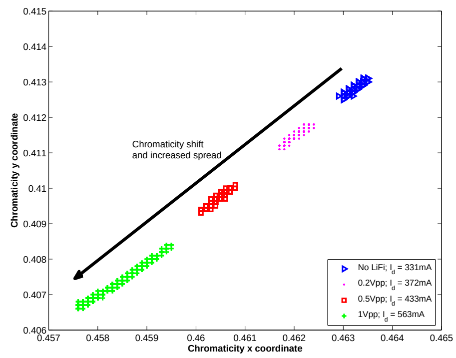
(a) Chromaticity of OOK modulated cool white LED



(b) Chromaticity of OOK modulated warm white LED

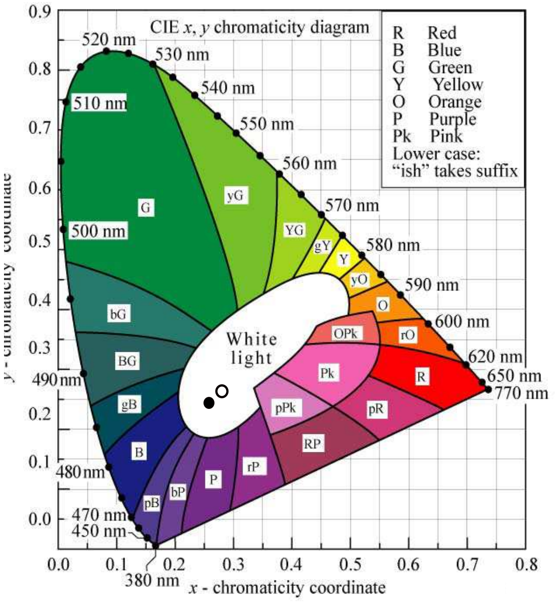


(c) Chromaticity of OFDM modulated warm white LED

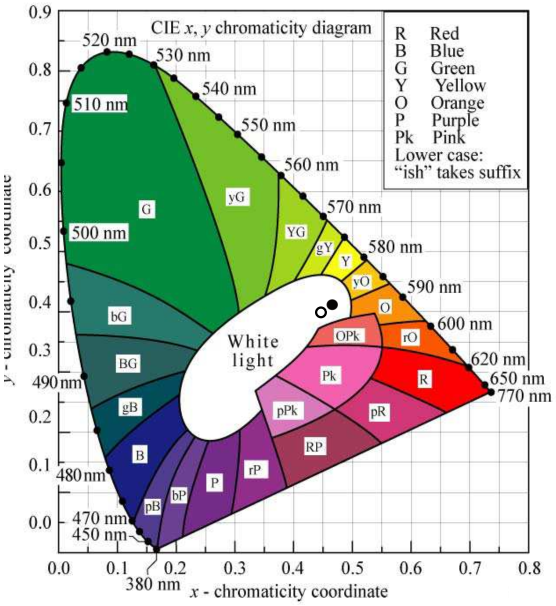


(d) Chromaticity of OFDM modulated warm white LED with additional DC offset

Fig. 5: Chromaticity results for both cool and warm white LED using OOK and OFDM modulation techniques



(a) Cool white LED



(b) Warm white LED

Fig. 6: CIE Chromaticity diagram with and without OOK data modulation for (a) cool and (b) warm phosphor converted white LEDs; ●–No LiFi; ❍–with LiFi.

under consideration here. Thus the emitted light quality with and without LiFi can be considered the same.

To further investigate these findings, we present in Fig. 7 the chromaticity plot of the warm white LED at five different but constant driving current with no modulation. It is clear from this figure that the different driving current correspond to different but close chromaticity coordinates; this is consistent with the previous results with data transmission.

This thus reinforces the fact that provided the illumination LED is operated within its stipulated dynamic range, with proper thermal management, then the quality of the emitted

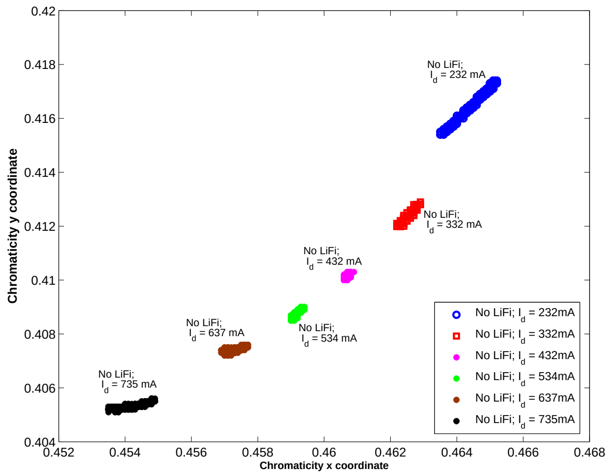


Fig. 7: Chromaticity metric for warm white LED with five different constant drive currents with no LiFi.

light is solely dictated by the average driving current. It is evident that any fluctuations in the instantaneous driving current due to data modulation has very little or no impact at all on the measured light quality metrics. As such, modulating a phosphor converted white LED for data transmission will not have any significant effect on its emitted light quality provided the expected average driving current is kept unchanged.

V. Conclusion

This work considered the impact of OOK and optical OFDM schemes on the CRI, CCT and chromaticity of phosphor converted white LEDs. These light quality metric are then compared with when the LEDs are driven with a constant current with no data modulation. The results showed that provided adequate thermal management is used, the average drive current dictates the emitted light quality (CRI, CCT and chromaticity) but not the instantaneous drive current. Hence to preserve the expected light quality of LEDs used for LiFi, the modulating signal must be DC balanced.

DCO-OFDM being a DC balanced signalling technique with non-varying average value for a given data symbol showed no significant impact on the light quality. In comparison with driving the LED with constant current with no data modulation, a maximum of 0.1 point shift in the CRI resulted with OFDM. While a randomly generated NRZ-OOK data sequence resulted in up to 0.45 point shift in the CRI. Any shift of less than 5 point in CRI is however trivial and there is no evidence of any meaningful shift in the chromaticity coordinates and the CCT of the LEDs with and without data modulation as well. It can thus be concluded that modulating an LED with either OFDM technique or a randomly generated NRZ-OOK data sequence does not impact negatively on the emitted light quality.

Acknowledgment

This work is supported by the research incentive grant (Trust Ref 70004) from the Carnegie Trust and the EPSRC (grant no: EP/N013468/1). The author also acknowledges the LiFi R & D centre, University of Edinburgh for providing the test facilities.

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