

Investigation into using compensation for the nonlinear effects of the output of LEDs in visible light communication systems

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Abstract— This paper investigate the effects of the nonlinear output power to the input current transfer function of a light emitting diode (LED) used as the transmitter in visible light communication systems, and proposes a compensation technique to mitigate the non-linearity. Using an off the shelf red, amber, blue, green (RAGB) LED the nonlinear transfer function is measured and then compensated for. The results show that, for the green LED, which has the highest degree of nonlinearity, an improvement in the received error vector magnitude (EVM) of almost 7 dB can be achieved. We also show that, the improvement in EVM over the uncompensated scheme decreases with increased LED linearity.

Keywords— LED; nonlinear; compensation; visible light communications; mCAP; EVM.

I. INTRODUCTION

With the popularity of the light emitting diodes (LEDs) as the new general luminary source increasing worldwide driven by the ecological and economic benefits, communication engineers are also taking advantage of these devices for their unique features. Due to their ability to have subtle or total changes to the optical output intensity controlled at speeds beyond which the human eye can perceive, LEDs are now offering the dual functionality of illumination and wireless data communication. Because of this, visible light communications (VLC) is presenting itself as a complementary technology to the radio frequency (RF) based WiFi systems in indoor environments.

VLC offers advantages over the RF based systems such as inherent security at the physical level as light cannot pass through walls; immunity to other RF induced electromagnetic interference, high-energy efficiency (LEDs use less energy compared to the traditional lights) and a free unregulated frequency spectrum. However, the generally accepted and widely used high power phosphor based white LED (WPLED), which are used for illumination, has a limited modulation bandwidth B_{mod} due to the fundamental constraint of the slow temporal response of the phosphor. The B_{mod} reported in the literature for such devices is typically in the range of 2 – 3 MHz [1, 2]. Of course, an alternative approach for the generation of a white light is to combine the optical output of red, green and blue (RGB) based chip LEDs.

Having no phosphor conversion, the B_{mod} for each of the colours have been reported up to an order of magnitude higher than that of the WPLEDs [2, 3].

Regardless of the type of LEDs, they all suffer from nonlinear effects associated with the output power - input drive current characteristic [4]. There are a number of schemes for addressing the non-linearity problem in VLC systems. The simplest method to avoid the linearity is to use binary transmission such as the on-off keying (OOK) or pulse position modulation (PPM), where non-linearity is not an issue since the LED is simply switched on and off at specific current values. However, higher spectral efficient modulation schemes such as the orthogonal frequency division multiplexing (OFDM) and multi-band carrierless amplitude and phase modulation (m-CAP) [5], which have been used to increase the data rates, are effected by the nonlinearity induced distortion, which in turn degrades the error vector magnitude (EVM) of the received constellations. Alternatively, a method to mitigate these effects was proposed in [6] for use with color shift keying (CSK) modulation, which was based on simulation only. Adaptive pre-distortion techniques was proposed in [7] using Wiener model consisting of a linear time-invariant and memoryless nonlinear model, greatly increasing the complexity of the VLC link, and was demonstrated by means of simulation only. For OFDM VLC links, a dynamic DC biasing and a look up table (LUT) based pre-distorter for mitigating the nonlinear effects was also proposed in [8], however this technique is extremely computationally intensive and once again has only been implemented in the simulation domain.

In this paper, we experimentally investigate how the harmonic distortions (mostly 2nd and 3rd) can effect each of the subcarriers in m-CAP and it contribute towards the EVM deterioration. Through employing a filter with the inverse response of the LED transfer function a linear response to the optical output can be achieved. Furthermore, the linearization enables a higher modulation depth (or index) of the output signal thus supporting an increased output signal power (i.e., higher signal to noise ratio (SNR)), which supports higher achievable transmission capacity or the transmission distance.

The rest of this paper is organized as follows; Section II demonstrates the non-linear effect experienced by each chip

of the RAGB LED with the resultant harmonic distortion. Section III describes the nonlinear compensation technique applied to the LED and shows the corrected linear output. Section IV covers the experimental results for transmitting m-CAP signals with and without the compensation filter, and finally Section V draws all of the conclusions.

II. RAGB LED NONLINEAR EFFECTS

To demonstrate the non-linear effects of the LED we have chosen a typical readily available off the shelf high power multi-chip RAGB LED. Fig. 1(a) shows the experimental setup used to carry out measurements. An arbitrary function generator (AFG) has been used to generate a highly linear ramp signal to drive the LED, which is driven by a drive current within 0 and 1 A in order to measure the transfer function of each of the colored chips. The intensity modulated optical signals is captured using an optical receiver (Thor labs - PDA36A-EC). The regenerated electrical signal $y(t)$ is captured using a digital oscilloscope (Agilent DSO954A) for offline processing in the Matlab domain. The transfer function of interest is the relationship for the received voltage as a function of the LED input current. Fig. 1(b) depicts the drive circuit used for each of the LED chips, whose function is a voltage to current transducer. The AFG provides the signal $s(t)$, which consists of a bipolar signal with a DC offset. The current driving the LED can then be found using Ohms law, which in this case is the AFG output voltage divided by the emitter resistance R . The distance d is fixed to 50 cm.

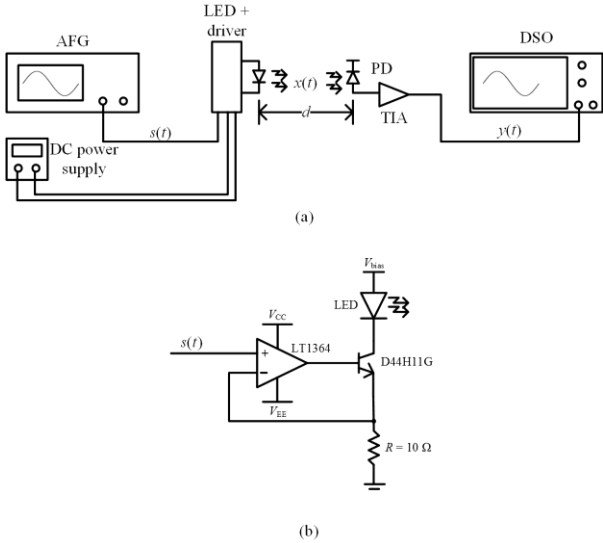


Fig. 1 (a) Experimental setup, and (b) the LED driving circuit.

Fig. 2 shows the voltage for the received signal (i.e., a ramp waveform) as a function of the LED drive current for the RAGB colors (note, only the rise cycle of the transmitted signal is required). In order to measure the linearity of the response, each trace has been normalised (i.e., to the unity) and compared with a linear trace between 0 and 1 for the same drive current using the root mean square (RMS) of the difference, which is given by:

$$xL_{RMS} = \sqrt{\frac{\sum_{i=1}^n d_i^2}{n}}, \quad (1)$$

where x is the LED color, d_i is the distance between corresponding samples of the measured and linear trace, i is the sample number and n is the total number of samples. The numerical results are given in Table I, which shows the descending order to which the LED chips are measured for linearity with the Red being the most and the Green showing

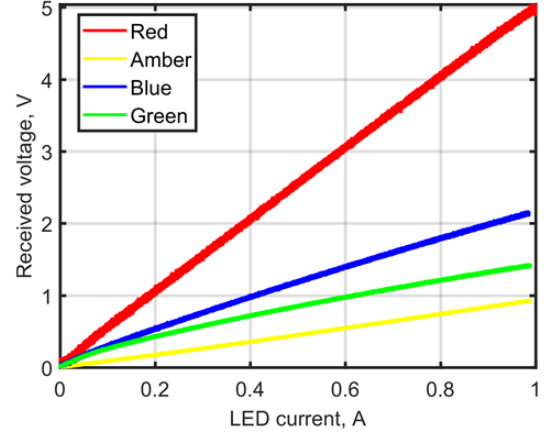


Fig.2 RAGB LED current to received voltage transfer function.

the least.

TABLE I RAGB LED RMS VALUES

LED chip	xL_{RMS}
Red	0.0086
Amber	0.0129
Blue	0.0405
Green	0.0789

The importance of the linearity within a VLC system is best illustrated in Fig. 3, whereby a sinewave of frequency 1 MHz is transmitted through the system and the total harmonic distortion (THD) is measured at the receiver. Fig 3(a) shows the THD as a function of modulation depth of the signal, where the modulation depth (MD) is given by:

$$MD = \frac{Sig_{peak}}{Sig_{bias}} \times 100 \%, \quad (2)$$

where Sig_{bias} has been fixed to 500 mA. Fig. 3(b) illustrates the THD (to the 5th harmonic) for the received Red waveform with a MD of 100 %. The harmonics produced from the nonlinearity of the system can be detrimental to the performance of multicarrier modulation schemes (i.e., OFDM and m-CAP) due to the lower subcarriers induced interference experience by the higher subcarriers. Note that, we have adopted m-CAP in this work for investigation. Furthermore, for reference in Fig. 3(a) the THD of the AFG has also been measured to ensure that the distortion does not originate from the generator. In this case the AFG shows greater than 10 dB reduction in the THD for the Red chip LED with a MD > 40%.

Hence, the AFG not being responsible for the main source of the distortion.

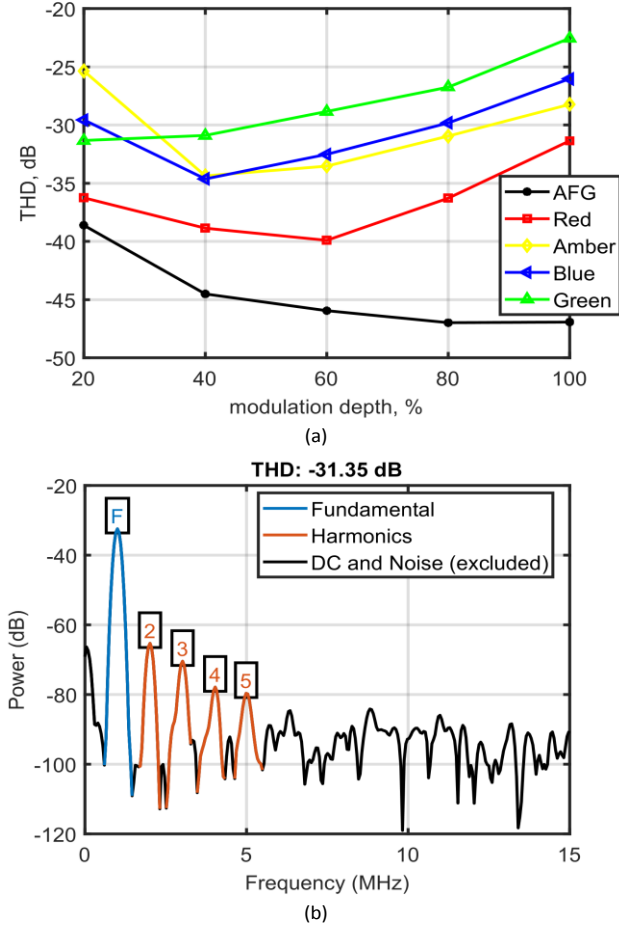


Fig. 3 (a) The THD as a function of MD, and (b) the THD of the Red LED with an MD of 100 %.

III. NONLINEAR COMPENSATION

In order to compensate for the nonlinear effects shown in Fig. 2, each of the RAGB traces are normalised once again to the unity, so that the maximum $f_{\text{color}}(I)$ is 1 (where I is the drive current) i.e.,:

$$V_{\text{color}}(I) = f_{\text{color}}(I), \quad (3)$$

where V_{color} is the received voltage for a particular color and f_{color} is the transfer function for a particular color. The compensation function is given by:

$$V'_{\text{color}}(I) = g_{\text{color}}(I), \quad (4)$$

where

$$g_{\text{color}}(I) = f_{\text{color}}^{-1}(I). \quad (5)$$

Using the normalised values of the transfer functions extracted from Fig. 2, the 5th order polynomial equations for each f_{color} have been obtained with Matlab using the curve fitting tools. The functions are given by:

$$f_{\text{Red}}(I) = 0.0875I^5 - 0.3939I^4 + 0.5381I^3 - 0.3168I^2 + 1.0724I + 0.0055, \quad (6)$$

$$f_{\text{Amber}}(I) = 0.1186I^5 - 0.2917I^4 + 0.1693I^3 + 0.1277I^2 + 0.8544I + 0.011, \quad (7)$$

$$f_{\text{Green}}(I) = 2.0774I^5 - 6.0086I^4 + 6.6062I^3 - 3.62I^2 + 1.9195I + 0.0179, \quad (8)$$

$$f_{\text{Blue}}(I) = 0.8209I^5 - 2.354I^4 + 2.5418I^3 - 1.3988I^2 + 1.3691I + 0.011. \quad (9)$$

By means of the inverse function outlined in (5) the compensation curves are given by:

$$g_{\text{Red}} = -0.2008I^5 + 0.6901I^4 - 0.8226I^3 + 0.4440I^2 + 0.9039I - 0.0040, \quad (10)$$

$$g_{\text{Amber}}(I) = -0.2044I^5 + 0.4575I^4 - 0.2457I^3 - 0.147I^2 + 1.1609I - 0.0120, \quad (11)$$

$$g_{\text{Green}}(I) = -0.8186I^5 + 2.5529I^4 - 3.0899I^3 + 2.1219I^2 + 0.246I + 0.0011, \quad (12)$$

$$g_{\text{Blue}}(I) = -0.7168I^5 + 2.0770I^4 - 2.2606I^3 + 1.2906I^2 + 0.6262I - 0.0048. \quad (13)$$

Fig. 4(a) shows the schematic diagram of the signal flow from the AFG through to the LED using the compensation curves given above. A linear ramp signal $r(I)$ from the AFG is applied to the compensation module, the output of which $g(I)$ is used for intensity modulation of the LED via the driver unit $f(I)$. Fig. 4(b) shows the normalized output as a function of the LED drive current for both $g(I)$ and $x(I)$ as well as for the measured and fitted $f_{\text{color}}(I)$ for the Green LED.

To measure the effectiveness of the compensation scheme on each of the colored LEDs, the linear RMS analysis has been re-run on the compensated outputs $x(I)$ and compared with the original values given in Table I. The results are given below in Table II.

TABLE II RAGB LED COMPENSATION COMPARISON RMS VALUES

LED chip	xL_{RMS} uncompensated	xL_{RMS} compensated	xL_{RMS} gain
Red	0.0086	0.0013	84.88 %
Amber	0.0129	9.8482e-04	92.37 %
Blue	0.0405	0.0024	94.07 %
Green	0.0789	0.0097	87.71 %

IV. EXPERIMENTAL RESULTS

To quantify the effectiveness of the compensation scheme outlined above, a series of m-CAP signals with orders ranging from $m = 1, 2, 3, 4$ and 5 have been transmitted through the VLC system shown in Fig. 1(a) and with the additional compensation shown in Fig. 4(a). The measured EVM of the received constellations are used to define the quality of the VLC transmission link. All the key experimental parameters adopted in this work are given in Table III. The mathematical description for generating and demodulating m-CAP signals are not included here as this is not the scope of the paper. The main focus of this work is on the LED non-linear compensation. However, for more information on m-CAP please refer to our previous publications [9-11] for a complete in depth analysis.

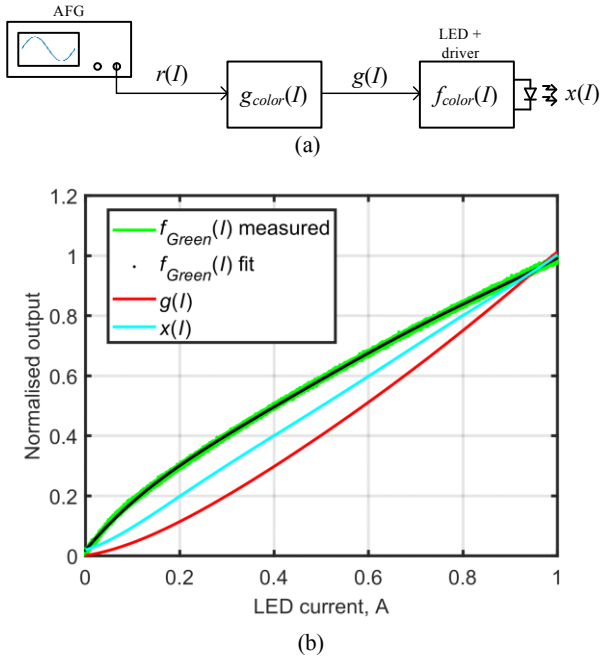


Fig. 4 (a) signal flow schematic, and (b) normalized output as a function of the LED drive current for both signals $g(I)$ and $x(I)$ as well as for the measured and fitted $f_{color}(I)$ for the Green LED.

Figs. 5(a)-(j) show the measured EVM results for both uncompensated and compensated m-CAP VLC systems. The left column shows the EVM for both schemes whereas the column on the right displays the difference between the schemes. A positive result defines that the compensation has been successful whereas a negative result shows that, the uncompensated scheme is more successful. In Fig. 5(e)-(j) the LED color has been abbreviated to the initial and the subscript denotes the subcarrier index.

It can be seen from the figure that, for the majority of the cases the compensation has been very effective. The green LED has the highest success rate with the compensation, as this was clearly the least linear of any of the colors. An improvement of 6 dB has been achieved for the 2-CAP system with the rest of the orders displaying between 2 – 3 dB. Likewise, the red LED being the most linear has shown the least improvement, and in some cases (i.e., $m = 4$ and 5) has shown a deterioration in performance. However, it must be noted that, the deterioration in response is < 2 dB so it can be said that the performance is almost the same for each scheme. The blue also show positive results for the compensation scheme; however, these improvements are marginal between 2 and 3 dB. The amber LED also shows similar results for each scheme with the exception of the first subcarrier for the $m = 4$ and 5 , thus with values of approximately -4 and -6 dB lower than the uncompensated scheme.

These results indicate that, the compensation scheme proposed in this paper is effective for VLC systems where the LED output to input transfer function is not very linear, as is the case for the green LED. The resultant enhancement of the EVM translates to an increased SNR, thus allowing for higher transmission capacity or increased transmission length. However, for LEDs with a higher degree of linearity such as the red color, the compensation scheme is an unrequired added complication to the system.

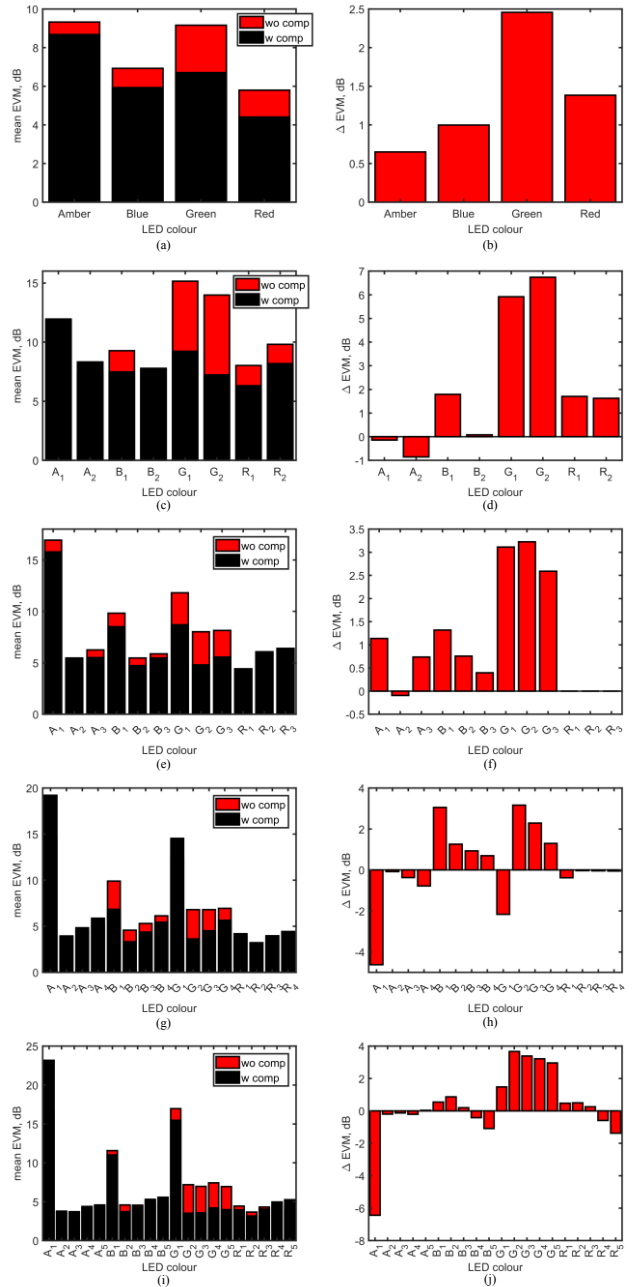


Fig. 5 compensated and uncompensated (a) EVM of each color for CAP, (b) difference in EVM for CAP, (c) EVM of each color for 2-CAP, (d) difference in EVM for 2-CAP, (e) EVM of each color for 3-CAP, (f) difference in EVM for 3-CAP, (g) EVM of each color for 4-CAP, (h) difference in EVM for 4-CAP, (i) EVM of each color for 5-CAP, (j) difference in EVM for 5-CAP

TABLE III EXPERIMENTAL PARAMETERS

Parameter	Value
LED bias (each color)	500 mA
Peak modulation current	500 mA
Signal bandwidth	1 MHz
QAM order (each subcarrier)	16
Symbol mapping	Gray
Roll off factor (Beta)	0.15
Number of subcarriers	1, 2, 3, 4 and 5
Min bits tested per subcarrier	1e6
Link distance	0.5 m

V. CONCLUSIONS

This paper investigated the effects of the nonlinear transfer function of power output to LED drive current in a VLC system. We showed that, the nonlinear effects led to harmonic distortion, which is detrimental to multi-tone modulation schemes such as m -CAP, which was investigated in this paper. A compensation scheme to reduce the nonlinearity affects was developed and tested. The results demonstrated that, for LEDs with a high degree of nonlinearity such as the green LED, an improvement in the received EVM was achieved showing 6-7 dB increase for the case of $m = 2$, and more than 2 dB over the other orders LEDs tested. The blue also showed a consistent improvement for each order of m -CAP, with the blue being the next nonlinear case after the green. For the cases of the amber and red LEDs however, little or no effect was measured on the EVM (i.e., < 1 dB) of the received constellations. We showed that, for the colors with highest linearity, the use of compensation scheme was least effective.

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