LED based Wavelength Division Multiplexed 10 Gb/s Visible Light Communications

Hyunchae Chun, Sujan Rajbhandari, *Member IEEE,* Grahame Faulkner, Dobroslav Tsonev, *Member IEEE*, Enyuan Xie, Jonathan J. D. McKendry, *Member IEEE,* Erdan Gu, Martin D. Dawson, *Fellow IEEE,* Dominic O'Brien, *Member IEEE,* and Harald Haas, *Member IEEE*

***Abstract*—LED based Visible Light Communications can provide high data rates to users. This can be further increased by the use of wavelength division multiplexing, using the different colours required to generate white light to transmit different data streams. In this paper a trichromatic approach is described, and the influence of colour combination on achievable data rate is analysed. A demonstration of LED based communications which achieves a data rate of >10 Gb/s by using a rate adaptive orthogonal-frequency-division-multiplexing scheme is also reported.**

***Index Terms*—** VLC, WDM, OFDM, LED, micro LED, Resonant cavity LED, Visible light communication, optical wireless communication, 10Gb/s, 5G

I. Introduction

Data traffic transmitted using wireless communications is expected to increase exponentially in the coming years, and this requires the development of Gbit/s class communication systems [1][2]. It is widely acknowledged that insufficient radio spectrum is the main challenge to develop such high-speed radio-frequency (RF) wireless systems. Optical wireless communications (OWC) use optical wavelengths in the infrared (IR), visible, and ultraviolet (UV) regions of the spectrum. OWC has the potential to provide ~THz of unlicensed bandwidth, a high degree of spatial reuse, and high security [3]. Visible light communications (VLC) is a class of OWC operating in the visible region of spectrum (390-700 nm). VLC uses the existing lighting infrastructure, which is designed for illumination. It therefore has the potential to provide considerable additional wireless transmission capacity at limited cost, using existing infrastructure.

Several demonstrations have shown that it is possible to construct Gbit/s class VLC links. They have used either a single-die white light emitting diodes (LEDs) or multi-colour LEDs as they are two representative methods to generate white light for illumination. Single-die white LEDs generate white light from a blue LED chip with phosphor material absorbing a portion of the blue light and re-emitting a broad yellow spectrum, resulting in the white light being made up of the combination of the blue and yellow. In practice, the slow temporal response of the phosphor limits the available bandwidth of the white-light source to a few MHz. In terms of communication performance, a trichromatic method, using independent sources allows higher capacity by avoiding the use of the slow response phosphor, and it further offers the opportunity to use WDM transmission techniques. Table 1 summarises recent demonstrations of LED based white light VLC systems.

Table 1. Recent demonstrations of LED based white light VLC

Ref. Year	Applied LED(s)	Applied schemes	Brightness	Data-rate
[4] 2015	Commercial R+Y+G+B	CAP WDM	450 lx	8 Gb/s
[5] 2015	Commercial R+Y+G+B	CAP WDM	720 lx	5.6 Gb/s
[6] 2015	Custom R+G+B	OFDM WDM	70 lx	2.3 Gb/s
[7] 2014	Custom single white	OFDM	240 lx	1.68 Gb/s
[8] 2012	Commercial single white	OFDM	400 lx	1 Gb/s

*R: red, Y: yellow, G: Green, B: blue, OFDM: orthogonal-frequency division multiplexing, CAP: carrierless amplitude-phase modulation, WDM: wavelength division multiplexing

In 2012, reference [8] showed the first demonstration achieving a data-rate of 1 Gb/s using a commercial phosphor based white LED. Two years later, reference [7] showed a BW improved single source using a GaN μLED and a fast polymer colour converter (BW > 200MHz), and achieved 1.68 Gb/s. In 2015, [6] reported a data rate of 2.3 Gb/s at an illumination level of only 70 lx, by using WDM from GaN μLEDs with fast colour converters. References [5] and [4] used commercial three or four colour LEDs, achieving rates of 5.6 Gb/s and 8 Gb/s, respectively. These data-rates were obtained at bit-error-rate between $2x10^{-3} \sim 3.8x10^{-3}$, considering the use of a forward-error-correction code. Recently, reference [9] presented the use of RGB laser diodes combined into white light and diffused to create wide coverage.

H. Chun, G. E. Faulkner, and D. C. O'Brien are with the Department of Engineering Science, University of Oxford, Oxford, UK. E-mail: {hyunchae.chun, grahame.faulkner, dominic.obrien}@eng.ox.ac.uk.

S. Rajbhandari is with School of Computing, Electronics and Maths, Coventry University, Coventry, UK. E-mail: ac1378@coventry.ac.uk.

E. Xie, J. J. D. McKendry, E. Gu, and M. D. Dawson are with the Institute of Photonics, Department of Physics, University of Strathclyde, Glassgow, U.K. E-mail: {enyuan.xie, jonathan.mckendry, erdan.gu, m.dawson}@strath.ac.uk.

D. Tsonev, and H. Haas are with the Institute for Digital Communications, Li-FI R&D Centre, The University of Edinburgh, Edinburgh EH9 3JL, U.K. e-mail: {d.tsonev; m.ijaz; h.haas}@ed.ac.uk.

We gratefully acknowledge support by the UK Engineering and Physical Sciences Research Council (EPSRC) under grant EP/K00042X/1.

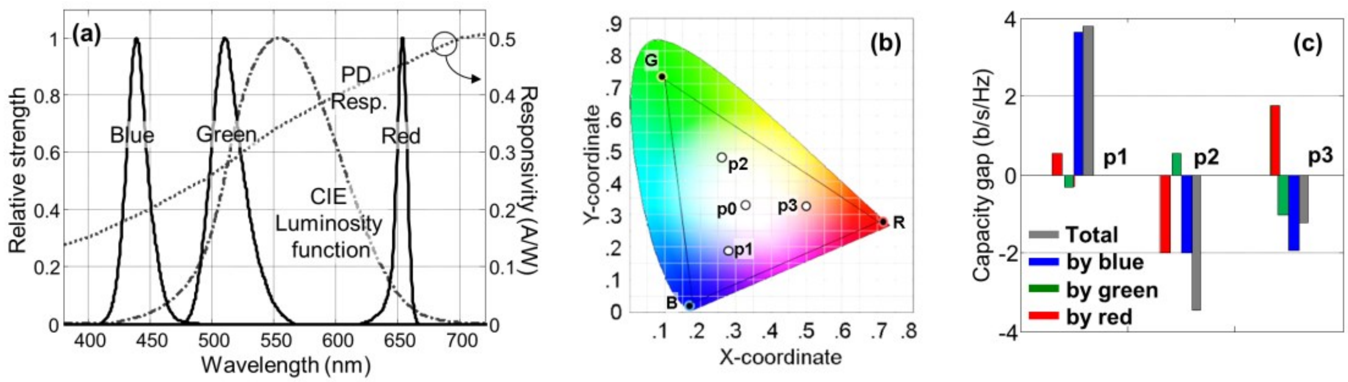

Fig. 1. (a) Measured optical spectrum of RGB sources, CIE luminosity function, and a typical silicon PD responsivity, (b) several colour points in CIE coordinate, and (c) capacity gap of different colour combinations with respect to the absolute white point, p0

However, these investigations do not take into account the colour property of the generated light, and do not show simultaneous WDM reception. In this paper the impact of different colour combinations on WDM based VLC is investigated. In section II, the influence of different colour combinations on WDM-VLC performance is analytically modelled using a general approach. Then, the colour combination point with the highest capacity is found in an arbitrary white-light boundary in CIE coordinates. In section III, the experiment demonstrates the actual data-rate at the highest capacity point. Lastly, conclusions are drawn in section IV.

II. Colour Combinations and VLC Performance

Trichromatic sources are most often used in lighting where variable ambient lighting conditions. However, the relatively higher cost of these sources, compared with the cheap single source approach, has not led to a large-scale adoption in general lighting. Despite the higher cost, the trichromatic sources supporting high data rate could still offer good value in applications where high rates are important.

In this paper we examine the effect of colour on data rate, and in order to do this, two different wavelength dependent functions must be considered. International Commission on Illumination (Commission Internationale de l'Eclairage, CIE) luminosity function, and the particular system photo-detector (PD) responsivity. Using these, the capacity can be derived from the available optical power, given an illumination constraint.

A. CIE Luminosity and Photo-detector Responsivity

Luminous flux is a photometric unit and represents the light output from an optical source as perceived by human eyes. It is defined such that a monochromatic light source emitting an optical power of 1/683 Watt at 555 nm has a luminous flux of 1 lumen (lm) [10]. The illuminance (lux=lx = lm/m^2) measures illumination level, and 400-1000 lx is recommended in indoor environments [11].

However, these photometric measures are directly relevant to communications, where the received signal is a function of photocurrent, and in turn detector responsivity. The conversion coefficient, K, from radiometric unit to photometric unit is shown as [10]:

$$K = 683 \int_\lambda V(\lambda)P(\lambda)d\lambda \Big/ \int_\lambda P(\lambda)d\lambda \quad [\text{ lm / w}] \qquad (1)$$

, where $P(\lambda)$ is optical spectrum of a light source, and $V(\lambda)$ is CIE luminosity function defining the colour sensitivity of human eyes. Equation (1) shows that when $P(\lambda)$ is centred at the peak of $V(\lambda)$, K becomes higher and the source is perceived brighter. On the other hand, for VLC, a smaller K may be preferred as it provides more optical power for a given brightness.

The responsivity of the PD used is the other wavelength dependent function affecting the performance of WDM based VLC. The main parameter defining such differences is its quantum efficiency, the percentage of incident photons generating electron-hole pairs [12]. The colour sensitivity of a PD is generally expressed by responsivity, $R(\lambda)$. Responsivity generally reduces as the wavelength becomes shorter due to the reduced quantum efficiency [12]. For VLC, therefore, a red colour channel can perform better than shorter wavelength channels, mainly by obtaining a higher electrical signal level for the same optical power.

B. Capacity for Different Colour Combinations

When the optical spectrum of the trichromatic sources, an illumination level, and target colour, is given, the available optical power and the corresponding electrical current are obtained by the CIE luminosity function and the PD responsivity. Fig 1 (a) shows optical spectrum of RGB LEDs, CIE luminosity function, and a PD responsivity function. The LEDs investigated are a commercial red resonant-cavity (RC) LED (RC650, Roithner), and custom green and blue μLEDs [13]. The responsivity function is obtained from the datasheet of a typical silicon photo-detector (FS1601, NewFocus). Fig 1 (b) shows the points on CIE colour coordinates generated by different RGB combinations, and Table 2 shows the proportion of the optical power supplied from each of the RGB sources proportion of the colour points. It can be seen that relatively higher red power is required to generate the reference white point (p0) and the other points (p1, p2, and p3), mainly due to a narrow spectral width of the red LED which has centre wavelength at the edge of the luminosity function. The points (R), (G), and (B) represent the coordinates of the individual sources themselves.

Table 2. RGB power proportion of different colours

	p0	p1	p2	p3
Red	63 %	55 %	46 %	83 %
Green	26 %	17 %	46 %	13 %
Blue	11 %	28 %	8 %	4 %

In order to investigate the communication performance, the maximum data rate of each point is calculated and compared. In this work, the conventional channel capacity equation in additive white Gaussian noise (AWGN) channel is used [14].

$$D = BW \log_2(1 + S/N) \quad (2)$$

, where BW, S, and N are bandwidth, the signal variance, and the noise variance. Strictly, this does not apply to optical intensity channel, such as described in [15] and [16].
However, when considering only the variance, excluding the power dissipation by the DC component, and assuming that the signal is within the system's linear operating range, this expression is a good approximation and has been used in several investigations [17]-[19].

To investigate the influence of different colour combinations, the capacity is compared with respect to the reference white point, p0. Assuming that the signal's standard deviation is proportional to the received optical power, capacity at the point p0 can be calculated as:

$$\begin{aligned} D_{p0} = \; & BW_R \log_2\left(1 + R_R^2 \cdot P_{p0R}^2/\sigma_n^2\right) \\ & + BW_G \log_2\left(1 + R_G^2 \cdot P_{p0G}^2/\sigma_n^2\right) \\ & + BW_B \log_2\left(1 + R_B^2 \cdot P_{p0B}^2/\sigma_n^2\right) \quad [\text{bit/s}] \end{aligned} \quad (3)$$

, where BW_R, BW_G, and BW_B are bandwidths of the RGB sources. P_{p0R}, P_{p0G}, and P_{p0B} are the RGB optical power at the point p0. σ_n^2 is receiver noise variance. R_R, R_G, and R_B are PD responsivity for the RGB spectrum, which is calculated by:

$$R_x = \frac{\int_\lambda R_x(\lambda) \cdot P_x(\lambda)\, d\lambda}{\int_\lambda P_x(\lambda)\, d\lambda} \quad (4)$$

, where R_x is responsivity for an arbitrary RGB source x with optical spectrum of $P_x(\lambda)$, and the available optical power, P_x. Given a photometric constraint, this can be obtained by using the conversion coefficient in (1):

$$\begin{aligned} P_x &= \int_\lambda P_x(\lambda) d\lambda \\ &= K_x^{-1} \cdot 683 \int_\lambda V(\lambda) \cdot P_x(\lambda) d\lambda = K_x^{-1} \phi_{lm} \end{aligned} \quad (5)$$

, where K_x is the Watt-to-Lumen conversion coefficient for the arbitrary RGB source x. ϕ_{lm} is a photometric constraint such as maximum allowed illumination level. In the case of using the same bandwidth (BW) for flat RGB channels, and assuming that a high SNR is generally provided in a typical illumination scenario [20], equation (3) can be rearranged as:

$$\begin{aligned} C_{p0} &= \frac{D_{p0}}{BW} \quad [\text{bit/s/Hz}] \\ &\simeq 2\log_2\left(\frac{R_R R_G R_B \cdot P_{p0R} P_{p0G} P_{p0B}}{\sigma_n^3}\right) \\ &= 2\log_2\left(R_R R_G R_B \cdot \bar{P}_{p0R} \bar{P}_{p0G} \bar{P}_{p0B} \cdot \left(\frac{K_{p0}^{-1}\phi_{lm}}{\sigma_n}\right)^3\right) \\ &\le 2\log_2\left(R_R R_G R_B \cdot \left(\frac{K_{p0}^{-1}\phi_{lm}}{3\sigma_n}\right)^3\right) \end{aligned} \quad (6)$$

, where $\bar{P}_{p0R}$, $\bar{P}_{p0G}$, and $\bar{P}_{p0B}$ is the proportion of RGB powers at the point p0, as shown in the first column of Table 2. Equation (6) shows that the capacity becomes a maximum when the RGB colours have equal power. Therefore, it can be seen that for the same colour point in the CIE coordinate there are optimum R/G/B spectra leading to the maximum capacity. It also shows that a smaller Watt-to-Lumen conversion coefficient leads to a higher capacity.

Setting C_{p0} as the reference, the capacity of various colour points can be compared regardless of the receiver noise. This is done by defining the capacity gap (Γ) as the capacity difference of each point from the reference point. For instance, the capacity gap for the point p1 is obtained by:

$$\begin{aligned} \Gamma_{p1} &= C_{p1} - C_{p0} \quad [\text{bit/s/Hz}] \\ &= 2\log_2\left(\frac{R_R R_G R_B \cdot P_{p1R} P_{p1G} P_{p1B}}{\sigma_n^3}\right) \\ &\qquad - 2\log_2\left(\frac{R_R R_G R_B \cdot P_{p0R} P_{p0G} P_{p0B}}{\sigma_n^3}\right) \end{aligned} \quad (7)$$

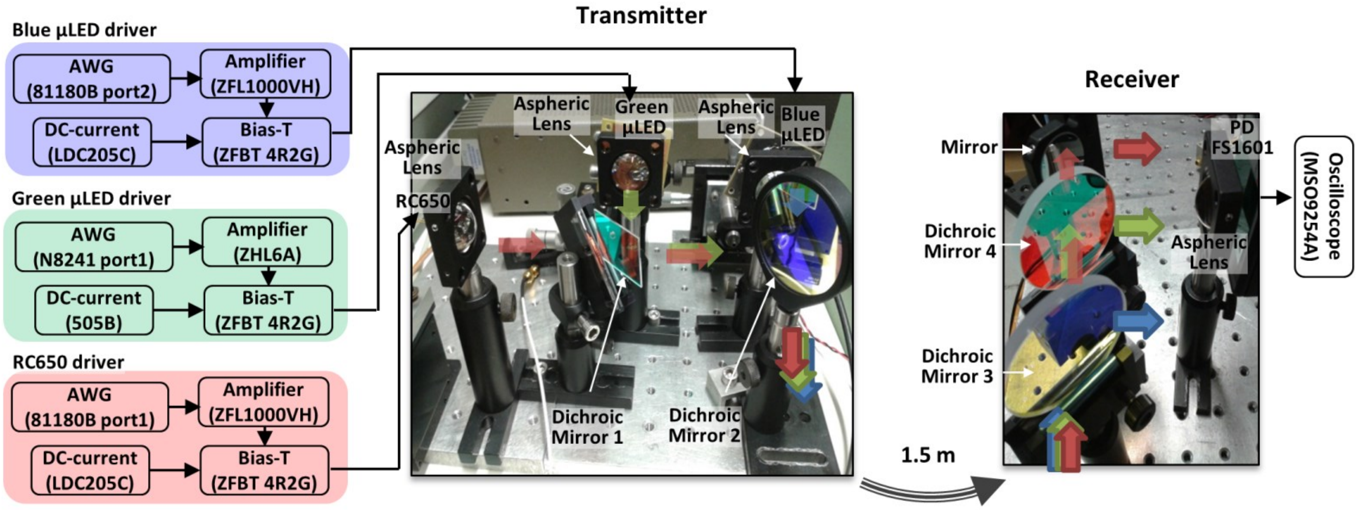

Fig. 2. Dichroic mirror based WDM-VLC experimental set-up

$$= 2\log_2 \frac{\bar{P}_{p1R}}{\bar{P}_{p0R}}\frac{K_{p0}}{K_{p1}} + 2\log_2 \frac{\bar{P}_{p1G}}{\bar{P}_{p0G}}\frac{K_{p0}}{K_{p1}} + 2\log_2 \frac{\bar{P}_{p1B}}{\bar{P}_{p0B}}\frac{K_{p0}}{K_{p1}}$$

$$= \Gamma_{p1R} + \Gamma_{p1G} + \Gamma_{p1B}$$

, where Γ_{p1R}, Γ_{p1G}, and Γ_{p1B} are the capacity gaps of each of the RGB channels. The optical power proportion changed from 63 % to 55 % for red, from 26 % to 17 % for green, and from 11 % to 28 % for blue. These changes result in the capacity differences of -0.39, -1.2, and 2.7bit/s/Hz. For this colour proportion change, there is overall a 1.1 bit/s/Hz capacity addition. In terms of the same photometric constraint, there is another 0.9 ($= 2\log_2 K_{p0}/K_{p1}$) bit/s/Hz addition for each colour. As a result, Γ_{p1R}, Γ_{p1G}, and Γ_{p1B} become 0.51, -0.3, 3.6 bit/s/Hz, respectively. In total, the capacity gap for the point p1 becomes 3.8 bit/s/Hz. Note that Equation (7) assumes the use of the same bandwidth from R/G/B sources. However, it is possible to extend the equation to accommodate the influence of different bandwidth. This can be done by scaling each R/G/B term in equation (7) with relative bandwidth terms ($\frac{BW_R}{BW_{avg}}$, $\frac{BW_G}{BW_{avg}}$, and $\frac{BW_B}{BW_{avg}}$), where BW_{avg} is the average bandwidth.

Fig1 (c) summarises the capacity gaps for the points p1, p2, and p3. A positive capacity gap is obtained only from the point p1. This is because for the point p2, there is a negative gap of -1.1 ($= 2\log_2 K_{p0}/K_{p2}$) bit/s/Hz, due to the same photometric (i.e., illumination) constraint. For the point p3, although there is a positive gap, the red optical power occupying ~80 % of total power leads to an unbalanced colour proportion, which leads to a negative capacity gap.

III. 10 Gb/s System Demonstration

In this section, the potential of a WDM based VLC system is tested, with the knowledge that for the tested RGB sources the bluish colours around the point p1 leads to the best communication performance.

A. Dichroic Mirror Based WDM-VLC Experimental Set-up

Fig 2 shows the experimental set-up used for the demonstration. First, a PC generates a communication signal, and this is turned into analogue signals by individual drivers for red, green, and blue sources. Each driver consists of an independent arbitrary waveform generator (AWG), an amplifier, a current source, and a bias-T. The RGB sources are collimated through aspheric lenses and are either reflected by or transmitted through dichroic mirrors. Mirror 1 is placed at 45 degrees to the beam from the blue emitter, and transmits this light. Green light propagating at 90 degrees to the blue beam is combined with it, as the Mirror 1 reflects at this wavelength. The combined green/blue beam passes through Mirror 2, and light from the red beam is combined with this using a similar approach. The use of dichroic mirrors allows a co-linear combined beam, thus removing problems of beam offset and consequent colour change as the overlap between beams varies with distance from the source.

The receiver module is located at a distance of 1.5 m, a typical value from a light source to a desk level [20]. This also uses dichroic mirrors to separate the combined beam. This is achieved sequentially by using the same approach as for the source. Each separated beam is focused by an aspheric lens. RGB polyester based film-type optical band-pass filters are used to get rid of any other residual signal from different colours, and no crosstalk is experimentally observed. Then, the light is detected by a high-speed PIN PD (FS1601). The signal from the PD is captured by an oscilloscope (MSO9254A), and sent back to the PC for analysis.

B. OFDM Results and Discussion

DC biased optical orthogonal frequency division multiplexing (DCO-OFDM) is used for communications, as it has the highest spectral efficiency among all optical OFDM schemes. For optimal DCO-OFDM operation, the signal has to be conditioned, depending on signal-to-noise ratio (SNR) and de-

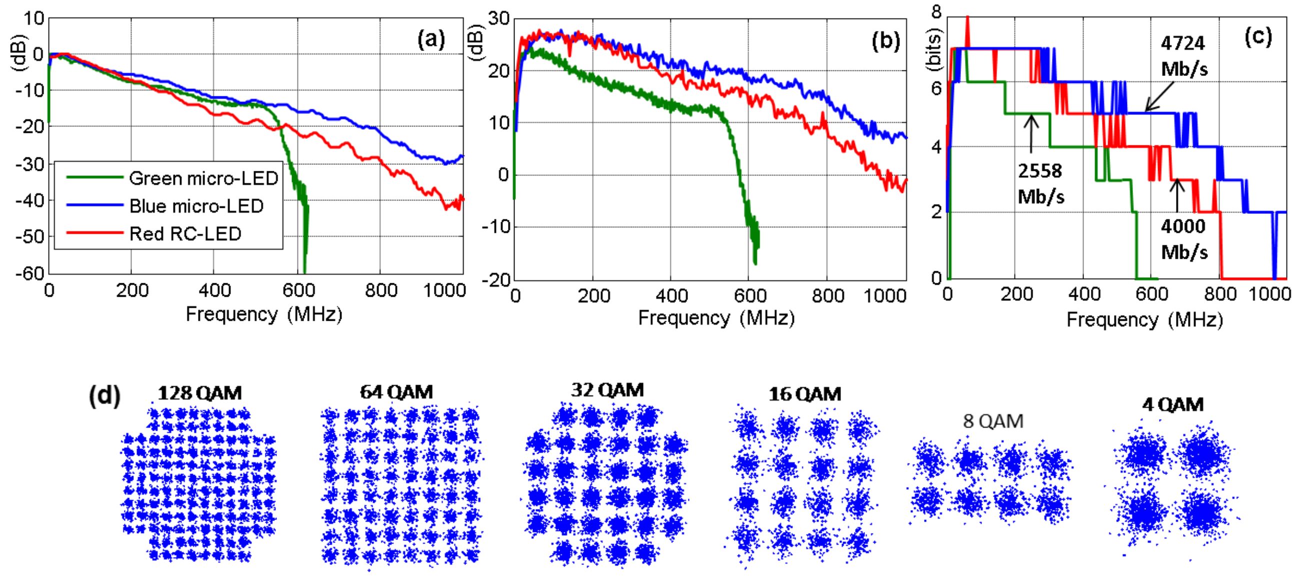

Fig. 4. (a) Channel gain, (b) measured SNR, (c) allocated bits by rate-adaptive DCO-OFDM algorithm, for RGB channel from the red RC-LED, green μLED, and Blue μLED, and (d) constellations from the blue channel

lay-spread of the channel, and in this demonstration parameters are optimised by the methods introduced in [21]. One important parameter is signal clipping level, which keeps the signal level above zero and mitigating the impairment from non-linear transfer function of LEDs. In general, the clipping level is expressed in relation to the time domain signal standard deviation (σ) [21]. This optimisation is undertaken for the colour point p1, under the illumination constraint of <1000 lx. The clipping levels are found to be ±3.5σ, ±2.6σ and ±3.3σ, for RGB channels respectively. Signal modulation bandwidth (1000, 625, 1000 MHz), Fast-Fourier-Transform size (512, 1024, 512), and cyclic-prefix size (4, 5, 4 samples) are used for the RGB channels, respectively. The optimal biasing point and AC voltage swing are determined for each LED, by maximising the SNR per subcarrier estimated from 200 BPSK training sequences.

Typical OFDM requires only a single tap post equalisation at a receiver side. However, to improve the performance further, either pre-equalisation with fixed-rate QAM or rate adaptive bit-loading can be used. Pre-equalisation is relatively straightforward to implement, with the same type of QAM decoder for all subcarriers, but more complex adaptive loading leads to a better performance than the fixed-rate case, and in this paper the adaptive approach is investigated, in order to achieve the highest possible data-rate.

Fig 4 (a) shows the frequency response of the RGB channels from the red RC-LED, green μLED, and blue μLED. The 3 dB (electrical to electrical) BWs available from the three channels are similar and approximately100 MHz. However, the blue μLED shows the lowest rate of fall-off with frequency, which allows a better utilisation of high frequency sub-carriers. The green channel has an abrupt channel gain drop from ~500 MHz. This is due to the AWG (N8241, 500 MHz BW) used for the green channel. The green channel shows a similar rate of fall-off when testing the green source with a higher speed AWG (81180B, 1GHz BW) which is used for the two other colour channels.

Fig 4 (b) shows the measured SNR of the RGB channels. Due to relatively small green proportion at the point p1, the green channel has lower SNR overall. Again, an abrupt SNR drop is observed at around 500 MHz, but the blue and red channel show more than 10 dB SNR up to ~ 800 MHz.

Table 3. Measured data-rate, BER, and Brightness

	Red (RC650)	Green (μLED)	Blue (μLED)
Data-rate	4000 Mb/s	2558 Mb/s	4724 Mb/s
	Aggregate = 11.28 Gb/s		
BER	$3.4\text{x}10^{-5}$	$3.7\text{x}10^{-5}$	$2.8\text{x}10^{-5}$
Brightness	984 lx		

Fig 4 (c) shows the assigned bits by a rate-adaptive DCO-OFDM algorithm based on [22], for the three colours. The algorithm iteratively examines available *SNR*, and allocates bits, according to the channel quality. The QAM level (M_n) on n^{th} subcarrier is then assigned according to the derived bits. By this method, the data rate is determined as:

$$\text{Data-rate} = \frac{\sum_{n=0}^{\frac{N_{fft}}{2}-1} \log_2 M_n}{(N_{fft}+N_{cp})/2BW_{mod}} \quad \text{[b/s]} \qquad (8)$$

, where M_n is set to 1 for the cases that no bit is allocated to the subcarrier, and BW_{mod} is the DCO-OFDM modulation BW. N_{fft} and N_{cp} mean Fast-Fourier-Transform (FFT) size and cyclic-prefix (CP) size. The denominator represents the total time duration for an OFDM frame, and numerator shows the number of bits sent per frame. The total number of bits to assign is changed until the highest data-rate with bit-error-rate (BER) < 3.8 x10^{-3} is achieved. This BER can guarantee a reliable communication system by taking advantage of a standard forward error correction (FEC) code with 7% overhead [23]. Fig 4 (d) shows different QAM constellations from the blue channel. This results in a data-rate of 4724 Mb/s at a BER less than 3.8 x10^{-3}.

Table 3 summarises the BER and data-rate achieved from the all three WDM-VLC channels. As shown in the Table 3, the achievable aggregate data-rate is 11.2 Gb/s at an illumination level of 984 lx. After 7 % FEC overhead reduction, the rate becomes 10.4 Gb/s. This result shows the considerable potential of the high-speed VLC system based on the WDM-VLC.

Next, the data-rate change with illumination level is investigated. The illumination level is altered by changing the optical power of each colour independently. Fig 5 shows the aggregate data-rate with a BER less than 3.8x10^{-3}, and it can be seen that even at an illumination level of 750 lx, more than 10 Gb/s is still achieved. This is because such brightness results in a high SNR, leading to a logarithmic change of data-rate. This is verified when the data points are plotted on a log-log scale, as shown in the Fig 5.

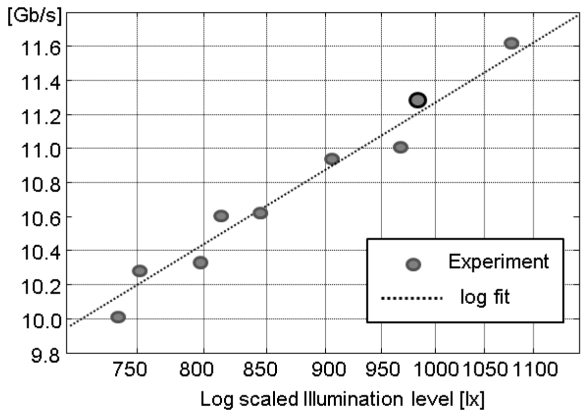

Fig. 5. Data-rate vs. illumination level

Results so far have been obtained for a colour around the colour point p1, for the purpose of achieving the highest possible data-rate. It is also feasible to estimate the data-rate at other colour points by using the capacity gap shown in Fig 1 (c). For instance, the point p1 has Γ_{p1R}, Γ_{p1G}, and Γ_{p1B} of 0.51, -0.3, 3.6 bit/s/Hz, with respect to the reference point p0. Therefore, by subtracting the capacity gap from the bits assigned for each colour in Fig 4 (c), the data-rate at the point p0 can be estimated. The estimated data-rate is 7.8 Gb/s at an illumination level of 984 lx.

IV. CONCLUSIONS

An RGB LED based WDM system supporting data rates of 11.28 Gb/s (10.4 Gb/s after FEC overhead reduction) was demonstrated. This used a commercial red RC-LED and custom blue and green μLEDs. To the best of our knowledge, this is the fastest VLC system based on RGB LEDs. The addition of a fourth colour (in the yellow region, around 575-625 nm) could further increase the capacity and improve the colour rendering performance.

In addition an algorithm to determine the effect of colour change on available data rate was introduced. This, together with an analysis of the effect of different illumination levels, shows that high data rates can be achieved for a wide range of colours and illumination levels.

Future modelling in this area will focus on the combination of the spatial and wavelength degrees of freedom. Our aim is that future demonstrations will use arrays of micro LEDs with WDM capability, thus providing high data-rate and coverage at the same time. This is being pursued under UPVLC program.

ACKNOWLEDGMENT

The authors gratefully acknowledge support by the UK Engineering and Physical Sciences Research Council (EPSRC) under grant EP/K00042X/1, and we acknowledge kind support of Dr. Johannes Herrnsdorf.

REFERENCE

[1] Cisco white paper, "Cisco Visual Networking Index: Forecast and Methodology, 2014-2019," (Cisco, 2015), http:// http://investor.cisco.com/files/doc_downloads/report_2014/white_paper_c11-481360.pdf
[2] L. Hanzo, H. Haas, and S. Imre, "Wireless myths, realities, and futures: from 3G/4G to optical and quantum wireless," IEEE Proc. Special Centennial Issue, pp. 1853–1888, May 2012.
[3] A. Jovicic, L. Junyi, and T. Richardson, "Visible light communication: opportunities, challenges and the path to market," IEEE Communications Magazine, vol. 51, pp. 26-32, 2013.
[5] G. Cossu, W. Ali, R. Corsini, and E. Ciaramella, "Gigabit-class optical wireless communication system at indoor distances (1.5 4 m)," Optics Express, vol. 23, pp. 15700-15705, 2015/06/15 2015.
[4] Y. Wang; L. Tao, X. Huang, J. Shi, N. Chi, "8-Gb/s RGBY LED-Based WDM VLC System Employing High-Order CAP Modulation and Hybrid Post Equalizer," in Photonics Journal, IEEE , vol.7, no.6, pp.1-7, Dec. 2015
[6] P. Manousiadis, H. Chun S. Rajbhandari, R. Mulyawan, D. A. Vithanage, G. Faulkner, D. Tsonev, J. J.D.McKendry, M. Ijaz, S. Videv, E.Xie, E. Gu, M.D. Dawson, H. Haas, G. A. Turnbull, I.D.W. Samuel, and D. O'Brien, "Demonstration of 2.3 Gb/s RGB White-light VLC using Polymer based Colour-converters and GaN micro-LEDs," IEEE Summer Topicals Meeting 2015, Visible Light Communications (VisC), Nassau, Bahamas, 2015 (to appear).
[7] H. Chun, P. Manousiadis, S. Rajbhandari, D. A. Vithanage, G. Faulkner, D. Tsonev, J. J. D. McKendry, S. Videv, X. Enyuan, G. Erdan, M. D. Dawson, H. Haas, G. A. Turnbull, I. D. W. Samuel, and D. C. O'Brien, "Visible light communication using a blue GaN μLED and fluorescent polymer color converter," IEEE Photonics Technology Letters, vol. 26, pp. 2035-2038, 2014.
[8] A. M. Khalid, G. Cossu, R. Corsini, P. Choudhury and E. Ciaramella, "1-Gb/s Transmission Over a Phosphorescent White LED by Using Rate-Adaptive Discrete Multitone Modulation," *IEEE Photonics Journal*, vol. 4, no. 5, pp. 1465 – 1473, Oct. 2012.
[9] Tsonev, D.; Videv, S.; and Haas, H.; "Towards a 100 Gb/s Visible Light Wireless Access Network", Optics Express, 2014 (invited).
[10] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," *IEEE Transaction on Consumer Electronics,*Vol. 50, pp. 100-107, Feb. 2004.
[11] Lighting of Indoor Work Places, European Stand. EN 12464-1, 2003.
[12] J. Palais, "Fiber Optic Communications- Fifth edition," 2004.
[13] J.J.D. McKendry et al., "Visible-light communications using a CMOS-controlled micro-light-emitting-diode array," J. Lightw. Technol., vol. 30, no. 1, pp. 61–67, Jan. 1, 2012.

[14] C. E. Shannon, “A mathematical theory of communication,” Bell System Technical Journal, vol. 27, pp. 379–423 and 623–656, 1948.

[15] A. Lapidoth, S.M. Moser, M.A. Wigger, "On the Capacity of Free-Space Optical Intensity Channels," in Information Theory, IEEE Transactions on , vol.55, no.10, pp.4449-4461, Oct. 2009.

[16] S. Hranilovic, F.R. Kschischang, "Capacity bounds for power- and band-limited optical intensity channels corrupted by Gaussian noise," in Information Theory, IEEE Transactions on , vol.50, no.5, pp.784-795, May 2004.

[17] D. Tsonev, S. Sinanovic; H. Haas, "Practical MIMO Capacity for Indoor Optical Wireless Communication with White LEDs," in Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th , vol., no., pp.1-5, 2-5 June 2013.

[18] J.Vucic, C. Kottke. S. Nerreter, K.D. Langer; J.W. Walewski, "513 Mbit/s Visible Light Communications Link Based on DMT-Modulation of a White LED," in Lightwave Technology, Journal of , vol.28, no.24, pp.3512-3518, Dec.15, 2010

[19] P. M. Butala, H. Elgala, T.D.C. Little, "SVD-VLC: A novel capacity maximizing VLC MIMO system architecture under illumination constraints," in Globecom Workshops (GC Wkshps), 2013 IEEE , vol., no., pp.1087-1092, 9-13 Dec. 2013.

[20] J. Grubor, S. Randel, K.-D. Langer, and J. W. Walewski, “Broadband Information Broadcasting Using LED-Based Interior Lighting,” Journal of Lightwave *Technology*, vol. 26, no. 24, pp. 3883–3892, Dec. 2008.

[21] H. Chun, S. Rajbhandari, G. Faulkner, D. Tsonev, H. Haas, and D. O’Brien, “Visible Light Communication using Laser Diode based Remote Phosphor Technique” IEEE International Conference on Communications (ICC), June 2015.

[22] H. E. Levin, “A Complete and Optimal Data Allocation Method for Practical Discrete Multitone Systems,” in *Proc. Of IEEE Global Telecommunications Conference (IEEE GLOBECOM 2001)*, vol. 1, San Antonio, Tx, USA, Nov. 25 – 29 2001, pp. 369 – 374.

[23] ITU-T, G.975.1: Forward error correction for high bit-rate DWDM submarine systems, 2004.