Laser Visible Light Communications[*]

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Abstract–Visible Light Communications (VLC) via lighting must overcome the slow white LED. We propose the addition of a fast red laser to improve data rate, coverage, and light quality.

Keywords: VLC, laser, light quality. lighting, LED.

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1 Introduction

"Dual-use" lighting, which provides Visible Light Communications (VLC) along with illumination, offers great advantages as a complement or alternative to existing networks [1]. VLC uses free spectrum. Signal can be directed and blocked by walls, allowing many non-interfering links to coexist in close proximity [2]. This provides security and high datarate area densities (Mb/s/m^2). VLC is safer to eyes than IR or UV, because the blinking reflex prevents long exposure [3]. The ubiquity and high "transmit" power of illumination bodes well for providing data coverage and robust links indoors.

VLC via lighting also brings many challenges, including: (1) Efficient illumination-power white LEDs have limited bandwidth. And (2) VLC must not compromise quality and functionality of illumination. Most cost-effective and efficient white LEDs are based on high-powered blue LEDs, which have a 3 dB bandwidth limited to $\sim$ 20 MHz [4]. To convert the blue light to a broad spectrum white, the LED is coated with a phosphor, which further lowers the bandwidth to $\sim$ 2 MHz. The faster blue signal can be accessed by optical filtering at the receiver. The receive power of this "blue channel" depends on the color spectrum of the LED. For example, using a "cool" white LED, with a higher proportion of blue light, is advantageous. However, this may conflict with lighting preferences, which often call for a warmer hue.

For datarates above 20 Mb/s, bandwidth-efficient modulation can be used. In this way datarates of $500+$ Mb/s have been demonstrated [5]. Operating at high bits/Hz requires very high receive power, making such links highly sensitive to dips in power due to link distance or misalignment. This can restrict link robustness, coverage and mobility.

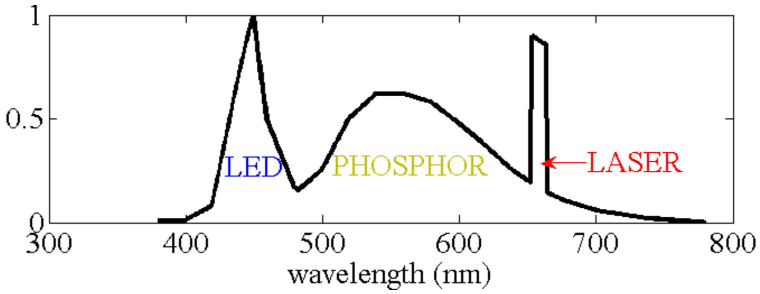

Figure 1: Combined color spectrum of cool white LED and red laser.

Thus, our strategy is to modulate data with an efficient visible red laser source integrated with the LED luminaire. The LED, phosphor and laser emissions are mixed together, diffused, and projected throughout the room, so that humans see only white light from a single source, and the red component is imperceptibly modulated with data (see Fig. 1). The major advantage is that lasers have greater modulation bandwidths than LEDs, resulting in greater rates at much lower receive power. Further, the narrow line width of a laser allows the use of a narrow optical filter for greater rejection of ambient noise. Also, optical detectors have higher detector responsivities (A/W) for red than blue. On the other hand, matching the higher bandwidth of the source requires use of a smaller area photodiode, which lowers SNR in high shot noise environments. We show that on balance the red laser strategy improves the datarate, coverage and link robustness under mobility, compared to modulating the LED.

The impact of the narrow linewidth red source on light color and quality is of concern. Recent

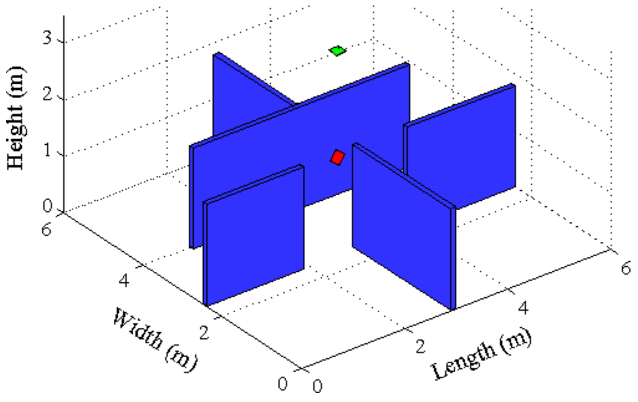

Figure 2: Simulated virtual office. A luminaire transmitter is on the ceiling, and 3600 receivers are distributed throughout the room area at desktop height.

work gives hope in this regard [6]; there, a white light constructed by mixing together four narrow line width laser sources was judged to have competitive and even superior color rendering properties compared to standard bulbs. Our proposal is less extreme, as we add only one narrow line laser source to the broad spectrum white LED. LED manufacturers Epistar and Siemens have recently publicized adding a red LED to the blue plus phosphor white LED to improve both the color temperature and energy efficiency of the light [7], [8]. We show that the red laser also improves the Color Rendering Index (CRI) and Color Quality Scale (CQS) scores, while enabling the tuning of Correlated Color Temperature (CCT).

2 Model and Results

We modeled the VLC system using CandLES [9]. In each of six cases, there is a single VLC lamp on the ceiling of the room in Fig. 2, emitting a total of 2000 lm of light. Only the proportion of LED to red laser light is varied. The 2000 lm converts to between 6-9.5 W of light power, depending on the combined spectrum of each case. The lamp uses multiple cool white Luxeon Rebel LXML-PWC1 LEDs and high power Rohm RLD65PZB5 laser diodes, to emit the 2000 lm total. The LEDs have 20 MHz bandwidth in the blue channel, and the lasers have 175 MHz (2 ns rise time). Ambient light irradiance producing shot noise is 5.8 μW/(cm$^2\times$nm) – a worst case indoor level; noise from the lamp is added.

Case 1 has no laser, and in only this case the LED is modulated with data – the "blue" channel. We match the 20 MHz LED with a large receiver – Hamamatsu S3204-08: 324 mm^2 active area, and 0.27 A/W responsivity at 450 nm. We add a wide FOV lens and a 450$\pm$20 nm optical filter.

In **cases 2-6**, only the red laser is modulated, with increasing power, to get 40, 80, 120, 160, and 200 lm. This is between 2 and 10% of the total 2000 lm. The laser gets $\sim$ 48 lm/W optical, so the transmit powers are between or 0.84 and 4.2 W. This is a small contribution to lighting, but very high power compared to allowed indoor free space IR or UV transmissions. We model a smaller faster photodiode receiver, the Hamamatsu S3883: 1.7 mm^2 area 300 MHz bandwidth and a 0.45 A/W at 658 nm. We add a lens equivalent to the blue case, and a n

Figure 3 shows the results for the six cases. All cases are bandwidth constrained – including the higher bandwidth and reduced receive power laser cases (2-6). We use a simple bandwidth-

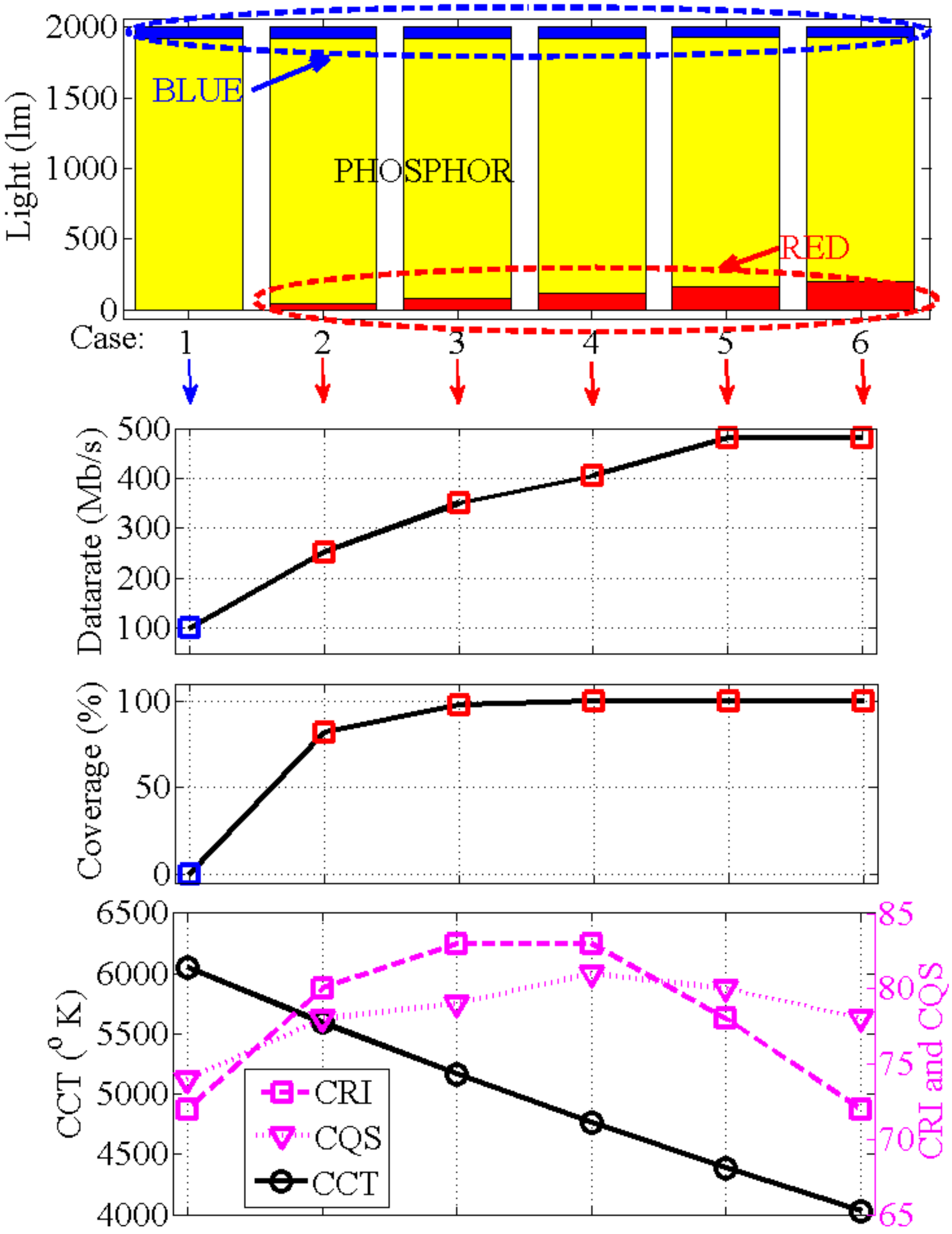

Figure 3: Case 1 (left) is the no laser case where the LED is modulated. In cases 2-6 the laser is modulated instead and at increasing output. Top graph shows the light content as perceived by the human eye (lm): the escaped blue from the LED, the broad spectrum yellow from the phosphor, and the red laser. The middle two graphs show the datarate and area coverage, and the bottom shows the light quality metrics: CCT, CRI and CQS.

efficient modulation: Mth order pulse amplitude modulation (M-PAM). All the laser cases do better than case 1 for both the top datarate in the room, and coverage – percentage of area above 100 Mb/s. The bottom graph shows the color temperature CCT and rendering metrics CRI and CQS, as evaluated by [10]. Clearly, CCT can be tuned by controlling the ratio of laser to LED power (for CCT, a lower temperature (°K) means "warmer" hues). The laser improves rendering, with the best marks for case 4: CRI=83, CQS=81. Case 4 also has rates between 110 and 405 Mb/s, 100% area coverage, and CCT=4767 °K – a neutral hue.

3 Conclusion

Adding high bandwidth laser sources to a white LED luminaire can improve both VLC datarate and coverage, and color rendering performance of the light.

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