Visible Light Communications: recent progress and challenges

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I. Introduction

Members of the wireless world research forum (WWRF) have recently completed a whitepaper on visible light communications (VLC). In this abstract recent developments in the field are outlined, together with their significance in overcoming the challenges of VLC.

The key challenges identified in the paper were (i) Improving data rate, (ii) Providing an uplink and (iii) Compatibility with illumination

The aim of the WWRF briefing is to bring members up to date with progress in the field.

II. Increasing data rate

The characteristics of the VLC channel are introduced in the following sections.

A. The VLC channel

1) Sources

White Light LEDs typically used blue LEDs that are coated in a yellow phosphor[1] for general illumination applications. When the light from the blue LED combines with the yellow phosphor there is a resulting white emission. Figure 1 shows the measured small signal modulation bandwidth of a Luxeon star device, showing a bandwidth of 3MHz for the white emission, with 12MHz for the blue component. This shows the effect of the slow yellow phosphor, which creates a major challenge for the use of these devices for high speed communication.

2) Propagation

Room illumination must meet minimum levels to meet standards for human occupancy, with levels in a range of 400lux - 800lux typically being specified[2]. These lighting levels ensure that high levels of optical power are available for modulation when compared with more traditional IR optical wireless systems. In the case of a 5x5x3m 'box' room illuminated at these levels a Signal to Noise Ratio (SNR) of >40dB is available for a typical receiver[3, 4].

The communications bandwidth available is determined by the multipath interference between the lines of sight from multiple LEDs and the diffuse reflections from the surface of the room. The LOS components dominate for a receiver in most positions in the room so the effect of multipaths is small. In [5] it is estimated that bandwidths of at least 88MHz are available.

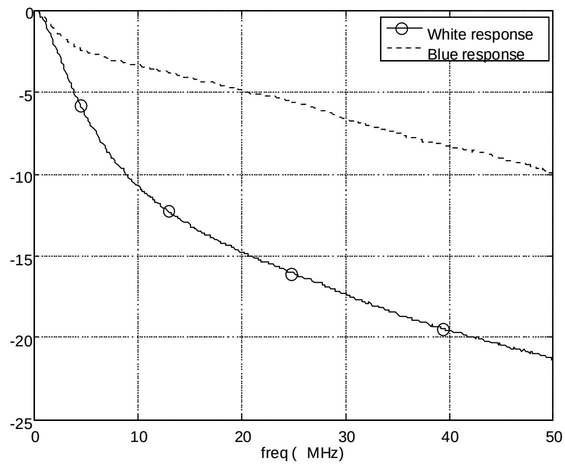

Figure 1. Measured bandwidths of Luxeon Star device, showing white and blue responses.

3) Receiver

Receivers that have sufficient collection area and high enough sensitivity for VLC are straightforward to fabricate for bandwidths approaching 100MHz, so in this case receiver performance does not limit the channel.

Overall, the VLC channel performance is limited by the LED for near and medium term applications, and only when the bandwidth required is greater than 100MHz must the receiver and propagation aspects be considered. Therefore, mitigating the poor performance of the LED is the most important step in increasing the data-rate.

B. Increasing data rate

The most straightforward method of improving the modulation bandwidth of the LED is to detect only the blue component at the receiver by using an optical filter to block the slow yellow component. Although this can improve the bandwidth by a substantial factor, the resulting VLC channel bandwidth is still low. However the very high signal to noise ratio can be used to overcome the penalties due to equalisation and/or provide the high SNR required for complex modulation schemes. In addition the large number of LEDs that can potentially transmit different data makes parallel communications an attractive prospect

Complex modulation has been studied by others[3, 5], and in this briefing we will focus on equalisation and parallel communications.

1) *Equalisation*

The channel response can be equalised at the transmitter (pre-equalisation), at the receiver (post-equalisation) of a combination of the two. A number of theoretical and practical studies have been undertaken in this area and two examples are shown in the next section.

a) Pre-equalisation

Most LED lighting applications will consist of an array of LEDs, and it is possible to equalise each device separately so that the overall response of the array provides higher bandwidth than individual devices.

Each device contains a significant amount of series inductance, so it is possible to 'tune' the peak optical output frequency by using a variable series capacitor to create a resonance and therefore peak driving current at a desired point. A link has been constructed using this technique and results are reported in[6]. This uses 16 LEDs, each with a bandwidth of 3MHz. Using resonant driving allows an overall bandwidth of 25MHz and a (Non-Return-to-Zero On-Off Keying (NRZ-OOK)) data rate of 40Mb/s over several metres. Figure 2 shows a diagram of the experiment.

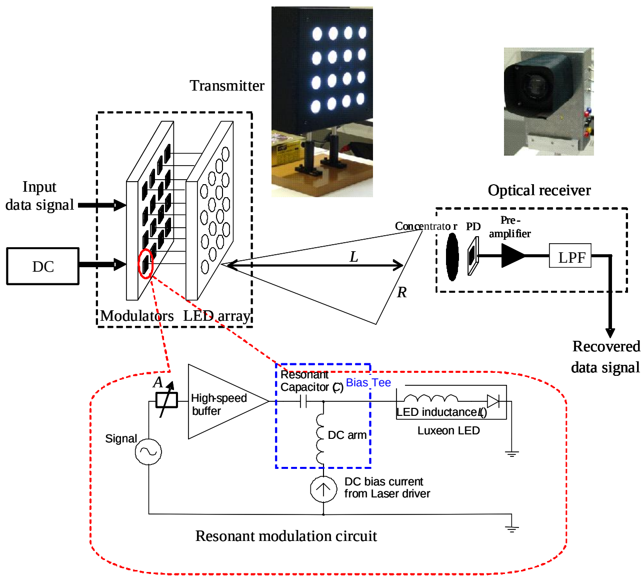

Figure 2. Optical link using resonant driving of LED array.

Equalisation of a single link has also been demonstrated. In [7] blue filtering is combined with transmitter equalisation to achieve a data rate of 80Mb/s (NRZ-OOK).

b) Post-equalisation

The use of a simple first order equaliser at the receiver can be used to compensate for the slow decay, (and hence narrow bandwidth) of the phosphor. This is achieved by estimating the cut-off frequency of the LED from the decay time of the impulse response and using a first-order pole to compensate for this.

Simulation results show that this can approximately double the available bandwidth, with 32Mbit/s NRZ-OOK achieved using the white response of the LED, and 73Mb/s NRZ-OOK achieved using the resonant array response (with a BER of 10^{-6})[4].

At present it is unclear whether complex modulation or equalisation, or a combination of the two is likely to provide the highest data rate for a given power penalty constraint. In addition the complexity of the circuitry required will also affect the choice of technique.

2) *Parallel data communication*

Parallel data communication involves sending different data from each LED to a receiver that can separate the information from each stream. A receiver array with each detector illuminated by a single source is the best possible arrangement, in that the overall data rate is increased (over the single channel rate) by the number of separate channels. However, this requires accurate alignment of transmitter and receiver.

An optical MIMO system does not require this alignment however, and simulations of a system have been undertaken. Different groups of illumination LEDs transmit different data to a receiver array, at which signals from different LEDs overlap. If the full-rank channel matrix is known this can be used to estimate the transmitted data given the overlapping received signals. Preliminary simulations show that this can perfectly recover the data signals, except at positions in the room the channel matrix is ill conditioned or of incomplete rank. Work to investigate this is underway.

III. Providing an Uplink

VLC is a natural broadcast medium, and providing an uplink is challenging. Several approaches have been considered; a different wavelength uplink can be used, although this may require a transmitter that can track the receiver position within the room. Modulated Retro-reflecting links[8] are attractive in that they do not require tracking, although available modulators are generally low-speed, and receiver placement requires further study. The use of RF to provide an uplink has also been considered[9]. At present there are no clear 'best' options, and further work is required to develop potential techniques and compare alternatives

IV. Compatibility with Illumination

VLC is compatible with the levels of illumination required in a room that is occupied, and any modulation for communications is at rates above those where there may be health effects. Perhaps the most challenging problem for VLC is compatibility with the commonly used Pulse Width Modulation (PWM) dimming systems, as the channel is not present, during the 'off' periods of the PWM waveform. Approaches that combine modulation with dimming have been proposed[10], but further work is required in this area.

V. Conclusions

VLC is a rapidly growing research area, with good progress being made in achieving high data rates. There are a number of challenges that must be addressed however, and the briefing will describe these in more detail

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