Indoor Visible Light Communications: challenges and prospects

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ABSTRACT
The rapid improvement in the efficiency of solid-state lighting has led to predictions that it will be the dominant source used for most indoor lighting applications in the future. At present an attractive candidate for generating white-light are blue LEDs that excite a yellow phosphor, with a resultant colour emission. Such solid state sources can be used for both illumination and communications simultaneously, offering the possibility of creating wireless broadcasting within a room or office space.
In this paper we outline a typical basic configuration, and the performance available using simple modulation schemes. Unmodified LEDs typically have modulation bandwidths of several MHz, but typical lighting levels provide a communications channel with a Signal to Noise Ratios in excess of 40dB. Techniques such as equalisation can be used to improve available data rate significantly, and in this paper we outline several approaches that have the potential to offer data rates of 100Mb/s and above.

Keywords: Visible light communications, optical wireless, solid-state lighting

1. INTRODUCTION
Solid-state lighting is a rapidly developing area, both in terms of commercial exploitation, and academic and industrial research. LEDs with a wide range of colours are available, including white emission, and the output power available and device efficiencies are increasing rapidly.
The field of applications is also expanding. In the automotive field all lights except the main headlights now use LEDs, and the first cars that use white LED headlights are now beginning to appear [1]. Traffic lights and signals now use solid-state lighting, as sources are reliable and compact. Architectural lighting using LEDs is also becoming common, as LEDs are low temperature compared with incandescent lights and are reliable enough to be 'built into' structures without the need for frequent replacement.
White LEDs are commonly used as replacements for incandescent lamps and as their performance improves these devices will become candidates for replacement of general illumination. These solid-state sources can be modulated at rates many times that of incandescent or fluorescent alternatives, thus offering the possibility of broadcasting information at the same time as providing illumination. Such Visible Light Communications (VLC) originated in Japan, with the Visible Light Communications Consortium (VLCC) [2] playing a major role. There is now growing interest in Europe [3], and work to develop standards within the IEEE [4]is also underway.
In this paper the focus is the use of white LEDs to provide illumination and data communication in indoor environments. Section 2 introduces the sources and components, methods to increase the data rate are set out in section 3 and future prospects are described in the conclusions.

2. VLC DATA TRANSMISSION

2.1. Sources
White light LEDs typically use two methods to generate white light. Red, Green and Blue devices are combined in a single package and white light is generated by mixing them in appropriate proportion. This approach has the advantage of being able to tune the colour by altering the current to each device. However, the additional complexity of packaging and drive electronics has made this approach to providing general illumination less attractive.

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The widely used alternative is to combine a blue LED with a coating of a phosphor that emits yellow light. The blue emission from the LED combines with the yellow from the phosphor to create white light. This has the advantage of requiring only a single electrically driven source, with a ‘fixed’ white emission. Figure 1 shows the measured emission spectrum of a typical source (LUXEON STAR[5]). The sharp feature is the emission from the LED and the broader peak is that of the phosphor. Figure 2 shows a typical (measured) VI curve for such a device (LUXEON STAR).

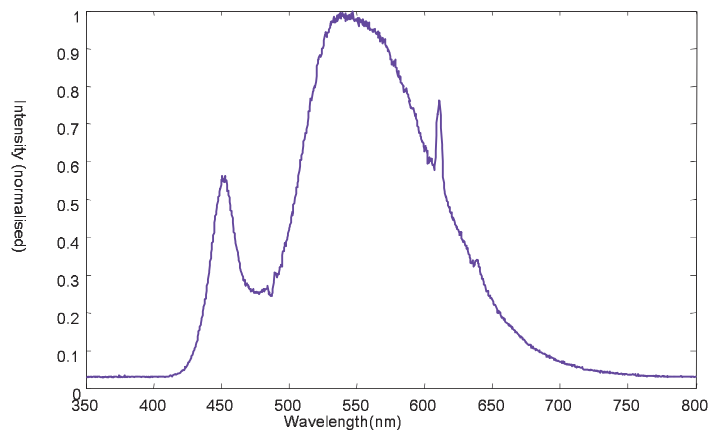

Figure 1. Measured emission spectrum of LUXEON STAR white LED.

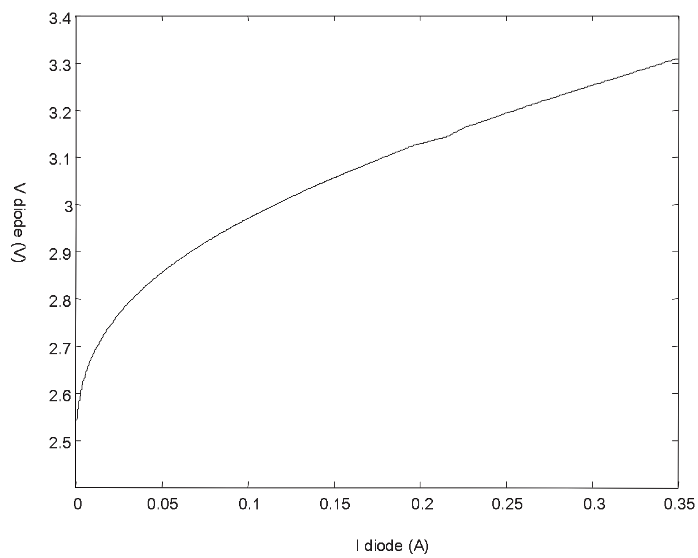

Figure 2. Measured VI curve of typical LUXEON STAR device

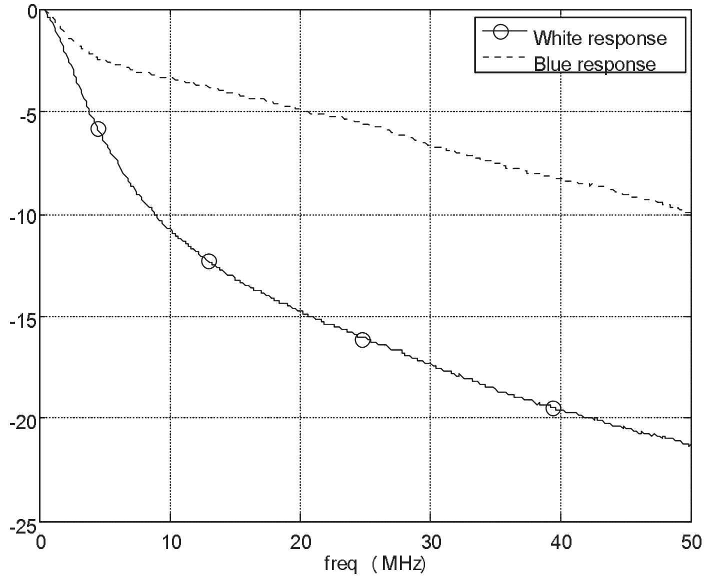

Figure 3. Measured modulation bandwidth of LUXEON star LED, for both white and blue emission. (Both curves are normalized by their respective low frequency value)

Figure 3 shows the measured modulation bandwidth of these devices. In this case an overall bandwidth of approximately 3MHz is measured, with a bandwidth of approximately 12MHz for the blue component, so it can be seen that the response of the yellow phosphor limits the modulation bandwidth of the overall white emission. These bandwidths are similar to the values measured for other devices [6, 7], and thus represent a major challenge for VLC using devices suitable for general illumination. Methods of improving the data rate are detailed in section 3.

2.2. Receiver

Optical wireless receivers typically consist of collection optics and an optical filter, which collect light of the correct wavelength range and 'concentrate' it on to a photodetector. The resulting photocurrent is amplified, normally using a transimpedance preamplifier. The optical filter is used to reduce the effect of ambient light by creating a narrowband optical system that only allows the modulated source wavelength to be detected. In the case of VLC the modulated energy covers the entire visible spectrum, so that filtering will reduce both the ambient light noise from daylight and the desired signal. Modelling indicates that there are modest gains (~3dB) available by using an 'optimum' filter (one that maximises the received SNR by altering the bandwidth and centre wavelength of the filter), so optical filtering for signal rejection is not likely to be very beneficial. However, as will be described in later sections, filtering the slow yellow emission component can lead to higher data transmission rates.

2.3. The VLC channel

In an indoor environment the primary use of the VLC sources is to provide illumination, and regulations (see for instance[8]) specify a minimum level for office work and other activities. Sources will therefore be provided to achieve this, and in practice this provides a 'self-regulating' VLC channel: modeling [7, 9, 10] shows that if the room is bright enough to work in there will be enough light to provide a VLC channel.

Figure 4 shows a model of a typical indoor environment (following that presented in [10]) with 4 LED arrays providing illumination. A receiver is placed at a communication plane approximately 1m from the floor, and light from the arrays propagates to the receiver, providing a communications channel. There is a line of sight (LOS) path from each LED to the receiver, and also a diffuse path via the reflections from surfaces within the room. The LOS path strength can be calculated using a knowledge of the emission patterns of each source and a simple propagation model, as described in[9, 10]. There are a number of different ray-tracing approaches [11, 12] that can be used to simulate the diffuse path, but these are complex and time-consuming. An alternative approach that models the room as an integrating sphere is described in [13] and this was used in [7, 9]. This also describes the effect of combining strong LOS paths and diffuse paths. The modeling approaches in [9] were used to calculated the available Signal to Noise Ratio (SNR) at a typical reference receiver. Table 1 shows the characteristics of the system.

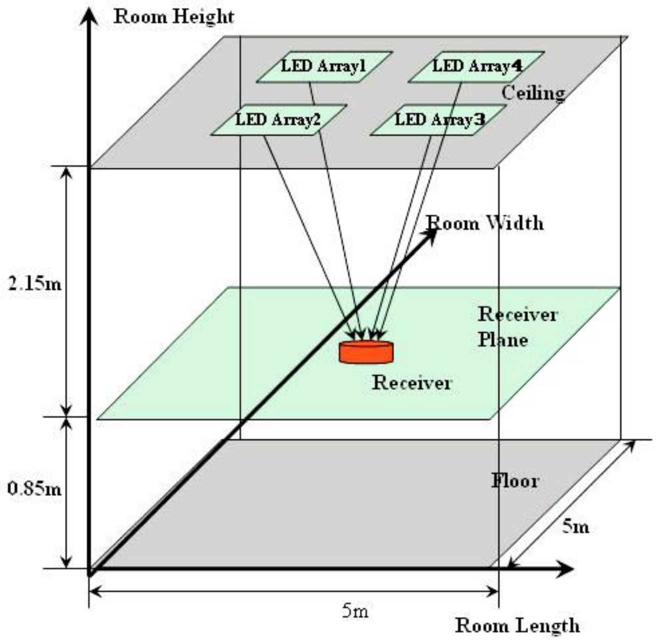

Figure 4. Typical indoor environment

Parameter	Value	Parameter	Value
LED power	20mW	Communications power	115.2W
Lambertian order	1	Receiver Area	$1cm^2$
No of LEDs in 1 lighting unit	60x60 on 1cm pitch	Input referred noise current	$100pA/\sqrt{Hz}$
No of lighting units	2x2 2.5m apart (centre to centre)	Detector responsivity	0.4A/W
Room	5x5x3m high		
Receiver plane	0.85m above ground		
Position of receiver	2.5m, 2.5 m from centre		
Reflectivities	0.54 All surfaces		

Table 1. Characteristics of the modeled system

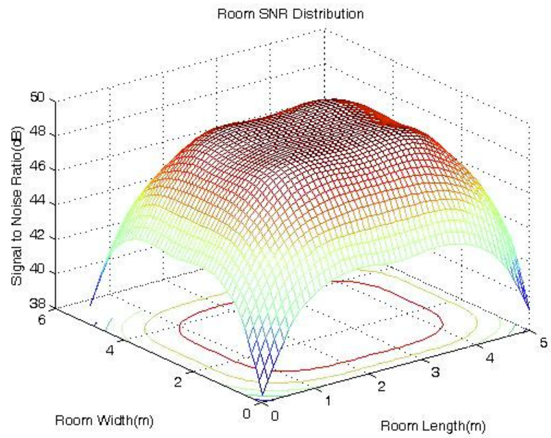

Figure 5. Available SNR with position in room (simulated).

A map of the available SNR is shown in Figure 5. This shows that SNRs>~40dB are available at all positions in the room. Modelling undertaken in [7] indicates that the diffuse paths are much weaker than the multiple LOS paths, and that bandwidths >~90MHz are available in a typical indoor illuminated space.

The VLC channel therefore has a bandwidth much greater than the currently available modulation bandwidth of the sources, and typical illumination levels create very high SNR at the receiver. The channel can therefore be characterized as low bandwidth, very high signal to noise ratio, and this allows a number different techniques to be used to achieve high data rates. These are discussed in the following sections.

3. IMPROVING DATA RATE

3.1. Optical filtering

The unmodified channel bandwidth is several MHz, and the most straightforward method of improving this is to use an optical filter that removes the slow yellow phosphor emission component at the receiver. At high data rates the emission from the yellow phosphor component is largely unmodulated, so that an electrically AC coupled receiver will not respond to this part of the signal. However the high levels of received signal creates shot noise that degrades receiver performance and can saturate the photodetector. The blue filter removes this largely static photocurrent component, thus improving the channel characteristics, although the resulting bandwidth is still low. The high SNR available (with or without blue filtering) makes the VLC channel attractive for multilevel modulation schemes, and for equalization techniques, and these are discussed in the following sections.

3.2. Transmitter equalisation

There are several potential methods of transmitter equalization. In [14] an array of LEDs is used as an illumination source and data transmitter. The LEDs electrical characteristics contain a significant series inductive component, likely to be due to the packaging, and a series LC circuit can be created that allows the optoelectronic response of the device to be ‘peaked’ at a certain frequency. An array of LEDs can be used with different peak frequencies and amplitudes, and this can create a channel with improved bandwidth. Figure 6 shows a schematic of the link. Each LED is driven using a DC bias current, which is combined with a high speed data signal fed via a low impedance buffer using a bias Tee. The capacitor within the bias Tee and the LED inductance form a resonant circuit, and an appropriate capacitor value allows the peak response frequency to be selected. Figure 7 shows the unequalised response of a single LED, and the response of the 16 LED array, showing an improvement in bandwidth of a factor of 10, from approximately 2.5MHz to 25MHz. A 40Mb/s data link that transmits Non-Return-to-Zero On-Off-Keying (NRZ OOK) data with a BER of 10^{-6} over a distance of 2m and a coverage area 2m in diameter was demonstrated using this enhanced transmitter. Equalization of a single LED is also feasible, and an 80Mb/s short range data link that also used blue filtering at the receiver has been demonstrated [15].

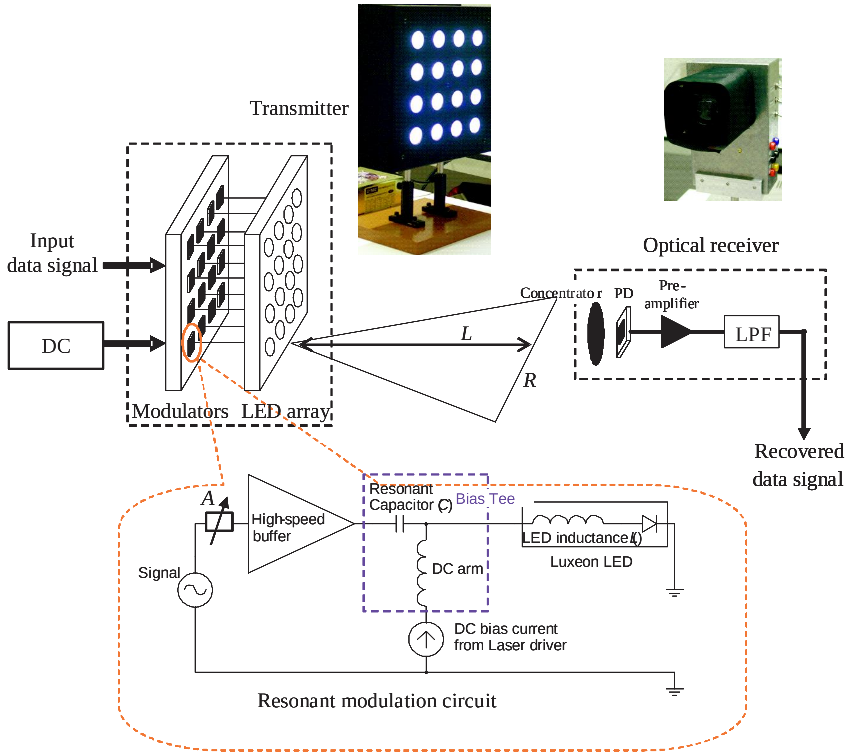

Figure 6. Equalised LED array data link

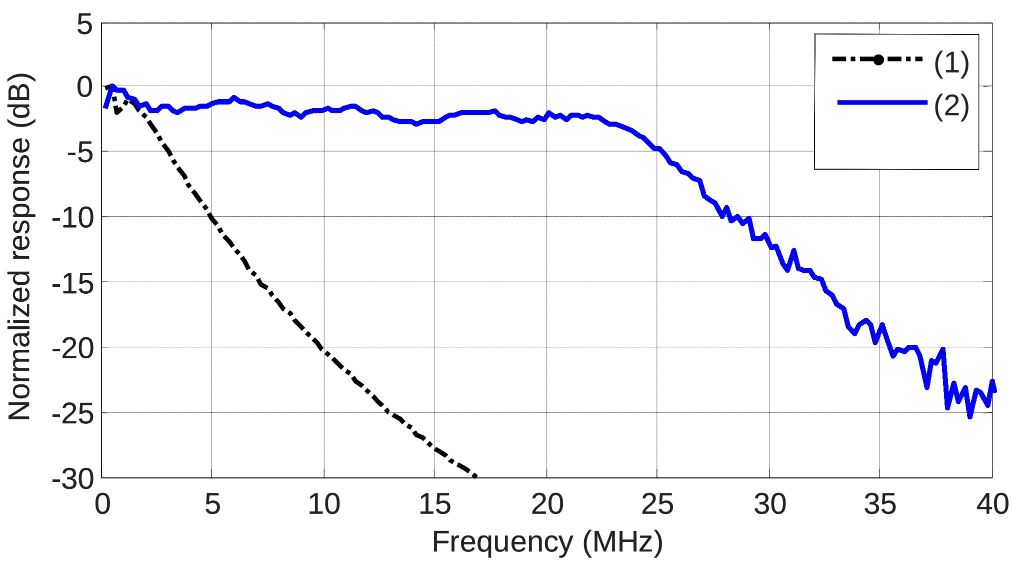

Figure 7. Frequency response of (1) single LED and (2) Aggregate response of LED array.

3.3. Receiver equalisation

Receiver equalization is advantageous as it does not require modification of the driver circuits for individual LEDs. Clearly there are a number of different approaches that can be used, but in this case using a simple analogue equalizer is attractive, as it removes the need for complex signal processing. An optical channel that operates in the room shown in

Figure 4 is simulated, using the measured impulse response of a Luxeon Star device, and the channel response is equalized using a simple first order equalizer. Figure 8 shows the simulated BER vs data rate for the receiver placed at the worst position (in terms of the BER) in the room. The graph shows that simple equalization can approximately double the available data rate, for both Non Return to Zero (NRZ) and Manchester coding schemes. For NRZ data the available data rate increases to 32Mb/s (using an unfiltered 'white' optical channel). Simulations indicate data rates of 73Mb/s are possible using the equalized LED array combined with a simple first order analogue receiver equalizer.

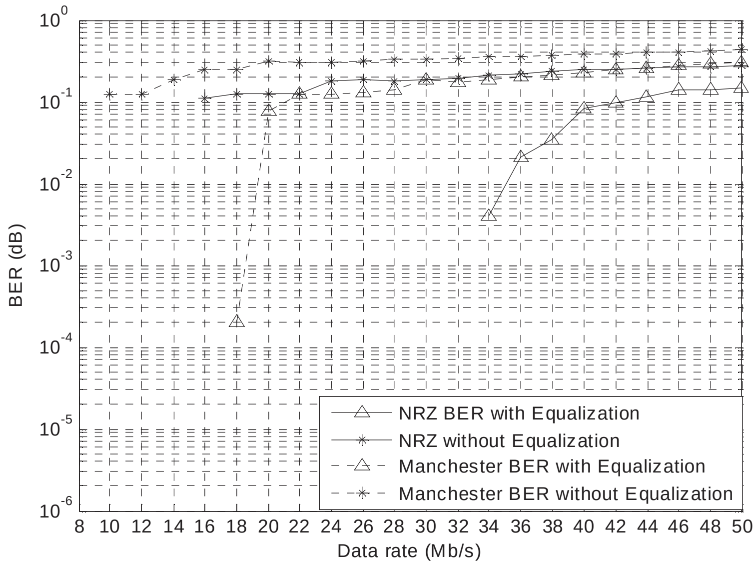

Figure 8. Simulated BER for unequalised and equalised channels

This preliminary work indicates that combinations of pre- and post- equalization and optical filtering have the potential to provide high-data rate communication, although there is no clear 'best' strategy at present.

The alternative approach is to use multilevel modulation schemes, and schemes such as DMT have been investigated [6]. This work indicates that data rates of >100Mb/s are feasible within typical indoor environments using this technique. There is also the advantage that schemes can adapt to conditions and channel impairments, due to the complex signal processing available. A potential disadvantage is the requirement for a linear response from the emitter devices, and the additional complexity of the signal processing. This is in contrast with the relatively inflexible approach of using simple modulation and analogue equalization, and further work is required to understand the tradeoffs between these two alternatives.

3.4. Optical Multi-Input Multi-Output (MIMO) transmission.

An alternative approach is to use the large numbers of LEDs used in illumination for parallel communications, and in this case the challenge is to maintain alignment between arrays of transmitters and the necessary receiver array. Optical MIMO [16] is a growing area of interest, and this offers a means to reduce the alignment required between transmitter and receiver.

Figure 9(a) shows a typical configuration. Four LED lighting units on the ceiling communicate with four receivers of the type described in Table 1. These are on a square grid of 0.1 m spacing on the receiver terminal. In operation training sequences are used to measure the transfer functions between individual sources and detectors. These are combined to create a channel transfer (or H) matrix. Independent data can then be transmitted on lighting unit, and the data at each receiver recorded. This is then multiplied by the inverse of the H matrix to estimate the transmitted data. For the system to operate the H matrix must be of full rank to allow it to be inverted.

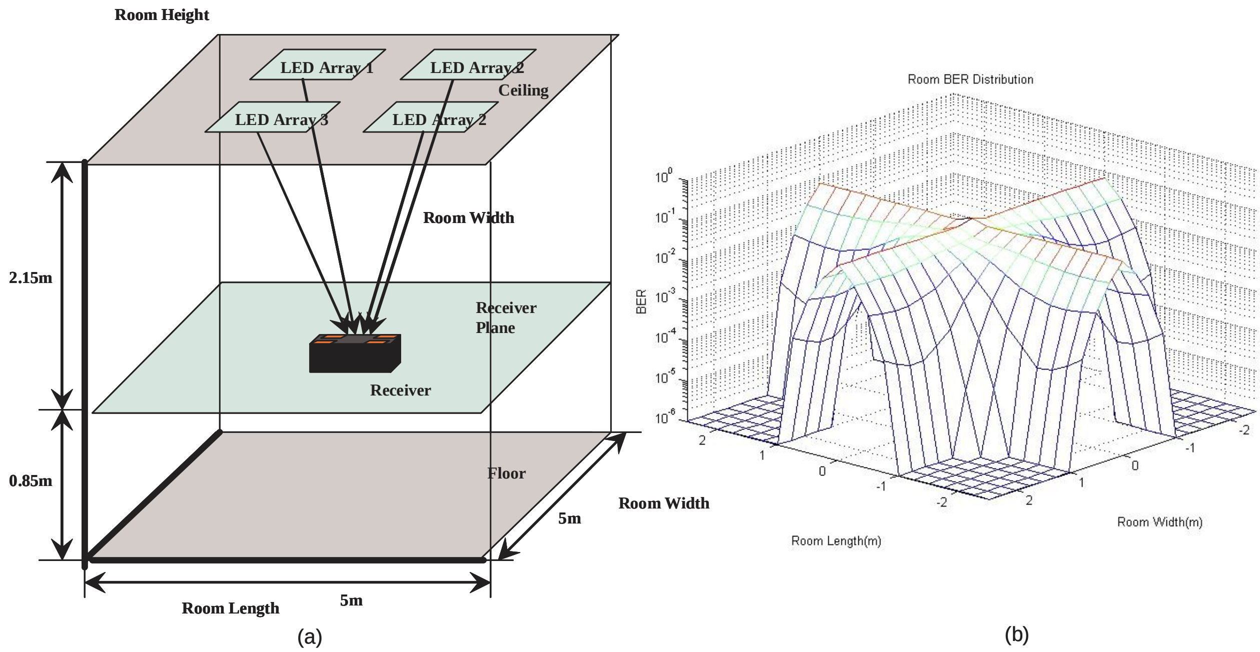

Figure 9. Visible Light MIMO system (a) Layout (b) Simulated BER with receiver position

Figure 9 (b) shows the simulated BER for the system in Figure 9(a) for all receiver positions in the room. The parameters used are those in Table 1 except the channel data rate is 20Mb/s NRZ. Certain positions in the room cannot be used for optical MIMO as the H matrix is not of full rank, and this can be seen by the rapid increase in BER in the figure at these points. These correspond to ‘lines of symmetry’ where different channels have the same gain coefficients. However, where this is not the case an aggregate BER of 80Mb/s can be achieved. This indicates partially correct operation of the MIMO system, but that modification is required to achieve MIMO operation at all points in the room. (Research into achieving complete coverage is underway). This preliminary result indicates that MIMO therefore offers the potential for very high data rate communications, albeit at the cost of increasingly complex systems.

4. FUTURE CHALLENGES

In addition to the technical challenge of achieving high data rates using low bandwidth channels, there are several distinct challenges for VLC in an indoor environment.

The VLC channel is a natural broadcast channel, so providing an uplink is likely to be challenging. Retro-reflecting links have been suggested [17], and there are likely to be the power levels available for the necessary link budget. However, high-speed retro-reflecting modulators are difficult to obtain, and it is likely that any link will only provide low speed data transmission. This may be suitable for data ‘hosepipe’ applications where asymmetric links are suitable, as all that is required is an acknowledgement of correct transmission. An alternative is for the VLC to cooperate with another wireless standard [18]. Work in [19] examined the use of a high speed downlink with a lower speed RF wireless LAN, and showed that the combined system had substantial benefits in terms of latency and throughput, so this method is attractive. Work in a European Community funded project [20] aims to combine different optical and radio wireless communications techniques to obtain the desired performance.

In addition there are specific challenges of standardization and regulation for VLC. Standards for lighting and control of lighting systems are developing and VLC systems must be compatible with these, as communications is a subsidiary function. Any standardization effort therefore requires closer collaboration between the two communities. At present there is an IEEE study group working on standardization efforts[4], and several Japanese standards [21, 22] exist in this area.

5. CONCLUSIONS

VLC is an attractive method of augmenting the capacity of in-building wireless communications. High data rate communications requires either equalisation, complex modulation and signal processing or parallel communications, and indications are this is relatively straightforward at rates up to 100Mb/s. Combinations of different techniques should allow much higher rates to be achieved, up to Gb/s in some cases, although this will require more complex systems.

REFERENCES

[1] Audi:Audi R8 promotional material,http://www.audi.co.uk/audi/uk/en2/new_cars/r8/Safety_Features.html

[2] vlcc:Visible Light Communications Consortium,www.vlcc.net, 2008

[3] Forum, W.W.R.:Wireless World Research Forum,http://www.wireless-world-research.org/?id=92, 2008

[4] IEEE 802.15 WPAN Visual Light Communication Interest Group (IGvlc) http://www.ieee802.org/15/pub/IGvlc.html, 2008

[5] Lumileds: 'Power light source Luxeon Star', Technical datasheet DS23, Philips, 2006

[6] Grubor, J., Lee, S.C.J., Langer, K.-D., Koonen, T., and Walewski, J.W.: 'Wireless High-Speed Data Transmission with Phosphorescent White-Light LEDs'. Proc. Post deadline session at European Conference on Optical Communications, pp.

[7] Grubor, J., Gaete, J.-O., Waleski-Js, Randel-S, and Langer-Kd: 'High-speed wireless indoor communication via visible light', ITG Fachbericht, 2007, pp. 203-208

[8] Occupational-Safety-and-Health-Branch-Labour-Department:A Simple Guide to Health Risk Assessment - Office Environment Series OE 2/99,http://www.oshc.org.hk/others/bookshelf/BB055E.pdf., 1998

[9] Zeng, L., Le-Minh, H., O'Brien, D.C., Lee, K., Jung, D., and Oh, Y.: 'Improvement of Date Rate by using Equalization in an Indoor Visible Light Communication System'. Proc. accepted for presentation at IEEE International Conference on Circuits and Systems for Communications 2008, , November 2007 pp.

[10] Komine-T, and Nakagawa-M: 'Fundamental analysis for visible-light communication system using LED lights', IEEE Transactions on Consumer Electronics, 2004, 50, (1), pp. 100-107

[11] Karppinen, M., Kataja, K., Makinen, J.T., Juuso, S., Rajaniemi, H.J., Paakkonen, P., Turunen, J., Rantala, J.T., and Karioja, P.: 'Wireless infrared data links: ray-trace simulations of diffuse channels and demonstration of diffractive element for multibeam transmitters', Optical Engineering, 2002, 41, (4), pp. 899-910

[12] Lopez-Hernandez, F.J., Perez-Jimenez, R., and Santamaria, A.: 'Ray-tracing algorithms for fast calculation of the channel impulse response on diffuse IR wireless indoor channels', Optical Engineering, 2000, 39, (10), pp. 2775-2780

[13] Jungnickel, V., Pohl, V., Nonnig, S., and von Helmolt, C.: 'A physical model of the wireless infrared communication channel', Ieee Journal on Selected Areas in Communications, 2002, 20, (3), pp. 631-640

[14] Le-Minh, H., O'Brien-Dc, Faulkner, G., Zeng, L., and Lee, K.: 'High-Speed Visible Light Communications Using Multiple-Resonant Equalization', Photonics Technology Letters, 2008, 20, (15), pp. 1243-1245

[15] Le-Minh, H., O'Brien-Dc, Faulkner, G., Zeng, L., Lee, K., Jung, D.J., and Oh, Y.: '80 Mbit/s Visible Light Communications Using Pre-Equalized White LEDs'. Proc. accepted for presentation at ECOC 2008, pp.

[16] O'Brien, D.C., Quasem, S., Zikic, S., and Faulkner, G.E.: 'Multiple input multiple output systems for optical wireless: challenges and possibilities'. Proc. Free-Space Laser Communications VI, 2006 pp. 630416

[17] Komine-T, Haruyama-S, and Nakagawa-M: 'Bidirectional visible-light communication using corner cube modulator'. Proc. Wireless and Optical Communication (WOC). Banff, Canada. IASTED. 2 4 July 2003., pp.

[18] O'Brien, D.C.: 'Cooperation and cognition in optical wireless communications', in Fitzek, M.K.a.F. (Ed.): 'Cognitive Wireless Networks: Concepts, Methodologies and Visions
- Inspiring the Age of Enlightenment of Wireless Communications -' (Springer, 2007)

[19] Hou-J, and O'Brien-Dc: 'Vertical handover-decision-making algorithm using fuzzy logic for the integrated Radio-and-OW system', IEEE transactions on wireless communications, 2006, 5, (1), pp. 176-185

[20] EU FP7 project 'Home Gigabit Access' (OMEGA),www.ict-omega.eu, 2008

[21] JEITA: 'CP-1221 Visible Light Communications System', 2007

[22] JEITA: 'CP-1222 Visible Light ID System', 2007