Visible Light Communications: challenges and possibilities

Dominic C. O'Brien[1], Lubin Zeng[1], Hoa Le-Minh[1], Grahame Faulkner[1], Joachim W. Walewski,[2] Sebastian Randel,[2]

[1]University of Oxford (UK); [2] Siemens AG, Corporate Technology, Information and Communications, Munich (Germany)

***Abstract*— Solid-state lighting is a rapidly developing field. White-light and other visible LEDs are becoming more efficient, have high reliability and can be incorporated into many lighting applications. Recent examples include car head-lights based on white LEDs, and LED illumination as an architectural feature. The prediction that general illumination will use white LEDs in the future has been made, due to the increased energy efficiency that such an approach may have. Such sources can also be modulated at high-speed, offering the possibility of using sources for simultaneous illumination and data communications. Such Visible Light Communications (VLC) was pioneered in Japan, and there is now growing interest worldwide, including within bodies such as the Visible Light Communications Consortium (VLCC) and the Wireless World Research Forum (WWRF).**

In this paper we outline the basic components in these systems, review the state of the art and discuss some of the challenges and possibilities for this new wireless transmission technique.

***Index Terms*—visible light communications, optical communications, wireless communications**

I. Introduction

Currently there is rapid development in the field of lighting and illumination. Concerns about energy consumption are leading to the phasing out of incandescent sources, and there is rapid growth in the use, and development of, solid-state sources. As the efficiency of these devices increases and their cost decreases there are predictions that they will become the dominant source for general illumination. At present they are widely used in automotive applications for indicator and tail lights, and the first LED based headlights are now becoming available. They are also commonly used in 'feature' and architectural lighting where the ability to change colour, or incorporate lights into building structure, without reliability concerns, makes them preferable to alternatives.

The use of solid-state sources offers the possibility of high data-rate communication, in addition to provision of illumination. Sources can be modulated at high-speed, providing a data channel in addition to the illumination, which is provided by the average signal level. Research on such Visible Light Communications (VLC) originated in Japan, where the Visible Light Communications Consortium (VLCC) [1] has been in existence for several years. Interest is now growing rapidly, both in Asia and Europe, where the Wireless World Research Forum [2] has worked in this area. This paper introduces the principles of VLC, and outlines some of its major challenges. Some potential solutions and future applications are also described.

In the next section an overview of VLC and its applications is presented.

II. Overview

VLC has potential applications in a number of areas. Each of these is briefly described in the following sections, together with the motivation for using this means of communication.

A. Visual Signalling and communication

Coloured signal lights are widely used in marine, automotive and other applications. In this case the colour provides a signal to the observer, such as 'red for danger', and augmenting this with data communications might improve safety and other aspects of traffic management. Due to their reliability, LEDs are widely used in these applications, and there have been several demonstrations of data transmission by modulation of these sources. In [3] data is transmitted from a traffic signal to a car, and in [4] a scheme for parallel communication is presented. An EU research project [5] examined car-to-car communication using white-light headlights.

B. Information display and communications

Displays, such as signboards and indicator boards, are often fabricated from arrays of LEDs, and these can be modulated to broadcast the signboard information to a PDA or handheld terminal. In [6] an example of a signboard used to transmit data is described. This might find application in airports, museums and other environments where location-dependent broadcast of data is required. Such location dependence and indoor positioning is an area of interest, particularly within the VLCC. In this case a locally generated signal can be transmitted to a terminal, thus determining its location by its proximity to a particular lighting fixture.

C. Communications

Point-to-point links between handheld terminals rely on there being 'sufficient' alignment between the two ends of the link. Using visible light allows the user to be involved in this, allowing smaller beam divergence, and therefore lower path-loss. Communication between two peripherals is described in [7], and it may be possible to create very high bandwidth links for secure media downloading using similar techniques.

D. Illumination and communications

White LEDs can be used for both illumination and communications, so that information can be broadcast within a room [8, 9], or transmitted via a car headlight [5], with the necessary illumination provided at the same time. Several examples of music broadcast demonstrators [7] have also been reported. This may be a wide area of application, and there is considerable interest in building systems that do this [10].

E. Positioning and communications

Obtaining the position of a mobile user indoors is challenging, and VLC allows the transmission of positioning information from a lighting fixture, so that a user knows their location in a building. There have been a number of schemes proposed [11-13] that use either triangulation or proximity to a beacon, or a combination to provide position estimation.

It can be seen that there are a number of different types of VLC link, but in most cases the communications is a secondary function. This makes it distinct from most other wireless standards, as VLC must be compatible with any standards for the primary function. This introduces a number of constraints, and also the necessity for co-development of standards with the primary body.

In the next section applications using white LEDs for illumination and communication are described in more detail

III. VLC LINKS

A VLC link consists of a transmitter, the propagation channel and a receiver. Each of these is described in the following sections.

1) Sources

White-light LEDs either use red, green and blue LEDs that mix to provide the desired colour, or a single LED (usually blue) that excites a yellow phosphor to create an overall white emission. The 'triplet' approach allows the colour to be altered by varying the colour to the LEDs, and also allows different data to be sent on each device. However, maintaining colour balance can be challenging and the devices are complex. The single LED approach is simpler, and is therefore more attractive for 'general' applications, so will be considered in the work described here.

Figure 1 shows the emission spectrum of a high-brightness LED (LUXEON STAR[14]), showing the peak from the LED (at 440nm) and the broad phosphor spectrum at wavelengths beyond this. The small-signal frequency response is shown in Figure 2, both for the blue component from the LED and for the overall white emission. It can be seen that the bandwidth is ~2MHz for the white, and ~10MHz for the blue component only. This is due to the long decay time of the phosphor, and provides a limitation on the overall bandwidth available. In addition the Blue LED die is not designed for high speed operation and is very large in area (and thus has high equivalent capacitance) compared with devices used for high speed communications. Although these measurements are for one specific device they are typical of those obtained for white-LEDs from different manufacturers. The limited bandwidth of the LEDs is therefore one of the major challenges for high-speed communications using these devices. Overcoming this is discussed in later sections.

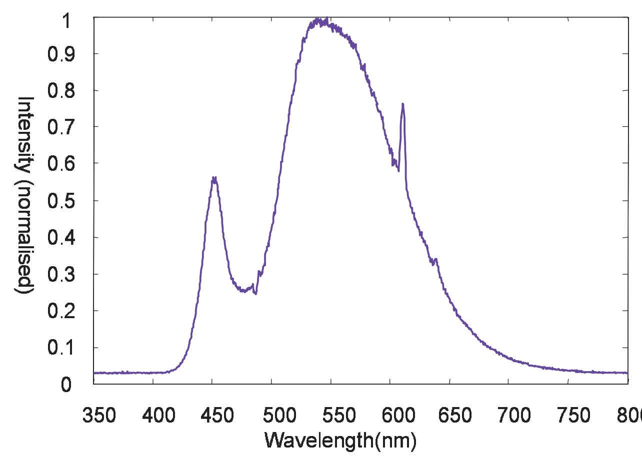

Figure 1. Emission spectrum from white-light LED (LUXEON STAR)

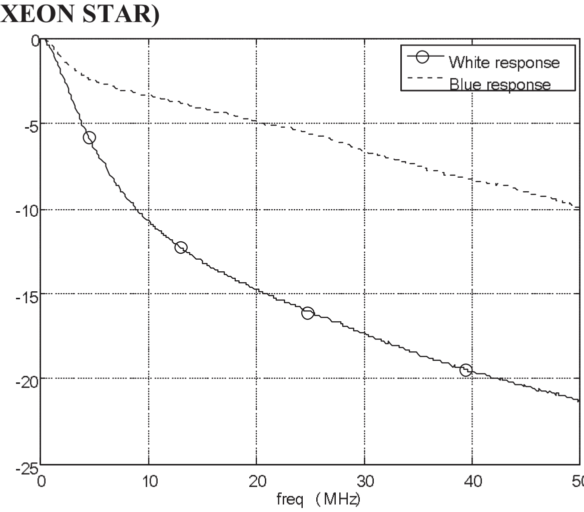

Figure 2. Small-signal modulation bandwidth of LUXEON STAR device

2) The VLC channel

Figure 3 shows a typical office space with four LED lighting units on the ceiling. A communication terminal might be placed on a desk anywhere within the room, and a channel exists between the lights and the terminal. The channel consists of a number of line of sight paths from the units to the terminal, together with a diffuse channel formed by the light from the source reflecting off multiple surfaces within the room. These two channels can be modelled separately and combined to obtain the overall power received at the terminal (and hence the Signal to Noise Ratio (SNR)) and the bandwidth of the channel.

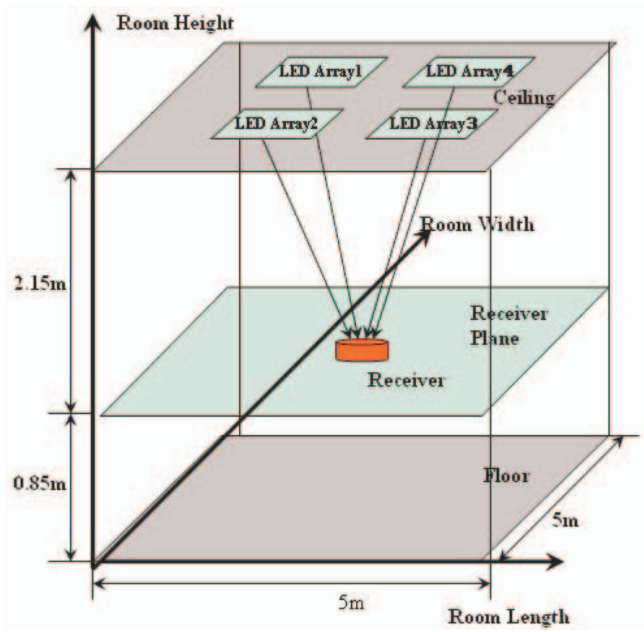

Figure 3. Typical VLC indoor lighting configuration

Parameter	Value	Parameter	Value
LED power(optical)	20mW	Total power used for optical communications	115.2W
Lambertian order	1	Receiver Area	$1cm^2$
No. of LEDs in 1 lighting unit	60x60 at 1-cm pitch	Input-referred noise current of receiver	100pA/ $\sqrt{Hz}$
No. of lighting units	2x2, 2.5m apart (centre to centre)	Detector responsivity (averaged over typical spectrum of Luxeon star LED)	0.4A/W
Room dimension	5x5x3m		
Receiver plane	0.85 m above ground		
Position of receiver	2.5 m, 2.5 m from centre		
Reflectivities	0.54 All surfaces		

Table 1. Simulation parameters

Several models of the optical wireless channel have been developed [9, 15]; in [15] the LOS and diffuse channels are combined to obtain the overall channel. Figure 4 shows the calculated signal to noise ratio at the receiver, using the parameters shown in Table 1.

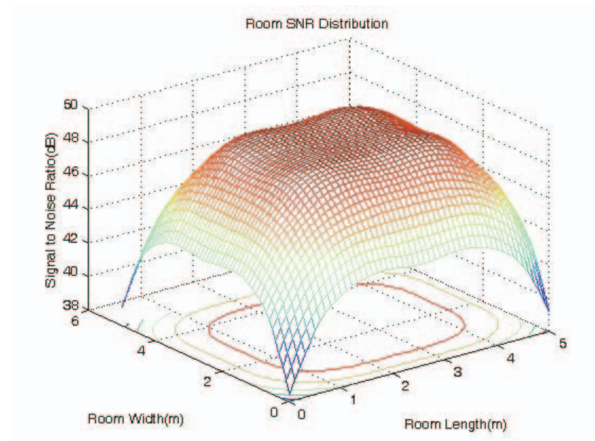

Figure 4. Signal to noise ratio as a function of receiver position

This, and other work [9, 16], shows that very high SNR channels are available. The requirement for levels of illumination suitable for reading and occupancy ensures that sufficient communication power will be available.

The bandwidth of the channel can be determined by the summation of the LOS and diffuse components, and there are various methods of simulating this [15]. Work in [9] suggests that bandwidths of at least 88MHz were available in 'typical' room environments. The bandwidth of the channel is therefore significantly higher than the sources, and does thus not currently constrain system performance.

3) Receiver

The receiver consists of an optical element to collect and concentrate the radiation onto the receiver photodetector. This converts the radiation into photocurrent, which is then pre- and post-amplified before data recovery.

The optical element, usually either a lens or nonimaging concentrator has a maximum 'gain' limited by constant-radiance considerations, so the photodetector area should be as large as possible, given the required receiver bandwidth.

As discussed above, if the LED modulation bandwidth is less than approximately 90MHz then the LED bandwidth constrains the system data rate. Achieving sufficient photodetector area at the LED constrained system bandwidth is relatively straightforward, so the receiver does not provide a significant constraint.

IV. CHALLENGES

A. Increasing data rate

Perhaps the simplest way of mitigating the low bandwidth of the transmitter is to block the phosphor component at the receiver by using a blue filter. In [16] it is shown that this can increase the bandwidth substantially, albeit at the penalty of a small reduction in received power due to filter losses.

It is also possible to improve the response by transmitter and/or receiver equalization, or the use of bandwidth-efficient modulation schemes that take advantage of the high available signal to noise ratio. In addition, for higher data rates it may be possible to use parallel data transmission from a number of LEDs. Each of these techniques is discussed in more detail below.

1) Transmitter equalization

Analogue equalization techniques can be used to compensate for the rapid fall-off in response of the white LEDs at high frequencies. It is possible to use an array of LEDs, each driven using a resonant technique with a particular peak output frequency to achieve this. Careful choice of a number of different frequencies allows the overall response to be ‘tuned’ to that desired. In [17] a 16 LED array is modified to have a bandwidth of 25MHz (without blue filtering) offering a data-rate of 40Mb/s for Non-Return to Zero (NRZ) On-Off Keying (OOK). More complex equalization can also be used for single devices, and data rates of 80Mb/s (NRZ OOK) [18] have been demonstrated.

2) Receiver equalization

Transmitter equalization has the disadvantage that the drive circuits for the LED (which often involve currents of several hundred milliamps) need modification, and in a typical coverage area there may be a number of sources, making the modifications potentially costly. In addition some of the signal energy used is not converted into light, thus reducing the energy efficiency of the emitter.

Equalisation at the receiver allows complexity to be at the receiver only. A simple first-order analogue equalizer is modeled in [15], and this shows there is substantial improvement in data-rates. More complex approaches are likely to yield higher data rates.

3) Complex modulation

A high-SNR, low-bandwidth channel is typically suited to high bandwidth efficiency multilevel modulation schemes. Work in [16] shows that 100Mbit/s is possible using Discrete Multi-Tone Modulation (DMT). At present there is little work in this area, and further studies are required in order to assess the relative benefits of analogue equalization with relatively simple modulation, or complex modulation and limited channel bandwidth.

4) Parallel communication (Optical MIMO)

In most illumination applications many LEDs are used to provide the necessary lighting intensity. This offers the opportunity of transmitting different data on each device or on different groups of emitters. For this to be successful a detector array is required at the receiver, and this creates a Multi-Input Multi-Output (MIMO) system. Radio-frequency MIMO techniques can be applied to such optical transmission systems to relax the necessary alignment between the array of detectors and array of sources. Work in [19] shows that such a system can allow multi-channel data communication, without the need to align a particular detector with a corresponding source.

It can be seen that there are many different methods of increasing data rates, and that a combination of these should allow data rates well in excess of 100Mb/s to be successfully transmitted.

B. Provision of an uplink

VLC using illumination sources is naturally suited to broadcast applications, and providing an uplink to the distributed transmitter structures can be problematic. Several approaches have been investigated. In [20] an infra-red uplink is used to a transmitter co-located with the VLC source, and in [21] a retro-reflecting transceiver is proposed. In this case the retro-reflector returns a proportion of the incident light to the transmitter, and this returned beam is modulated to provide a data path from the terminal to the infrastructure. This is potentially very attractive, although the data-rates that can be achieved using available modulators are low. Co-operation between VLC and RF wireless standards would also allow full connectivity for a terminal [22]. A VLC downlink can be combined with an RF uplink, and this can also reduce the load on shared RF channel, including overall network performance.

C. Regulatory challenges

In most cases VLC is subject to regulation by a non-communications standard. This can be an eye-safety standard, illumination regulation, or an automotive standard in the case of traffic signals or signal lights. A VLC standard must therefore encompass both communications and associated illumination practices. This is distinct from most other communication standards, and presents the challenge of coordination across regulatory bodies and frameworks. Currently there are activities in several areas. Within Japan VLCC has developed several national standards [23, 24], and the IEEE 802.15c Study Group on VLC [20] is currently working on producing the necessary documents to become a working group. Interest in these activities continues to grow, but perhaps the major challenge for the VLC community is to develop links with other relevant regulatory bodies to ensure compatibility of any techniques.

V. CONCLUSIONS

VLC offers the advantage of a communications channel in an unregulated, unlicensed part of the electromagnetic spectrum. In applications where a visible beam is desirable for security it can provide high data rates. There are a number of technical and regulatory challenges to be overcome; rapid technical progress is being made, but the challenges of standardization will require cooperation and agreement from a number of different bodies. However, success should bring a low-cost high data-rate infrastructure that can increase wireless capacity substantially.

ACKNOWLEDGEMENT

The authors thank colleagues involved in the preparation of the whitepaper on Visible Light Communications within the Worldwide Wireless Research Forum(WWRF); Olivier Bouchet, France Telecom, Jose A. Rabadan Borges, ETSIT Universidad de Las Palmas de Gran Canaria, Klaus-Dieter Langer and Jelena Grubor, Heinrich-Hertz-Institute, Kyungwoo Lee and Eun Tae Won, Samsung Electronics.

REFERENCES

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

[2] Wireless World World Research Forum, http://www.wireless-world-research.org

[3] Wada-M, Yendo-T, Fujii-T, and Tanimoto-M: 'Road-to-vehicle communication using LED traffic light'. Proc. 2005 IEEE Intelligent Vehicles Symposium Proceedings. Las Vegas, NV, USA. IEEE Intelligent Transportation Syst. Soc. 6 8 June 2005., pp.

[4] Iwasaki, S., Wada, M., Endo, T., Fujii, T., and Tanimoto, M.: 'Basic Experiments on Paralle Wireless Optical Communication for ITS'. Proc. Intelligent Vehicles Symposium, 2007 IEEE, pp. 321-326

[5] ISLE:http://www.pb.izm.fraunhofer.de/p2sa/030_Projects/Optik/Pr_isle.html , 2006

[6] S.-B. Park, D.K. Jung, H.S. Shin, D.J. Shin, Y.-J. Hyun, K. Lee, and Oh, Y.J.: 'Information Broadcasting System based on Visible Light Signboard'. Proc. Wireless and Optical Communications 2007, Montreal, Canada, 5/30/2007 - 6/1/2007 2007

[7] Le-Minh, H., Zeng, L., O'Brien, D.C., Bouchet, O., Randel, S., Walewski, J., Borges, J.A.R., Langer, K.-D., grubor, J.G., Lee, K., and Won, E.T.: 'Short-range Visible Light Communications', Wireless World Research Forum, 2007

[8] 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

[9] 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

[10] Bouchet, O., El Tabach, M., Wolf, M., O'Brien-Dc, Faulkner, G.E., Walewski, J., Randel, S., Franke, M., Langer, K.-D., Grubor, J., and Kamalakis, T.: 'Hybrid Wireless Optics (HWO):Building the Next-Generation Home Network'. submitted to CSNDSP08, Graz Austria, August 2008

[11] Hugh-Sing-Liu, and Pang-G: 'Positioning beacon system using digital camera and LEDs', IEEE Transactions on Vehicular Technology, 2003, 52, (2), pp. 406-419

[12] Liu, X., Makino, H., Kobayashi, S., and Maeda, Y.: 'Design of an Indoor Self-Positioning System for the Visually Impaired-Simulation with RFID and Bluetooth in a Visible Light Communication System', Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE, 2007, pp. 1655-1658

[13] Yoshino, M., Haruyama, S., and Nakagawa, M.: 'High-accuracy positioning system using visible LED lights and image sensor', Radio and Wireless Symposium, 2008 IEEE, 2008, pp. 439-442

[14] Lumileds:Luxeon design guides,www.lumileds.com, 2006

[15] 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'. accepted for presentation at IEEE International Conference on Circuits and Systems for Communications 2008

[16] 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'. Post deadline session at European Conference on Optical Communications.

[17] Le-Minh, H., O'Brien-Dc, Faulkner, G., Zeng, L., and Lee, K.: 'High-Speed Visible Light Communications Using Multiple-Resonant Equalization', accepted for publication in IEEE photonics technology letters, 2008

[18] 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'. Submitted to ECOC 2008.

[19] O'Brien-Dc, Zeng, L., Le-Minh, H., and Faulkner, G.: 'VLC with white-light LEDs: strategies to increase data-rate', Presented at IEEE 802.15c meeting Jacksonville, Fl, USA, May, 2008, https://mentor.ieee.org/802.15/documents.

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

[21] 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.

[22] 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)

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

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