Proceedings Paper:

Alresheedi, MT, Hussein, AT orcid.org/0000-0002-2519-082X and Elmirghani, JMH (2016) Hybrid diffuse IR transmitter supporting VLC systems with imaging receivers. In: 18th International Conference on Transparent Optical Networks (ICTON 2016). ICTON 2016, 10-14 Jul 2016, Trento, Italy. IEEE . ISBN 9781509014675

https://doi.org/10.1109/ICTON.2016.7550290

Hybrid Diffuse IR Transmitter Supporting VLC Systems with Imaging Receivers

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ABSTRACT
Indoor visible light communication (VLC), using white-LED lighting, generally assumes lights are ON during communications. In this paper, we propose a new Hybrid diffuse Infrared transmitter (HDIrT) coupled with an imaging receiver to support VLC system when the light is dimmed or is totally turned off. Infrared (IR) optical communications boasts similar advantages as VLC systems. It can also provide high transmission rates. The ultimate goal of our proposed system is to increase the signal to noise ratio (SNR), mitigate the channel delay spread and the effect of inter-symbol-interference (ISI) when the system operates at a high data transmission rate. The delay spread is reduced from 1.55 ns to about 0.1 ns when a narrow field-of-view (FOV) imaging receiver replaces a wide FOV non-imaging receiver. At a higher data rate of 2.5 Gb/s, the simulation results show that the imaging HDIrT system achieves about 17 dB SNR in the presence of multipath dispersion, receiver noise and mobility.

Keywords: Hybrid diffuse transmitter, mobile optical wireless, signal-to-noise ratio, imaging receiver.

1. INTRODUCTION

Over the last decade, visible light communication (VLC) has gained serious consideration in various research circles [1]-[6]. The concept of VLC systems revolves around the use of light emitting diodes (LEDs) for both lighting and communications. The main drives for this new technology include the recent development of solid state lighting, longer lifetime of high brightness LEDs compared to other artificial light sources such as florescent and incandescent light bulbs, data security at the physical layer (as optical signals are typically contained in the room in which they originate), high data rate, low power consumption and green communications [2]-[3]. The first VLC system was introduced in 2003 at Nakagawa Laboratory in Keio University, Japan [2]. This generated a lot of interest worldwide and led to further research and development. The dual functionality of VLC system (i.e., lighting and communications simultaneously from LEDs) has led to a number of significant and variable applications that include indoor positioning (2D and 3D) and navigation systems, vehicle-to-vehicle communication, under water communication, aircraft and hospital communication [1]-[3].

Recently, many researchers have studied and demonstrated high-speed VLC using white-LEDs for indoor communications [3]-[7]. However, the accomplishment of high transmission rates is a demanding task. This is due to the slow response of phosphor, which limits the modulation bandwidth of white LEDs to a few MHz [1]-[2]. There are however, some approaches that aim to improve the modulation bandwidth of white LEDs. This is achieved for example by employing different equalization schemes including the use of simple on-off keying (OOK) together with simple first order RC equalization circuits [4] or post-equalization at the receiver [5]. Another method has also been proposed to achieve high speed transmission, up to 513 Mb/s, uses Discrete Multi-tone Modulation (DMT) in combination with Quadrature Amplitude Modulation (QAM) [6]. In [7] researchers proposed a 3 Gb/s VLC system that employs orthogonal frequency division multiplexing (OFDM) and a Gallium Nitride µLED. OFDM is employed as a modulation scheme, in addition pre- and post-equalization techniques are used, as well as adaptive data loading in order to achieve 3 Gb/s. It is worth noting here although the state of the art VLC Gb/s system is able to achieve 3 Gb/s, it requires complex signal processing and advanced modulation formats. Additionally, there is an issue with using VLC systems when the user dims the light or totally switches it off. Radio frequency RF can be used as a backup. However, achieving a high transmission rate (up to Gb/s) and security are the most challenging parts.

In this paper, we propose a new Hybrid diffuse Infrared transmitter (HDIrT) that utilizes a Laser diode (LD) source to support VLC systems when the light is dimmed or is totally switched off. IR optical communications has the same advantages as VLC systems. It can also provide high transmission rates similar to VLC systems and potentially higher data rates (data rate up to 10 Gb/s employing OOK modulation can be achieved) [8]-[12]. This is mainly because of the wider modulation bandwidth of LD sources used in IR optical wireless instead of white LEDs. Despite these advantages, wireless IR systems encounter two major impairments. The first is concerned with sensitivity to additive shot noise owing to sunlight or artificial background lighting. The second is the multipath dispersion associated with reflections from walls, ceiling and room surfaces and the non-line-ofsight (non-LOS) transmission of optical wireless (OW) signals. Various techniques have recently been proposed to combat the impairments of IR systems, and higher bit rates have been achieved [9]-[18]. Adaptive multi-beam OW links can provide high-speed communication with the potential for achieving data rates well beyond 10 Gb/s [9]-[12], with full mobility. However, such high data rates have yet to be experimentally demonstrated. Experimental multi-gigabits IR systems with limited mobility have been successfully demonstrated in [13]-[18]. Our goal in this paper is to achieve high data rates when the VLC system / lighting is switched off, by employing a hybrid system (HDIrT) coupled with a custom design imaging receiver. The reminder of this paper is divided into sections as follows: Section 2 explains the system design and model of our proposed system. Link budget and simulation results are given in Section 3. Finally, conclusions are drawn in Section 4.

2. SYSTEM DESCRIPTION AND MODEL

2.1 System Design

Fig.1 shows the IR communication architecture of our proposed system. The transmitter consists of a hybrid diffuse IR source (HDIrT) located at the centre of the ceiling, which can provide a direct LOS link at the receiver on the communication plane (CP). In this case, the majority of the power is collected from the direct link and lower power is collected through reflections. Our proposed transmitter (HDIrT) uses a single-wide beam source, typically with a Lambertian pattern where the transmitted optical signal fully diffuses over the environment. The IR transmitter is connected to all visible light sources via fiber links (to link to main network in the building) and simple control circuits. When the light is dimmed or the received optical power falls below a certain threshold, the receiver sends a feedback signal at low rate to the VLC transmitter in order to switch the link to the supporting HDIrT system.

The receiver consists of VLC and IR detectors connected through an electronic switch to control their functions. In this study we examine the conventional wide filed-of-view (FOV) non-imaging receiver and also a custom design imaging receiver proposed in [9], [12]. The imaging receiver offers two main advantages over the traditional non-imaging receivers. Firstly, all detectors share a common concentrator (e.g. a lens). Hence, it can be fabricated in a smaller size and costs less. Secondly, all photodetectors can be placed on a single plane. Therefore, the designer can opt to use a larger number of detectors with small detector area and narrow FOV. This reduces the impact of multipath dispersion and reduces the high capacitance associated with large area detectors, consequently improving the receiver bandwidth.

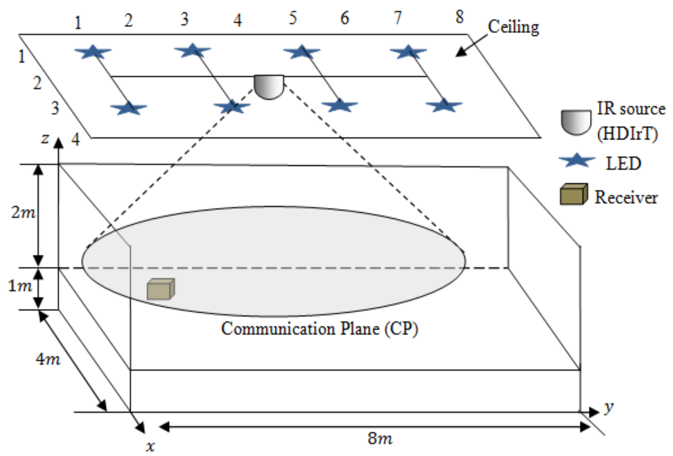


Figure 1. IR communication architecture for our proposed HDIr system.

2.2 System Model

In indoor IR communication links, intensity modulation and direct detection (IM/DD) is a suitable simple approach that is widely used. The indoor OW IM/DD channel can be fully identified by its impulse response $h(t)$ and this can be modelled as a baseband linear system given by [8]-[10]:

$$I(t, Az, El) = \sum_{m=1}^{M} Rx(t) \otimes h_m(t, Az, El) + \sum_{m=1}^{M} Rn(t, Az, El) \quad (1)$$

where $I(t, Az, El)$ is the received instantaneous current in the photodetector at certain positions due to m refelcting elements, t is the absolute time, Az and El are the directions of arrival in the azimuth and elevation angles, M is the total number of receiving elements, $x(t)$ is the transmitted instantaneous optical power, $\otimes$ denotes convolution, R is the photodetector responsivity. Finally, $n(t, Az, El)$ is the background noise which is independent of the received signal and is modelled as white and Gaussian. In this study, we do not consider the background noise from other artificial lights, since the light is off when the IR communication link is used. Due to the nature of diffuse transmission and the fact that the optical rays reach the receiver through multiple paths each with different length and delay, IR links are affected by multipath dispersion. Multipath dispersion in turn results in the introduction of inter-symbol-interference (ISI). The root mean square delay spread (DS) is a good measure of signal spread due to temporal dispersion. The delay spread of an impulse response is given by [8], [18]:

$$DS = \sqrt{\left(\sum_{\forall i}(t_i - \mu)^2 P_{r_i}^2\right) / \sum_{\forall i} P_{r_i}^2} \qquad \text{where} \qquad \mu = \sum_{\forall i} t_i P_{r_i}^2 \ / \ \sum_{\forall i} P_{r_i}^2, \tag{2}$$

where t is the time delay associated with the received optical power P_{r_i} and μ is the mean delay. To examine the effects of multipath dispersion on indoor OW systems, a propagation simulator was set up for the case of an empty room with dimensions of 4m (width) × 8m (length) × 3m (height). Prior findings have established that plaster walls tend to reflect light rays in a form close to a Lambertian function [2], [8]. Therefore the walls (including the ceiling) and floor are modelled as diffuse elements with reflectivity coefficients of 0.8 and 0.3 respectively. To simulate the behaviour of the rays upon reflecting from the surrounding surfaces, the reflecting surfaces of the room are sub-divided into a small number of equally sized, reflecting elements with area dA. These reflecting elements retransmit the received signal from their centres, in the form of a diffuse pattern. The rays that were reflected up to a maximum of second order reflection were considered [10], [19]. More details about the model of the room (total number of reflecting elements, size of each element and the time bin used) are explained in our previous works [10], [11], which can be adapted and extended to our new hybrid system (HDIrT).

The Hybrid transmitter is positioned at the centre of the room at (2m, 4m, 3m) and is pointed downwards and emitted 1 W with an ideal diffuse pattern. Exposure to optical radiation at such power levels can be hazardous to the skin and eyes. Nevertheless, different techniques can be used to reduce the impact of the high laser power such as extending the source size, destroying its spatial coherence using holograms mounted on the transmitter or the use of arrays of transmitters. Pohl et al. have shown that such a source may use an integrating sphere as a diffuser to emit optical powers in the range 100mW – 1W [20]. Therefore, a transmitter power of 1 W will be assumed. Furthermore, the SNR improvement of our imaging system proposed in Section 3 is used to reduce the transmit power to 100 mW, reducing the power density on the diffuser and helping with eye safety.

To help understanding the characterization of the received data, the receiver has been placed in various locations over the CP, a plane 1 m above the floor, as shown in Fig.1. A wide FOV= 90° non-imaging receiver is coupled with our proposed system. Moreover, a custom design imaging receiver is used to reduce the impact of multipath dispersion. In this work, we employed the imaging receiver design proposed in [9], [12]. It is comprised of a single imaging lens and detector array that is subdivided into 200 pixels. The receiver detector array has a photosensitive area of 2 cm^2 and each pixel has an individual area of 1 mm^2. The reception zone of each pixel (on the ceiling) is varied as the receiver terminal moves around the room over the CP. The calculation of the new reception zone associated with each pixel is discussed in detail in [12]. The calculation of the received optical power is discussed in [8], [10]. The Simulation results were obtained at various receiver positions within the indoor environment.

3. LINK BUDGET AND SIMULATION RESULTS

3.1 Link Budget

In IM/DD the received optical power at the detector is converted to electrical current. OOK is the simplest modulation technique for IR systems. It uses a rectangular pulse with duration equal to the bit period. Taking P_{s1} and P_{s0} , the power levels associated with logic 1 and logic 0, respectively, into account (hence ISI), the SNR is given by [19]:

$$SNR = \left(\frac{R(P_{s1} - P_{s0})}{\sigma_0 + \sigma_1}\right)^2 \tag{3}$$

where R is the responsivity of the photodetector which in our case is $R = 0.6\ A/W$. σ_0 and σ_1 are the noises associated with the signal and can be calculated from [19]:

$$\sigma_0 = \sqrt{\sigma_{pr}^2 + \sigma_{bn}^2 + \sigma_{s0}^2} \ \ \text{and} \ \sigma_1 = \sqrt{\sigma_{pr}^2 + \sigma_{bn}^2 + \sigma_{s1}^2} \tag{4}$$

where σ_{pr}^2 represents the receiver noise which is a function of the design used for the preamplifier. σ_{bn}^2 represents the background shot noise component. Since the HDIrT system operates when the VLC system is off (dark area), we ignore the background noise component. The component of the noise that is a direct result of the received signal power consists of two elements. The first element is the shot noise component σ_{s0}^2 which is the noise associate with P_{s0} and the second element is σ_{s1}^2, associated with P_{s1}. These components can be calculated from:

$$\sigma_{s0} = \sqrt{2 \times q \times P_{s0} \times R \times BW} \text{ and } \sigma_{s1} = \sqrt{2 \times q \times P_{s1} \times R \times BW} \quad (5)$$

where q and BW are the electron charge and the receiver bandwidth, respectively. Higher bit rates of 1.25 Gb/s and 2.5 Gb/s are evaluated in our proposed HDIrT system. We used the preamplifier design proposed in [21].

3.2 Simulation Results

This section explores the performance of our proposed system (HDIrT) under the influence of multipath dispersion, receiver noise and mobility. The proposed system was simulated to generate power distribution, delay spread and SNR. Spatial distribution of the signal power at various locations, gave a useful visualisation of the power variation in the room, where the received optical power decreases towards the room corners, as shown in Fig. 2. The received optical power of our proposed HDIrT with a single wide FOV receiver has its maximum value at the room centre where our transmitter is located. This enhancement is due to the short distance between the transmitter and the receiver. Comparison of the channel delay spreads of our proposed system using different reception techniques, imaging and non-imaging receivers, is given in Fig. 3. The receiver moves along the x=1 m line. The delay spread result of our imaging system is quoted when the system employs selection combining (SC) to select the imaging receiver pixel with the best SNR [10]. The non-imaging receiver system shows much more signal delay spread due to the wide receiver FOV (FOV=90°) which accepts a wide range of rays with different path lengths from the transmitter to the receiver. The delay spread of our proposed configuration is reduced from almost 1.55 ns to 0.1 ns when an imaging receiver replaces the non-imaging receiver. This is attributed to the narrow FOV associated with each pixel, which limits the rays received by using 200 small FOVs (11.3°) pixels and selecting the best imaging receiver pixel result. Note that maximum ratio combining (MRC) can be used to combine the signals from all the pixels of the imaging receiver [9], [12], which will result in higher SNR.

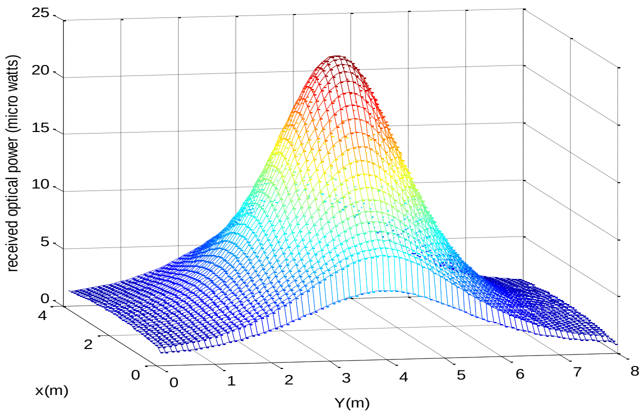


Figure 2. The received optical power of our proposed system using wide FOV receiver with total transmission power equal to 1 W.

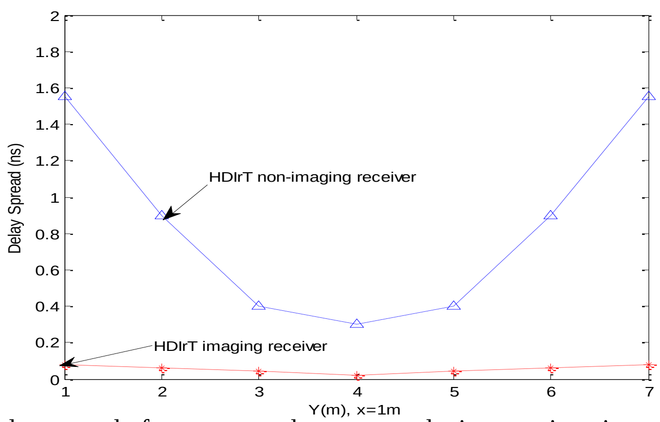
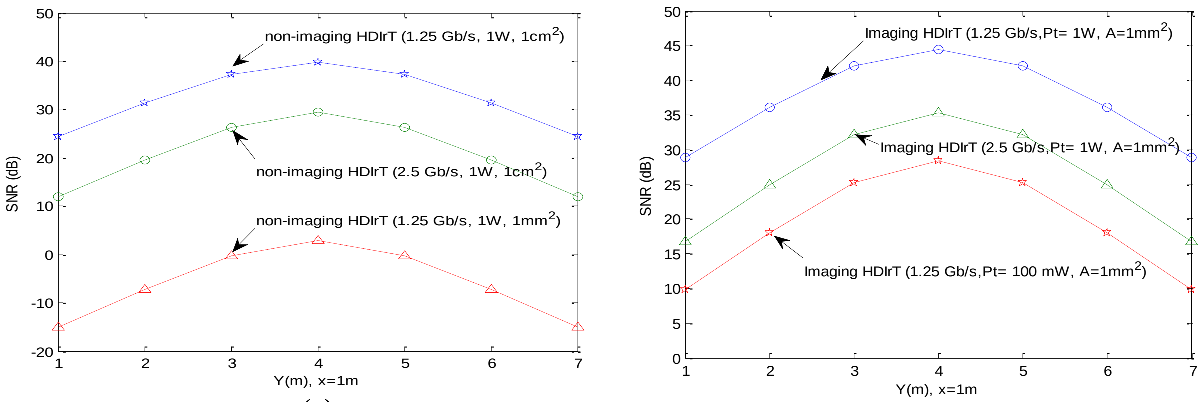


Figure 3. The channel delay spread of our proposed system employing non-imaging and imaging receiver, when the receiver moves along the x=1m line.

The SNR evaluation of the Hybrid HDIrT configuration, employing imaging and non-imaging receivers, is performed under the effect of receiver noise, mobility and multipath propagation. The proposed system is set to operate at 1.25 Gb/s and 2.5 Gb/s with photodetector areas of 1 cm^2 (non-imaging receiver) and 1mm^2 (imaging and non-imaging receivers). A small detector area is needed to reduce the high capacitance, hence improving the receiver bandwidth. The SNR result of our imaging receiver is given when the system employs maximum ratio combining (MRC). SNR calculations associated with the MRC technique can be found in our previous work in [9]. The SNR results of the proposed systems are shown in Figs. 4 (a) and (b), when the receiver moves near to the wall, at 1m steps along the x = 1 m line. Our proposed HDIrT wide FOV receiver with 1 cm^2 detector area achieves around 24 dB SNR when the system operates at 1.25 Gb/s. However, the detector capacitance is proportional to its active area. This means that if the active area of the detector is large, such as 1 cm^2, the detector capacitance will be large, which results in a restriction on the achievable bandwidth. Therefore the detector active area has to be reduced at higher data rates. Reducing the detector area to 1mm^2 will lead to a reduction in SNR to about 40 dB, see Fig 4 (a). Our imaging receiver with HDIrT performs better than the non-imaging wide FOV receiver. This is due to the ability of the imaging receiver to combine the signals from the optimum pixels that observe the best received signal during mobility. The imaging receiver uses a large number of detectors with a narrow FOV and small detector area. Our proposed system (HDIrT) coupled with 200 pixels imaging receiver provides around 29 dB and 17 dB SNR at 1.25 Gb/s and 2.5 Gb/s, respectively, under the effect of multipath dispersion, receiver noise and mobility. The SNR improvement obtained in our imaging system allows us to reduce the total diffuse transmission power to 100 mW level. The SNR achieved in this case was about 9.8 dB at 1.25 Gb/s. Forward error correction (FEC) can be used to reduce the BER form 10^{-3} to 10^{-9} in our proposed imaging system.



(a) (b)

Figure 4. The SNR results of our proposed system with (a) non-imaging receiver and (b) imaging receiver, when the transmitter transmits Pt=1W and 100 mW and operates at 1.25 Gb/s and 2.5 Gb/s and while the receiver (with A=1 cm^2 and 1 mm^2) moves along x=1m line.

4. CONCLUSIONS

In this paper, a new hybrid IR (HDIrT) system to support VLC communications is introduced. The proposed system is coupled with non-imaging and imaging receiver in order to improve the received optical signal SNR in the presence of multipath dispersion, receiver noise and mobility. The imaging receiver is shown to be efficient in reducing the channel delay spread from 1.55 ns (non-imaging receiver) to about 0.1 ns. Simulation results show that the proposed system coupled with imaging receiver achieved around 29 dB and 17 dB SNR at 1.25 Gb/s and 2.5 Gb/s, respectively. Further improvement of our new proposed system can be achieved by employing more than one IR source and by distributing these sources on the ceiling (for example, attached to white-LED sources).

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