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Development of Visible Light Communications: Emerging Technology and Integration Aspects

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Invited paper

Abstract—The global green agenda is having its impact in the field of communications and information exchange. More efficient lighting is considered to be one of the areas that would contribute to the reduction in the carbon foot print. Light emitting diodes (LED) are extremely power efficient in comparison to other light sources and have the potential to be used for data communications. In this paper we give an overview of visible LEDs (both in-organic and organic) for both illumination and data communications.

Index Terms—LED, OLED, Visible light communications

I. INTRODUCTION

Full use of the capacity provided by the fiber to home technology will necessitate the use of broadband links including indoor wireless access technologies capable of operating at Gb/s. In recent years we have seen optical wireless communication (OWC) as an emerging strong technology candidate for high speed indoor communications [1-3] as a complementary scheme to the RF systems. Indoor OWC systems are composed of two main technologies: the visible light communications (VLC) and the infra-red communications (IRC). The IRC technology is well developed over the last three decades with a number of applications and devices [4, 5]. The visible light communications (VLC) as part of OWC systems are becoming an attractive technology for both illumination and data communications, which has seen a growing research and development interest at a global level. The advantages VLC provides for illumination as well as wireless data communications are (i) immunity to electromagnetic interference as well as being highly secure; (ii) easy to install lighting equipment, license free and safe for the human eye, (iii) offering different shapes and sizes, (iv) low cost, low electric power consumption and long life expectancy, and (v) high-speed data communications. Predominantly current research in VLC involves increasing the data throughput, as the raw bandwidth of commercially available white light emitting diodes (LEDs) are limited to only a few MHz [6, 7].

In recent years we have seen the use of VLC in a number of applications including: intelligent transportation system (ITS) covering vehicle to vehicle / road to vehicle communication [8], information display [9], and home networking [3] - Ethernet/Fast-Ethernet speeds (10/100 Mbps) have been achieved [6,7]. A number of schemes have been proposed to overcome the problem of limited

bandwidth including; equalization and coding techniques (up to 100 Mb/s) [7, 10, 11]; the resonant driving technique for multiple LEDs (up to 40-Mb/s) [6]; and the discrete multi-tone modulation (DMT) in combination with the multi-level modulation schemes such Quadrature Amplitude Modulation (QAM) scheme which supports data rates up to 1 Gb/s [12-14].

OLEDs have begun to attract significant attention in recent years mainly for high-end gadgets and high-definition television display applications because OLEDs are a light source of variable wavelength, so they do not require colour filtering or a backlight and hence are more efficient than liquid crystal displays. From the first practical devices reported by Tang and Van Slyke in 1987 [15], the devices have become highly efficient (in line with modern LEDs [16], available in a broad gamut of colours with high brightness and contrast, mechanically flexible and above all, low production costs [17]. OLEDs can also offer extremely large panel size, which is restricted only by the size of the equipment while LED crystals are brittle and can only offer point sources. As the advancement of the technology continues and evolves so does the targeted applications. Large area RGB OLED panels with high brightness efficiency are now becoming available for general white light illumination purposes including homes and office environment. This has naturally lead to the crossover into the visible light communication (VLC) systems currently occupied by the solid state indium gallium nitride (InGaN) LED devices whereby the illuminating light beam can also be intensity modulated for the transmission of data [3] [18].

II. WHITE LIGHT EMITTING DIODES

White LEDs used for general illumination are of two types: (i) devices that combine separate red-green-blue (RGB) emitters and (ii) devices that use a blue emitter in combination with the yellowish phosphor, known as white phosphor LEDs (WPLEDs). The latter is the preferred option for lighting due to the cost reduction in producing just a single diode in combination with the decreased complexity compared to the three-diode device. The disadvantage of the WPLED, however is typical modulation bandwidths are a few MHz in comparison to a few hundred MHz for each wavelength of RGB LEDs [6, 19]. Bandwidth limitation is mainly due to the slow transient response of the phosphor. A typical VLC link utilizing a white LED is shown in Figure 1, where lighting and the communication

link are both provided by the LED. The blue light could be readily extracted from the incoming optical beam by using an optical filter at the receiver. Figure 2 and Figure 3 show the optical spectrum of the emitted white light and the measured modulation bandwidth of the blue-phosphor LED, respectively. It is observed that the bandwidth of the white component of LED (~ 2 MHz) is much smaller than bandwidth of the blue component ($\sim 15 - 20$ MHz, dependent on the manufacturers) [7, 19].

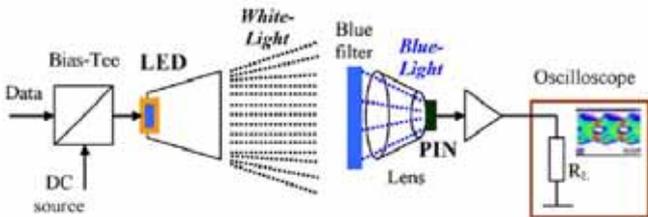


Figure 1 (a) VLC link,

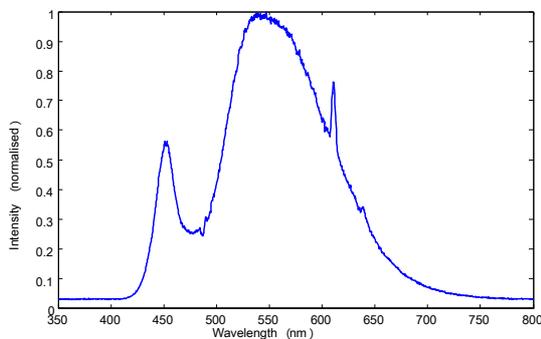


Figure 2 Optical spectrum of Luxeon Star white LED

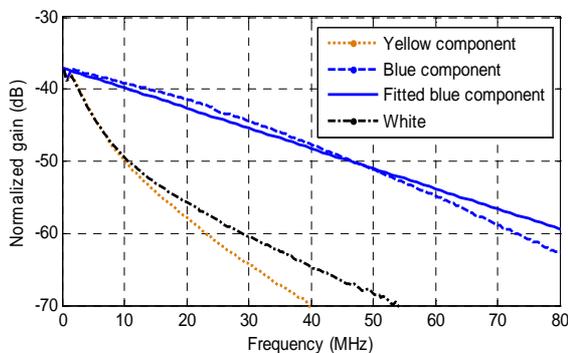


Figure 3 Modulation bandwidths of white/yellow/blue components and blue-response fit

Transmitting high data rates over a narrow modulation bandwidth is very challenging. There are a number of approaches to improve the modulation bandwidth, including using a blue-filter at the receiver to filter out the slow-response yellowish components, pre-equalization at the LED driving module [6, 20], post-equalization at the receiver [7, 20] or a combination of three techniques. Another approach to achieve a high-speed data transmission over a limited bandwidth is to employ more complex

modulation schemes where multiple bits can be carried by each transmitted symbol. Literature shows that higher data rates are achievable utilizing a blue channel in combination with pre/post equalization or complex modulation schemes [21, 22]. Transmission of OOK-NRZ over an equalized channel is simpler compared to the complex modulation schemes since the latter require a large amount of signal processing at both transmitting and receiving ends. In both cases the ratio of the achievable transmission data rate over the raw LED modulation bandwidth (~ 2 MHz) is significantly enhanced. However, to achieve a wide modulation bandwidth using equalizations or employing multi-level modulation schemes the system will require a very high signal-to-noise ratio as outlined in [7, 13].

Table 1 gives a summary of achievable data rates for different VLC systems for white and blue channels as well as non-return to zero (NRZ) on-off keying (OOK) and DMT-QAM modulation schemes.

III. ORGANIC LIGHT EMITTING DIODE

Organic devices, which are at the early stage of development, on the other hand suffer from much lower carrier mobility [23], and thus have a considerably reduced frequency response. The carrier mobility within the OLED panel is largely dependent upon the materials and the overall size of the emissive area. Figure 4 shows the formation of a bi-layer OLED including the emissive layer (or electron transport layer ETL) and a conductive layer (or hole transport layer HTL) and its electrical equivalent circuit.

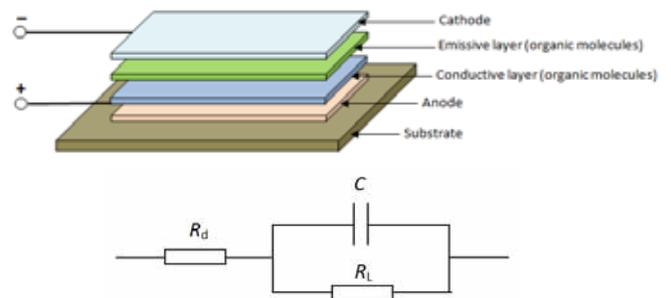


Figure 4 OLED structure and equivalent circuit

A number of schemes have been proposed to improve the OLED frequency response to make them more suitable for data communications. As the material can have a major impact on the device performance, carefully selecting the organic layers will help to improve the fluorescent lifetime (FL) of OLEDs. Different materials have been tested in [24] showing the influence of the material on FL. As FL contributes to the transmission speed, the faster the device releases the photon the higher the speed that can be achieved. In [25] the current density and the temperature are investigated and a high bias voltage has been applied to increase the mobility, thus allowing faster transmission rates. Ultimately the large panel size of the device reduces the modulation bandwidth due to the capacitive effect between the anode and cathode; however there is a trade-off between larger area devices offer superior lighting performance for

Table 1 Performance of high speed VLC systems

	LED/OLED	Pre-equalisation	Post-equalisation	Modulation scheme	Modulation bandwidth	Demonstrated data rate
White channel	LED			OOK-NRZ	2 MHz	10 Mb/s (BER < 10 ⁻⁶)
White channel	LED	RC		OOK-NRZ	25 MHz	40 Mb/s (BER < 10 ⁻⁶) [8]
Blue channel	LED	RC		OOK-NRZ	45 MHz	80 Mb/s (BER < 10 ⁻⁶) [12]
Blue channel	LED		RC	OOK-NRZ	50 MHz	100 Mb/s (BER < 10 ⁻⁹) [10]
Blue channel	LED			DMT-QAM	25 MHz	100 Mb/s (BER < 10 ⁻⁶) [9]
Blue channel	LED			DMT-QAM	50 MHz	231 Mb/s (BER < 10 ⁻³) [11]
Blue channel	LED			DMT-QAM	80 MHz	1 Gb/s [P1]
White channel	OLED		RC	OOK-NRZ	150 kHz	N/A [P3]
White channel	OLED		ZFE	OOK-NRZ	90 kHz	425 kb/s [P3]
White channel	OLED		ANN	OOK-NRZ	90 kHz	550 kb/s [P3]

given materials and their bandwidth. In this paper we will deal with a large panel OLED, which is more realistic in terms of future domestic lighting.

A. How to mitigate small OLED bandwidth

For band-limited channels, inter-symbol interference (ISI) is the mitigating factor of a high data rate transmission. In order to overcome this, both time and frequency domain equalizations schemes could readily be used, including (i) the analogue resistor-capacitor (RC) equalizer [7], which can show considerable data rate increases when considering high speed VLC applications, (ii) more complicated digital finite impulse response (FIR) equalizers such the zero-forcing equalizer (ZF), which offers a limited improvement over the RC equalizer [21], and (iii) a decision feedback equalizer (DFE) offering significant improvements in comparison to other, owing the feedback channels.

Both the ZF and DFE [21] are well established, however this is the first time they are being adopted for such a low bandwidth OLED. The equalizer performance is based on the number of filter taps. Increasing the number of taps will enhance the available data rates but at the cost of increased complexity. Thus, achieving very high data rates is not a straightforward task in real time. Furthermore, over-increasing the number of taps will result in marginal performance enhancement; hence the trade-off between the performance and complexity.

B. Bit rate performance of an OLED-VLC system

The RC, ZF and ANN equalizer BER performance is verified using the test setup shown in Figure 5.

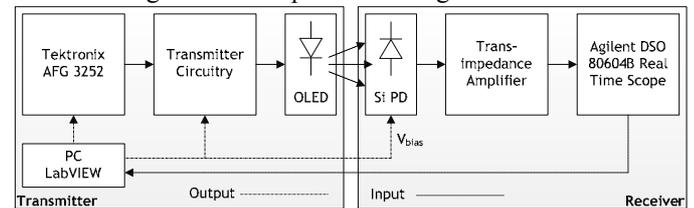


Figure 5 OLED-VLC test setup

The pseudo-random binary sequence (PRBS) of length 2¹³-1 is generated in MATLAB. An arbitrary function generator controlled using the LabVIEW environment which transmits the PRBS sequence, which then mixed with the DC bias current prior to intensity modulation of the OLED. At the receiver a silicon (Si) photodetector (10 dB transimpedance gain, 5 MHz bandwidth) is used to recover the electrical signal followed by the RC equalizer. ZF and ANN equalization are both carried offline in MATLAB. The digital scope performs the data acquisition (DAQ) under the control of the MATLAB environment, and is programmed to record at least 10 million bits. The BER performance of the link is shown in Figure 6. The raw performance is shown to be 80 kb/s, which closely matches the raw system bandwidth. The RC filter is shown to support to useful data rate. The reason for this is due to the baseline wander phenomena introduced by the removal of the low frequency components

causing threshold detection to fail. ZF and ANN work on the basis of ISI removal. ZFE can mitigate the ISI until data rates of 425 kb/s while ANN can offer 550 kb/s. The data rate increase up to 550 kb/s offers a significant improvement over the raw response of 80 kb/s, and a bit-rate to bandwidth ratio of over 6 times

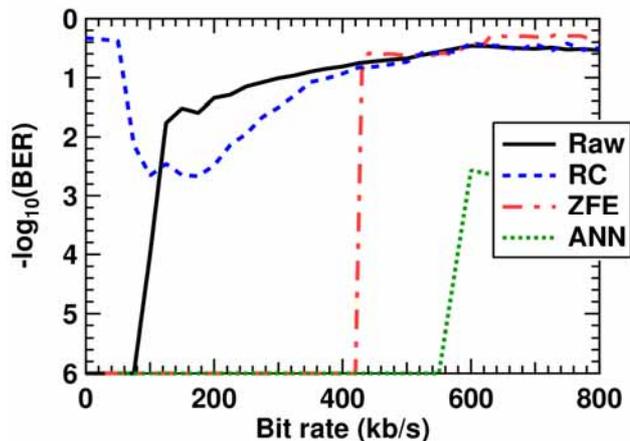


Figure 6 BER performance of OLED-VLC with various equalizers

IV. VLC-LAN

White LEDs can be applied in various VLC applications. Of these the indoor VLC wireless local area network is very attractive as it directly provides the flexibility and usability for millions of consumers. Here we will discuss the concept of this system and demonstrate the room-scale system. A scalable white LED, high luminosity, wide angle OOK-NRZ VLC transmitter with error free transmission at 10 Mbps (10Base-T Ethernet) over distances up to 2-3m is presented. The LAN connections are designed such that

their operation is very reliable and at low cost. VLC LAN has been demonstrated before however this was on a point to point basis with a single white phosphor LED and a blue filter, without the intension of added room illumination functionality. The system shown in Figure 7 consists of a duplex LAN configuration with a VLC down link and an IR uplink.

The Ethernet signal from the PC1 is buffered and used to drive 5 LED units. An analogue RC equalization is used to increase the frequency response of the system and connect directly to each of the five transmitter units. The optical receiver consists of a concentration lens, a PIN photodetector (PD) and a Transimpedance amplifier (TIA). The output of the TIA is passed through a limiting amplifier (LA) and a differential amplifier, increasing the level of the electrical signal to the required LAN voltages and connected into PC2. The feedback signal from PC2 to PC1 will be transmitted via an IR uplink. The experiment parameters are given in Table 2 [26].

Table 2 System parameters for VLC-LAN

Figure 8 shows the actual room model for VLC LAN system. A pseudo random bit streams (PRBS) of binary data (length $2^{10}-1$) using OOK NRZ is sent across the link at 10 Mbps to test the error-rate of WLAN physical layer. In a number of tests at different illumination levels the measured BER are well below 10^{-9} . Table 3 summaries the measurement.

Ethernet throughput is evaluated using packet generator from PC1. Figure 9 demonstrates the results collected for the Ethernet throughput. The network loads (number of packets injected into the system from PC1) were gradually increased from 100 to 800 Pktsps and the corresponding throughput was noted by PC2. It has been clearly observed that the VLC

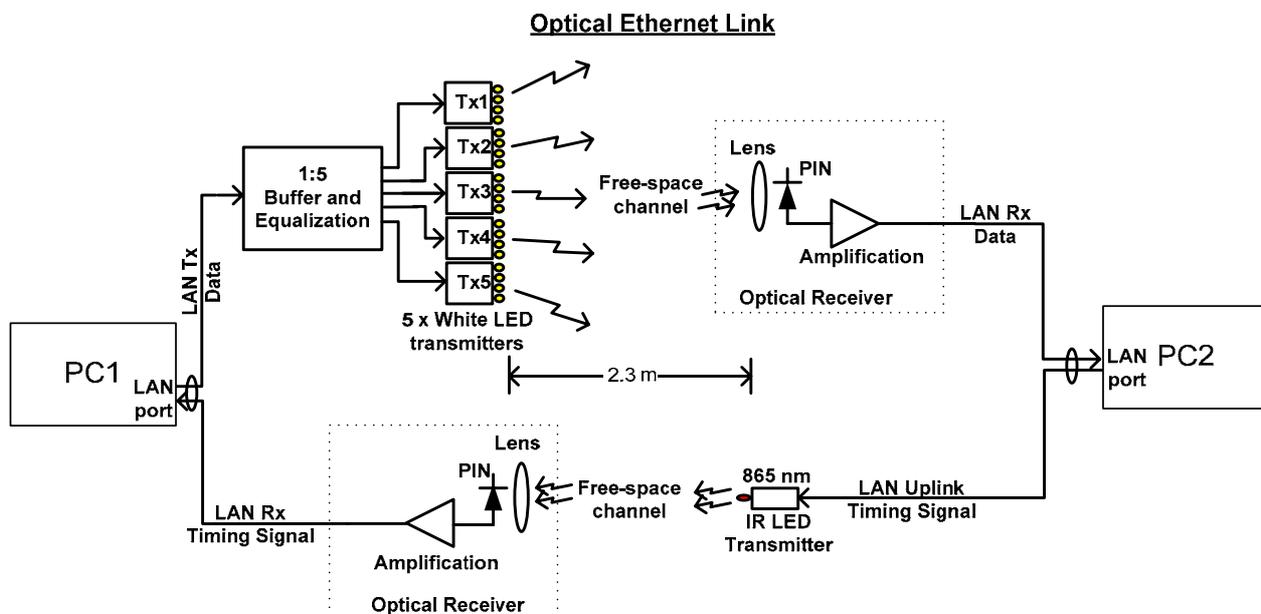


Figure 7 The proposed VLC-based WLAN

system is able to support all loads without incurring any losses (Figure 9 (a)). Similarly all the other tests demonstrate a stable behavior for the system throughput, as observed for all other cases. The experimental results in Figure 9 (b) represent a point-to-point Ethernet link under identical conditions as in the VLC case, however using a copper LAN crossover cable between PC1 and PC2.

Table 3 Illumination levels vs measured BER

Illumination level	Measured BER
276 lux	4.4×10^{-10}
322 lux	2.3×10^{-10}
437 lux	2.4×10^{-13}
831 lux	1.24×10^{-13}

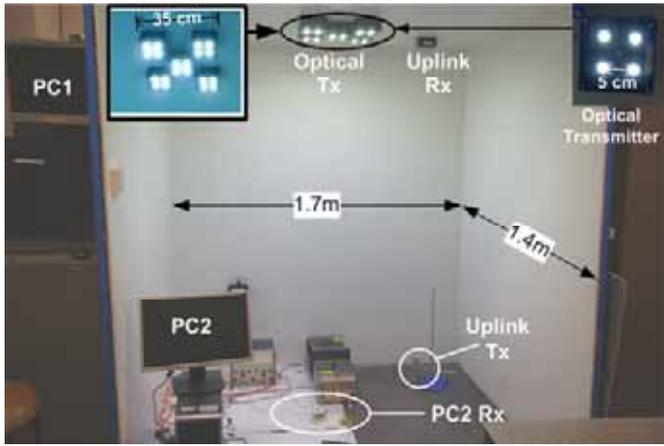


Figure 8 White LED LAN experimental setup

Parameter	Value
LED Transmitter (Down link)	
Wavelength λ	450-900 nm
Bias current	350 mA
Transmit power P_T	175 mW
Rise time T_R	42 ns
Fall time T_F	62 ns
Beam angle	120°
Optical bandwidth	10 MHz
Optical modulation index	23 %
Illuminance (mean) at RP	387 lx
N° of LEDs per transmitter	4
LED pitch	5 cm
Transmitter spacing $l \times w$	35 cm \times 35 cm
Infra-Red (IR) Transmitter (Up link)	
Wavelength λ	865 nm
Rise time T_R	30 ns
Fall time T_F	15 ns
Optical bandwidth	20 MHz
Transmit power P_T	11.5 mW
N° of LEDs	1
Transmission beam angle	7.3°
Lens <i>diameter/ focal length</i>	20 mm / 20 mm
Channel	
Maximum length	2.3 m
Room Dimensions $l \times w \times h$	1.4 \times 1.7 \times 2 m ³
Receiver (uplink and downlink)	
PD responsivity \mathcal{R}	0.2 A/W @ 450 nm

	0.43 A/W @ 850 nm
PD active area	15 mm ²
PD reverse bias	60 VDC
TIA bandwidth	240 MHz
TIA gain G	90 Ω
TIA sensitivity	-36 dBm @ 155 Mbps
Lens <i>diameter/ focal length</i>	25 mm / 25 mm

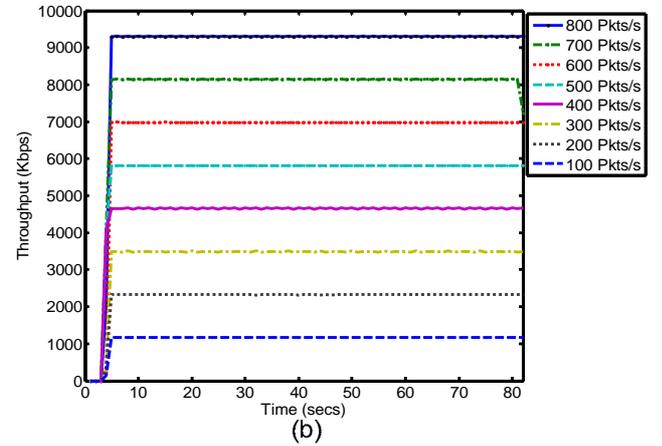
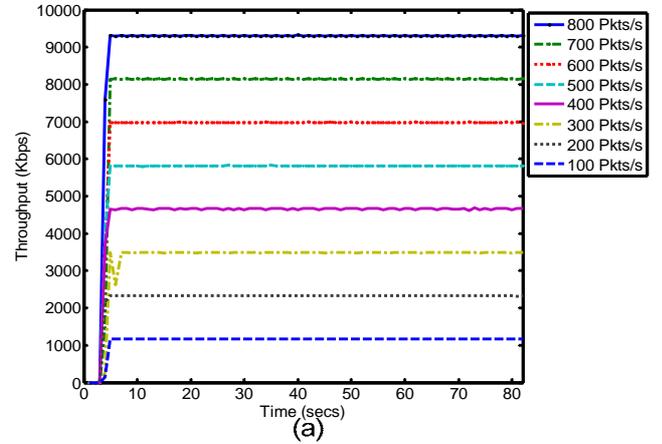


Figure 9 Ethernet throughput using (a) VLC system and (b) wired LAN crossover cable

V. MULTIPLE-INPUT MULTIPLE-OUTPUT

In MIMO systems multiple transmitters (i.e. LEDs) and receivers (i.e. photodetectors) are used to improve the link bit rate [27, 28]. The MIMO technology offers increased link range and higher data throughput without the need for additional power or bandwidth, by the way of higher spectral efficiency (more b/s/Hz) and link reliability and/or diversity. Thus, it is of prime importance in wireless communications. Figure 10 illustrates a typical VLC MIMO system.

Four LED arrays are used for room lighting as well as for transmitting four independent data streams simultaneously. A receiver array is composed of four photo-detector elements with non-imaging concentrators [27]. Figure 11 depicts the schematic of the MIMO model.

Serial input data stream is interleaved and used to modulate the individual LED arrays (transmitters). Light

emitted from each of the LED arrays is collected by all receivers, but with different intensity due to the geometric configuration. Received signals from all four channels are processed using a channel matrix H to recover the transmitted data streams corresponding to individual channels. Results obtained from [27] show that it is possible to transmit a non-return to zero and off keying (NRZ-OOK) data format exceeding Gb/s in many applications. The system parameters and the detail of simulation setup are reported in [27].

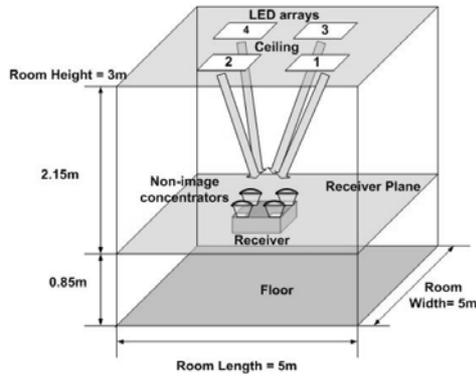


Figure 10 Typical VLC-MIMO system

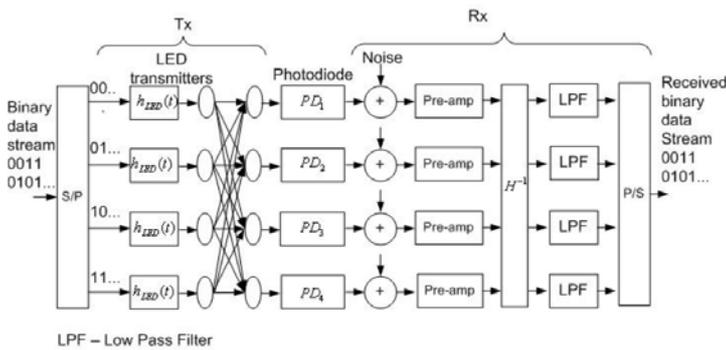


Figure 11 VLC-MIMO schematic

VI. CHALLENGES

Perhaps the simplest method to alleviate the low modulation bandwidth of a white LED is to filter out the phosphor component using a blue filter, see Table 1. However a significant amount (~90 %) of the transmitted optical power will be removed (Figure 2). Data transmission rates could be increased by employing an equalizer and complex modulation schemes. MIMO systems offer much higher transmission capacity up to Gb/s by transmitting data in parallel and continuously updating the channel matrix to separate data at the receiving end. In the scenario where the channel matrix is ill-conditioned, data from different sources cannot be properly recovered, thus resulting in full errors. In [28] it is shown that it is possible to improve the channel matrix rank by employing the imaging lens system, however this method introduces additional expense and complexity.

At the system level, integration of VLC to an application is another challenge and it could be varied from application to application. Here we demonstrated the usage of VLC in 10BASE-T WLAN using OOK-NRZ. For the system of 100BASE Ethernet, the signaling is multiple-level PAM that imposes the difficulty of maintaining high SNR for PAM signal over VLC. In addition 100s Mb/s VLC is unlikely in OOK-NRZ format with the room scale communications (e.g. they are mostly in OFDM/DMT) therefore signal adaptation and synchronization are required.

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