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Invited Paper

A 2 × 2 imaging MIMO system based on LED Visible Light Communications employing space balanced coding and integrated PIN array reception

Jiehui Li [a], Yinfan Xu [a], Jianyang Shi [a], Yuanquan Wang [a], Xinming Ji [b], Haiyan Ou [c], Nan Chi [a,*]

[a] The Key lab of Electromagnetic Wave Information Science, Department of Communication Science and Engineering, Fudan University, Shanghai, China
[b] The State Key Lab of ASIC and System, Department of Microelectronics, Fudan University, Shanghai, China
[c] Technical University of Denmark, DTU Fotonik, Ørsteds Plads 343, 2800 Kongens Lyngby, Denmark

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ABSTRACT

In this paper, we proposed a 2 × 2 imaging Multi-Input Multi-Output (MIMO)-Visible Light Communication (VLC) system by employing Space Balanced Coding (SBC) based on two RGB LEDs and integrated PIN array reception. We experimentally demonstrated 1.4-Gbit/s VLC transmission at a distance of 2.5 m. The proposed imaging system not only overcomes the limitation of bandwidth existing in LEDs, but also can reject the second-order nonlinearity distortion. It turned out to be very promising to use integrated antennas in the VLC system in the future.

1. Introduction

Visible Light Communication (VLC) based on Light Emitting Diodes (LEDs) has drawn significant research interest because it can support illumination and communication simultaneously. As the main device for the next generation illumination, it has been widely investigated in [1–3]. However, one of the technical challenges is that the intrinsic narrow bandwidth existed in different types of commercial LEDs: Red–Green–Blue (RGB) LED and phosphor-based LED. To overcome this problem, many research efforts have been dedicated in such as digital signal processing (DSP) [4–7], high-order modulation [8] and equalizations [9]. However, few cases have been reported on parallel transmission which can offer a higher capacity than Single-Input-Single-Output (SISO) systems and integrated Positive-Intrinsic-Negative (PIN) array reception.

Multiple-input Multiple-output (MIMO) is widely used in radio communication and multimode fiber communication, where scattering and interference creates channels that are de-correlated from one to another [10–13]. This allows MIMO channels to have higher capacity than their Single-Input Single-Output (SISO) counterparts given a fixed level of total transmission power. Wang et al. experimentally demonstrated a high-speed 2 × 2 non-imaging MIMO visible light communication system that is capable of delivering 500 Mb/s 4-QAM Nyquist Single Carrier Frequency Domain Equalization (N-SC-FDE) signals over 40 cm free-space transmission [12]. Zeng et al. made a simulation comparison of non-imaging MIMO and imaging MIMO. For non-imaging MIMO, the precise alignment is not required, and the tolerance to the misalignment become larger, but at the symmetry position, the channel matrix becomes less well conditioned. As for imaging MIMO, the channel matrix is always full-rank and diagonal matrix. Although it needs precise alignment to make each LED image onto a dedicated detector, the channel matrix will be conditioned well as long as the position is symmetric [13]. Additionally, Balanced Detection (BD) is an efficient solution to the second-order nonlinearity distortion and it also can eliminate common mode intensity noise to improve the output Signal to Noise Ratio (SNR). In the previous work, *Wang* et al. have proposed a Quasi-Balanced Detection (QBD) technique in Orthogonal Frequency Division Multiplexing (OFDM) VLC system by employing opposite signals to odd and even consecutive symbols with one single Avalanche Photodiodes (APD) [14]. When using the traditional single detector, the inherent intensity noise even quantum noise of vibration light becomes the main limited factor which restraints the

* Corresponding author.
E-mail addresses: xmji@fudan.edu.cn (X. Ji), haou@fotonik.dtu.dk (H. Ou), nanchi@fudan.edu.cn (N. Chi).

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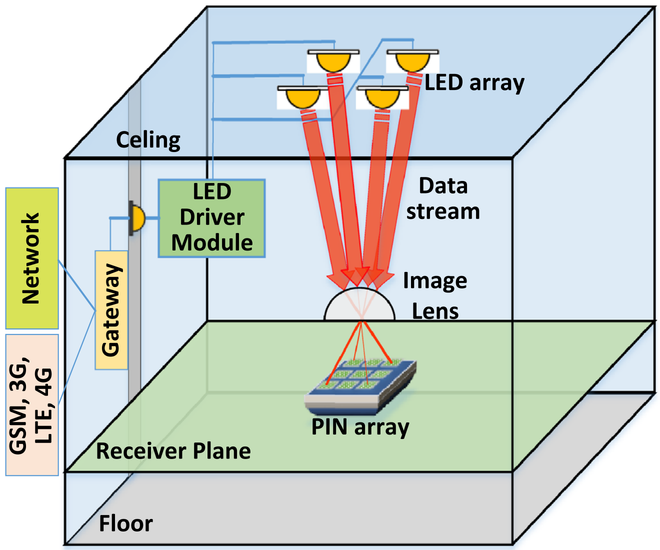

Fig. 1. Indoor network using imaging MIMO VLC.

output SNR of detector for further improvement.

Fig. 1 illustrates the configuration of a visible light indoor optical wireless system. In order to maintain the typical illumination level, there would be of course many LEDs in a real room, which provide the natural setup for MIMO transmission. The imaging MIMO requires each LED array imaging onto a detector array, while the non-imaging MIMO only needs non-imaging concentrators before each of the RXs. In this paper, we proposed a 2×2 imaging MIMO-VLC system based on Space Balanced Coding (SBC) technology in OFDM by employing opposite signals with two RGB LEDs as Transmitters (TXs) and an integrated PIN array as the Receivers (RXs). Using this scheme, the second-order intermodulation distortion and Direct Current (DC) can be eliminated, and the sensitivity of integrated PIN array receiver can be improved. We achieved physical data rate of 1.4-Gbit/s at a distance of 2.5 m by employing a commercial available RGB LED and the proposed integrated PIN array receiver. To the best of our knowledge, this is the highest data rate and the farthest distance ever achieved by employing an integrated PIN array receiver in VLC system.

This paper is organized as follows. In Section 2, we describe the fabrication of integrated PIN array. In Section 3, the theoretical model and de-multiplexing algorithm of space balanced coding were described. In Section 4, the experimental setup including the system model and integrated PIN array testing system is introduced. The experimental results and discussions are provided in Section 5. Concluding remarks are presented in Section 4.

2. Fabrication of integrated PIN array

As the fabrication of PIN diode described in reference [15,16], the boron doped p-Ge/i-Ge layer was grown on n-type Si wafers by using Rapid Thermal Chemical Vapor Deposition (RTCVD). The cross-sectional view of the PIN photodiode fabricated from p-Si/i-Ge/n-Ge hetero structure is shown in Fig. 2(a). The Si wafers were cleaned with 6:1 HF: DI solution before Ge growth. First, Ge buffer layers of ~110 nm were grown at 350 °C under a process pressure of 20 Torr. GeH_4 (20% in H_2) source gas was used at 30 sccm with 20 slm H_2 as carrier gas. Subsequently, high temperature i-Ge layers of ~1.40 µm were grown at 500 °C under similar gas flow conditions. Finally, phosphorus-doped n-type Ge layers of ~0.61 µm were grown at 500 °C. For the synthesis of phosphorus-doped n-type Ge layer, 100 ppm PH_3 in H_2 was used under dopant number (source × injection/source+dilution) of ~0.049. The phosphorus doping concentration was estimated to be 2×10^{19} cm^{-3}.

Regular lithography techniques were used on the n-Ge/i-Ge layer surface. Samples were spin-coated with photoresist for 30 s at 5000 rpm. Then, they were placed in an oven for soft baking at 90 °C for 30 min. Photo lithography was performed by using a mask aligner under an ultra violet light source typically having i-line (365 nm) with an intensity of approximately 5 mW. The mesa was formed by ICP high density plasma dry etching. Helium back-side cooling has been incorporated to allow the temperature of the substrate to be more effectively controlled. After the n-Ge / i-Ge layer mesa formation, a 400 nm Si_3N_4 layer was deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) and contact metallurgies of Ti (3000 Å)/Au (3000 Å) were deposited sequentially by electron-beam evaporation and patterned by photo-resist lift-off.

The detector-induced current on the receiver board is the dominate noise source for the VLC system. In order to increase the effective photosensitive area and the receiver current, we mainly focused on investigation of an integrated PIN array on the receiver board of VLC system. A 3×3 matrix-structure packaged PIN array is shown in Fig. 2(b). The cell size is 3mm × 3mm. The n-contact is on the top surface, and the p-contact is on the bottom surface. The p-contact of PIN photodiode is attached to the bottom bonding pad on the Printed Circuit Board (PCB) by conductive plastic. Then, the n-contact of the PIN is bonded to the nearby bonding pad by a 1-mil gold wire.

3. Principle of SBC

The OFDM signals are usually divided into several blocks. The heterodyne signal as a differential mode is detected through subtracting one channel from another. Thus, the intensity noise as a common mode is eliminated when the valid signal is doubled.

In the scheme of SBC, the baseband OFDM signals in the kth block are given by

$$E_k(t) = \sum_{m=1}^{N} c_m e^{j2\pi f_m t} \tag{A.1}$$

$$\overline{E_k(t)} = -\sum_{m=1}^{N} c_m e^{j2\pi f_m t} \tag{A.2}$$

where N is the number of subcarriers, c_m is the information symbol at the mth subcarrier, and f_m is the frequency of the OFDM subcarrier.

The OFDM signals modulated to the LED light through bias-tee can be expressed as *Wang* et al. [14]

$$s_k(t) = (V_0 - V_\alpha)e^{j2\pi w_0 t} + \alpha e^{j2\pi(w_0+w_1)t} \cdot E_k(t) \tag{A.3}$$

where V_0 and V_α are respectively the bias voltage and reversal voltage of LED. The coefficient α is used to describe the ratio of OFDM band strength related to the main carrier. w_0 is the center frequency of LED. w_1 is the up-converted frequency of the OFDM signals.

After the space transmission, the OFDM signals are considered frequency deviation and phase noise can be approximated as Wang et al. [14]

$$r_k(t) = (V_0 - V_\alpha)e^{j(2\pi(w_0+\Delta f)t+\varphi(t))} + \alpha e^{j(2\pi(w_0+w_1+\Delta f)t+\varphi(t))} \cdot E_k(t) + n_{0,k}(t) \tag{A.4}$$