

Performance Analysis of Spatial Multiplexing in MIMO Based Visible Light Communication System

Ratan Kumar Mondal^{*}, Nirzhar Saha^{*}, Yeong Min Jang^o

ABSTRACT

Visible light communication (VLC) is a rapidly growing area of research and applications, due to the potential and predicted high efficiency of bandwidth. One of the key challenges in VLC technology is the choice of devices which are going to be deployed VLC features. Smartphone rationally uses the most widely deployed visible light sensor i.e. image sensor in camera, which could be used to receive the intensity modulated data. Image sensor based VLC system would be the most deployable scenario but initially the capacity was not much attractive compared with photodetector based VLC system. Here, the spatial multiplexing is proposed in MIMO based VLC system to increase the system capacity by utilizing the property of spatial separation of optical light sources in smartphone's camera module. The active pixels of imaging plane act as the multiple receivers which could be able to use on MIMO spatial multiplexing to enhance the system performance.

Key Words : Visible light communication, MIMO, multiplexing, image sensor, LED

I. Introduction

Visible light communication (VLC) is a promising technology for indoor wireless communications. By using visible light as the transmission medium, VLC has many advantages, such as harmlessness to human health, high data rate, high security, unlicensed frequency band usage, high signal-to-noise ratio (SNR), and etc. The release of IEEE 802.15.7 MAC and PHY specifications represents a significant milestone in promoting deployment of visible light communication in short range wireless personal area networks (WPAN)^[1]. Illumination is typically provided by an array of LEDs, with levels of 400-800 lux being specified as the minimum required for sufficient illumination. The modulation by the LEDs light must provide the dimming support for the human eye safety. In contrast, achieving high data rates is challenging

simultaneously with illuminating consistently due to the low modulation bandwidth of the existing LED light sources (several MHz)^[2]. Nevertheless, the levels of illumination specified for occupation ensure that a very high SNR is available. The availability of a large number of high SNR channels with sufficient bandwidth makes MIMO techniques a promising approach both using as a diversity and a multiplexing^[3]. The number of transmitter and receiver are much more than the current RF MIMO system, which provides a large number of degrees of freedom by enabling the multiplexing gains over the multiple channels. The potential of this paper is to investigate the performance of MIMO spatial multiplexing in camera based visible light communication. MIMO is widely used in optical communications^[4], where scattering of light and interference creates channels that are de-correlated from one another. This allows MIMO channels to

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◆ First author : Department of Electronics Engineering, Kookmin University, rataneee2k6@yahoo.com, Student member

o Corresponding author : Department of Electronics Engineering, Kookmin University, yjang@kookmin.ac.kr, Lifelong member

* Department of Electronics Engineering, Kookmin University, nirzharsaha_eee@yahoo.com

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have higher capacity than their Single Input Single Output (SISO) without increasing the transmit power and the bandwidth.

Rest of this paper is organized as follows: the system model is described in section II. Proposed MIMO spatial multiplexing is outlined in section III. The performance evaluation is described in section IV. Finally, we conclude the proposed scheme in section V.

II. System Model

2.1. Transmitter and Receiver

Consider the simplified imaging system as shown in Fig. 1. The transmitting panel consists of multiple arrays of LEDs and each LED or a group of LEDs can operate as a transmitter. Here the modulation is guaranteed to provide dimming support by the LED transmitters. For providing dimming support, the average light intensity must be constant over the time interval of 1ms to 10ms, during the data transmission.

For modulation, we assume that frequency shift on-off keying (FSOOK) is employed at the LEDs transmitter for the communication over the optical channel. The modulation process is similar to frequency shift keying inasmuch as there are defined mark and space ON-OFF keying frequencies for encoding bits. Consider that the imaging plane can be demodulated the bit as a two dimensional lightwave-to-digital conversion. The pixel photodetector produces a signal proportional to the incoming integrated light intensity which is then held for the scanning analog-to-digital conversion (ADC), thus establishing the frame rate of the video camera. The bit information will be acquired by sampling two times of each frame. The zero-force (ZF) equalizer has been introduced in the receiver to detect the multiple signals more accurately with less complexity.

2.2. Channel Model

Consider an optical wireless MIMO system with N_t optical transmit arrays (TX) and N_r imaging receiver (pixel area) as illustrated in Fig. 1. One

optical TX array consists of a number of optical sources and, in the context of this paper, it is regarded as a single unit which sends the same transmit signal over the optical wireless channel. The i -th data stream is converted to an electrical current signal, $x_i(t)$, which is given by

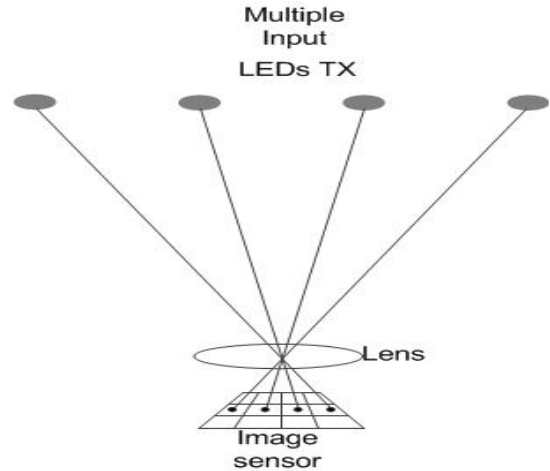


Fig 1 : MIMO spatial multiplexing offered by imaging plane

$$x_i(t) = \sum_{k=-\infty}^{\infty} x_i[k] \delta(t - kT), i = 1, 2, \dots, N_t \quad (1)$$

where $x_i[k]$ is the symbol loaded into the k -th signal on the signal space, T is the symbol duration. A simplified model of sampling using the Fourier series representation of the Dirac comb sampling function can be introduced as $\sum_{k=-\infty}^{\infty} \delta(t - kT) = (1/T) \sum_{k=-\infty}^{\infty} e^{jk\omega_s t}$ where ω_s is the sampling frequency. Let us assume simplified manner that the OOK frequency is a sinusoidal at ω_{OOK} frequency with a random phase σ_{OOK} . If the sampling frequency is harmonic with the OOK frequency and then the OOK frequency as a harmonic of sampling frequency, ω_s where $\omega_{OOK} \geq \omega_s$, thus the OOK frequency is, $\omega_{OOK} = n\omega_s \pm \omega_o$, where $\omega_o \leq |\omega_s/2|$. After the integration and hold the comparatively low frequency signal $x_i(t)$ would be as expressed below

$$x(t, \omega_o) = \text{sgn}[\sin(\omega_o t + \sigma_{OOK})] \quad (2)$$

For the time being, the frequency offset has one of the two values taken from $[0, \pm \omega_s/2]$. For space frequency the offset frequency is zero, thus the frequency of FSOOK would be $\omega_{OOK} = n\omega_s$ where n is the number of sampling. For mark frequency (logic 1), let the offset frequency $\omega_o = \pm \omega_s/2$, then the frequency of FSOOK would be $\omega_{OOK} = n\omega_s \pm \omega_s/2$. The detection of the mark and space can be expressed as follows [2]

$$x(t, \omega_o) = \begin{cases} \text{sgn} \left[\sin \left(\frac{\omega_s}{2} t + \sigma_{OOK} \right) \right], & \text{logic 1} \\ \text{sgn} \left[\sin(\sigma_{OOK}) \right], & \text{logic 0} \end{cases} \quad (3)$$

III. MIMO Spatial Multiplexing

Fig.1 shows, the visible-light indoor optical wireless system with four LED TXs. An imaging receiver [2] is used in place of the non-imaging devices (PD). Light propagates from the four LED TX to the receiver, and each LED TX is imaged onto an image sensor, where images may strike any pixels or group of pixels on the imaging plane, and be in arbitrary alignment with them. Each pixel on the image sensor acts like a receiver channel, and measuring the H matrix describing the optical connection between each pixel and each LED TX, allows the received signals to be separated as described in section II.

At the receiver, each pixel fulfills direct detection (DD) to produce an electrical current signal proportional to the received intensity signal. Denoting the channel impulse response between the i -th TX array and the j -th pixel as $h_{ji}(t)$, thus the received signal of the j -th pixel can be written as

$$r_j(t) = \sum_{i=1}^{N_i} h_{ji}(t) \otimes x_i(t) + n_j(t) \quad (4)$$

where $n_j(t)$ is the additive noise to the high-intensity shot noise generated by the ambient illumination which can be modeled as an additive white Gaussian noise with zero mean and σ_n^2

variance. Here, the input SNR of the given modulation scheme is $\gamma_s = E_s/N_0$. The channel impulse response can be written as

$$h_{ji} = \begin{cases} \sum_{k=1}^K \frac{A'_{rx}}{d'^2_{ik}} R_0(\phi'_{ik}) \cos(\psi'_{ik}), & 0 \leq \psi'_{ik} \leq \psi'_c \\ 0 & \psi'_{ik} > \psi'_c \end{cases} \quad (5)$$

where A'_{rx} is the imaging receiver collection area, d'_{ik} is the distance between the k -th LEDs in transmitter i and the center of the receiver collection lens, ϕ'_{ik} is the emission angle, ψ'_{ik} is the angle of incidence of the light at the receiver, and ψ'_c is the receiver field of view (FOV). Here, the SNR of i -th LED at the j -th pixel of the given modulation scheme is $\gamma_{j,k}$. Thus the channel capacity of the MIMO system can be calculated as [3],

$$C = \omega_s \log_2 \left(1 + \sum_{r=1}^j \gamma_{j,k} \right) \quad (6)$$

$$\text{where, } \gamma_{j,k} = \frac{\sum (h_{ji} x_i)^2}{\sum n_i^2}$$

The receive vector function can be written as follows,

$$x = [x_1 \ x_2 \ \dots \ x_{N_T}]^T$$

$$n = [n_1 \ n_2 \ \dots \ n_{N_R}]^T$$

$$H = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1N_T} \\ h_{21} & h_{22} & \dots & h_{2N_T} \\ \vdots & \vdots & h_{ij} & \vdots \\ h_{N_R1} & h_{N_R2} & \dots & h_{N_RN_T} \end{bmatrix} \quad (7)$$

$$(8)$$

Here, the superscript T indicates a transpose. Also, h_{ij} , which is an element of the i -th row and the j -th column in the matrix H , denotes a channel from the j -th TX LED to the i -th RX pixel.

As will be stated next, the measured MIMO channels have mutual coupling effects. When mutual coupling matrices in the TX and RX arrays are defined C_{TX} and C_{RX} , respectively, the measured channel matrix H is expressed as

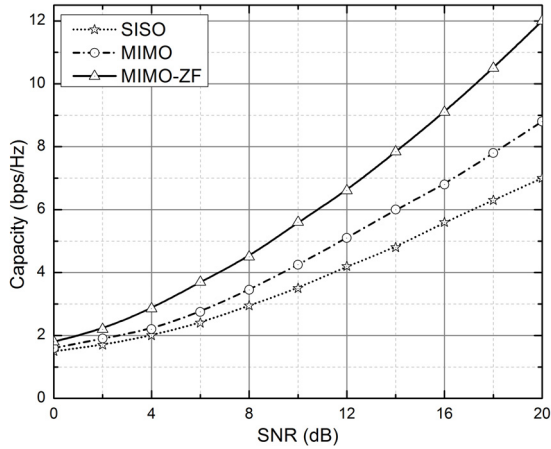


Fig. 2. System capacity performance along with SNR for different scenarios.

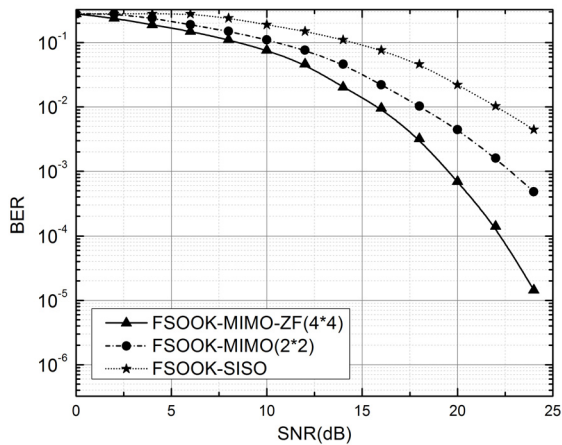


Fig. 3. BER vs. SNR performance comparison for different system scenarios.

$H = C_{RX} \bar{H} C_{TX}^T$, where \bar{H} is an $N_r \times N_t$ real channel matrix which does not include mutual coupling effects. At the decision-point SNR of the k -th signal stream is obtained as

$$\gamma_{j,k} = \gamma_s / [(H^T H)^{-1}] \approx \gamma_s g_{j,k}^2 \quad (9)$$

where $g_{j,k}^2 \approx 1 / [(H^T H)^{-1}]$ denotes the optical power gain. The average bit error rate (BER) of the above receivers can be evaluated as

$$\bar{P}(\gamma_s; g_k^2) = \frac{1}{N_t} \sum_{k=1}^{N_t} Q(\sqrt{2\gamma_s g_k^2}) \quad (10)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-y^2/2} dy$; and g_k^2 will

depend on the imaging reception plane.

Table 1. Simulation parameters

Parameter	Value
Number of LED arrays	2 and 4
Number of LEDs per array	3600 (60x60)
Distance between TX and RX	1 m
Average transmitted power per LED	10/1 mW
RX's optical resolution	640x480
RX's diagonal FOV	68 (degree)
Focal length	2.3 mm
Frame rate at camera	30 fps
Transmission coefficient of filter	1.0
Modulation scheme	FSOOK

IV. Performance Analysis and Discussions

The performance of spatial multiplexing of MIMO based VLC system has been evaluated by representing the capacity and BER analysis. The simulation parameters are shown in table 1. Fig. 2 depicts the average capacity performance along with the SNR. As explained before, the overall data rate is increased due to the spatial separation of LEDs lightwave signal in image sensor. This figure illustrates that the capacity of (4×4) MIMO-ZF system is increased more rapidly rather than the SISO and (2×2) MIMO system. The capacity of the proposed system has been enhanced by increasing the number of parallel optical channel provided by the multi-array LED in TX and active pixels in RX.

Fig. 3 shows the BER versus SNR performance with three different scenarios. Usually, VLC system has very high SNR through the downlink channel using LEDs lighting, i.e., IM/DD system. As shown in the figure, FSOOK-MIMO (2×2) system has the better BER performance than the SISO system as MIMO system improves the overall channel gain. The channel gain is raised with the number of multiple LEDs transmitters. It is also shown that BER performance is improved while the receiver is

deployed ZF detection system for (4×4) MIMO system. Thus, it could be implied that MIMO spatial multiplexing system with FSOOK modulation has an enormous profile towards the improvement of average data rate with less bit error performance.

V. Conclusion

In this paper, we present a performance analysis of MIMO spatial multiplexing of image sensor based VLC system. Here, spatial multiplexing of MIMO operation is deployed for improving the throughput performance. Although, the parallel optical channels and proximity of pixels (i.e. receivers) may cause bit error, but the error rate is reduced by using ZF equalizer. Thus, MIMO operation with spatial multiplexing is enhanced the performance and in future image sensor based multiple access operation will deploy vastly in VLC system.

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Ratan Kumar Mondal



He received his B.Sc. in Electrical and Electronic Engineering from Khulna University of Engineering Technology (KUET), Bangladesh in 2011. Currently he is working towards his M.Sc. degree in the department of Electronics Engineering at Kookmin University, Korea. His research interests include visible light communication, localization, and MIMO.

Nirzhar Saha



He received his B.Sc. in Electrical and Electronic Engineering from Khulna University of Engineering and Technology, Bangladesh in 2011. Currently he is working towards his M.Sc. degree in the department of Electronics Engineering at Kookmin University, Korea. His research interests include visible light communication networks, QoS management, cognitive radio networks.

Yeong Min Jang



He received the B.E. and M.E. degree in Electronics Engineering from Kyungpook National University, Korea, in 1985 and 1987, respectively. He received the doctoral degree in Computer Science from the University of Massachusetts, USA, in 1999. He worked for ETRI between 1987 and 2000. Since September 2002, he is with the School of Electrical Engineering, Kookmin University, Seoul, Korea. His research interests include B4G, radio resource management, femtocell networks, Multi-screen convergence services, and WPANs.