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On indoor visible light communication systems with spatially random receiver

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ABSTRACT

This paper studies the performance of an indoor optical wireless communication system with visible light communication (VLC) technology in a cuboid room with a spatially random receiver. Considering that the receiver is uniformly distributed on the floor of a $4a$ m $\times$ $4b$ m $\times$ H m (where $a > 0$, $b > 0$ and $H > 0$) cuboid room, 4 light emitting diode (LED) lamps are all located at the center of $2a$ m $\times$ $2b$ m rectangle, which is a quarter of the ceiling area. The receiver chooses the best channel link to receive the information from the LED lamps, which depends on the distance between the receiver and each lamp. By using stochastic geometry theory, we derive the exact/approximated analytical expressions for the outage probability and the ergodic capacity, respectively. Finally, our derived analytical results are verified by Monte Carlo simulations.

1. Introduction

As an age-long technology that can entail the transmission of information-laden optical radiation through the free-space channel [1], optical wireless communications have attracted plenty of attentions of the researchers from both academia and industry due to the features such as good security, free licensed frequency band, immunity to induced electromagnetic interference (EMI), and so on. Among various kinds of optical wireless communication systems, we have seen a growing research in visible light communications (VLC), the idea of which is using light emitting diodes (LEDs) for both illumination and data communications.

LEDs have been demonstrated to have ability to provide a high data rate with considerable energy consumption [2,3] and to achieve considerable coverage space via the help of relays [4]. Certainly, it is true that VLC has an advantage to transmit radio frequency (RF) signal with less background noise, non-interference, free of health concern and higher security [5–7]. Moreover, some of previous literatures, such as, [8,9] laid foundations for LED lighting communication systems and contributed to the knowledge base that would provide high data rate and slow growing communication needs, while bringing light to the people or be a decoration.

It is worthwhile to note that one of the features of VLC is the 380 nm–780 nm optical spectrum VLC occupied [10]. Although the frequency band is unlicensed, an appropriate choice for VLC system is given to the indoor VLC due to the fact that the bandwidth is a short-range with limited operating voltage range and coverage. That is to say that, indoor VLCs have an ability to propagate information to the whole room coverage with multiple distributed light emitting diodes, while the LEDs illuminate the room [11]. Furthermore, this is certainly true in the indoor optical wireless system that the channel is typically deterministic.

In addition, intensity modulation (IM)/direct detection (DD) is adopted in indoor VLC systems, which is the most practical modulation technique for indoor scenarios. The receiver would generate electrical signal according to the fluctuations in the intensity carrying the information [12]. Interesting enough, the system also has an ability to obtain a more accurate position information with photo-detector (PD), which could generate photocurrent by the received optical power [13]. Acquiring an accurate indoor localization became more and more possible by the received signal power, as the power of the received optical signal or the received signal is greatly affected by the transmission distance and angles [13–16].

In addition to position research, many studies on other important indoor systems have been presented. [17] investigated the influence of interference and reflection in VLC indoor system. [18] investigated non-direct line-of-sight (LOS) indoor VLC system performance, which applied repetition code and spatial multiplexing. [19] proposed a new realistic indoor VLC channel model and applied it to multiple-input multiple-output (MIMO) communication system, which uses non-sequential ray tracing approach for the channel impulse responses. [20]

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illustrated an indoor VLC system with MIMO orthogonal frequency division multiplexing and receiver angular diversity module. [21] proposed centralized or decentralized transmitted power allocation algorithms for multiple input multiple output system considering multiple LEDs and photodetectors. [22] characterized the performance of MIMO systems considering spatial modulation and spatial multiplexing with both imaging and non-imaging receivers. [23] concluded that mobile receivers with adaptive modulation and per antenna rate coding gain higher system capacity compared to the fixed and vertically oriented receivers. [24] demonstrated the superior performance of non-orthogonal multiple access indoor channel. The secrecy outage performance of the VLC downlink was studied in [25], while considering the randomness of the positions of both the legitimate receiver and a group of eavesdroppers. In [26], the secrecy outage performance of the RF uplink was investigated in a VLC-RF hybrid system with light energy harvesting, while considering the randomness of the locations of the legitimate terminal and the eavesdropper. A 3-dimensional indoor VLC-RF model with light energy harvesting was proposed and analyzed in [27], while independent and correlated Rician fading channels are considered for the RF uplinks.

1.1. Motivation and contributions

The aforementioned researches [18–20,24] only investigated the cases of fixed room sizes (5 m × 5 m × 3 m) or fixed receiver positions, which result in the fixed distances between the transmitters and the receivers. However, in practice, the viewpoint that the transmission distance and angle largely determine the received power within a same indoor environment is strongly believed. In a more realistic case, a small vary in position will result in a large variation of the received signal, thus we should take the spatial distribution of the receiver and the uncertainty of the room size into consideration. Though [28] considered the random location of the person in the environment and body movements, and [29] took a W m × L m × H m room into account, they have not derived the closed-form expressions for outage probability (OP).

Motivated by the above observations, in this paper we analyze the performance of an indoor optical wireless communication system with VLC and a randomly distributed receiver by making use of stochastic geometry theory [30]. To investigate the impact of the receiver location, we suppose the receiver is uniformly distributed on the floor of the room with a general size $2a$ m × $2b$ m × H m (where $a > 0$, $b > 0$ and $H > 0$). In other words, the possibility of falling at each point on the ground in the considered room is the same. It is also important to note here that which point in the room is unknown. For indoor wireless communication structure, considering 4 LED lamps are respectively located at the center of $2a$ m × $2b$ m (where $a > 0$ and $b > 0$) rectangle which is a quarter of the ceiling area $4a$ m × $4b$ m, with the room height, H m ($H > 0$). A key concept here is that the receiver only chooses the best channel link among the 4 LEDs to receive the information with the aim of improving channel gain and energy utilization. Main contributions of this work are summarized as follows:

(1) We characterize the probability density function (PDF) and cumulative distribution function (CDF) of the signal-to-noise-ratio (SNR) over the VLC channel with two particularities. First, we consider the location of the receiver randomly distributed in the room; Second, the room size is not fixed which is more practical for real scenarios.

(2) We study the outage performance of the targeted VLC system and derive the exact closed-form expression for OP.

(3) We demonstrate the approximated ergodic capacity for excellent and bad channel environments, which has not been well investigated in the previous works.

In this paper, due to the complexity invoked by the randomness of the terminal's position, VLC channel fading and unfixed room size, we employ stochastic geometry and Meijer G-functions to achieve performance analysis models.

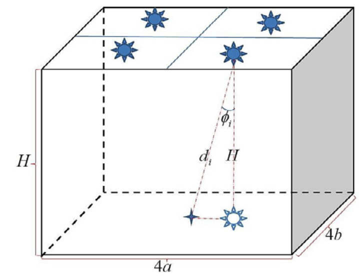

Fig. 1. System model.

1.2. Organization

The remainder of the paper is organized as follows: The considered indoor VLC system model is given in Section 2. The exact analytical expression for outage probability (OP) is derived in Section 3. The approximate analytical expression for ergodic capacity is presented in Section 4. Numerical results are given in Section 5. Finally, the conclusion will be given in Section 6.

2. System model

As shown in Fig. 1, an indoor optical wireless communication system with VLC technology is considered here, which consists of four LED lamps placed in the center of each 1/4 rectangle on the ceiling of the room. All LEDs attempt to deliver information to a receiver equipped with photodiode, which is uniformly distributed on the floor of a $4a$ m × $4b$ m × H m room (where $a > 0$, $b > 0$ and $H > 0$). In order to improve the channel gains and energy consumption, we also assume that the receiver would like to receive the strongest information signal emitted by the optimal VLC transmitter among the four LED lamps.[1]

To motivate our discussion about the performance of the system, it is useful to clarify some channel parameters. Due to the fact that the system adopts IM and DD, assuming PD's active area is A, the distance between the ith, ($i \in \{1, 2, 3, 4\}$) LED lamp and the receiver is d_i, the concentrator field of view is Ψ_c, the gain of the non-imaging concentrator and optical filter adopted at the receiver denoted as $g(\psi_i)$ and $T_s(\psi_i)$ respectively, which are related to the angle of incidence with respect to the receiver axis ψ_i and defined by Eq. (8) in [31]. ϕ_i is the LED irradiation angle, while $\phi_{i,1/2}$ is the semi-angle of the LED at half power which determines the light beam Lambertian order m_i, denoted as

$$m_i = \frac{-\ln 2}{\ln\left(\cos\left(\phi_{i,1/2}\right)\right)}. \tag{1}$$

Thus, the channel gain between the ith LED lamp and the receiver, h_i, ($i \in \{1, 2, 3, 4\}$), can be defined as

$$h_i = \begin{cases} \frac{(m_i+1)A}{2\pi d_i^2}\cos^{m_i}\phi_i T_s(\psi_i)\, g(\psi_i)\cos\psi_i, & 0 \le \psi_i \le \Psi_c \\ 0, & \psi_i > \Psi_c. \end{cases} \tag{2}$$

We can obtain the expression for the received optical power P_{Ri} at the receiver, which was transmitted by the ith LED with the same transmit power, P_t, as

$$P_{Ri} = P_t \frac{(m_i+1)A}{2\pi {d_i}^2}\cos^{m_i}\phi_i T_s(\psi_i)\, g(\psi_i)\cos(\psi_i). \tag{3}$$

[1] In the considered system, each lamp adopts an unique random sequence to encode the information bits, and the four random sequences are orthogonal with each other, which are available at the terminal. Then, after PD, the terminal can respectively decode the four signals from the four lamps by using the random sequences, and compare the SNR of them. In this way, the terminal can find out the signal with the maximum SNR and choose it for information decoding.