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Rate optimization for relaying VLC system with simultaneous lightwave information and power transfer

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Abstract: In this paper, the rate optimization problem in a relaying visible light communication system with simultaneous lightwave information and power transfer (SLIPT) is investigated, where the power splitting (PS) transmission strategy is adopted. The expressions of the transmission rate and energy harvesting at the target node are derived, based on which, the rate maximization problem is formulated. Then, this problem is solved by optimizing the PS factor, and a closed-form solution is given. Numerical results reveal that the existence of the relay node improves the system performance.

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1. Introduction

With the emergence of the Internet-of-Things (IoT), the demand for transferring the power and enabling IoT devices to harvest energy using light or radio frequency (RF) transmission is increasing, especially in indoor applications [1]. The number of Internet-connected mobile devices is rapidly increasing, and most of the data consumption occurs indoors [2]. On this basis, optical wireless communication (OWC), especially visible light communication (VLC), is considered as a promising complementary technology for RF to provide access to IoT devices for indoor applications [3,4]. Compared with wireless fidelity (WiFi), the advantages of OWC technologies include: increased available bandwidth, easy bandwidth reuse, high energy efficiency, considerable energy savings, no RF radiation, and free from RF interference [3].

Due to the following two characteristics of VLC system, some radio communication technologies are not suitable for VLC system. First, since the information is modulated as the instantaneous optical intensity, the transmitted signals must be real and non-negative. Second, the average optical intensity should be limited for the sake of eye safety [5]. Based on the characteristics, the modulation methods and the access methods suitable for VLC system have been extensively studied. A novel hybrid system combining asymmetrically clipped optical orthogonal frequency division multiplexing (ACO-OFDM) with on-off keying (OOK) modulation scheme was proposed in [6], which can reach high spectral efficiency. In order to realize the multi-user indoor VLC system based on hybrid full-duplex, a network model with lighting/communication terminal and the corresponding multi-access scheme are proposed in [7].

In recent years, light energy harvesting and communication rate have been investigated for VLC system with different system configurations and constraints. A framework for the simultaneous lightwave information and power transfer (SLIPT) was first proposed in [3], and the different transmission strategies were proposed in order to balance the trade-off between harvested energy and quality of service (QoS). In addition, the performance of the SLIPT system for serving multiple users in multiple cells is investigated in [8] .

At the same time, the relaying systems have been extensively studied in vast literatures for their ability to improve system performance. Firstly, the relay path is able to extend the coverage of the VLC systems. In this case, a hybrid relaying VLC/RF system is proposed in [9]. Moreover,

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the investigation in [10] reveals that the relay node helps to achieve higher diversity gain over direct communications between the source node and the target node. Finally, the light from the LED sources is confined to a small area, which introduces a problem that the communication links may be blocked. The outage probability of the communication link can be decreased by adopting the relay node, so that the reliability of the system is improved. However, there are few researches on utilizing the relay node to cooperate the communication between the source and the target nodes in VLC systems.

In this paper, a relaying system has been proposed, which contains three nodes: the source node, the relay node, and the target node. Unlike most articles that adopt time-switching (TS) strategies, a power splitting (PS) transmission strategy is applied in this work considering SLIPT. Then, the problem of maximizing the transmission rate of the target node is formulated subject to the minimum harvested energy requirements and power constraints, so as to determine the PS factor of the system. Moreover, a closed-form solution of the optimization problem is further proposed through rigorous derivation.

The rest of the paper is organized as follows. In Section 2, the relaying VLC system with SLIPT is introduced, which is achieved by PS. The optimization problem for rate maximization is formulated and solved in Section 3. Section 4 presents the simulation results and discussions about the impact of each factor. Finally, the paper concludes in Section 5.

2. System model

A point-to-point indoor SLIPT VLC system is considered where a cooperative relay node helps data transmission between the source node and the target node. Half duplex transmission mode is adopted, and the transmission process is divided into two phases, i.e., Phase I and Phase II. In Phase I, the information is first modulated by the electrical modulator at the transmitter of the source node. Then, the signal is amplified via the power amplifier and a DC bias is added to the signal. After that, the LED turns the electrical signal into an optical signal and sends it to the receivers, including the relay and target nodes. In this process, the relay and the target nodes collect energy while receiving information. In Phase II, assuming that the energy used to receive and process the signal is negligible, the relay node uses all the collected energy to transmit the information received from the source node to the target node. In this work, the amplify-and-forward relay node is considered. During this phase, we focus on the transmission rate between the relay and the target nodes. The block diagram of the VLC SLIPT system with two-phase transmission is shown in Fig. 1.

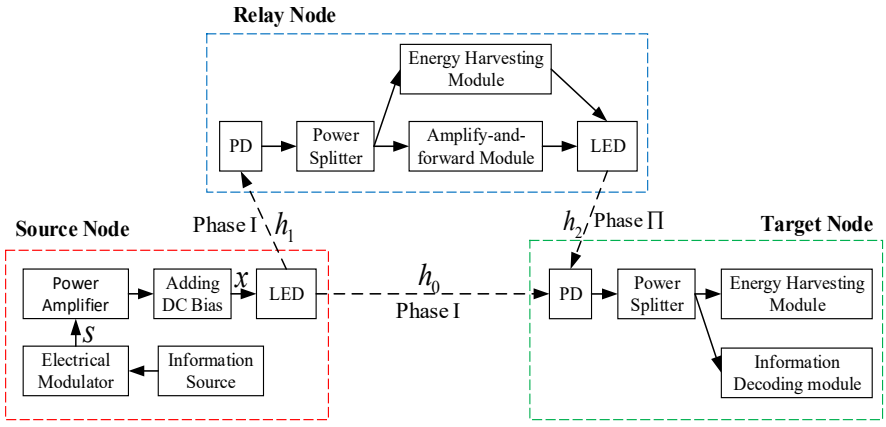


Fig. 1. Block diagram of the relaying VLC system with SLIPT.

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2.1. Transmitted signal at the source node

Let s represents the continuous data symbol obtained from the original data after modulation with $\mathbb{E}[s] = 0$. Its peak amplitude satisfies $-\varepsilon<s<\varepsilon$ and its variance can be given as $\mathbb{E}[s^2] = 1$, where ε is a real number and $\varepsilon>0$. After the power amplifier and added by a DC bias, the transmitted signal can be expressed as

$$x = \sqrt{p}s + b, \tag{1}$$

where p denotes the allocated electric power, and b denotes the DC offset. According to (1), the average electrical power P_e of the transmitted signal can be given as

$$P_e = \mathbb{E}[|x|^2] = \mathbb{E}[|\sqrt{p}s|^2 + b^2] = p + b^2. \tag{2}$$

To satisfy the nonnegative requirement, i.e., $x = \sqrt{p}s + b>0$, the value of p should be limited to

$$0 \le p \le \frac{b^2}{\varepsilon^2}. \tag{3}$$

In order to make the electrical signal input to the LED within the linear region of the LED operation, the value of p and b should be adjusted to keep the instantaneous input current within a certain range, i.e., $\sqrt{p}s + b \in [I_L, I_H]$, where I_L and I_H denote the minimum and the maximum input currents, respectively. Thus, the following limitation is induced

$$p \le \min\left(\frac{(I_H - b)^2}{\varepsilon^2}, \frac{(b - I_L)^2}{\varepsilon^2}\right). \tag{4}$$

2.2. Channel model

The geometric structure of the system are presented in Fig. 2. The optical channel between any two nodes is considered as a line-of-sight (LOS) link, since the gain of reflection links can be negligible. The channel gain can be given as [11]

$$H(\varphi, \psi, d) = \begin{cases} \frac{\eta(m+1)A}{2\pi d^2}\cos^m(\varphi)g(\psi)\cos(\psi), & \psi<\psi_{\mathrm{FOV}}, \\ 0, & \text{otherwise}, \end{cases} \tag{5}$$

where η is the photo-detector (PD) responsivity in A/W. d is the distance from the LED to the PD of the corresponding node, φ is the irradiance angle, ψ is the incidence angle, $g(\psi)$ is the gain of the optical filter, ψ_{FOV} denotes the half of PD's field-of-view (FOV), and $m = -1/\log_2(\cos(\phi_{1/2}))$ is the order of Lambertian emission, where $\phi_{1/2}$ is the semi-angle at half power. $A = \rho^2 A_{\mathrm{PD}}/\sin^2(\psi_{\mathrm{FOV}})$, where A_{PD} denotes the PD's detector area, ρ is the refractive index.

We assume that the PD of the relay node has the same parameters as the PD of the target node, including η, A_{PD}, and ρ. Therefore, let h_0 denote the channel gain between the source node and the target node, which can be given as

$$h_0 = H(\varphi_0, \psi_0, d_0), \tag{6}$$

where d_0, φ_0, and ψ_0 denote the distance, the irradiance angle, and the incidence angle from the source node to the target node, respectively.

Similar to above, the channel gains between the source node and the relay node, the relay node and the target node can be respectively given as

$$h_1 = H(\varphi_1, \psi_1, d_1), \tag{7}$$

$$h_2 = H(\varphi_2, \psi_2, d_2), \tag{8}$$

respectively, where d_1, φ_1, and ψ_1 denote the distance, the irradiance angle, and the incidence angle from the source node to the relay node, respectively. d_2, φ_2, and ψ_2 denote the distance, the irradiance angle, and the incidence angle from the relay node to the target node, respectively.

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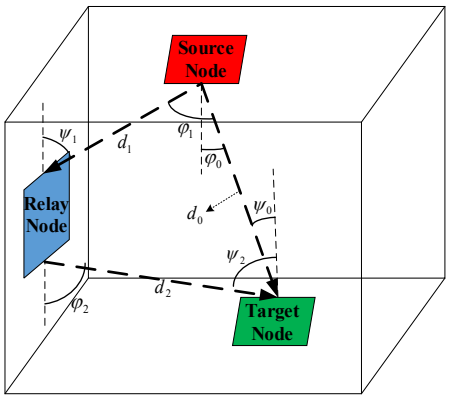


Fig. 2. Geometric structure of the indoor relaying VLC system with SLIPT.

According to the above analysis, after Phase I, the signal received by the target node can be given as $y_0 = h_0 x + n_0$, where $n_0 \sim \mathcal{N}(0, \sigma_0^2)$ denotes the additive white Gaussian noise (AWGN). Similarly, the signal received by the relay node can be given as $y_1 = h_1 x + n_1$, where $n_1 \sim \mathcal{N}(0, \sigma_1^2)$ denotes the AWGN at the relay node.

Let E_r, T_1, and T_2 denote the energy collected by the relay node during Phase I, the duration of Phase I, and Phase II, respectively. So the transmitted signal from the relay node to the target node can be given as $x_r = \sqrt{E_r/(T_2 \mathbb{E}[y_I])} y_I$, where y_I denotes the part of the signal received by the relay node, which is used for information decoding and $\mathbb{E}[y_I]$ is the average power of y_I. After Phase II, the signal received by the target node can be expressed as $y_2 = h_2 x_r + n_2$, where $n_2 \sim \mathcal{N}(0, \sigma_2^2)$ denotes the AWGN at the target node.

2.3. Transmission strategy for SLIPT

In order to transmit energy and signal simultaneously in the proposed system, the PS transmission strategy is considered. According to the PS policy, the received signal is divided into two parts, one of which is used for energy harvesting and the other is applied for information decoding. Here, the parameters α_1 and α_2 are introduced, which denote the PS factors at the target node and the relay node, respectively. In Phase I, for the target node, the part of energy harvesting is $y_{t,E} = \sqrt{\alpha_1} y_0$, and the part of information decoding is $y_{t,I} = \sqrt{1-\alpha_1} y_0 + n_{t,1}$, where $n_{t,1}$ denotes the thermal noise, which is zero-mean AWGN with a variance of $\sigma_{t,1}^2$. Thus, the signal-to-noise ratio (SNR) received by the target node can be given as

$$\gamma_0 = \frac{(1-\alpha_1)(h_0 \varepsilon)^2 p}{(1-\alpha_1)\sigma_0^2 + \sigma_{t,1}^2}. \tag{9}$$

The harvested energy can be given as [12]

$$E_t = f I_{\mathrm{DC}}^t V_{oc} T_1, \tag{10}$$

where f is the fill factor, I_{DC}^t is the DC component of the received signal, which is given by $I_{\mathrm{DC}}^t = \sqrt{\alpha_1} h_0 b$, and V_{oc} is the open circuit voltage, which is given by

$$V_{oc} = V_t \ln\left(1 + \frac{I_{\mathrm{DC}}^t}{I_0}\right), \tag{11}$$

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where V_t is the thermal voltage and I_0 is the dark saturation current of the PD. So the energy harvested by the target node can be rewritten as

$$E_t = fI_{\mathrm{DC}}^t T_1 V_t \ln(1 + \frac{I_{\mathrm{DC}}^t}{I_0}). \tag{12}$$

Similarly, for the relay node, the part of energy harvesting is $y_{r,E} = \sqrt{\alpha_2} y_1$, and the part of forwarding is $y_{r,I} = \sqrt{1-\alpha_2} y_1 + n_{t,2}$, where $n_{t,2}$ denotes the thermal noise, which is zero-mean AWGN with a variance of $\sigma_{t,2}^2$. Similar to the deduction above, the SNR received by the relay node can be given as

$$\gamma_1 = \frac{(1-\alpha_2)(h_1\varepsilon)^2 p}{(1-\alpha_2)\sigma_1^2 + \sigma_{t,2}^2}. \tag{13}$$

To simplify subsequent analysis, we assume that $\sigma_{t,1}^2 = \sigma_{t,2}^2 = \sigma_t^2$. The energy harvested by the relay node is formulated as

$$E_r = fI_{\mathrm{DC}}^r T_1 V_t \ln(1 + \frac{I_{\mathrm{DC}}^r}{I_0}), \tag{14}$$

where $I_{\mathrm{DC}}^r = \sqrt{\alpha_2} h_1 b$. Assuming that the durations of two transmission phases are the same, i.e., $T_1 = T_2$, the transmission power of the relay node is $P_r = fI_{\mathrm{DC}}^r V_t \ln(1 + I_{\mathrm{DC}}^r / I_0)$. In Phase II, the relay node forwards $y_{r,I}$ to the target node with power budget P_r. The transmitted signal at the relay node can be given as

$$x_r = \sqrt{\frac{P_r}{(1-\alpha_2)[h_1^2(p\varepsilon^2 + b^2) + \sigma_1^2] + \sigma_t^2}}\, y_{r,I}. \tag{15}$$

After Phase II, the SNR at the target node can be given as

$$\gamma_2 = \frac{(1-\alpha_2)(h_1 h_2 Z\varepsilon)^2 p}{(h_2 Z)^2[(1-\alpha_2)\sigma_1^2 + \sigma_t^2] + \sigma_2^2}, \tag{16}$$

where $Z = \sqrt{P_r / ((1-\alpha_2)[h_1^2(p\varepsilon^2 + b^2) + \sigma_1^2] + \sigma_t^2)}$.

Applying maximum ratio combining (MRC) to y_0 and y_2 at the target node. For ease of analysis, we assume that the variance of noise from the source node to the target node is the same as that from the relay node to the target node, i.e., $\sigma_0^2 = \sigma_2^2$. Thus, the total SNR at the target node can be given as $\gamma = \gamma_0 + \gamma_2$ due to MRC [13].

Based on the above analysis, a lower bound of the achievable rate with normalized bandwidth at the target node can be given as [14]

$$R = \frac{1}{2} \log_2(1 + \frac{e}{2\pi}\gamma), \tag{17}$$

where e is the natural constant.

3. Problem formulation and solution

The SLIPT induces a trade-off between the rate and harvested energy. We should not only consider the energy and data rate collected by the target node, but also consider the performance of the relay node. In this work, our goal is to maximize the the rate of the target node, subject to the minimum harvested energy requirements and power constraints. The aforementioned trade-off can be balanced by solving the optimization problems for the proposed system. The corresponding optimization problems are formulated and optimally solved in the this section.

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For the convenience of subsequent analysis, assuming that σ_0^2 and σ_2^2 are negligible compared to σ_1^2 and σ_t^2. In addition, we set $K_1 = (h_0\varepsilon)^2/\sigma_t^2$ and $K_2 = fT_1V_t$. Mathematically, the rate optimization problems for PS can be formulated as

$$\max_{\alpha_1,\alpha_2,p} \ \frac{1}{2}\log\{1+\frac{e}{2\pi}[K_1(1-\alpha_1)p+\frac{(h_1\varepsilon)^2p}{\sigma_1^2+\frac{\sigma_t^2}{1-\alpha_2}}]\} \tag{18a}$$

$$s.t. \quad K_2 I_{\mathrm{DC}}^t \ln(1+\frac{I_{\mathrm{DC}}^t}{I_0}) \geq E_{th,1}, \tag{18b}$$

$$K_2 I_{\mathrm{DC}}^r \ln(1+\frac{I_{\mathrm{DC}}^r}{I_0}) \geq E_{th,2}, \tag{18c}$$

$$\frac{(h_1\varepsilon)^2p}{\sigma_1^2+\frac{\sigma_t^2}{1-\alpha_2}} \geq \gamma_{th}, \tag{18d}$$

$$0 \leq p \leq \frac{b^2}{\varepsilon^2}, \tag{18e}$$

$$p \leq \min(\frac{(I_H-b)^2}{\varepsilon^2}, \frac{(b-I_L)^2}{\varepsilon^2}), \tag{18f}$$

$$I_L \leq b \leq I_H, \tag{18g}$$

$$0 \leq \alpha_1, \alpha_2 \leq 1, \tag{18h}$$

where $E_{th,1}$ denotes the harvested energy threshold of the target node, and a harvested energy threshold $E_{th,2}$ and a SNR threshold γ_{th} were set for the relay node.

From 18a and 18d, it can be obviously seen that both R_1 and γ_1 are increasing with respect to p, hence the maximum value of p should be found while satisfying the constrains. According to 18f and 18g, for maximizing p, the value of the DC bias b should be $b = (I_H + I_L)/2$. Therefore, these two constraints 18f and 18g can be combined into one as:

$$p \leq \frac{(I_H-I_L)^2}{4\varepsilon^2}. \tag{19}$$

And then via the constraint in 18e, p should satisfy the inequality as

$$p \leq \frac{(I_H+I_L)^2}{4\varepsilon^2}. \tag{20}$$

From the physical meaning of $I_L \geq 0$, we have $(I_H + I_L)^2/(4\varepsilon^2) \geq (I_H - I_L)^2/(4\varepsilon^2)$. As a result, the optimal value of p can be given as

$$p^* = \frac{(I_H-I_L)^2}{4\varepsilon^2}, \tag{21}$$

where $(\cdot)^*$ denotes optimality.

From 18a, it can be seen that R_1 is decreasing with respect to both α_1 and α_2, so the minimum value of α_1 and α_2 should be found while satisfying the constrains. According to 18d, α_2 should satisfy the limitation as

$$\alpha_2 \leq 1 - \frac{\sigma_t^2\gamma_{th}}{(h_1\varepsilon)^2p^* - \sigma_1^2\gamma_{th}}. \tag{22}$$

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Considering the constrains (18b) and (18c), we construct a function $f(x) = x\ln(1+ax)$, $(a>0, x>0)$. The first derivative of $f(x)$ can be given as

$$f'(x) = \ln(1+ax) + \frac{ax}{1+ax}. \tag{23}$$

Because of the condition $a>0, x>0$, we have $f'(x)>0$. Therefore, $f(x)$ is increasing with respect to x. Then, due to the previous analysis that $I^t_{\mathrm{DC}} = \sqrt{\alpha_1}h_0 b, I^r_{\mathrm{DC}} = \sqrt{\alpha_2}h_1 b$, for minimizing α_1 and α_2, the inequalities in (18b) and (18c) should take the equal sign. Thus, two transcendental equations can be derived as

$$K_2 I^t_{\mathrm{DC}} \ln(1 + \frac{I^t_{\mathrm{DC}}}{I_0}) = E_{th,1}, \tag{24a}$$

$$K_2 I^r_{\mathrm{DC}} \ln(1 + \frac{I^r_{\mathrm{DC}}}{I_0}) = E_{th,2}, \tag{24b}$$

which can be solved easily by the toolbox of MATLAB. Let x_1 and x_2 be the solutions of 24a and 24b, respectively, so that the optimal value of α_1 and α_2 can be given as

$$\alpha_1^* = \frac{4x_1^2}{h_0^2(I_H+I_L)^2}, \quad \alpha_2^* = \frac{4x_2^2}{h_1^2(I_H+I_L)^2}. \tag{25}$$

Note that if $\alpha_1^*>1$ or $\alpha_2^*>1$, the optimization problem in (18) is infeasible, due to 18h. Moreover, if $\alpha_2 * > 1 - \sigma_t^2\gamma_{th}/((h_1\varepsilon)^2 p^* - \sigma_1^2\gamma_{th})$, the optimization problem in (18) is also infeasible, due to the contradiction between 18c and 18d.

4. Simulation result and discussion

This section presents an appropriate set of figures to illustrate the key factors affecting the performance of the proposed architecture. We assume the transmitter plane is parallel to the receiver one in the downlink SLIPT system, i.e., $\varphi_0 = \psi_0, \varphi_1 = \psi_1, \varphi_2 = \psi_2$. Unless stated otherwise, the simulation parameters are given in Table 1.

Table 1. Simulation parameters

Parameter	Value	Parameter	Value
ψ_0	0	I_L	0 mA
ψ_1, ψ_2	30°	I_H	12 mA
f	0.75	ρ	1.5
$\varphi_{1/2}$	60°	γ_{th}	10 dB
A_{PD}	0.01 m^2	V_t	25 mV
σ_1^2	10^{-19}	ψ_{FOV}	60°
σ_t^2	10^{-18}	d_0	2.60 m
I_0	10^{-9} A	d_1, d_2	1.5 m

Figure 3 shows the target data rate versus the energy harvesting threshold $E_{th,1}$ for different values of the PD responsivity. In this case, the relay node harvested energy threshold is set to $E_{th,2} = 1$ mJ. According to the optimization problem, as the energy requirement increases, the rate gradually decreases because the PS factors become larger to allocate more amount of the signal to the energy harvesting. In addition, with the increase of the PD responsivity η, the downward trend of the curves with relay becomes slower. For example, when $\eta = 0.2$, the value of R goes down from 11.1 to 10.9, and the value of R decrease from 12.99 to 12.93 when $\eta = 0.4$. Because $I^r_{\mathrm{DC}} = \sqrt{\alpha_2}h_1 b$ and $h_1 \propto \eta$, where $\propto$ is the symbol for being proportional to, the

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relationship between α_2 and η can be formulated as $\alpha_2 \propto 1/\eta^2$. Therefore, with the increase of η, α_2 decreases, which means that the part of information transmitted from the relay node to the target node increases, so that the influence of α_1 on the value of R is impaired. In order to verify the role of the relay node in the system, the curves of R changing with $E_{th,1}$ in the absence of the relay node are also plotted in Fig. 3 as a comparison. It is observed that there still a large value at the end of each curve with the relay node compared to those without the relay node. This is because the communication channel between the relay and the target nodes can provide a significant data rate when the target node sacrifices rate performance to harvest more energy. In addition, it can be found that the curve with the relay node is always higher than that without the relay node, which means the relay node increases the communication rate of the system. Therefore, it can be concluded that the communication rate of the system can be increased by using a relay node when the energy requirements are low.

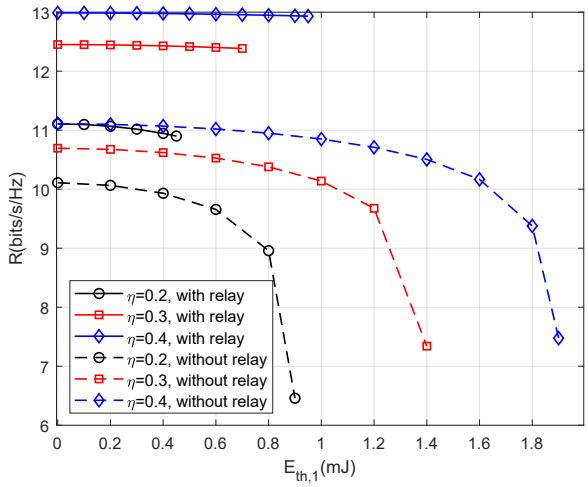


Fig. 3. The rate versus the energy threshold of the target node, when $E_{th,2}$=1 mJ.

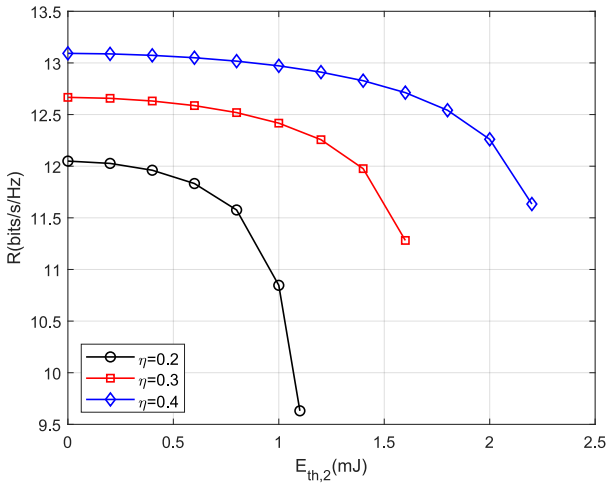


Fig. 4. The rate versus the energy threshold of the relay node, when $E_{th,1}$=0.45 mJ.

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Figure 4 presents the impact of the harvested energy at the relay node on the rate of target node when $E_{th,1} = 0.45$ mJ. It is generally observed that, as the PD responsivity increases, the solution space of the optimization problem also increases, which means that the system can harvest more energy and achieve a higher data rate. It can also be seen that, regardless of the value of η, the downward trend of the curve is obvious. This can be explained by the fact that the relay node is closer to the source node than the target node, hence the power splitting factor α_2 plays a greater role in the variation of data rate compared with α_1.

5. Conclusion

This paper presents the proposed relaying VLC system with SLIPT based on the PS transmission strategy. Due to the existence of the relay node, the expressions of the transmission rate and harvested energy are different from the system without the relay node. These expressions are derived and the rate optimization problem is established, subject to the minimum harvested energy requirements and power constraints. We further solve this problem and derive the closed-form solutions. Simulations validate that the communication rate of the system can be increased by using a relay node. The proposed framework with a relay node can serve as a promising candidate for the VLC including IoT devices in the future communication systems.

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References

1. M. Obeed, H. Dahrouj, A. M. Salhab, S. A. Zummo, and M.-S. Alouini, "DC-bias and power allocation in cooperative VLC networks for joint information and energy transfer," IEEE Trans. Wireless Commun. **18**(12), 5486–5499 (2019).
2. M. Ayyash, H. Elgala, A. Khreishah, V. Jungnickel, T. Little, S. Shao, M. Rahaim, D. Schulz, J. Hilt, and R. Freund, "Coexistence of WiFi and LiFi toward 5G: concepts, opportunities, and challenges," IEEE Commun. Mag. **54**(2), 64–71 (2016).
3. P. D. Diamantoulakis, G. K. Karagiannidis, and Z. Ding, "Simultaneous lightwave information and power transfer (SLIPT)," IEEE Trans. Green Commun. **2**(3), 764–773 (2018).
4. T. Wang, F. Yang, J. Song, and Z. Han, "Dimming techniques of visible light communications for human-centric illumination networks: State-of-the-art, challenges, and trends," IEEE Wireless Commun. **27**(4), 88–95 (2020).
5. Y. Li, N. Huang, J. Wang, Z. Yang, and W. Xu, "Sum rate maximization for VLC systems with simultaneous wireless information and power transfer," IEEE Photonics Technol. Lett. **29**(6), 531–534 (2017).
6. F. Yang, J. Gao, and S. Liu, "Novel visible light communication approach based on hybrid OOK and ACO-OFDM," IEEE Photonics Technol. Lett. **28**(14), 1585–1588 (2016).
7. T. Shang, T. Jiang, Y. T. Yang, P. Wang, and Y. Liu, "Multi-users network model and the corresponding networking scheme for indoor VLC systems," Opt. Express **23**(9), 11600–11618 (2015).
8. A. M. Abdelhady, O. Amin, B. Shihada, and M. Alouini, "On the optimization of multi-cell SLIPT systems," in *2018 IEEE Global Communications Conference (GLOBECOM)*, (2018), pp. 1–6.
9. T. Rakia, H. Yang, F. Gebali, and M. Alouini, "Optimal design of dual-hop VLC/RF communication system with energy harvesting," IEEE Commun. Lett. **20**(10), 1979–1982 (2016).
10. H. Lee, C. Song, S. Choi, and I. Lee, "Outage probability analysis and power splitter designs for SWIPT relaying systems with direct link," IEEE Commun. Lett. **21**(3), 648–651 (2017).
11. T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," IEEE Trans. Consum. Electron. **50**(1), 100–107 (2004).
12. C. Li, W. Jia, Q. Tao, and M. Sun, "Solar cell phone charger performance in indoor environment," in *2011 IEEE 37th Annual Northeast Bioengineering Conference (NEBEC)*, (2011), pp. 1–2.
13. H. T. Hui, "The performance of the maximum ratio combining method in correlated rician-fading channels for antenna-diversity signal combining," IEEE Trans. Antennas Propag. **53**(7), 2357 (2005).
14. J. B. Wang, Q. S. Hu, J. Wang, M. Chen, and J. Y. Wang, "Tight bounds on channel capacity for dimmable visible light communications," J. Lightwave Technol. **31**(23), 3771–3779 (2013).