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Energy-efficient power allocation for cross-media communications with hybrid VLC/RF

Yufeng HAN[1], Yue XIAO[1*], Yulan GAO[1], Mingming WU[1], Gang WU[1*] & Wei XIANG[2]

[1]*National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China, Chengdu* 611731*, China;*
[2]*School of Engineering and Mathematical Sciences, La Trobe University, Melbourne* 3086*, Australia*

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Dear editor,

In the sixth generation (6G), considerable research has been devoted to millimeter wave (mmWave) and terahertz with the objective of addressing the expected spectrum scarcity and massive connectivity. Moreover, various transmission media, such as visible light, have been explored to enhance the data rate and adapt diverse scenarios [1].

Recently, visible light communication (VLC) is poised to be a promising technology for supplementing traditional radio frequency (RF) communications and enabling new devices to enhance data services [2]. Consequently, combining VLC and RF has the potential to capitalize on their joint advantages [3]. In the spirit of these studies, a vast corpus of literature focused on the optimization of hybrid VLC/RF networks [4–6]. Therefore, for constituting a fully-connected network, we propose a hybrid VLC/RF cross-media communication system, where two terminals operating on visible light and microwave exchange information through a cross-media relay, as developed in [7].

Problem formulation. Consider a cross-media relay system in the hybrid VLC/RF network, where the VLC and RF terminals are denoted by A and B, respectively. There is no direct path between A and B, so the information exchange is only possible via the cross-media relay, R. This transmission scheme consists of two phases over two time slots, which take place simultaneously for consecutive data blocks. In the first phase, A and B transmit their signals to R. In the second phase, R decodes the signal received from one terminal and forwards it to the other terminal. We then study the transmit power allocation problem with the objective of maximizing the energy efficiency (EE) of the hybrid network under the following constraints.

(1) Considering quality-of-service (QoS) requirements of all terminals, we have the following rate constraints while balancing the rates of the forward and backward links, as

$$C_{ar} \leqslant C_{rb}, \tag{1}$$

$$C_{br} \leqslant C_{ra}, \tag{2}$$

where the achievable rates of the A-R, R-B, B-R and R-A links are respectively expressed as $C_{ar} = \frac{1}{2}B_v\log_2(1+\frac{e}{2\pi}\frac{\rho^2 {p_a}^2\bar{h}_{ar}}{B_vN_0})$, $C_{rb} = \frac{1}{2}B_f\log_2(1+\frac{p_{rb}\,\bar{g}_{rb}}{B_fN_0})$, $C_{br} = \frac{1}{2}B_f\log_2(1+\frac{p_b\,\bar{g}_{br}}{B_fN_0})$, and $C_{ra} = \frac{1}{2}B_v\log_2(1+\frac{e}{2\pi}\frac{\rho^2 {p_{ra}}^2\bar{h}_{ra}}{B_vN_0})$.

(2) The transmit powers of the nodes are limited by

$$p_a \leqslant p_a^{\max}, \tag{3}$$

$$p_b \leqslant p_b^{\max}, \tag{4}$$

$$p_{ra} + p_{rb} \leqslant p_r^{\max}, \tag{5}$$

where $p_a^{\max}$, $p_b^{\max}$ and $p_r^{\max}$ stand for the maximum transmit powers of A, B and R, respectively.

Based on the constraints, the aforementioned optimization problem can be formulated as

$$\max_{p_a,p_b,p_{ra},p_{rb}} \eta = \frac{C_{ra}+C_{rb}}{p_a+p_b+p_{ra}+p_{rb}} \quad \text{s.t. Eqs. (1)–(5).} \tag{6}$$

Notably, the two-phase rate balancing restrictions (1), (2) are essentially incurring from the individual characteristic of the communication capacity over different media. Different from the previous studies, the proposed optimization problem cannot be solved directly by the Dinkelbach algorithm or Lagrangian multiplier method owing to the rate balancing constraints. To deal with such problems, it is beneficial to introduce the variable substitution.

Problem transformation. The optimization problem in (6) is non-convex due to the fractional form of the objective function and the non-convex constraints. To achieve an efficient power allocation (PA) solution, we propose an iterative two-layer optimization EE maximization-based PA (EEM-PA) algorithm. The original problem is transformed into an equivalent optimization problem in a subtractive form through variable substitution and the Dinkelbach algorithm.

* Corresponding author (email: xiaoyue@uestc.edu.cn, wugang99@uestc.edu.cn)

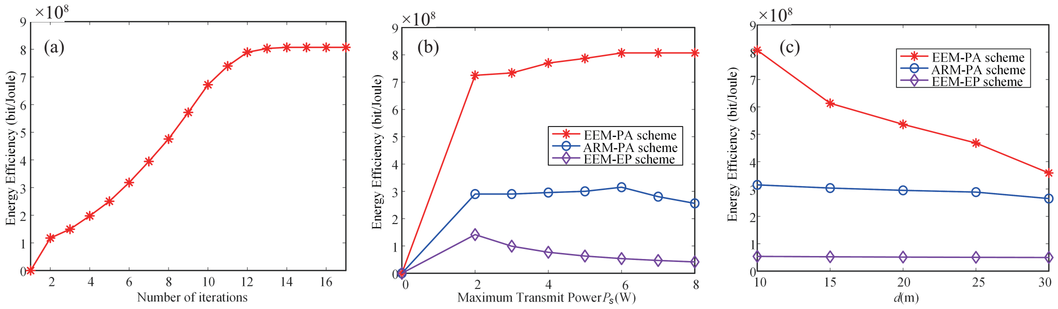

Figure 1 (Color online) (a) EE against the number of iterations of the considered EEM-PA algorithm; (b) EE versus the maximum transmit power P_s for the proposed EEM-PA, achievable rate maximization based PA (ARM-PA), and EEM-based equal transmit power allocation (EEM-EP) schemes; (c) EE versus the distance between B and R for the proposed EEM-PA, ARM-PA, and EEM-EP schemes.

By introducing variables z_1, z_2 with $z_1 = C_{rb}, z_2 = C_{ra}$, $p_a = e^{\widehat{p}_a}$ and $p_b = e^{\widehat{p}_b}$, problem (6) can be reformulated as

$$\begin{aligned} & f(\eta) = \max_{\boldsymbol{p},\boldsymbol{z}} z_1 + z_2 - \eta(e^{\widehat{p}_a} + e^{\widehat{p}_b} + p_{ra} + p_{rb}) \\ & \text{s.t.} \quad \frac{1}{2}\log\left(\frac{2^{\frac{2z_1}{B_v}} - 1}{M}\right) - \widehat{p}_a \geqslant 0, \ z_1 = C_{rb}, \\ & \qquad \log\left(\frac{2^{\frac{2z_2}{B_f}} - 1}{N}\right) - \widehat{p}_b \geqslant 0, \ z_2 = C_{ra}, \\ & \qquad e^{\widehat{p}_a} \leqslant p_a^{\max}, \ e^{\widehat{p}_b} \leqslant p_b^{\max}, \ p_{ra} + p_{rb} \leqslant p_r^{\max}, \end{aligned} \tag{7}$$

where $M = \frac{e}{2\pi}\frac{\rho^2 \bar{h}_{ar}}{B_v N_0}$, $N = \frac{\bar{g}_{br}}{B_f N_0}$.

We introduce the Lagrange $L(\boldsymbol{p}, \boldsymbol{z}, q, \mu)$ of the problem (7) and then the dual problem is expressed by

$$\max_{q\geqslant 0, \mu\geqslant 0} \min_{\boldsymbol{p},\boldsymbol{z}} L(\boldsymbol{p}, \boldsymbol{z}, q, \mu). \tag{8}$$

In order to solve the above dual problem, problem (8) can be divided into two layers. Layer 1 is the unconstrained optimization problem, while layer 2 is the master dual problem that is tackled with the aid of the gradient method. Firstly, we initialize the maximum number of iterations $k_{\max}$, $n_{\max}$, the error tolerance ε, the maximum EE $\eta^0 = 0$, and $k = 0$. Next, on the basis of the given η^k, we use the augmented Lagrangian multiplier method to derive an efficient solution which can be applied to update the value of η^{k+1} in the outer layer iteration.

Conclusion and simulation results. We proposed the EEM-PA scheme with the objective of improving the EE performance, while satisfying the rate balancing requirements and the power constraints. Since the original problem is non-convex, we proposed an iterative two-layer optimization algorithm. Subsequently, an augmented Lagrange multiplier method was applied to achieve an efficient solution. Finally, simulation results were presented to demonstrate that the proposed algorithm can perform closely to the optimal EE. Moreover, the proposed algorithm was shown to be capable of outperforming its conventional power allocation counterparts.

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