Cognitive Multi-Cell Visible Light Communication With Hybrid Underlay/Overlay Resource Allocation

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***Abstract*— In order to improve the spectral efficiency of indoor visible light communication (VLC) systems, in this letter, motivated by the concept of cognitive radio, we propose a new multi-cell cognitive VLC (C-VLC) system. The proposed multi-cell C-VLC system is comprised of both primary users and secondary users (SUs), by defining them based on users' service requirements. We investigate the unique optical constraints of transmitters in our proposed C-VLC system, and further propose a flexible hybrid underlay/overlay resource allocation approach to maximize the sum rate of SUs for the multi-cell C-VLC system, which is very different from radio frequency communication systems. Numerical results show that the proposed C-VLC system with hybrid overlay/underlay resource allocation achieves sum rate improvements of up to 29.2%, 20.6%, and 9%, compared with the conventional non-cognitive VLC system, the C-VLC system with only the underlay mode and the C-VLC system with only the overlay mode, respectively.**

***Index Terms*— Visible light communication (VLC), cognitive radio, overlay/underlay spectrum access, resource allocation.**

I. Introduction

VISIBLE light communication (VLC) based on white light emitting diodes (LEDs) has been emerging as a promising technology for next generation indoor wireless communication, due to its many distinct advantages such as low cost, abundant bandwidth and electromagnetic interference-free operation [1]. However, one key drawback of VLC systems is the small modulation bandwidth of LEDs, which limits VLC to achieve rival data rates. So far, various techniques have been proposed to improve the system capacity, such as multiple-input multiple -output (MIMO) [2], quadrature amplitude modulation (QAM) based orthogonal frequency division multiplexing (OFDM) [3], non-orthogonal multiple access (NOMA) [4]–[6], etc.

In practical VLC systems, multiple LEDs are generally employed to support communication services and the concept of optical attocells has been introduced to VLC systems, where each of the LEDs creates an optical attocell and serves multiple users [7], [8]. Such a cellular VLC system is referred to as a multi-cell VLC system [9]. However, the illumination areas of adjacent attocells inevitably overlap with each other and the users located within the overlapping area would suffer from inter-cell interference (ICI), which reduces the overall spectral efficiency of the multi-cell VLC system. In [10], orthogonal frequency division multiple access (OFDMA) was applied to enhance the spectral efficiency of multi-cell VLC systems.

Moreover, NOMA has been recently introduced in multi-cell VLC systems by multiplexing users in the power domain [5], which can greatly improve the spectral efficiency compared with OFDMA. Although the above works [2]–[10] can achieve a considerable capacity improvement in typical VLC systems, the spectrum of some users may not be occupied in a given time or only partially occupied, while some other users need more spectrum to meet their quality-of-service (QoS) requirements. Under such scenarios, the spectrum utilization is not efficient and the overall spectral efficiency of the VLC system is limited due to the inefficient spectrum access mechanism.

To improve the spectrum utilization efficiency, cognitive radio (CR) has been proposed as a proposing candidate for high-speed wireless communication, where the secondary users (SUs) are allowed to share the spectrum resource of the primary users (PUs) by applying two transmission modes, i.e. overlay mode and underlay modes [11], [12]. In the overlay mode, SUs can access to PUs' frequency bands if PUs do not currently use their bands. Whereas, in the underlay mode, SUs are allowed to coexist with PUs in the same frequency bands under a certain interference threshold.

Recently, the performance of the radio frequency (RF) and free-space optical (FSO) dual-hop CR networks has been investigated in [13] and [14]. Moreover, a cognitive VLC system was recently proposed by defining PUs and SUs based on users' locations [15]. However, only the overlay mode was adopted in [15], where ICI was not taken into account and simple equal-power allocation was used.

In this letter, motivated by the concept of CR, we propose a new multi-cell cognitive VLC (C-VLC) downlink system to improve the overall spectral efficiency, by defining PUs and SUs based on users' different service requirements. We further propose a flexible hybrid underlay/overlay subchannel and power allocation approach for the multi-cell C-VLC system considering the unique optical constraints of VLC systems and the minimum rate requirements, while keeping the interference introduced to PUs below a given threshold. Numerical results show that the proposed C-VLC system achieves significantly improved sum rate than that of the non-cognitive VLC system, the C-VLC with only the underlay mode, and the C-VLC system with only the overlay mode.

II. System Model and Problem Formulation

A. System Model

Here, we consider an indoor downlink VLC system, where multiple LEDs are placed in the ceiling to create a multi-cell

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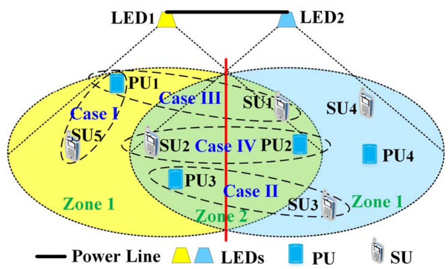

Fig. 1. A two-cell C-VLC system with hybrid overlay/underlay mode.

VLC system and a number of users are randomly distributed over the receiving plane. We consider that the system employs OFDMA to serve multiple users. The total bandwidth is equally divided into many subchannels, and the pre-frequency domain equalization technique [3] can be used to obtain a quasi-flat system frequency response. We also assume that users report their information to their associated LEDs through the Wi-Fi channel in the uplink [1], and these LEDs cooperate with each other to exchange information (e.g. users' working statuses) by the power line communication (PLC) [9], [13].

In this indoor multi-cell VLC system, we divide the users into two groups based on their different service requirements:

Group 1: users in this group have specific requirements of high data rate, stringent delay constraint and service steadiness, such as video/voice and instant messaging services.

Group 2: users in this group have much looser constraints on the date rate, time delay and QoS requirements, such as short message, web browsing and email services.

Motivated by the concept of CR [11], we define the users in group 1 as PUs with a higher priority to access the spectrum resource and the users in group 2 as SUs with a lower priority to access PUs' spectrum resource. Hence, a multi-cell C-VLC system model is proposed as shown in Fig. 1, where a two-cell C-VLC system is considered. LED 1 serves the users located on the left side of the red line, and LED 2 serves the users located on the right side of the red line. PUs and SUs are randomly distributed over the receiving plane. In this multi-cell C-VLC system, SUs access the subchannels of PUs through applying the overlay and underlay spectrum access modes. In the overlay mode, SUs access the subchannels of PUs if PUs do not occupy their subchannels in one time slot. In the underlay mode, SUs access the subchannels of PUs under the interference constraint imposed by PUs when PUs currently use the subchannels. Each LED knows the working status of users in its cell and share the information to adjacent cells instantaneously, and we assume the delay is negligible.

As shown in Fig. 1, the coverage of the two-cell C-VLC system can be divided into two regions, namely Zone 1 (non-overlapping area) and Zone 2 (overlapping area). According to the locations of users in the two zones and the interference relationship between users, we consider the following four cases when SUs access the subchannels of the PUs. **Case I:** SUs access the subchannels of PUs in the same zone with the same associated LED, and both PUs and SUs receive interference in the underlay mode. **Case II:** SUs in Zone 1 access the subchannels of PUs in Zone 2, and only PUs receive ICI from the adjacent LED in the underlay mode. **Case III:** SUs in Zone 2 access the subchannels of PUs in Zone 1, and only SUs receive ICI from the adjacent LED in the underlay mode. **Case IV:** SUs in Zone 2 access the subchannels of PUs in Zone 2 with different associated LEDs, and both PUs and SUs receive ICI from the adjacent LED in the underlay mode. In addition, some subchannels are directly allocated to SUs, and this mode is called the regular mode.

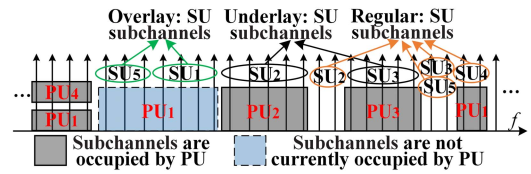

Fig. 2. The hybrid overlay/underlay spectrum access mode.

The spectrum access strategy of SUs with the hybrid overlay/ underlay mode is illustrated in Fig. 2, where we assume that one of the spectrum access situations is that the SUs in **Case I** and **Case III** apply the overlay mode, while the SUs in **Case II** and **Case IV** apply the underlay mode.

In the two-cell C-VLC system, we assume there are $M + N + Z$ subchannels allocated to $2L$ PUs and $2K$ SUs (L PUs and K SUs on each side of the red line), where M and N denote the numbers of the overlay and underlay subchannels, respectively; Z is the number of subchannels allocated to SUs in the regular mode. The subchannel bandwidth is $B_{sub} = B/(M + N + Z)$, where B is the modulation bandwidth of each LED. We assume that each PU and SU can be allocated with a number of subchannels, but one subchannel is only allocated to at most one SU.

According to [5], [7], and [15], the achievable rates of the k-th SU on the subchannel z in the regular mode, on the subchannel m in the overlay mode and on the subchannel n in the underlay mode can be expressed as

$$\text{Regular Mode: } C_{k,z} = \frac{B_{sub}}{2}\log_2(1 + P_{k,z}h_{k,z}^2/\delta^2), \quad (1)$$

$$\text{Overlay Mode: } C_{k,m} = \frac{B_{sub}}{2}\log_2(1 + P_{k,m}h_{k,m}^2/\delta^2), \quad (2)$$

$$\text{Underlay Mode: } C_{k,n} = \frac{B_{sub}}{2}\log_2(1 + P_{k,n}h_{k,n}^2 /(P_{l,n}h_{l,k,n}^2 + \delta^2)), \quad (3)$$

where the scaling factor 1/2 is due to the Hermitian symmetry [5]. $P_{k,z}$, $P_{k,m}$ and $P_{k,n}$ denote the electrical powers allocated to the k-th SU on the subchannel z, m and n at the associated LED, respectively. $h_{k,z}$, $h_{k,m}$ and $h_{k,n}$ are the channel gains between the k-th SU and its associated LED on the subchannel z, m and n, respectively. $P_{l,n}$ is the transmit power allocated to the l-th PU on the subchannel n. $h_{l,k,n}$ is the channel gain from the l-th PU' associated LED to the k-th SU on the subchannel n. $\delta^2 = N_0 B_{sub}$ is the power of the additive Gaussian noise, where N_0 is the power spectral density (PSD) of the additive noise. The total allocated power and the sum rate of the k-th SU can be given by: $P_k = \sum_{z=1}^{Z}\rho_{k,z}P_{k,z} + \sum_{m=1}^{M}\rho_{k,m}P_{k,m} + \sum_{n=1}^{N}\rho_{k,n}P_{k,n}$ and $C_k = \sum_{z=1}^{Z}\rho_{k,z}C_{k,z} + \sum_{m=1}^{M}\rho_{k,m}C_{k,m} + \sum_{n=1}^{N}\rho_{k,n}C_{k,n}$, respectively. The variable $\rho_{k,z}$, $\rho_{k,m}$ or $\rho_{k,n}$ determines whether the subchannel z, m or n is allocated to the SU k or not. If it takes value 1, the subchannel is allocated to the k-th SU. Otherwise, it is 0.

Considering the limited linear optical power range of LEDs and the non-negativity of the transmitted signal in VLC systems [5], [7], the constraints on the allocated power are given by

$$D_1 \le \sum\nolimits_{k=1}^{K} \sqrt{P_k} s_k + \sum\nolimits_{l=1}^{L} \sqrt{P_l} s_l \le D_2;$$
$$D_1 \le \sum\nolimits_{k=K+1}^{2K} \sqrt{P_k} s_k + \sum\nolimits_{l=L+1}^{2L} \sqrt{P_l} s_l \le D_2 \quad (4)$$

where P_l is the transmit electrical power allocated to the l-th PU, $D_1 = A_{\min} - A$ and $D_2 = A_{\max} - A$ with A being the DC bias which is added to satisfy the non-negativity of the transmitted signal, and $A_{\min}$ and $A_{\max}$ being the minimum and the maximum optical powers in the linear region. s_k and s_l are the massages for the k-th SU and the l-th PU, respectively.

B. Problem Formulation

Different from the conventional RF communication systems, the unique optical constraints in (4) for power allocation should be considered in VLC systems.

In the multi-cell C-VLC system, the goal of our proposed flexible resource allocation approach is to maximize the sum rate of SUs, and the optimization problem is expressed as

$$\underset{\substack{\rho_{k,z},\ \rho_{k,m},\ \rho_{k,n} \\ P_{z,m},\ P_{k,m},\ P_{k,n}}}{\text{maximize}} \quad \sum\nolimits_{k=1}^{2K} \left(\sum\nolimits_{z=1}^{Z} \rho_{k,z} C_{k,z} + \sum\nolimits_{m=1}^{M} \rho_{k,m} C_{k,m} + \sum\nolimits_{n=1}^{N} \rho_{k,n} C_{k,n} \right) \quad \text{(5a)}$$

$$s.t. \ \sum\nolimits_{k=1}^{K} P_k \le P_{\max}; \quad \sum\nolimits_{k=K+1}^{2K} P_k \le P_{\max} \quad \text{(5b)}$$

$$D_1 \le \sum\nolimits_{k=1}^{K} \sqrt{P_k} s_k + \sum\nolimits_{l=1}^{L} \sqrt{P_l} s_l \le D_2;$$
$$D_1 \le \sum\nolimits_{k=K+1}^{2K} \sqrt{P_k} s_k + \sum\nolimits_{l=L+1}^{2L} \sqrt{P_l} s_l \le D_2 \quad \text{(5c)}$$

$$P_{k,z} \ge 0, \quad \forall k,\ z; \ P_{k,m} \ge 0, \ \forall k,\ m; \quad P_{k,n} \ge 0, \quad \forall k,\ n \quad \text{(5d)}$$

$$\sum\nolimits_{k=1}^{2K} \sum\nolimits_{n=1}^{N} \rho_{k,n} P_{k,n} h_{k,l,n}^2 \le I_l^{\text{th}}, \quad \forall l \quad \text{(5e)}$$

$$C_k \ge C_k^{\text{tar}}, \quad \forall k \quad \text{(5f)}$$

$$\sum\nolimits_{z=1}^{Z} \rho_{k,z} \le Z; \quad \sum\nolimits_{m=1}^{M} \rho_{k,m} \le M; \quad \sum\nolimits_{n=1}^{N} \rho_{k,n} \le N \quad \text{(5g)}$$

where $h_{k,l,n}$ is the channel gain from the k-th SU' associated LED to the l-th PU on the subchannel n. Constraint (5b) is that the total transmit power allocated to all SUs per cell across all selected subchannels should not exceed the maximum transmit electrical power $P_{\max}$ for SUs per cell. (5c) is the constraint due to the limited liner optical power range, the peak optical intensity and the non-negativity of the transmitted signal [5], [7]. (5d) is the non-negative power constraint across all subchannels. (5e) is that the generated interference to PUs must below a specified interference threshold I_l^{th}. (5f) is to ensure that the sum rate of the k-th SU must satisfy the minimum rate (C_k^{tar}) requirement of each k-th SU. (5g) is imposed to guarantee that the sum of assembled subchannels should not exceed the number of the available subchannels.

III. Optimal Subchannel and Power Allocation

As we can see, the optimization problem in (5) is a mixed programing problem since both the subchannel assignment and power allocation are involved, which is hard to solve in general. Here, we divide it into two separate subproblems: a subchannel allocation problem and a power allocation problem, and solve these two subproblems separately, and then apply an iteration scheme to converge to an optimal point [12].

A. Subchannel Allocation Approach

In this subsection, we show how to achieve the optimal subchannel allocation for the given power allocation. We first define the channel-to-noise ratio (CNR) in the regular mode as $G_{k,z}^{\text{rg}} = h_{k,z}^2/\delta^2$, in the overlay mode as $G_{k,m}^{\text{ov}} = h_{k,m}^2/\delta^2$, and in the underlay mode as $G_{k,n}^{\text{un}} = h_{k,n}^2/(P_{l,n}h_{l,k,n}^2 + \delta^2)$. The key principle of the proposed subchannel allocation approach is that the SU whose rate is farthest away from its target minimum rate requirement has the priority to be allocated with the optimal subchannel with high CNR so as to meet its QoS requirement firstly. After satisfying QoS requirements of all SUs, we allocate the excess subchannels to maximize the SUs' sum rate.

B. Power Allocation Approach

Here, for the given subchannel allocation, the problem (5) is expressed as

$$\underset{P_{z,m},\ P_{k,m},\ P_{k,n}}{\text{maximize}} \quad \sum\nolimits_{k=1}^{2K} \left(\sum\nolimits_{z=1}^{Z} \rho_{k,z} C_{k,z} + \sum\nolimits_{m=1}^{M} \rho_{k,m} C_{k,m} + \sum\nolimits_{n=1}^{N} \rho_{k,n} C_{k,n} \right) \quad \text{(6a)}$$

$$s.t. \ (5b), (5c), (5e), (5f) \quad \text{(6b)}$$

Clearly, the problem in (6) is nonconvex as (5b), (5c) and (5f) are nonconvex. However, we can apply the Sequential Quadratic Programming (SQP) method [16] to achieve the electrical transmit electrical power solution P, which is a powerful iterative algorithm for solving the non-linearly constrained optimization problems [16]. In addition, the interior point method is also used in the SQP programming, and the solution details can be seen in [16].

IV. Numerical Results

In this section, we evaluate the performance of the multi-cell C-VLC system with the proposed hybrid overlay/underlay resource allocation (C-VLC hybrid) and compare it with the following systems: 1. conventional non-cognitive VLC system (Non-C-VLC); 2. C-VLC system with only overlay mode (C-VLC overlay); 3. C-VLC system with only underlay mode (C-VLC underlay).

We consider an indoor two-cell C-VLC system with two LEDs, where the spacing between two LEDs is 3 m and the vertical distance between the LEDs and the users is 2.15 m. The served coverage on the receiving plane of one cell is a circular area with a radius of 3 m. We choose the 4-quadrature amplitude modulation (4-QAM) scheme in the system. We only consider the LOS components [4], and the DC bias $A = 20\sqrt{\text{dBm}}$, $A_{\min} = 0$ and $A_{\max} = 30\sqrt{\text{dBm}}$ [5]. There are $L = 2$ PUs, $N = 20$ underlay subchannels, $M = 5$ overlay subchannels and Z=5 regular subchannels allocated to SUs. The power allocated to PUs per cell is 15 mW. The modulation bandwidth B is set to 20 MHz and the noise PSD is $N_0 = 10^{-21}\text{A}^2$/Hz. We repeat the simulation 1000 times with random locations of users in each time and present the average sum rate of PUs and SUs.

Fig. 3(a) shows the average sum rate of PUs and SUs per cell versus the maximum transmit electrical power $P_{\max}$ for SUs per cell when $I_{\text{th}} = 10^{-11}$ mW and $K = 3$.

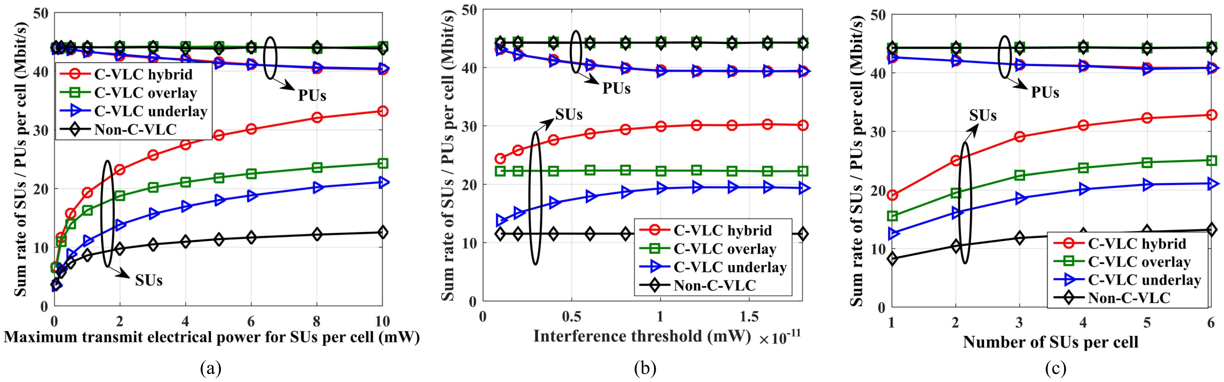

Fig. 3. Sum rate of SUs and PUs versus: (a) maximum transmit electrical power for SUs per cell, (b) interference threshold, and (c) number of SUs per cell.

We can observe that all the three C-VLC systems achieve much higher sum rates of SUs than that of the Non-C-VLC system, while the sum rates of PUs in the C-VLC hybrid and C-VLC underlay systems are slighted reduced. The C-VLC system allows SUs to access the subchannels of PUs by applying the overlay or underlay modes, which can enhance the spectral efficiency. However, the SUs' associated LED generates interference to PUs in the underlay mode, leading to the sum rate degradation of PUs. In addition, for the C-VLC hybrid system and the C-VLC underlay system, the sum rate of PUs is constant and the sum rate of SUs is not obviously improved in the high power region due to the interference threshold constraint. When $P_{\max} = 10$ mW, the C-VLC hybrid system improves the sum rate up to 29.2%, 20.6% and 9% compared with the Non-C-VLC system, the C-VLC underlay system and the C-VLC overlay system, respectively.

For $P_{\max} = 6$ mW and $K = 3$, the sum rate of PUs or SUs per cell versus the interference threshold I_{th} is presented in Fig. 3(b). Both the proposed C-VLC hybrid system and the C-VLC underlay system improve the sum rate of SUs when I_{th} is less than 1.2×10^{-11} mW with a slight decrease of the sum rate of PUs, and then they becomes roughly constant due to the limited transmit electrical power. This is because the two systems apply the underlay mode and the electrical power allocated to SUs increases as the increase of I_{th} to a certain value. The sum rate of C-VLC overlay and Non-C-VLC systems maintains at a horizontal level over the whole I_{th}, because I_{th} only affects the underlay mode, while these two systems do not apply this underlay mode.

For $P_{\max} = 6$ mW and $I_{\text{th}} = 10^{-11}$ mW, Fig. 3(c) shows the sum rate of SUs or PUs per cell versus the number of SUs. The SUs' sum rates of the four systems are improved with the increased number of SUs, because more SUs can increase the probability of having good channel gains for resource allocation, which leads to the sum rate improvement of SUs [11]. In addition, our proposed C-VLC hybrid system achieves the best performance.

V. Conclusion

In this letter, in order to improve the spectral efficiency of VLC systems, we have proposed a multi-cell cognitive VLC system with the flexible hybrid underlay/overlay subchannel and power allocation approach by considering the optical constraints of VLC systems. Simulation results show that the C-VLC hybrid system achieves sum rate improvements of up to 29.2%, 20.6% and 9% compared with the Non-C-VLC system, the C-VLC with only the underlay mode and the C-VLC system with only the overlay mode, respectively.

References

[1] M. Ayyash *et al.*, "Coexistence of WiFi and LiFi toward 5G: Concepts, opportunities, and challenges," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 64–71, Feb. 2016.

[2] C. Chen, W.-D. Zhong, and D. Wu, "On the coverage of multiple-input multiple-output visible light communications [invited]," *J. Opt. Commun. Netw.*, vol. 9, no. 9, pp. D31–D41, Sep. 2017.

[3] C. Chen, W.-D. Zhong, and D. Wu, "Non-Hermitian symmetry orthogonal frequency division multiplexing for multiple-input multiple-output visible light communications," *J. Opt. Commun. Netw.*, vol. 9, no. 1, pp. 36–44, Jan. 2017.

[4] H. Marshoud, V. M. Kapinas, G. K. Karagiannidis, and S. Muhaidat, "Non-orthogonal multiple access for visible light communications," *IEEE Photon. Technol. Lett.*, vol. 28, no. 1, pp. 51–54, Jan. 1, 2016.

[5] Z. Yang, W. Xu, and Y. Li, "Fair non-orthogonal multiple access for visible light communication downlinks," *IEEE Wireless Commun. Lett.*, vol. 6, no. 1, pp. 66–69, Feb. 2017.

[6] C. Chen, W.-D. Zhong, H. Yang, and P. Du, "On the performance of MIMO-NOMA-based visible light communication systems," *IEEE Photon. Technol. Lett.*, vol. 30, no. 4, pp. 307–310, Feb. 15, 2018.

[7] H. Kazemi and H. Haas, "Downlink cooperation with fractional frequency reuse in DCO-OFDMA optical attocell networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2016, pp. 1–6.

[8] C. Chen, S. Videv, D. Tsonev, and H. Haas, "Fractional frequency reuse in DCO-OFDM-based optical attocell networks," *J. Lightw. Technol.*, vol. 33, no. 19, pp. 3986–4000, Oct. 1, 2015.

[9] T. V. Pham, H. L. Minh, and A. T. Pham, "Multi-cell VLC: Multi-user downlink capacity with coordinated precoding," in *Proc. IEEE Int. Conf. Commun.*, May 2017, pp. 469–474.

[10] D. Bykhovsky and S. Arnon, "Multiple access resource allocation in visible light communication systems," *J. Lightw. Technol.*, vol. 32, no. 8, pp. 1594–1600, Apr. 15, 2014.

[11] S. Haykin, "Cognitive radio: Brain-empowered wireless communication," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[12] G. Bansal, M. J. Hossain, V. K. Bhargava, and T. Le-Ngoc, "Subcarrier and power allocation for OFDMA-based cognitive radio systems with joint overlay and underlay spectrum access mechanism," *IEEE Trans. Veh. Technol.*, vol. 62, no. 3, pp. 1111–1122, Mar. 2013.

[13] N. Varshney and A. K. Jagannatham, "Cognitive decode-and-forward MIMO-RF/FSO cooperative relay networks," *IEEE Commun. Lett.*, vol. 21, no. 4, pp. 893–896, Apr. 2017.

[14] H. Arezumand, H. Zamiri-Jafarian, and E. Soleimani-Nasab, "Outage and diversity analysis of underlay cognitive mixed RF-FSO cooperative systems," *J. Opt. Commun. Netw.*, vol. 9, no. 10, pp. 909–920, Sep. 2017.

[15] M. Hammouda, J. Peissig, and A. M. Vegni, "Design of a cognitive VLC network with illumination and handover requirements," in *Proc. IEEE Int. Conf. Commun. Workshops*, May 2017, pp. 451–456.

[16] P. T. Boggs and J. W. Tolle, "Sequential quadratic programming," *Acta Numer.*, vol. 4, pp. 1–51, Jan. 1995.