Hybrid Lightwave/RF Cooperative NOMA Networks

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Abstract—We propose an indoor lightwave downlink wireless communication network with the non-orthogonal multiple access (NOMA) technology, that consists of one visible light communication (VLC) access point (AP) and a pair of randomly located users. Although both users can directly receive information from the AP, the performance of the far user is degraded compared to the near one due to the asymmetrical channel gains. Thus, the user cooperation strategy is proposed to improve the performance of the far user by using mixed VLC/RF relaying technique in parallel with the wireless optical direct link. To efficiently exploit the available heterogeneous links, the concept of cross-band selection combining (CBSC) is introduced, according to which the far user is continuously served by either the mixed VLC/RF or the direct VLC link. Meanwhile, the performance of the proposed scheme is thoroughly investigated and compared to appropriate baselines. To this end, we derive closed-form expressions for the outage probability of each user as well as the system sum throughput. Finally, simulation results are provided to verify the effectiveness of the proposed scheme and the accuracy of the corresponding analysis.

Index Terms—Lightwave, hybrid system, decode-and-forward relaying, non-orthogonal multiple access (NOMA), cross band selection combining (CBSC).

I. INTRODUCTION

The main challenge to meet the ever-growing demands for high connectivity, reliability and data rates in the fifth generation (5G) of communication networks and beyond, is the saturation of the radio frequency (RF) spectrum. This problem, if not properly addressed, can create a bottleneck in the performance of future wireless networks, the development of novel applications as well as the potential profits of the communications service providers. In order to deal with the aforementioned challenges, the integration of optical spectrum in the design of wireless communication systems has been considered as a promising direction to deal with the spectrum scarcity problem. Consequently, the effective utilization of wireless technologies that operate across RF and optical spectrum bands under a cross-band design in the PHY and MAC layers is of paramount importance, with the aim to increase not only the available spectrum but also the overall spectral efficiency.

A. State-of-the-Art and Motivation

Visible light communication (VLC) occupies the frequency range from 400 THz to 800 THz, while RF holds the spectrum from 3 KHz to 300 GHz [1], [2]. VLC has recently attracted both academic and industrial interest, due to the inherent advantages of optical communication systems [1]–[6], as well as the adoption of the easy-to-modulate light emitting diodes (LEDs) in common lighting applications, which enables the utilization of existing lighting infrastructure for communication purposes. With the two-fold exploitation of LEDs-based systems, a vast amount of unused electromagnetic spectrum in the visible light region is enabled, which can be used to offer very high data rate and multi-connectivity. Moreover, by confining light into a limited space and referring to the aforementioned features, the realization of VLC system can substantially contribute to the emerging trends in communication systems. More specifically, it can provide enhanced security service, easy bandwidth reuse, increased energy efficiency and considerable energy savings, along with the immunity to RF interference, without contributing to RF contamination, etc. Due to these advantages, VLC has been recognized as a promising alternative/complementary technology to RF and envisioned to be one of the potential candidate technologies in the 5G Public-Private-Partnership (PPP) project, with the aim to facilitate wireless access to devices, especially in indoor applications [7]. However, the main challenges of VLC include users’ mobility, as well as the mitigation ability of severe channel degradation at the absence of a strong direct link [8]. A promising direction to overcome these challenges is the utilization of hybrid VLC/RF systems [9]–[13], where RF and VLC are employed in parallel in order to extend the coverage and increase the quality-of-service (QoS) of VLC systems.

On the other hand, connectivity and spectral efficiency, which are the major objectives of the proposed cross-band design, can be increased through the use of non-orthogonal multiple access (NOMA) [14]. It is noted that NOMA has already been approved as a study item of the 3rd Generation Partnership Project (3GPP) in Release 15 [15]. According to NOMA, multiple users’ messages can be superposed on the power domain, while the successive interference cancellation...
hybrid VLC/RF relaying network with NOMA in a two-user context of VLC communications networks [22]–[25]. More specifically, to enhance spectral efficiency and fairness in the NOMA-VLC systems, a gain ratio power allocation has been proposed in [22], while the impact of user paring in NOMA VLC networks has been studied in [13], [23], [24].

In addition, mixed optical/RF relaying systems have also recently attracted the research interest [26]–[33]. Similarly to conventional RF relaying technique [34]–[37], the use of a VLC/RF relay improves the system performance in terms of capacity and/or coverage, with the additional benefit of easier full-duplex implementation, due the non-interfering nature of optical and RF technologies. Moreover, it is commonly assumed that the relay is a user of the network, i.e., it receives and forwards another user’s messages voluntarily for the common purpose. Based on this assumption, VLC/RF relaying has been investigated in [26] considering a near-far user setup, in which the VLC access point (AP) simultaneously transmits both users’ messages using the superposition coding (SC) technique. Assuming that the far user is out of the coverage of the VLC system, it receives its message solely via the near user, which acts as an RF relay. In this work, SC technique is used in a point-to-point communication, i.e., between the VLC AP and the near user, and thus, it does not offer any gain compared to the time-division multiplexing (TDM) technology in terms of channel capacity. On the other hand, as it has been shown in [38], SC technology outperforms time-division multiple access (TDMA) in the broadcast channels which have asymmetric gains. Moreover, in [27], [28], a dual-hop mixed VLC/RF cooperative system with simultaneous lightweight information and power transfer (SLIPT) [29], [39], [40] has been investigated. Although the utilization of SLIPT is out of the scope of this work, it deserves to be mentioned that it can further facilitate the user cooperation, since, in this case, the relay can solely consume the harvested energy to retransmit the received message. Furthermore, mixed free-space optical (FSO)/RF relaying systems with the use of decode-and-forward (DF) and amplify-and-forward (AF) schemes have been introduced in [32] and [33], respectively, while the secrecy performance in mixed FSO/RF relaying systems has been investigated in [30], [31]. However, to the best of our knowledge, the combined use of direct optical links and mixed optical/RF relaying links to serve the same user has not been investigated yet in the existing literature.

B. Contribution

Motivated by the advantages and vulnerabilities of the aforementioned technologies, i.e., RF, VLC, relaying and NOMA, this paper focuses on the design of a downlink hybrid VLC/RF relaying network with NOMA in a two-user scenario. Specifically, the VLC is used to provide access to both users, while the RF technology is solely used as a complementary technology to reduce the outage probability for the far user, by forwarding another copy of its message from the near user. Consequently, in contrast to [26], we assume that the far user receives two copies of its message, one from the VLC AP and one from the near user via RF. Moreover, in contrast to [26], we also consider the randomness of the users’ locations. Furthermore, we derive closed-form expressions for the achievable rate, taking into account the VLC particularities, according to which VLC signals are non-negative and constrained by the desired illumination [38].

More specifically, the contributions of this work can be summarized as follows:

- We introduce the cross-band selection combining (CBSC) concept in a two-user hybrid VLC/RF relaying network with NOMA, according to which the far user adaptively chooses to decode the information from either the mixed VLC/RF link or the direct VLC link, based on the achievable rate and the required user’s QoS on each of the links. For the sake of comparison, two fixed policies are used as baselines, according to which the far user is continuously served by either the mixed VLC/RF or the direct VLC link.
- We derive closed-form expressions for the user outage probability for all suggested policies, i.e., the CBSC and the two fixed ones. To obtain more insights on the outage performance of CBSC, upper and lower bounds are also derived.
- We derive a closed-form expression for the system sum throughput for all suggested policies to quantify the data rate of successful message delivery to both users.
- Finally, Monte-Carlo simulation results are provided to verify the effectiveness of the proposed scheme and the accuracy of the analysis. Specifically, it is shown that CBSC can obtain better outage performance and higher system sum throughput, in contrast to the fixed policies. Additionally, it becomes evident from the simulation results, that the proposed analysis can be used to optimize the system’s parameters, such as the semi-angle of illumination, the vertical distance of the VLC AP, and the users’ power allocation at the VLC AP.

C. Structure

The rest of the paper is structured as follows. The system model for hybrid VLC/RF cooperative relaying is introduced in Section II. In Section III, the users’ outage probability and system throughput, for the fixed policies, i.e., the mixed VLC/RF policy and the direct VLC policy, are derived, respectively. The corresponding performance analysis for the proposed CBSC policy is investigated in Section IV, where the upper and lower bounds for the outage probability are also illustrated. Simulation results are given and discussed in V. Finally, conclusions are summarized in Section VI.
with vertical distance $L$ from the ground floor plane. For the sake of the analysis and without loss of generality, two types of users are considered, namely the near and the far one, denoted by $U_1$ and $U_2$ respectively. It is assumed that the locations of $U_1$ and $U_2$ are uniformly distributed inside a circle with horizontal radius $R_0$ and an annular area bounded by radii $R_0$ and $R_v$ ($R_0 < R_v$), respectively. Specifically, in polar coordinates, users’ positions can be represented by $(r_i, \theta_i)$, with $r_i$ and $\theta_i$ being the radial and angular coordinate from the fixed reference axis, respectively.

It is assumed that both users belong inside the coverage area of the VLC AP and they both receive their messages from the direct VLC links using NOMA. However, in order to assist the far user, the near user also acts as a relay, using mixed VLC/RF DF relaying protocol. Also, considering that VLC is transparent to the communication at the RF band, $U_1$ operates in full-duplex mode [41], [42], i.e., it simultaneously receives and transmits information. In practice, the received symbol by $U_2$ at the RF band is delayed by one timeslot, i.e., during timeslot $j$, $U_2$ receives the symbols $x_{2,j}$ and $x_{2,j-1}$ by the VLC AP and $U_1$, respectively. However, for a sufficiently high number of transmitted symbols, the impact of this delay on the system’s performance is insignificant and can be ignored. Moreover, the timing synchronization for hybrid RF/FSO systems has already been discussed in [43].

In a practical deployment, it’s not possible to consider instantaneous channel state information (CSI) due to the large CSI feedback latency [25]. Motivated by this, to reduce the overhead and complexity, the performance of the considered system is evaluated assuming that solely the statistical CSI is available at the transmitter. Subsequently, a fixed rate requirement is considered for each receiver, with $\Gamma_1$ and $\Gamma_2$ being the target rates for $U_1$ and $U_2$, respectively. In this case, the key performance metrics are the outage probability and system throughput.

A. VLC Transmission

By employing intensity modulation-direct detection (IM-DD) in the optical communication system, the light intensity modulator at the transmitter is used to perform the electrical-to-optical conversion, while the electrical current carrying the signal information can be retrieved from the received lightwave via a photo-detector. Moreover, due to its inherent characteristics, the operation of the VLC is subject to the following constraints [38], [44], [45]:

- non-negativity of input $x_v$: the input signal modulates the optical intensity of the emitted light, as a result, the input signal $x_v$ is non-negative and proportional to the light intensity, while the photo-detector produces an output signal whose optical power is proportional to the detected intensity, corrupted by AWGN.
- peak optical power $A$ and average optical power $\xi$ constraints: In VLC systems, the control of the transmitted optical power is vital for safety reasons and/or for dimming control in order to satisfy the illumination requirements.

Based on the above assumptions, the non-negativity signal $x_v$ transmitted from the VLC AP, which is the superposition of the desired signals that correspond to $U_1$ and $U_2$, respectively, and can be expressed as

$$x_v = x_1 + x_2.$$  (1)

In (1), $x_1$ and $x_2$ are the messages to the users $U_1$ and $U_2$, respectively. To satisfy the peak and average constraints mentioned above, we let $A_1 = \beta_1 A$, $A_2 = \beta_2 A$, and $E(x_1) = E(x_2) = \xi$, where $E(\cdot)$ denotes expectation and $A_i$ is the peak intensity constraints of $x_i (i \in \{1, 2\})$. Also, $\beta_1$ and $\beta_2$ are the corresponding power allocation values, which are subject to the constraints $\beta_1 + \beta_2 = 1$ and $\beta_2 > \beta_1$, to ensure user fairness in the utilized downlink NOMA protocol [46]. Furthermore, $A$ and $\xi = \alpha A$ denote the peak and average illumination of the transmitted $x_v$, respectively, where $\alpha$ is the corresponding illumination parameter with $\alpha \in [0, 1]$. Due to these constraints, the average illumination should satisfy

$$\beta_1 \alpha A + \beta_2 \alpha A = \xi.$$  (2)

Accordingly, at the user $U_i$ (i.e., $U_1$ or $U_2$), direct detection (DD) scheme is utilized to retrieve the electrical current from the received optical signal, thus, the corresponding received information can be expressed as

$$y_i = h_i \eta x_v + n_i,$$  (3)

with $\eta$ being the photo-detector responsivity in A/W and $n_i$ being the additive white Gaussian noise (AWGN). Also, $h_i$ denotes the VLC channel gain from the VLC AP to the $i$-th user, which is given by [47]

$$h_i = \frac{(m+1) A_r}{2 \pi d_i^2} \cos^m(\phi_i) T(\psi_i) g(\psi_i) \cos(\psi_i),$$  (4)

where $A_r$ is the detector area of the $i$-th user, $\phi_i$ and $\psi_i$ are the irradiance and incidence angles of the $i$-th user, respectively, and the Lambertian emission order $m$ can be obtained by

$$m = -\ln 2 / \ln \left(\cos \Phi_{1/2}\right),$$  (5)
with $\Phi_{1/2}$ being the transmitter semi-angle corresponding to the half illumination power. Moreover, $d_i = \sqrt{r_i^2 + L^2}$ denotes the distance between the VLC AP and the $i$-th user. Assuming that the optical detector of each user side is vertical to the horizontal plane, it holds that $\phi_i \approx \psi_i$. Besides, $T(\psi_i)$ and $g(\psi_i)$ are defined as the gains of the optical filter and optical concentrator, respectively. Moreover, the idealized gain of nonimaging optical concentrator is given by

$$g(\psi_i) = \begin{cases} \frac{n^2}{\pi \Psi_C}, & 0 \leq \psi_i \leq \Psi_C, \\ 0, & \psi_i > \Psi_C, \end{cases},$$

(6)

where $\Psi_C$ denotes the receiver’s field-of-view and $n$ is the internal refractive index, which takes a typical value between 1 to 2 for visible light [47].

As it becomes evident from (4), $h_i$ is directly affected by the distance between the VLC AP and $i$-th user. Also, recalling that $U_1$ and $U_2$ are assumed to be uniformly distributed in a disk of radius $R_0$ and an annular area bounded by $[R_0, R_c]$, respectively, the polar coordinates of each user $(r_i, \theta_i)$ follow the uniform distribution. The channel gain in (4) can easily be expressed as a function of the users’ location, as in [23], i.e.,

$$h_i = \frac{(m+1)A_c T(\psi_i) g(\psi_i)}{2\pi} \frac{L^{m+1}}{(r_i^2 + L^2)^{\frac{m+3}{2}}},$$

(7)

where $C = A_c T(\psi_i) g(\psi_i)$. To derive the cumulative density function (CDF) of the channel power gains, we define $Y_i = |h_i|^2$, $Y_i \in [Y_{i,\text{min}}, Y_{i,\text{max}}]$, which receives its minimum and maximum value when the user is located at $r_{i,\text{min}}$ and $r_{i,\text{max}}$, respectively. Moreover, by plugging $r_1 \in [0, R_0]$ and $r_2 \in [R_0, R_c]$ into (7), the ranges for $Y_1$ and $Y_2$ can be written as

$$[Y_{1,\text{min}}, Y_{1,\text{max}}] = \left[ \frac{(C(m+1)L^{(m+1)})^2}{(R_0^2 + L^2)^{(m+3)}}, \frac{(C(m+1)L^{(m+1)})^2}{L^{2(m+3)}} \right],$$

$$[Y_{2,\text{min}}, Y_{2,\text{max}}] = \left[ \frac{(C(m+1)L^{(m+1)})^2}{(R_0^2 + L^2)^{(m+3)}}, \frac{(C(m+1)L^{(m+1)})^2}{(R_c^2 + L^2)^{(m+3)}} \right],$$

(8)

respectively. Subsequently, the corresponding CDF of $Y_i$ can be expressed as

$$F_{|h_i|^2}(y) = \Pr \left[ \frac{(C(m+1)L^{(m+1)})^2}{(r_i^2 + L^2)^{(m+3)}} < y \right] = 1 - \Pr \left[ r_i < T(y) \right],$$

(9)

where $T(y)$ is defined as

$$T(y) = \sqrt{\left( \frac{(C(m+1)L^{(m+1)})^2}{y} \right)^{\frac{1}{m+3}} - L^2}.$$

Recalling the assumption of uniform distribution and predefined locations for $r_1$ and $r_2$, the corresponding probability density functions (PDFs) can be written as [48]

$$f_{r_1}(d_1) = \frac{2d_1}{R_0^3}, \quad 0 \leq d_1 \leq R_0,$$

(10)

and

$$f_{r_2}(d_2) = \frac{2(d_2 - R_0)}{(R_0 - R_c)^2}, \quad R_0 \leq d_2 \leq R_c,$$

(11)

respectively. Accordingly, the corresponding CDFs of the random variables $r_1$ and $r_2$ can be obtained by integrating (10) and (11) with respect to $d_1$ and $d_2$, respectively, which can be expressed as

$$F_{r_1}(d_1) = \int_0^{d_1} f_{r_1}(d_1)\,d_1 = \frac{d_1^2}{R_0^3}, \quad 0 \leq d_1 \leq R_0$$

(12)

and

$$F_{r_2}(d_2) = \int_{R_0}^{d_2} f_{r_2}(d_2)\,d_2 = \frac{d_2^2 + R_0^2 - 2R_0d_2}{(R_c - R_0)^2}, \quad R_0 \leq d_2 \leq R_c.$$
where $B_r$ is the bandwidth of the VLC network, $[\cdot]^+ = \max(0, \cdot)$, $\epsilon_\phi = 0.016$, $\epsilon_\mu = 0.0015$, $\sigma^2$ is the noise variance [38].

### B. RF transmission

The received signal by $U_2$ at the RF frequency band is

$$y_R = \sqrt{P_t} x_R h_R + n_R,$$  

(19)

where $P_t$ represents the available power at $U_1$ for retransmission, $x_R$ is the transmit signal with normalized power, i.e., $\mathbb{E}[|x_R|^2] = 1$. Also, $h_R \sim \text{Nakagami}(K_n, d_R^n)$ is the RF channel gain between $U_1$ and $U_2$, which is modeled by the Nakagami-$m$ fading channel, with $K_n$ being the fading parameter. Moreover, a special case is expected when $K_n = 1$, which corresponds to Rayleigh fading. Furthermore, $d_R$ is calculated by the Euclidean distance, as

$$d_R = \sqrt{r_1^2 + r_2^2 - 2r_1r_2 \cos(\theta_2 - \theta_1)}$$  

(20)

and $v$ being the path loss parameter. Also, $n_R$ is the AWGN noise at the RF receiver of $U_2$, with average power $\sigma_R^2$. Thus, according to Shannon capacity, the achievable data rate for the information transmission between $U_1$ and $U_2$ via the RF link is [14]

$$R_{2,R} = B_r \log_2 \left( 1 + \frac{P_t}{\sigma_R^2} h_R^2 \right),$$  

(21)

with $B_r$ being the bandwidth of the RF system.

### III. FIXED POLICIES

In this section, two fixed baseline policies are investigated in terms of outage probability and system throughput, according to which either the VLC direct link or the cooperative RF link from $U_1$ to $U_2$ is continuously used for information decoding by $U_2$. Hereinafter, $P_t[\cdot]$ denotes the probability of an event.

### A. VLC and RF cooperative link

This subsection focuses on the scenario that the superposition signal transmitted by the VLC AP is exploited solely by $U_1$, while $U_2$ only uses the signal transmitted from $U_1$ over the RF frequency band for information decoding. As one can easily observe, in this case, $U_2$ can successfully decode its message only if it is successfully decoded by $U_1$. Next, the outage probability for each user is defined and analyzed.

1) Outage probability for $U_1$: Assuming that $\Gamma_i$ is the required threshold transmission rate of the desired message $x_i$ for $U_i$, then the outage probability for $U_1$ is defined as the probability that the achievable rate of the desired $x_1$ at $U_1$ is smaller than its corresponding $\Gamma_1$, which also depends on the SIC procedure.

**Theorem 1.** The outage probability for $U_1$ can be expressed in closed-form as

$$P_1^1_{\text{VLC}} = \begin{cases} 1 - \frac{T(\zeta^*)^2}{\zeta_1^2}, & \gamma_2 < \frac{\beta^2}{\beta_2^2} \\ 1, & \text{otherwise}, \end{cases}$$  

(22)

where

$$\gamma_i = \frac{(2^{\Gamma_i + \epsilon_\phi})}{\sigma_R^2} - 1 + (1 + \epsilon_\mu)^2,$$  

(23a)

$$\zeta^* = \min\{\min\{\zeta, Y_{1,\min}\}, Y_{1,\max}\},$$  

(23b)

$$\zeta_1 = \frac{9\gamma_1}{(\eta \beta_1)^2 (\alpha \rho_c)^2},$$  

(23c)

$$\zeta_2 = \frac{9\gamma_2}{((\eta \beta_2)^2 - (\eta \beta_1)^2)^2 (\alpha \rho_c)^2},$$  

(23d)

and $(\alpha \rho_c)^2 = (\frac{\eta A}{2})^2$ denote the average transmit signal-to-noise (SNR) from the VLC AP.

**Proof.** The outage probability for user $U_1$ is defined as

$$P_{1,\text{VLC}} = P_t[R_{2,R} < \Gamma_2] + P_t[R_{2,R} \geq \Gamma_2, R_{2,R} < \Gamma_1]$$  

(24)

where step (a) follows from the fact that the desired $x_1$ can be received only after decoding $x_2$ successfully, which also can be expressed as the complementary event of successful decoding by using step (b). Next, by plugging (16) and (17) into above (24), $P_{1,\text{VLC}}$ can be deduced as

$$P_{1,\text{VLC}} = \left\{ \begin{array}{ll} F_{h_1}[\gamma^*], & \gamma_2 < \frac{\beta^2}{\beta_2^2} \\ 1, & \text{otherwise}. \end{array} \right.$$  

(25)

Consequently, by substituting (14) into (25), we can obtain a closed-form expression as given in (22), which completes the proof. \qed

2) Outage probability for $U_2$: When the mixed VLC/RF relaying link is used, the outage probability for $U_2$ can be expressed as

$$P_{2,\text{VLC/RF}} = P_t[\min\{R_{2,R}, R_{2,R} < \Gamma_2].$$  

(26)

By considering the complementary event of the one in (26), the latter can be rewritten as

$$P_{2,\text{VLC/RF}} = 1 - P_t[R_{2,R} > \Gamma_2] \cap R_{2,R} < \Gamma_2]$$  

(27)

where step (c) follows the concept of conditional probability and the fact that channels $h_1$ and $h_R$ are not independent due to the impact of the users’ locations on the quality of the RF link, according to (20). Then, by using similar steps as in the proof of Theorem 1, the following expression is derived:

$$P_t[R_{2,R} > \Gamma_2] = \begin{cases} P_t[r_1 < r_1^*], & \gamma_2 < \frac{\beta^2}{\beta_2^2} \\ 1, & \text{otherwise}, \end{cases}$$  

(28)

where

$$r_1^* = \sqrt{(C(m + 1) L(m+1))^{(m+1)}} \frac{1}{\zeta_{2,1}} - L^2,$$  

(29)

and

$$\zeta_{2,1}^* = \min\{\min\{\zeta_2, Y_{1,\min}\}, Y_{1,\max}\}.$$  

(30)
Next, by using the result of (28), the conditional probability of \( [R_{2, R} > \Gamma_2] \) given \( [R_{2, R} > \Gamma_1, V > \Gamma_2] \) in (27), can be calculated as
\[
P_r[R_{2, R} > \Gamma_2 | R_{2, R} > \Gamma_1, V > \Gamma_2] = P_r\left[|h_{R}|^2 > \frac{\gamma_{R}}{\rho_t} r_1 < r_1^c\right] = P_r\left[|h_{R}|^2 > \frac{\gamma_{R}}{\rho_t} r_1 < r_1^c\right].
\]
(31)

where \( \gamma_{R} = 2^{r_{2}/B_{r}} - 1, \rho_t = \frac{P_t}{\sigma_n^2} \) is the transmit SNR at \( U_1 \), and the distance \( d_R \) given in (20) with \( v \) being assumed as an even number, for mathematical tractability [49]. Under the assumption of Nakagami-m fading over the RF, i.e., \( h_R \), with fading parameter \( K_n \), the corresponding channel gain \( |h_{R}|^2 \) is gamma-distributed with shape \( K_n \) and scale \( \frac{r_{1}}{\rho_t} \), i.e.,
\[
|h_{R}|^2 \sim \text{Gamma}(K_n, \frac{r_{1}}{\rho_t}).
\]
Accordingly, as \( K_n \) is a positive integer, (27) can be obtained as
\[
P_{O, VLC/RF}^{2} = 1 - e^{-\frac{\gamma_{R} K_n}{\rho_t} \sum_{j=0}^{K_n-1} \frac{\left(\frac{2 \rho_t}{\gamma_{R}} r_1^c\right)^j}{j!}}, \quad r_1 < r_1^c.
\]
(32)

Moreover, by taking into account the randomness of users’ locations, \( \theta_i \) is also uniformly distributed in the interval \([0, 2\pi]\) and its PDF is given by \( f_{\theta}(x) = \frac{1}{2\pi} (i \in \{1, 2\}) \), thus, we rewrite (26) while considering the limited area given in (29), as
\[
P_{O, VLC/RF}^{2} = 1 - E[e^{-\frac{\gamma_{R} K_n}{\rho_t} \sum_{j=0}^{K_n-1} \frac{\left(\frac{2 \rho_t}{\gamma_{R}} r_1^c\right)^j}{j!}}], \quad r_1 < r_1^c.
\]
(33)

**Theorem 2.** A closed-form expression in the high SNR regime for the outage probability for \( U_2 \) is
\[
P_{O, VLC/RF}^{2} = \frac{\left(\frac{2 \rho_t}{\gamma_{R}} r_1^c\right)^K_n}{2 \pi R_0^2(R_v - R_0)^2 K_n n!} \sum_{k=0}^{\nu K_n/2} \left(\frac{v K_n}{2}\right)(-1)^{\nu K_n - k} J_1 J_2
\]
(34)

with
\[
J_1 = \sum_{q=0}^{\nu K_n/2-k} \left(\frac{v K_n}{2} - k\right) B\left(\frac{v K_n}{2} - k, q + \frac{1}{2}\right) \times \left[\frac{1}{2}\right] \left(1 - \frac{v K_n/k - q}{2}\right) \left(1 + \left(-\frac{v K_n/k - q}{2}\right)^2\right) \left(-1\right)^{\nu K_n - k - q},
\]
(35)

where \( B(x, y) \) is the beta function [50]. Moreover, a closed-form expression of \( J_2 \) is given by
\[
J_2 = 2 \frac{\nu K_n/k - k}{k} \sum_{l=0}^{k} \left(\frac{k}{l}\right) \left(\frac{1}{2l + \nu K_n/k + 2 - k + 2} \left(r_1^2 + \frac{v K_n}{2}\right)^{2l + \nu K_n/k - k + 2}ight)
\]
\[
\times \left[\frac{1}{k - 2l + \nu K_n/k + 2} \left(R_v^{k - 2l + \nu K_n/k} - R_0^{k - 2l + \nu K_n/k + 2}\right)
\right]
\]
\[
- \frac{R_v}{R_0} \left(\frac{R_v^{k - 2l + \nu K_n/k} - R_0^{k - 2l + \nu K_n/k + 2}}{R_v^{k - 2l + \nu K_n/k + 1} - R_0^{k - 2l + \nu K_n/k + 1}}\right).
\]
(36)

**Proof.** To obtain a closed-form expression, we consider the expectation operation in the above (34) in the high SNR regime, by using the approximation given in [51], thus we have
\[
e^{-\frac{\gamma_{R} K_n}{\rho_t} \sum_{j=0}^{K_n-1} \frac{\left(\frac{2 \rho_t}{\gamma_{R}} r_1^c\right)^j}{j!}} \approx 1 - \frac{\left(\frac{2 \rho_t}{\gamma_{R}} r_1^c\right)^K_n}{K_n!} \frac{\gamma_{R} K_n}{\rho_t} \left(r_1^2 + r_1^c - 2r_1r_2 \cos(\theta_2 - \theta_1)\right)
\]
\[
\cdot \left(\frac{v K_n}{2}\right) \left(-1\right)^{\nu K_n - k}.
\]
(37)

As users are randomly deployed, it holds that
\[
E\left[e^{-\frac{\gamma_{R} K_n}{\rho_t} \sum_{j=0}^{K_n-1} \frac{\left(\frac{2 \rho_t}{\gamma_{R}} r_1^c\right)^j}{j!}}\right] \approx 1 - \frac{\left(\frac{2 \rho_t}{\gamma_{R}} r_1^c\right)^K_n}{2 \pi R_0^2(R_v - R_0)^2 K_n n!} \int_{R_v}^{R_0} \int_{0}^{2\pi} \int_{0}^{\pi} \int_{0}^{0} \int_{0}^{(r_2 - R_0)} (r_1^2 + r_1^c - 2r_1r_2 \cos(\theta_2 - \theta_1)) \left(\frac{v K_n}{2}\right) \left(-1\right)^{\nu K_n - k}) d\theta_1 d\theta_2 d_{r_1} d_{r_2}.
\]
(38)

While considering the independence of the variables (radius and angle) in the users’ polar coordinates \((r_i, \theta_i)\), (38) can be further reduced into two separate double integrals, i.e., radial-based and angle-based integrals. Moreover, by applying binomial theorem, \( J \) in (38) can be rewritten as
\[
J = \sum_{k=0}^{\nu K_n/2-k} \left(\frac{v K_n}{2} - k\right) \left(-1\right)^{\nu K_n - k} \int_{0}^{2\pi} \int_{0}^{\pi} \int_{0}^{0} \int_{0}^{(r_2 - R_0)} \int_{0}^{(r_1^2 + r_1^c) \left(2r_1r_2 \cos(\theta_2 - \theta_1)\right)} \left(\frac{v K_n}{2}\right) \left(-1\right)^{\nu K_n - k} r_1(r_2 - R_0) d_{r_1} d_{r_2}.
\]
(39)

Considering Lemma 2 in [49], (35) can be derived by utilizing the equation (2.5.12.44) in [50] and the sum-difference formulas of trigonometric functions. Moreover, by considering the constrained areas of \( U_1 \) and \( U_2 \), we can evaluate the double-integral \( J_2 \) as
\[
J_2 = \int_{R_v}^{R_0} \int_{0}^{(r_1^2 + r_1^c) \left(2r_1r_2 \cos(\theta_2 - \theta_1)\right)} \left(\frac{v K_n}{2}\right) \left(-1\right)^{\nu K_n - k} r_1(r_2 - R_0) d_{r_1} d_{r_2},
\]
\[
= 2 \frac{\nu K_n/k - k}{k} \sum_{l=0}^{k} \left(\frac{k}{l}\right) \int_{0}^{(r_1^2 + r_1^c) \left(2r_1r_2 \cos(\theta_2 - \theta_1)\right)} \left(\frac{v K_n}{2}\right) \left(-1\right)^{\nu K_n - k} r_1(r_2 - R_0) d_{r_1} d_{r_2},
\]
\[
\int_{R_v}^{R_0} \int_{0}^{(r_2 - k - \frac{v K_n}{2}) \left(2r_1r_2 \cos(\theta_2 - \theta_1)\right)} \left(\frac{v K_n}{2}\right) \left(-1\right)^{\nu K_n - k} r_1(r_2 - R_0) d_{r_1} d_{r_2},
\]
(40)

from which (36) is derived.

By substituting (38), (39), (35) and (36) into (33), (34) is derived and the proof is completed. \( \square \)
B. Direct VLC link

In this subsection, we investigate the policy according to which $U_2$ directly receives its message from the VLC AP, i.e., mixed VLC/RF relaying is never used.

**Theorem 3.** When only the wireless optical link is used, the outage probability for $U_2$ can be expressed as

$$P_{O,VLC}^{2} = \left\{ \begin{array}{ll}
1 - \frac{T(\zeta^{*}_{2,2})^2 - 2R_0T(\zeta^{*}_{2,2}) + R_0^2}{(R_0 - R_0)^2}, & \gamma_2 < \frac{\beta^2}{\beta^2}, \\
1, & \text{otherwise},
\end{array} \right. \quad (41)$$

where

$$\zeta^{*}_{2,2} = \min\{\max\{\zeta_2, Y_{2,\min}\}, Y_{2,\max}\}. \quad (42)$$

**Proof.** According to the decoding procedure, in this case holds that

$$P_{O,VLC}^{2} = P_r[\mathcal{R}_{2,V} < \Gamma_2]$$

$$= \left\{ \begin{array}{ll}
F_{|h|^2}(\zeta^{*}_{2,2}), & \gamma_2 < \frac{\beta^2}{\beta^2}, \\
1, & \text{otherwise},
\end{array} \right. \quad (43)$$

Then, a closed-form expression for the outage probability for $U_2$ can be obtained by using (15) and (43) and the proof is completed.

C. System Sum Throughput

In order to characterize the successful message delivery over the communication channels, sum throughput is provided in this subsection, taking into account the predefined target rates $\Gamma_i$. The system sum throughput for the two fixed policies can be expressed by utilizing their corresponding outage probabilities, as

$$R_{VLC/RF} = (1 - P_{O,VLC}^{1})\Gamma_1 + (1 - P_{O,VLC/RF}^{2})\Gamma_2 \quad (44)$$

and

$$R_{VLC} = (1 - P_{O,VLC}^{1})\Gamma_1 + (1 - P_{O,VLC}^{2})\Gamma_2, \quad (45)$$

respectively, where the specific closed-form expressions of the outage probabilities (i.e., $P_{O,VLC}^{1}, P_{O,VLC/RF}^{2}, P_{O,VLC}^{2}$) have been provided in (22), (34) and (41).

IV. CROSS-BAND SELECTION COMBINING

A cross-band selection combining policy (CBS) is introduced according to which $U_2$ uses the best from the two links, i.e., either the VLC/RF or the direct one, to decode its message. Consequently, CBS is expected to reduce the outage probability for $U_2$ compared to the fixed policies presented in the previous section. CBS is also motivated by the fact that although $U_2$ receives two copies of its message over the two bands, linear coherent combining technique (e.g., MRC) is not applicable to this scenario.

A. Outage Probability Analysis

When CBSC is used, the outage probability at $U_2$ is defined as the probability that the achievable rate at combiner output (both RF receiver and lightwave receiver) is lower than a predefined target rate $\Gamma_2$. Accordingly, the outage probability in this scheme can be determined by

$$\begin{align*}
P_{O,CBSC}^{2} &= P_{r}[\mathcal{O}^{VLC}_{2} \cap \mathcal{O}^{VLC+RF}_{2}] \\
&= P_{r}[\mathcal{O}^{VLC}_{2}]P_{r}[\mathcal{O}^{VLC+RF}_{2}].
\end{align*} \quad (46)$$

For simplicity and tractability, $\mathcal{O}^{VLC+RF}_{2}$ and $\mathcal{O}^{VLC}_{2}$ are denoted as the outage events of the message $x_2$ performing at the far user $U_2$, from the direct VLC link and the mixed VLC/RF relaying link, respectively.

In order to analyze the conditional probability in (46), we first define the probability of event $\mathcal{O}^{VLC}_{2}$ as

$$P_{r}[\mathcal{O}^{VLC}_{2}] = P_{r}[\mathcal{R}_{2,V} < \Gamma_2] = P_{r}(r_2 > r_1^*), \quad (47)$$

where the constrained distance $r_2^*$ of the far user is

$$r_2^* = \sqrt{\left(\frac{C(m + 1)L(m + 1)^2}{\zeta^{*}_{2,2}}\right)^{\frac{1}{m}} - L^2}. \quad (48)$$

Subsequently, the outage event $\mathcal{O}^{VLC+RF}_{2}$ can be decomposed into two cases: i) decoding $x_2$ at $U_1$ using VLC link is not successful; ii) $x_2$ can be decoded by $U_1$ correctly but outage occur due to the RF link from $U_1$ to $U_2$. Thus, the corresponding outage probability can be expressed as

$$P_{r}[\mathcal{O}^{VLC+RF}_{2}] = P_{r}[r_1 > r_1^*] + P_{r}[\mathcal{H}_1^2 < \frac{\gamma R}{\rho T} | r_1 < r_1^*]. \quad (49)$$

Considering the above two outage events, we have

$$\begin{align*}
P_{r}[\mathcal{O}^{VLC+RF}_{2} | \mathcal{O}^{VLC}_{2}] &= P_{r}(r_1 > r_1^*, r_2 > r_2^*) \\
&\quad + P_{r}[\mathcal{H}_1^2 < \frac{\gamma R}{\rho T} | (r_1 < r_1^*, r_2 > r_2^*)].
\end{align*} \quad (50)$$

**Theorem 4.** While considering the randomness of users’ locations, the outage probability for $U_2$ can be expressed in closed-form, as

$$\begin{align*}
P_{O,CBSC}^{2} &= \frac{(2R_0^2 - (r_1^*)^2)}{R_0^2(R_0 - R_0)^2} \left( \frac{1}{2} R_0 - R_0 - \frac{1}{2} (r_2^*)^2 + (R_0^2 R_0)^2 \right) + \\
&\quad \frac{2\gamma\kappa_{\alpha}}{\pi R_0^2(R_0 - R_0)^2K_n} \sum_{l=0}^{\kappa_{\alpha}/2} \left( \frac{\kappa_{\alpha}}{2} - k \right) \frac{\gamma_{\alpha}^{2k}}{k} J_1 J_2,CBSC, \quad (51)
\end{align*}$$

where $J_1$ is given in (35) and $J_2,CBSC$ can be expressed as

$$\begin{align*}
J_2,CBSC &= 2^{\frac{\kappa_{\alpha}}{2} - k} \sum_{l=0}^{k} \left( \frac{1}{2l + \kappa_{\alpha} - k + 2} \right) \\
&\quad \times \left[ \frac{1}{\kappa_{\alpha} - 2l + \kappa_{\alpha} + 2} - \frac{1}{\kappa_{\alpha} + 2} \right] \left( \frac{R_0^{k-2l+\frac{\kappa_{\alpha}}{2}+2} - (r_2^*)^{k-2l+\frac{\kappa_{\alpha}}{2}+2}}{\kappa_{\alpha} + 2} \\
&\quad - \frac{R_0^{k-2l+\frac{\kappa_{\alpha}}{2}+2} - (r_2^*)^{k-2l+\frac{\kappa_{\alpha}}{2}+1}}{\kappa_{\alpha} + 1} \right].
\end{align*} \quad (52)$$

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**Proof.** Considering the randomly deployed users in the constrained area, the average of the first term in (50) can be obtained as

\[
P_{r}[r_{1} > r_{1}^{c}, r_{2} > r_{2}^{c}] = \int_{r_{1}^{c}}^{R_{v}} \int_{r_{2}^{c}}^{R_{v}} 2r_{1} 2(r_{2} - R_{0}) \frac{r_{1}}{R_{0}^{2} - (r_{2} - R_{0})^{2}} \, dr_{1} \, dr_{2} = \frac{2(R_{0}^{2} - (r_{1}^{c})^{2})}{R_{0}^{2}(R_{v} - R_{0})^{2}} \left(\frac{1}{2} R_{v}^{2} - R_{0} R_{v} - \frac{1}{2}(r_{1}^{c})^{2} + R_{0} r_{1}^{c}\right),
\]

(53)

As for the second term in (50), the Euclidean distance between users’ polar coordinates, according to which we calculate the average outage probability by utilizing the users’ polar coordinates, according to which we obtain

\[
P_{r}[(h_{R}^{2} < \frac{\gamma_{R}}{\rho_{l}} | (r_{1} < r_{1}^{c}, r_{2} > r_{2}^{c})] \approx \frac{\rho_{l} r_{1}^{2} + r_{2}^{2} - 2r_{1}r_{2} \cos(\theta_{2} - \theta_{1})}{\pi^{2} R_{0}^{2}(R_{v} - R_{0})^{2}} \int_{r_{1}^{c}}^{R_{v}} \int_{0}^{2\pi} \int_{0}^{2\pi} r_{1}(r_{2} - R_{0}) \times
\]

\[
(\rho_{k}^{2} - 2r_{1}r_{2} \cos(\theta_{2} - \theta_{1}))^{\frac{v K_{n}/2}{2}} d_{01} d_{02} d_{r_{1}} d_{r_{2}},
\]

where step (d) follows from the high SNR approximation that given in (37). Then (54) can be further expressed as

\[
P_{r}[(h_{R}^{2} < \frac{\gamma_{R}}{\rho_{l}} | (r_{1} < r_{1}^{c}, r_{2} > r_{2}^{c})] \approx \frac{\rho_{l} r_{1}^{2} + r_{2}^{2} - 2r_{1}r_{2} \cos(\theta_{2} - \theta_{1})}{\pi^{2} R_{0}^{2}(R_{v} - R_{0})^{2}} \sum_{k=0}^{v K_{n}/2} \left(\frac{v K_{n}/2}{2}\right)^{k} (-1)^{\frac{v K_{n}}{2} - k} \times
\]

\[
\int_{0}^{2\pi} \cos^k(\frac{v K_{n}}{2} - k)(\theta_{2} - \theta_{1}) \, d_{01} \, d_{02} \int_{J_{1}} \int_{J_{2}} \frac{r_{1}(r_{2} - R_{0}) \times}
\]

\[
(\rho_{k}^{2} - 2r_{1}r_{2} \cos(\theta_{2} - \theta_{1}))^{\frac{v K_{n}/2}{2}} d_{01} d_{02} d_{r_{1}} d_{r_{2}},
\]

(55)

where a closed-form expression of $J_{1}$ is given in (35). Then, by recalling the procedure in (40) but with different constraints of the users’ locations, i.e., $[0, r_{1}^{c}], [r_{2}^{c}, R_{v}]$, $J_{2, CBSC}$ can be deduced as (52).

Finally, we can obtain the analytical expression for $P_{r}^{UPP,CBSC}$ by plugging (53) and (54) into (50), which completes the proof.

**B. Bounds on the Outage Probability**

In order to intuitively figure out the behavior of the proposed CBSC method while reducing the computational complexity which is high due to the dependency of the direct and mixed VLC/RF links, following the upper and lower bounds are provided [53]. Specifically, the upper and lower bounds of $P_{r}[(O_{1}^{VLC} \cup O_{2}^{VLC/RF})]$ can be achieved by plugging (34) and (41) into the following expressions,

\[
P_{r}^{UPP, CBSC} = \min \{P_{r}[(O_{1}^{VLC})], P_{r}[(O_{2}^{VLC/RF})]\}
\]

and

\[
P_{r}^{LOW, CBSC} = P_{r}[(O_{1}^{VLC})] + P_{r}[(O_{2}^{VLC/RF})] - 1,
\]

where $P_{r}^{UPP, CBSC}$ and $P_{r}^{LOW, CBSC}$ have already expressed in (22) and (51).

**C. System Sum Throughput**

Along with the outage probability analysis, the system sum throughput of this policy can be written as

\[
R_{CBSC} = (1 - P_{0}^{UPP, VLC}) \Gamma_{1} + (1 - P_{0}^{UPP, CBSC}) \Gamma_{2},
\]

(58)

where $P_{0}^{UPP, VLC}$ and $P_{0}^{UPP, CBSC}$ have already expressed in (22) and (51).

**V. SIMULATIONS AND DISCUSSION**

In this section, Monte Carlo simulations are performed to validate the proposed analytical framework and assess the impact of the VLC AP parameters (i.e., average transmit SNR, semi-angle, vertical height) and the users’ power allocation ($\beta_{1}, \beta_{2}$) on the system’s performance. Note that the value of the bandwidth for VLC is expressed with respect to the corresponding one for the RF. The values of all parameters are given in Table-I, if not otherwise specified. The performance metrics of the three policies (i.e., the two fixed that consider the direct VLC link only or the cooperative VLC-RF link to $U_{2}$ and the proposed CBSC) are investigated and compared. Hereinafter, to facilitate reading, “VLC”, “Mixed VLC/RF relaying”, and “Proposed CBSC” are used to refer to the aforementioned policies. Also, let $\Gamma'_{1}$ denote the normalized rate requirement, i.e., $\Gamma'_{1} = \Gamma_{1}/B_{r}$.

Fig. 2 illustrates the outage probability of the three different policies versus the average SNR of the VLC AP, i.e., $(\alpha_{\nu}^{2})$, where the power allocation factors are set as $\beta_{1} = 0.3, \beta_{2} = 0.7$, and $\Gamma'_{1} = 2.2$ bits/s, $\Gamma'_{2} = 2.2$ bits/s. The comparison is performed for the two different SNR settings: $\rho_{l} = 0.5(\alpha_{\nu}^{2})^{2}$ and fixed value of $\rho_{l} = 30$ dB, with different fading parameters assumed, i.e., $K_{n} = [1, 2]$. Note that the RF transmission is employed in order to help the far user and therefore it makes sense to set the average SNR $\rho_{l}$ lower than $(\alpha_{\nu}^{2})^{2}$, while considering the system fairness. Then, variable and constant transmit power at the RF link, $\rho_{l}$, are both considered to further investigate the impact of the RF link between $U_{1}$ and $U_{2}$ to the overall system’s performance.
Overall, the average outage probability of each user in the different policies decreases, when the SNR increases from 70 dB to 90 dB, except for the $U_2$ in cooperative VLC-RF link with $\rho_t = 30$ dB. This presents an error floor in the high SNR region, due to the constraint of fixed transmit power over the RF link. Compared with the above cases which consider only the direct VLC link, when the mixed VLC/RF relaying or the proposed CBSC policy are used, we focus on the outage probability for $U_2$. Additionally, as it is observed, both the mixed VLC/RF relaying and the proposed CBSC policy can be divided into two regions with different slopes. More specifically, since the direct VLC link to $U_2$ performs worse compared to the mixed VLC/RF relaying policy, the proposed CBSC is mainly affected by the mixed VLC/RF link. For this reason, the first region of the two policies are almost the same. On the other hand, with an increase of the average transmitted SNR from the VLC AP $(\alpha \rho_v)^2$, CBSC outperforms the mixed VLC/RF relaying policy. Additionally, the upper bound coincides with the cooperative VLC-RF link in this setup, which is in accordance with (56), while the lower bound is tight in the low SNR region.

The outage probabilities for each user in the above three policies are evaluated for several VLC AP semi-angles in Fig. 3, where the results can help to choose the proper value for the parameter. Furthermore, with $\beta_1 = 0.2$, $\beta_2 = 0.8$, $\Gamma_1' = 2.3$ bits/s, $\Gamma_2' = 2.3$ bits/s and $(\alpha \rho_v)^2 = 85$ dB, $\rho_v = 32$ dB, $K_n = \{1, 2\}$, the outage probability is illustrated versus the VLC AP semi-angle, which varies from $5^\circ$ to $60^\circ$. For this configuration, it is notable that the outage probability for $U_1$ in the VLC link can acquire the optimal outage probability for the semi-angle value around $30^\circ$.

Next, the outage probabilities are calculated for different realizations of the vertical distance of the VLC AP in Fig. 4, which helps to figure out the optimum position of the VLC AP, with $K_n = 2$, $\beta_1 = 0.3$, $\beta_2 = 0.7$, $\Gamma_1' = 4.5$ bits/s, $\Gamma_2' = 2.82$ bits/s, $(\alpha \rho_v)^2 = 90$ dB, $\rho_v = 30$ dB. Regarding the impact of the AP’s vertical distance on performance, an interesting observation is that setting $L = 3$ m minimizes the outage probability for $U_2$ when CBSC or the fixed direct VLC policy are utilized. However, the vertical distance of the VLC AP has no significant effect on the outage probabilities for $U_2$ when the mixed VLC/RF relaying is applied, due to the constant transmit power at the RF link. On the other hand, with the increase of the vertical distance of the VLC AP in the above settings, the outage probability for $U_1$ increases.

Furthermore, because of the power-domain NOMA protocol applied in this system, it’s important to investigate the impact of the users’ power allocation on the corresponding outage probabilities. In Fig. 5, we consider three different cases for the average transmit power, i.e., $(\alpha \rho_v)^2 = \{82, 85, 88\}$ dB and $\rho_v = 30$ dB, with $\Gamma_1' = 3.5$ bits/s, $\Gamma_2' = 3.5$ bits/s, and $K_n = 2$. As expected, the proposed CBSC performs better than the
mixed VLC/RF relaying, in terms of outage probability for $U_2$. However, as the transmit power at the VLC link increases and more power is allocated to $\beta_1$, the mixed VLC/RF relaying and CBSC asymptotically approach the same outage probability. This finding can be used to achieve a better performance by using proper power allocation. For example, when $(\alpha \rho_v)^2 = 82$ dB, the smallest power allocation leads to the same outage probability for $U_2$ in the mixed VLC/RF and the proposed CBSC is $\beta_1 = 0.35$, while $\beta_1 = \{0.4, 0.45\}$ corresponding to $(\alpha \rho_v)^2 = \{85, 88\}$ dB, respectively.

On the other hand, in Fig. 6, the system sum throughput is evaluated versus the average VLC AP transmit power $(\alpha \rho_v)^2$ in the range $[88 - 100]$ dB with fixed value, $\rho_t = 35$ dB or variables $\rho_t = \frac{1}{2}(\alpha \rho_v)^2$, $\Gamma_1 = 2.5$ bits/s, $\Gamma_2 = 2.5$ bits/s and $\beta_1 = 0.3$, $\beta_2 = 0.7$, $K_n = 2$. It is shown that the proposed CBSC is superior to the mixed VLC/RF relaying policy. Note that these results ignore the performance of the direct VLC policy, which is not competitive compared with the other two policies, i.e., the proposed CBSC and the mixed VLC/RF relaying. Furthermore, as the average SNR, i.e., $(\alpha \rho_v)^2$, increases, the throughput of the proposed CBSC approaches the total target rate, i.e., 5 bits/s, in the high SNR region.

In Fig. 7, the system throughput of the proposed CBSC is illustrated to further investigate the joint effect of the parameters, $(\alpha \rho_v)^2$ and $\beta_1$. We assume that the transmitted SNR for the RF link is $\rho_t = \frac{1}{2}(\alpha \rho_v)^2$ and target rates are $\Gamma_1 = 3$ bits/s, $\Gamma_2 = 3$ bits/s, with $K_n = 2$. By using the results in this figure, we can find the optimal parameter pair $(\beta_1^*, (\alpha \rho_v)^2)$, with the other VLC AP parameters fixed. Consequently, this figure can be used as a guide to achieve system performance.

VI. CONCLUSIONS

In this paper, we have introduced a novel cross-band selection combining (CBSC) method for a two-user hybrid lightwave/RF cooperative networks with NOMA, with the aim to improve the communication QoS for both users, as well as to extend the coverage of the network. According to CBSC, the far user adaptively chooses either the mixed VLC/RF relaying link or the direct VLC link to decode the information. In order to identify the performance of all the policies, closed-form expressions for the outage probability and the system sum throughput for the high SNR region were derived, taking into account the random locations of the near and far user. Moreover, upper and lower bounds for the outage probability of the proposed CBSC were presented. Furthermore, simulation results have been performed to verify the effectiveness of the proposed CBSC and the accuracy of the theoretical study. Specifically, it has been shown that the proposed CBSC offers significant improvement of the weaker user’s outage probability and increases the system sum performance.
throughput compared to the fixed policies. Finally, it is noted that in order to increase energy sustainability, the integration of SLIPT technology in hybrid lightwave/RF cooperative systems is a promising future direction.

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