On the Performance Optimization of Two-Way Hybrid VLC/RF-Based IoT System Over Cellular Spectrum

Sutanu Ghosh\textsuperscript{c}, Member, IEEE, and Mohamed-Slim Alouini\textsuperscript{d}, Fellow, IEEE

Abstract—This article investigates the system outage performance of a useful architecture of two-way hybrid visible light communication/radio-frequency (VLC/RF) communication using overlay mode of the cooperative cognitive radio network (CCRN). The demand of high data rate application can be fulfilled using VLC link and communication over a wide area of coverage with high reliability can be achieved through RF link. In the proposed architecture, cooperative communication between two licensed user (LU) nodes is accomplished via an aggregation agent (AA). AA can perform as a relay node and in return, it can access the LU spectrum for two-way communications with the Internet-of-Things (IoT) device. First, closed-form expressions of outage probability of both LU and IoT communication are established. On the basis of these expressions, optimization problems are formulated to achieve minimum outage probability of both LU and IoT network. The impacts of both VLC and RF system parameters on these systems outage probability and throughput are finally shown in simulation results.

Index Terms—Cooperative cognitive radio network (CCRN), hybrid visible light communication/radio-frequency (VLC/RF) systems, Internet-of-Things (IoT) network, outage probability, spectrum sharing.

I. INTRODUCTION

The heavy demand of high data rate wireless applications (such as network conference and telemedicine) and due to numerous device connectivity, growing congestion over radio-frequency (RF) spectrum makes visible light communication (VLC) an attractive solution to manage the issue of spectrum scarcity and to support high speed information transmission [1]. VLC can provide high bandwidth over a very high-frequency band (430–790 THz) for future generation of wireless communication [2]. However due to the limitation of narrow area of coverage and also the challenging issue of uplink transmission over VLC link, the combined utilization of both VLC and RF system is proposed in the existing literature to achieve the potential benefits of high bandwidth, mitigation of the problem of blockage of line-of-sight transmission, provision of wide area of coverage, and better uplink transmission of data stream [3], [4] for future 6G applications. Additionally, the reliability and significant range of effective communication is also possible to enhance through cooperative communication using intermediate relay nodes [5], [6]. Those nodes may operate over hybrid VLC/RF system for various indoor/outdoor implementations of wireless communication [7], [8]. The indoor approach of VLC communication is more popular for light fidelity (Li-Fi) communication [9] and the outdoor approach is convenient to implement vehicular network applications [10].

The relay nodes are mostly small gadgets such as Internet of Things Devices (IoDs) or sensor nodes, which harvest energy either from VLC communication using the simultaneous light-wave information and power transfer (SLIPT) protocol [11] or from RF communication using the simultaneous wireless information and power transfer (SWIPT) protocol [12] for transmission of their information. SWIPT is typically classified as power splitting (PS), time switching (TS), and hybrid power TS (HPTS) schemes [13]. Various studies on one-way relaying using SLIPT protocol is reported in previous works [14]–[16]. In [7] and [14]–[16], the relay node harvests energy from the received signal over VLC link and forwards the received information to the destination over RF link. The goal of [14] is to maximize the end-to-end data rate of the hybrid VLC/RF system and the outage minimization problem is investigated in [7] and [16]. In [15], the nonorthogonal multiple-access (NOMA) principle is applied and the strong user of the proposed system performs the relaying action to forward information toward the weak user over RF link.

Furthermore, the issue of energy harvesting (EH)-enabled large number of device connectivity in next-generation Internet-of-Things (IoT) applications (such as healthcare, industrial IoT, traffic monitoring, environmental monitoring, etc.) is also an important aspect in 5G/6G wireless networks to exchange data between two or more nearest users [17]. Devices may communicate with each other either accessing unlicensed frequency band (such as industrial-scientific-medical band) following the out-band approach of device-to-device (D2D) communication or accessing the licensed band of frequency spectrum (such as cellular spectrum) following the in-band approach of D2D communication [18], [19].

Moreover, the efficient usage of frequency spectrum is desirable to enhance the spectrum efficiency (SE) of wireless...
networks [20], SE is possible to increase by implementing two-way communications over one-way communication. In addition to that, the utilization of two-way communications applying the spectrum sharing strategies (interweave, underlay, and overlay) of cognitive radio (CR) technology is also beneficial to achieve high SE [21]. To the best of our knowledge, the performance of two-way communications in the cooperative CR network (CCRN) over VLC/RF system has not been investigated earlier. Motivated by this issue, the current work studies the system performance of the communication between the aggregation agent (AA) and IoD over licensed spectrum using the CR-overlay mode of spectrum sharing and hybrid VLC/RF EH technique. The architecture is analyzed for outdoor VLC applications.

Scope and Contributions: In the existing literature on EH, the research works consider EH either from VLC link or from RF link. However, the combined usage of these two different sources is not considered together for EH. In addition to that, previously all the existing works related to hybrid VLC/RF communication consider one-way communication. This work, on the contrary, explores the issue of two-way cooperative communications between VLC system and platform server (PSe) and two-way IoD communications over licensed spectrum using the SLIPT- and SWIPT-enabled DF relaying mechanism to enhance SE of the system. In case of RF-EH, the HPTSR protocol is followed to utilize both time and power in an effective manner to maximize both throughput and reliability of two-way licensed user (LU) communications and two-way IoT communications. The main contributions of this work can be summarized as follows.

1) A novel four-phase two-way LU communication and two-way IoT communications using harvesting energy from different energy sources (from VLC system over VLC link and from PSe over RF link) is proposed to enhance the utilization of VLC and radio resources.

2) The overlay mode of CR framework is used by AA and IoD for sharing the spectrum of LU network. Closed-form analytical outage expressions of both LU communications and IoT communications are derived.

3) An optimization framework is also developed to maximize the throughput of both LU communications and IoT communications and to minimize the outage of both LU and IoT communications to boost up reliability of the proposed system. The optimal range of time allocation for EH from both VLC link and RF link is achieved to realize the effectiveness of two different links in the hybrid system.

4) Finally, numerical results provide the usefulness of various parameters, such as PS factor, TS factor, light emitting diode (LED) power, and RF power on the performance of the proposed system.

Various symbols and their meaning are shown in Table I. The remainder of the portion of this article is arranged as follows. The system model and the operational procedure are discussed in Section II. Both licensed network and IoT network outage expressions are derived and the optimization problem of the minimization of both the outage probabilities is also formulated in Section III. The numerical results are shown in Section IV, and finally, this article is concluded in Section V.

II. SYSTEM MODEL AND OPERATIONAL PROCEDURE

Fig. 1(a) and (b) shows two-way communications between a pair of LUs (VLC system and PSe) and co-existing unlicensed user nodes (AA and IoD). The system can be modeled following the overlay mode of CCRN [22].

1) VLC transceiver system consists of one VLC transmitter (VT) and one VLC receiver (VR) [23]. The VT has one LED array. A VLC link is considered between the VLC system and AA and an RF link is considered between PSe and AA [24].

2) Due to small coverage area of the VLC link and poor as well as heterogeneous channel condition over the RF link between VLC system and PSe, the cooperation from neighbor node (AA) is needed. In return of this cooperation, AA can access the licensed cellular spectrum to transmit and to receive information from IoD [25]. An RF link is considered between AA and IoD.

3) AA and IoD are considered to be energy constraint node. It harvests energy from the signal transmission of both VT and PSe over VLC link using the SLIPT protocol and over RF link using the SWIPT protocol, respectively. IoD harvests energy from power transmitter using a wireless power transfer (WPT) protocol.

4) The time frame structure of the proposed system is shown in Fig. 2. In the first phase, VT transmits signal to AA and in the second phase, PSe sends its signal to AA.

5) Transmission from the VLC system and PSe to AA are considered in two different phases to avoid the problem of decoding at AA.
7) The IoD transmits its information to AA in a fourth and last phase.
8) During the first two phases, AA harvests energy. During the first three phases, the IoD harvests energy.

The signal descriptions are provided in the subsequent portion of this section.

Signal transmission from VT LED source can be expressed as [14], [26]

\[ Y_{ST}^{(1)}(t) = \sqrt{N_L P_L} s(t) + B_{dc} \]  

where \( N_L \) is number of LEDs present in LED array system, and \( P_L \) is the power of each LED considering the identical structure of LEDs. \( s(t) \) is the RF subcarrier to carry binary data. In (1), \( B_{dc} \) is the direct current (dc) bias current, and \( I_l \) and \( I_h \) are the minimum and the maximum input bias current.

After the conversion from optical to electrical form, the received electrical signal at photodetector of AA can be expressed as

\[ Y_{PDs}^{(1)}(t) = \theta h_{vc} h_L \sqrt{N_L P_L} s(t) + B_{dc} \]  

\[ n_{vc}(t) \]

where \( \theta \) indicates optical to electrical conversion efficiency of the receiver at AA, and \( h_{vc} \) is the VLC channel coefficient. The path loss of VLC channel can be modeled as

\[ h_L = (A_s (\zeta + 1) \cos(\Phi)/(2\pi d^2)) \]  

( for, \( 0 \leq \Phi \leq \theta_{FOV} \)) and \( h_L = 0 \) (for, \( \Phi \geq \theta_{FOV} \)) [27].

\( \theta_{FOV} \) indicates the angle of field of view (FOV). The symbol \( A_s \) indicates the physical area of the photodetector, \( \zeta \) is the Lambert index, which depends on semiangle at half luminance \( \theta_{1/2} \) and \( \zeta = -(1/|\log_{10}(\cos(\theta_{1/2}))|) \), \( \Theta \) signifies the irradiance angle, and \( \Phi \) is the incidence angle. \( d_i \) is the distance traveled from the VLC system to AA. \( n_{vc}(t) \) is additive white Gaussian noise (AWGN) at AA.

\( I_D \) is the dc component of \( Y_{PDs}^{(1)}(t) \) and it can be defined as

\[ I_D = \theta h_{vc} h_L \sqrt{N_L P_L} s(t) \]

\( I_D(t) \) is the alternating current (ac) component of \( Y_{PDs}^{(1)}(t) \) and it can be defined as

\[ I_D(t) = \theta h_{vc} h_L \sqrt{N_L P_L} s(t) \].

AWGN variance is \( \sigma_q^2 \approx N_s W = q I_o W \)

where \( q \) is the electronic charge \( (1.6 \times 10^{-19}) \), \( I_o \) is the induced current in the photodetector that comes from ambient light source, and \( W \) is the effective noise bandwidth.

The received electrical signal power at photodetector \( P_{dc} = (\theta h_{vc} h_L \sqrt{N_L P_L} A_p)^2 \), where \( A_p \) is the peak amplitude of\( s(t) \).

\( A_p = B_{dc} - I_l, \) for \( B_{dc} < (I_h + I_l)/2 \) and \( A_p = I_h - B_{dc}, \) for \( B_{dc} \geq (I_h + I_l)/2 \). The instantaneous signal-to-noise ratio (SNR) at the photodetector can then be expressed as

\[ \gamma_p = \frac{P_{dc}}{\sigma_q^2} = \frac{(\theta h_{vc} h_L \sqrt{N_L P_L} A_p)^2}{q I_o W} \]  

The maximum available harvested energy (in first phase) at AA is

\[ E_{h1} = f_D V_o (r T/2), \]

where \( V_o = V_T \ln(|I_D/I_o| + 1) \). \( V_T \) is the thermal voltage and \( V_T \approx 25 \text{ mV} \). \( I_o \) is the dark saturation current of photodetector and it may vary between \( 10^{-9} \) to \( 10^{-12} \). \( f \) is the fill factor and its value is to be considered for the subsequent section as 0.75.

For simplicity, the upper bound of \( E_{h1} \) is considered as \( f V_T[(I_D^2 r T)/(2I_o)] \) and the harvested power in the first phase

6) AA reencodes (Ex-OR operation is performed for encoding purpose) the decoded received information from the LU nodes. It transmits combined data to both the LU nodes and also sends its own operational data to IoD in a third phase.
is used for data transmission in the third phase. The maximum harvested power in the first phase can be defined as $P_{h1} = \frac{E_{h1}}{(T/4)}$.

The received signal in the second phase at AA from PSe over the RF channel can be expressed as

$$Y^{(2)}_{r}(t) = \sqrt{\frac{P_m}{(d_m)^{\nu}}} h_r X_m(t) + n_r(t). \quad (4)$$

$X_m(t)$ is the transmitted signal from PSe to AA. AA can harvest the energy from RF signal following the HPTS scheme of the SWIPT protocol and the PS factor is defined by $\rho$ ($0 < \rho < 1$). The maximum available harvested energy (in second phase) at AA can be expressed as $E_{h2} = \eta \rho (P_m/[(d_m)^{\nu}])|hr|^2 \{((1-\tau)T)/2\}$. The symbol $\eta$ ($0 < \eta \leq 1$) indicates RF-to-dc conversion efficiency. $P_m$ is the maximum transmission power of PSe. $d_m$ is the distance between PSe and AA and $n_r(t)$ is the channel noise over RF link. The maximum harvested power in the second phase can be defined as $P_{h2} = \frac{E_{h2}}{(T/4)}$. The RF link path-loss exponent is defined by $\nu$.

Rest $(1-\rho)$ fraction of received power from PSe is used for decoding received information in the second phase. The received signal for information decoding is written as

$$Y^{(2)}_{r}(t) = \sqrt{(1-\rho)\frac{P_m}{(d_m)^{\nu}}} h_r X_m(t) + n_r(t). \quad (5)$$

The instantaneous SNR at AA from PSe is $\gamma_2 = \{(1-\rho)\frac{P_m|hr|^2}{[(d_m)^{\nu}\sigma_r^2]\} \}$ and $\sigma_r^2$ is noise variance over the RF channel. The total harvested power in first (using the HPTS protocol over VLC link) and second (using SWIPT protocol over RF link) phase can be combined and expressed as $P_h = P_{h1} + P_{h2}$.

In the third phase, AA uses the harvested power and divide it into two parts based on the power allocation factor $\varphi$ $(0 < \varphi < 1)$. $\varphi$ portion of $P_h$ is applied for relaying network-coded LU information and remaining $(1-\varphi)$ portion is applied for transmitting its own information $X_{t1}(t)$ to IoD. The combined signal of AA can be expressed as

$$X_{t3}(t) = \sqrt{\varphi P_h s(t) \oplus X_m(t)} + \sqrt{(1-\varphi)P_h X_{t1}(t)}. \quad (6)$$

Now, the transmitted signal from the LED transmitter of AA to VR of the VLC system is expressed as

$$Y^{(3)}_{r}(t) = \sqrt{P_h w(t) + B_{dc}} + \sqrt{(1-\varphi)P_h X_{t1}(t) + B_{dc}} \quad (7)$$

where $w(t)$ is the network coded signal and it can be defined as $w(t) = s(t) \oplus X_m(t)$.

As self-interference components are known at both VLC system and PSe. Therefore, it is possible to remove by the applying self-interference cancellation (SIC) technique.

After optical to electrical conversion, the received signal at photodetector of VR can be expressed as

$$Y^{(3)}_{r}(t) = \sqrt{\varphi P_h s(t) + B_{dc}} + \sqrt{(1-\varphi)P_h X_{t1}(t) + B_{dc}} \quad (8)$$

where $h_{rv}$ reverses the VLC channel coefficient. The received electrical signal is used for information processing at VR. Now, the signal-to-interference and noise ratio (SINR) at photodetector of VR can be expressed as

$$\gamma_3 = \frac{\varphi \rho |hr|^2 |P_h h_r|^2}{(1-\varphi)P_h h_r + \sigma_r^2}. \quad (9)$$

The received signal at PSe can be written as

$$Y^{(3)}_{m}(t) = \sqrt{\frac{\varphi P_h}{(d_m)^{\nu}}} h_r w(t) + \sqrt{(1-\varphi)P_h h_r X_{t1}(t) + n_r(t)}. \quad (10)$$

Now, the instantaneous SINR at PSe can be expressed as

$$\gamma_4 = \frac{\varphi P_h |hr|^2 (d_m)^{\nu}}{(1-\varphi)P_h h_r + \sigma_r^2}. \quad (11)$$

More harvested power (using the SLIPT protocol in Phase-1 and SWIPT protocol in Phase-2) is allocated for the transmission of LU information and less harvested power is allocated for IoT information transmission from AA by setting $\varphi > 0.5$. The received signal at IoD in the third phase can then be written as

$$Y^{(3)}_{t2}(t) = \sqrt{(1-\varphi)P_h h_r X_{t1}(t)} + \sqrt{\frac{\varphi P_h}{d_r^{\nu}}} h_r w(t) + n_r(t). \quad (12)$$

Based on the power level of two received signals, IoD can separate the stronger signal by perfect decoding of received LU signal and the desired IoT information (received weak signal). Finally, it can remove the stronger signal and therefore, the received signal at IoD is reexpressed as

$$Y^{(3)}_{t2}(t) = \sqrt{(1-\varphi)P_h h_r X_{t1}(t)} + n_r(t). \quad (13)$$

The instantaneous SNR at IoD from AA is expressed as

$$\gamma_5 = \frac{(1-\varphi)P_h |hr|^2}{\sigma_r^2}. \quad (14)$$

where $h_t$, $n_r(t)$, and $\sigma_r^2$ indicate channel co-efficient between AA and IoD, channel noise, and noise variance, respectively.

Now, the harvesting energy at IoD from power transmitter (following WPT principle) can be written as

$$E_{h3} = \frac{P_{ht} 3T}{4} |hr|^2 \quad (15)$$

where $P_{ht}$, $h_{ht}$, and $d_{ht}$ indicate the transmitted power from power transmitter, channel co-efficient of the link between
power transmitter and IoT, and the distance between power transmitter and IoT, respectively.

The harvested power at IoT (\(P_{h3} = [E_{h3}/(T/4)]\)) is applied in the fourth phase for signal transmission from IoT to AA. The received signal at AA can be written as

\[
y^{(4)}(t) = \frac{P_{h3}}{d^\gamma} h(t) X(t) + n(t)
\]

(16)

where \(X(t)\) indicates the transmitted signal from IoT to AA.

The instantaneous SNR at AA from IoT is

\[
y_0 = \frac{P_{h3}|y|^2}{\sigma^2}.
\]

(17)

III. OUTAGE ANALYSIS AND PROBLEM FORMULATION

A. LU Network Outage Analysis

The LU network outage can be expressed as

\[
\mathcal{P}_{\text{out}} = (1 - \mathcal{P}_{y_1 \geq \gamma_1}) \times \mathcal{P}_{y_2 \geq \gamma_2} \times \mathcal{P}_{y_3 \geq \gamma_3} \times \mathcal{P}_{y_4 \geq \gamma_4}
\]

where \(\gamma_1 = 2^{(2R_1 + 1)} - 1\), \(\gamma_2 = 2^{(2R_2 + 1)} - 1\), and \(\gamma_3 = 2^{4R_1} - 1\). \(R_1\), \(R_2\), and \(R_4\) indicate fixed transmission rates of LU communication in Phase-1, Phase-2, and Phase-3, respectively. Since Phase-1 is related to the transmission from VLC system over VLC link and Phase-2 is related to transmission over RF link, therefore, the target rates are considered to be different for Phase-1 and Phase-2. In addition to that, the transmission in Phase-3 is related to relaying of information based on the available harvesting energy and the harvesting energy is limited. As the amount of harvested energy is limited, therefore, it can support very small data rate compared to uplink and downlink transmission.

\[\mathcal{P}_{[y_1 \geq \gamma_1]}\] is determined using the probability density function (PDF) of VLC link coefficient. LED source is located at height \(L\) from AA and Euclidian distance \(d\), \(r_i\) is the radial distance as \(\cos(\theta) = \cos(\Phi) = (L/d_i)\) and \(d_i = (L^2 + r_i^2)^{1/2}\). Now, \(h_{vc}\) can be found as [28]

\[
h_L = \frac{\varepsilon(\varepsilon + 1)L^{5+1}}{(d_i)^{5+1}} = \frac{\varepsilon(\varepsilon + 1)L^{5+1}}{(L^2 + r_i^2)^{5+1}}
\]

(18)

where \(\varepsilon = (A_1/2\pi n)\). Since we consider the outdoor VLC link between VLC system and AA, therefore, the link follows Nakagami fading with gamma distribution as follows: \(\varepsilon(\varepsilon + 1)L^{5+1} = \frac{n_{ps}^{5+1} e^{-n_{ps}}}{\Gamma(n_{ps})}\). Symbol \(n_{ps}\) is used to indicate the shape factor of the Nakagami fading model.

Now, \(\mathcal{P}_{[y_2 \geq \gamma_2]}\) can be expressed as [29]

\[
\mathcal{P}_{[y_2 \geq \gamma_2]} = \mathcal{P}_{y_{vc} \geq \gamma_1} \Gamma\left(\frac{n_{ps} e^{-n_{ps} y_{vc}}}{\Gamma(n_{ps})}\right)
\]

(20)

where \(\gamma_{vc} = |h_{vc}|^2\), \(\gamma_1 = \left(\frac{\Phi L_{AP}^2}{4L^2\Delta W}\right)\), and \(\Gamma(\cdot, \cdot)\) indicates the upper incomplete Gamma function.

\(h_r\) and \(h_i\) also follow the Nakagami distribution. \(h_{jl}\) follows the Rayleigh distribution. \(|h_r|^2 = X_r\), \(|h_{jl}|^2 = X_{jl}\) and \(|h_l|^2 = X_l\). Now

\[
\mathcal{P}_{y_{vc} \geq \gamma_2} = \frac{\Gamma(n_{ps} e^{-n_{ps} y_{vc}})}{\Gamma(n_{ps})}
\]

(21)

where \(a_1 = \left([\gamma_2 d^{*}_n \rho^2] / ((1 - \rho) P_m)\right)\).

Here, the VLC link is considered to be reciprocal in nature. Therefore, \(y_{vc}\) can be written as \(y_{vc} = \gamma_{vc}\). Now, \(\mathcal{P}_{y_3 \geq \gamma_3}\) can be written as

\[
\mathcal{P}_{y_3 \geq \gamma_3} = \left[\mathcal{P}_{y_{vc} \geq \gamma_2} \left[\frac{a_1}{a_2} (a_1 y_{vc} + b_1 X_r) y_{vc} + 1 \geq \gamma_c \right]ight] + \left[\mathcal{P}_{y_{vc} \geq \gamma_2} \left[\frac{a_1}{a_2} (a_1 y_{vc} + b_1 X_r) y_{vc} + 1 \geq \gamma_c \right]ight]
\]

(22)

Now, \(\mathcal{P}_{y_{vc} \geq \gamma_2} \geq \left(\frac{u_{1c}}{a_1 y_{vc} + b_1 X_r}\right)\) can be determined as [30]

\[
\mathcal{P}_{y_4 \geq \gamma_4} = \left[\mathcal{P}_{X_r \geq \gamma_c} \frac{a_2}{a_1 y_{vc} + b_1 X_r} \right] + \left[\mathcal{P}_{X_r \geq \gamma_c} \frac{a_2}{a_1 y_{vc} + b_1 X_r} \right]
\]

(23)

Now, \(\mathcal{P}_{X_r \geq \gamma_c} \geq \left(\frac{u_{2c}}{a_1 y_{vc} + b_1 X_r}\right)\) can be determined as follows.

\[
\mathcal{P}_{X_r \geq \gamma_c} = \left[\frac{n_{ps} e^{-n_{ps} X_r}}{\Gamma(n_{ps})}\right]
\]

(24)

Now, \(\mathcal{P}_{X_r \geq \gamma_c} \geq \left(\frac{u_{2c}}{a_1 y_{vc} + b_1 X_r}\right)\) can be determined as follows.

\[
\mathcal{P}_{X_r \geq \gamma_c} = \left[\frac{n_{ps} e^{-n_{ps} X_r}}{\Gamma(n_{ps})}\right]
\]

(25)

where \(u_{1c} = \frac{\gamma_c}{\gamma_c y_{vc}}\), \(u_{2c} = \frac{\gamma_c}{\gamma_c y_{vc}}\), \(u_{1c} = \frac{\gamma_c^2 \delta A_{p}^2}{\sigma^2}\).
where \( \gamma_i = 2^{R_i} - 1 \), \( R_i \) indicates the fixed transmission rate of IoT communication.

\[
\beta_{out_c} = 1 - \left\{ \frac{\Gamma\left(\frac{\gamma_{1c}}{m_n, \gamma_{1c}(b_h^r)\Gamma(\gamma_m)}\right)}{\Gamma(n_m)} \times \left\{ \frac{n_m - 1}{\Gamma(n_m)} \sum_{l=0}^{\infty} \frac{\left(\frac{\gamma_{1c}}{m_n, \gamma_{1c}(b_h^r)\Gamma(\gamma_m)}\right)^l}{l! (\frac{\gamma_{1c}}{m_n, \gamma_{1c}(b_h^r)\Gamma(\gamma_m)})^{l+1}} \times \left\{ \frac{n_m - 1}{\Gamma(n_m)} \sum_{l=0}^{\infty} \frac{\left(\frac{\gamma_{1c}}{m_n, \gamma_{1c}(b_h^r)\Gamma(\gamma_m)}\right)^l}{l! (\frac{\gamma_{1c}}{m_n, \gamma_{1c}(b_h^r)\Gamma(\gamma_m)})^{l+1}} \right\} \right\}
\]

Now, (28) can be determined as [29, Sec. 3.381.2] and [30] with \( c_i = (\Gamma(1 - \varphi)/(\Gamma(\gamma_i^2/\sigma_i^2))) \).

\[
\beta_{out_a} = 1 - \left\{ \frac{\Gamma\left(\frac{\gamma_{1a}}{m_n, \gamma_{1a}(b_h^r)\Gamma(\gamma_m)}\right)}{\Gamma(n_m)} \times \left\{ \frac{n_m - 1}{\Gamma(n_m)} \sum_{l=0}^{\infty} \frac{\left(\frac{\gamma_{1a}}{m_n, \gamma_{1a}(b_h^r)\Gamma(\gamma_m)}\right)^l}{l! (\frac{\gamma_{1a}}{m_n, \gamma_{1a}(b_h^r)\Gamma(\gamma_m)})^{l+1}} \times \left\{ \frac{n_m - 1}{\Gamma(n_m)} \sum_{l=0}^{\infty} \frac{\left(\frac{\gamma_{1a}}{m_n, \gamma_{1a}(b_h^r)\Gamma(\gamma_m)}\right)^l}{l! (\frac{\gamma_{1a}}{m_n, \gamma_{1a}(b_h^r)\Gamma(\gamma_m)})^{l+1}} \right\} \right\}
\]
Finally, the closed-form outage expression of IoT communication can be found in (31), shown at the bottom of the previous page, using (20), (21), (29), shown at the bottom of the previous page, and (30).

C. Throughput Analysis

The throughput of LU network and IoT network can be expressed as

\[ T_C = 2 \times (1 - \mathcal{P}_{\text{out}}) \times R_c \times \frac{T}{4T} \]  
(32)

\[ T_I = 2 \times (1 - \mathcal{P}_{\text{out}}) \times R_I \times \frac{T}{4T}. \]  
(33)

D. High SNR Approximation

At high SNR region, closed-form expressions of LU outage and IoT outage can be approximated to (34) and (35), respectively. In case of high SNR approximation, \( \Gamma(N, x) \approx \Gamma(N) \exp(-x) \) for \( x < 1 \), \( \exp(-x) \approx 1 - x \) and \( K_0(x) \approx (1/2) \Gamma(\sigma)(2/\sigma)^{\sigma/2}, \sigma > 0 \) [29].

Now, the LU outage expression is approximated as

\[ \mathcal{P}_{\text{out}} \approx 1 - \left( 1 - \frac{n_m y_{1,m}}{y_{\sigma}(h_l)^2} \right) \times \left( 1 - n_m a_{l,m} \right) \times \left\{ n_m \sqrt{\frac{u_{l,m}}{a_h} + C_p \left( \frac{1}{b_h} \right)^{p_a+l} \left( \frac{1}{b_h} \right)^{p_a+l} \sum_{l=0}^{\infty} \frac{1}{l!} \sum_{j=0}^{\infty} \frac{1}{j!} \sum_{i=0}^{\infty} \frac{1}{i!} \right\} \right\} \]  
(34)

where

\[ C_p = \sum_{p_a=0}^{\infty} \left( n_m \right)^{p_a+l} \sum_{r=0}^{\infty} \left( \frac{p_a}{r+1} \right)^{n_a+p_a+l} \frac{1}{r!} \frac{1}{(2r+n_m-p_a-l+2n_l)} \frac{1}{(n_m)!} \]  
(35)

At high SNR, the IoT outage expression is approximated as

\[ \mathcal{P}_{\text{out}} \approx 1 - \left( 1 - \frac{n_m y_{1,m}}{y_{\sigma}(h_l)^2} \right) \times \left( 1 - n_m a_{l,m} \right) \times \left\{ C_i(a_h b_h)^{r}(b_h-a_h)^{p_a+r} \frac{1}{\Gamma(n_m)} \sum_{p_a=0}^{\infty} \frac{1}{r!} \sum_{r=0}^{\infty} \frac{1}{r!} \sum_{i=0}^{\infty} \frac{1}{i!} \right\} \right\} \]  
(36)

where

\[ C_i = \sum_{p_a=0}^{\infty} \left\{ \left( \frac{n_m}{r} \right)^{p_a-r} \left( \frac{p_a}{r} \right)^{p_a+r} \sum_{r=0}^{\infty} \frac{1}{r!} \sum_{i=0}^{\infty} \frac{1}{i!} \right\} \times \frac{1}{\Gamma(n_m)^2} \]  
(37)

E. Problem Formulation

Problem-1: The minimization of IoT network outage (\( \mathcal{P}_{\text{out}} \)), under the constraints of LU network outage threshold (\( \mathcal{P}_{\text{th}} \)), threshold of power allocation factor (\( \varphi_{th} \)), maximum transmission power limit of PSe and LED array of VT, and power transmitter (\( P_{tm} \), \( P_{dt} \), and \( P_{kt} \)), and target rate threshold of IoT communication (\( R_{th} \))

\[ \min_{\tau} \mathcal{P}_{\text{out}} \]  
(38)

s.t. \( C_1 : \mathcal{P}_{\text{out}} \leq \mathcal{P}_{\text{th}} \)  
\( C_2 : \varphi \geq \varphi_{th} \)  
\( C_3 : P_m \leq P_{tm}, P_L \leq P_{dt}, P_{bt} \leq P_{kt} \)  
\( C_4 : R_i \geq R_{th}. \)  
(39)

Problem-2: The minimization of IoT network outage (\( \mathcal{P}_{\text{out}} \)), under the constraints of IoT network outage threshold (\( \mathcal{P}_{\text{th}} \)), threshold of power allocation factor (\( \varphi_{th} \)), maximum transmission power limit of PSe and LED array of VT (\( P_{tm} \) and \( P_{dt} \)), and target rate threshold of IoT communication (\( R_{th} \))

\[ \min_{\tau} \mathcal{P}_{\text{out}} \]  
(40)

s.t. \( C_1 : \mathcal{P}_{\text{out}} \leq \mathcal{P}_{\text{th}} \)  
\( C_2 : \varphi \geq \varphi_{th} \)  
\( C_3 : P_m \leq P_{tm}, P_L \leq P_{dt}, P_{bt} \leq P_{kt} \)  
\( C_4 : R_i \geq R_{th}. \)  
(41)

Due to the nonlinear nature of the first derivative of both Problem-1 and Problem-2, it is not possible to determine the closed-form optimal solution of \( \tau \). Therefore, the range of \( \tau \) is possible to obtain through the one-way exhaustive searching technique.

IV. NUMERICAL RESULTS

The necessary parameters and their considered values are: \( \Theta_{1/2} = 20^\circ \), \( A_s = 0.04 \text{ m}^2 \), \( L = 3 \text{ m} \), \( r_i = (0, 2) \), \( d_i = (3, \sqrt{13}) \text{ m} \) [6], \( B_{dc} = 10 \text{ mA} \), \( \varphi = 0.4 \text{ A/W} \), \( \nu = 2.7 \), \( \sigma_1 = 10^{-21} \text{ W} \), \( A_p = 10 \text{ mA} \), \( f = 0.75 \), \( I_0 = 10^{-9} \text{ A} \), \( P_m = 1 \text{ W} \) (Figs. 3–6), \( \sigma_2 = 8 \mu\text{W} \), \( \rho = 0.9 \), \( \tau = 0.1 \), \( \eta = 0.9 \), \( P_{bt} = 1 \text{ W} \) (Figs. 4–8), \( d_m = 4 \text{ m} \), \( \varphi = 0.85 \), \( d_i = 6 \text{ m} \), \( d_{bt} = 10 \text{ m} \), and \( \sigma_2 = 3 \mu\text{W} \). Monte-Carlo simulation is executed to verify the validity of analytical output. The LU outage threshold and and IoT outage threshold are considered as \( \mathcal{P}_{\text{th}} = 0.1 \) and \( \mathcal{P}_{\text{th}} = 0.2 \), respectively.

Fig. 3 illustrates the outage performances of both LU and IoT network with respect to the variation of \( \tau \) for different values of \( \varphi \) (considering \( \varphi_{th} = 0.7 \)) with \( N_L = 15 \), \( P_L = 150 \text{ mW} \), \( P_{bt} = 2 \text{ W} \), \( R_{c1} = R_{c2} = R_c = 0.4 \text{ bps} \), and \( R_i = 0.25 \text{ bps} \). Simulation results match analytical outputs properly. Due to more power allocation for relaying LU information and less power allocation for IoT communication, LU outage performance improves and IoT outage performance deteriorates with increasing \( \varphi \). As shown in this figure, it is also observed that initially, the outage performances of both LU and IoT networks are improved with increasing \( \tau \) and after reaching the minimum value, the outage performances are degraded with the further increase in \( \tau \).
Fig. 4 depicts both LU and IoT outage performances with the variation of $A_P$ for different values of $\tau$. As achievable rate of information transmission from VT to AA is increased with the increase in $A_P$, therefore, both the outage performances are improved with increasing $A_P$. The worst outage performance is found at $\tau = 0.5$ and the variation of IoT outage is insignificant as compared to LU outage for different values of $\tau$. LU outage performance is found to be the best at $\tau = 0.1$.

Fig. 5(a)–(c) shows the LU network outage performance, IoT network outage, and throughput performances, respectively, with respect to the variation of both $\rho$ and $\tau$ for $N_L = 20$, $P_L = 200$ mW, $P_{bt} = 1$ W, $R_{c1} = 1.4$ bps, $R_{c2} = 0.8$ bps, $R_c = 0.4$ bps, and $R_i = 0.25$ bps. The nature of the plot of Fig. 5(a) is exactly convex in nature. When $\tau$ is very less for fixed value of $\rho$, the achievable rate of VT→AA is very poor. The outage performance is gradually improved with the increasing value of $\tau$ and it attains the minimum value for an optimum value of $\tau$. If $\tau$ is increased beyond 0.1, then the performance is degraded further. From Fig. 5(b), it is found that the performance of IoT outage is also improved with the increasing value of $\tau$ and it is also observed from the set of results that the performance is degraded when $\tau$ is found to be very high. Even if the transmission power of PSe is very high, the performance of IoT outage is also degraded with the increasing value of target rate threshold.

As shown in Fig. 5(a), the LU outage performance is found to be worse at $\rho \to 0$ and $\rho \to 1$ for some fixed $\tau$. Gradually, the outage performance is improved with the increase in $\rho$ and it reaches the minimum value for an optimum value of $\rho$. Further enhancement of $\rho$ results in the deterioration of LU performance in terms of outage. The reason behind this graphical plot can be demonstrated as follows. Initially, when $\rho$ is very small, the harvesting energy (following the SWIPT protocol in Phase-2) is insufficient to transmit information from AA. The harvesting energy is improved with an increase in $\rho$. After reaching the minimum value of outage, if $\rho$ is increased again, then the data transmission from PSe to AA is failed to meet the target rate of data transmission. Consequently, the outage performance is degraded. Over the certain range of $\rho$ ($\sim 0.58–0.99$) and $\tau$ ($\sim 0.09–0.34$), the outage probability of the LU network is found to be less than or equal to 10% outage threshold. This specific range is used to investigate outage probability and throughput of the IoT network. As shown in Fig. 5(b) and (c), the minimum IoT outage (9.56%) and the maximum IoT throughput (0.113 bps/Hz) are found at $\tau = 0.09$ and $\rho = 0.98$, respectively. Similar plot is also obtained in Fig. 6(b) to minimize the LU outage probability maintaining 20% IoT outage threshold constraint [in Fig. 8(a)]. Over the range of $\rho$ ($\sim 0.44–0.96$) and $\tau$ ($\sim 0.09–0.69$), IoT network outage is found to be less than or equal to 20% outage threshold. As shown in Fig. 6(b) and (c), the minimum LU outage (5%) and the maximum LU throughput (0.19 bps/Hz) are found at $\tau = 0.11$ and $\rho = 0.96$.

Fig. 7(a)–(c) illustrates the LU network outage performance, IoT network outage, and throughput performances, respectively, with respect to the variation of both VT LED power and PSe power for $N_L = 25$, $R_{c1} = 1.4$ bps, $R_{c2} = 0.8$ bps, $R_c = 0.4$ bps, and $R_i = 0.25$ bps. Outage plot is exactly intuitive in nature and the performances are improved with the increase in both LED power and PSe power. The outage performance is also reflected in the performance of IoT throughput. LU outage is found to be less than or equal to 10% outage threshold for $P_L \geq 50$ mW and $P_m \geq 0.55$ W. IoT outage and throughput are investigated over this region. As shown in Fig. 7(b) and (c), the minimum IoT outage is found as 10% and the maximum IoT throughput is found as 0.1123 bps/Hz, respectively. Similar result is also obtained in Fig. 8(b) to minimize LU outage maintaining 20% IoT outage threshold constraint [in Fig. 8(a)]. IoT outage is found to be less than or equal to 20% outage threshold for $P_L \geq 50$ mW and $P_m \geq 0.1$ W. As shown in Fig. 8(b) and (c), the minimum LU outage is found as 4% and the maximum LU throughput is found as 0.192 bps/Hz, respectively.
V. CONCLUSION

This work shows the efficacy of the hybrid VLC and RF system to enhance data rate with better reliability. Closed-form outage expressions of both two-way LU and two-way IoT communications are derived for the overlay mode of spectrum-sharing technique of CCRN using the DF relaying scheme. Exhaustive searching technique is applied to solve constrained outage minimization problems of both LU and IoT.
communications. Simulation results are used to validate the mathematical analysis of the proposed system. From the numerical results, it is found that optimum outage performance is possible to achieve by allocating more time for EH from RF source compared to VLC source.

REFERENCES

[1] L. E. M. Matheus, A. B. Vieira, L. F. M. Vieira, M. A. M. Vieira, and O. Gnawali, “Visible light communication: concepts, applications and challenges,” IEEE Commun. Surveys Tuts., vol. 21, no. 4, pp. 3204–3237, 4th Quart., 2019.

[2] J. Al-Khorni, G. Nauryzbayev, M. M. Abdalllah, and M. Hamdi, “Joint beamforming design and power minimization for friendly jamming relaying hybrid RF/VLC systems,” IEEE Photon. J., vol. 11, no. 2, pp. 1–18, Apr. 2019.

[3] V. K. Papanikolou, P. D. Diamantoulakis, P. C. Sofotasios, S. Muhaidat, and G. K. Karagiannidis, “On optimal resource allocation for hybrid VLC/RF networks with common backhaul,” IEEE Trans. Cogn. Commun. Netw., vol. 6, no. 1, pp. 352–365, Mar. 2020.

[4] S. I. Mushfique, P. Palathingal, Y. S. Eroglu, M. Yuksel, I. Guvenc, and N. Pala, “A software-defined multi-element VLC architecture,” IEEE Commun. Mag., vol. 56, no. 2, pp. 196–203, Feb. 2018.

[5] C. Zhang, J. Ye, G. Pan, and Z. Ding, “Cooperative hybrid VLC/RF systems with spatially random terminals,” IEEE Trans. Commun., vol. 66, no. 12, pp. 6396–6408, Dec. 2018.

[6] H. Peng, Q. Li, A. Pandharipande, X. Ge, and J. Zhang, “End-to-end performance optimization of a dual-hop hybrid VLC/RFIoT system based on SLIPT,” IEEE Internet Things J., vol. 8, no. 24, pp. 17356–17371, Dec. 2021.

[7] M. Obeed, H. Dahrouj, A. M. Salhab, S. A. Zummo, and M.-S. Alouini, “User pairing, link selection, and power allocation for cooperative NOMA hybrid VLC/RF systems,” IEEE Trans. Wireless Commun., vol. 20, no. 3, pp. 1785–1800, Mar. 2021.

[8] M. G. Nauryzbayev, M. Abdalllah, I. S. Ansari, N. Al-Dhahir, and K. Qaraqe, “Outage of cognitive electric vehicle networks over mixed RF/VLC channels with signal-dependent noise and imperfect CSI,” IEEE Trans. Veh. Technol., vol. 69, no. 6, pp. 6828–6832, Jun. 2020.

[9] Y. Wang, D. A. Basnayaka, X. Wu, and H. Haas, “Optimization of load balancing in hybrid LiFi/RF networks,” IEEE Trans. Commun., vol. 65, no. 4, pp. 1708–1720, Apr. 2017.

[10] G. Pan, P. D. Diamantoulakis, Z. Ma, Z. Ding, and G. K. Karagiannidis, “Simultaneous lightwave information and power transfer: Policies, techniques, and future directions,” IEEE Access, vol. 7, pp. 28250–28257, 2019.

[11] H.-V. Tran, G. Kaddour, P. D. Diamantoulakis, C. Abou-Rjeily, and G. K. Karagiannidis, “Ultra-small cell networks with collaborative RF and lightweight power transfer,” IEEE Trans. Commun., vol. 67, no. 9, pp. 6243–6255, Sep. 2019.

[12] B. Clerckx, K. Huang, L. R. Varshney, and G. K. Karagiannidis, “Wireless power transfer for future networks: Signal processing, machine learning, computing, and sensing,” IEEE J. Sel. Topics Signal Process., vol. 15, no. 5, pp. 1060–1094, Aug. 2021.

[13] S. T. Shah, K. W. Choi, S. F. Hasan, and M. Y. Chng, “Throughput analysis of two-way relay networks with wireless energy harvesting capabilities,” Elsevier J. Ad Hoc Netw., vol. 53, pp. 123–131, Dec. 2016.

[14] T. Elgohary, H. Yang, F. Gebali, and M.-S. Alouini, “Optimal design of dual-hop VLC/RF communication system with energy harvesting,” IEEE Commun. Lett., vol. 20, no. 10, pp. 1979–1982, Oct. 2016.

[15] M. Obeed, H. Dahrouj, A. M. Salhab, A. Chaaban, S. A. Zummo, and M.-S. Alouini, “Power allocation and link selection for multicell cooperative NOMA hybrid VLC/RF systems,” IEEE Commun. Lett., vol. 25, no. 2, pp. 560–564, Feb. 2021.

[16] Y. Xiao, P. D. Diamantoulakis, Z. Fang, L. Hao, Z. Ma, and G. K. Karagiannidis, “Cooperative hybrid VLC/RF systems with SLIPT,” IEEE Trans. Commun., vol. 69, no. 4, pp. 2532–2545, Apr. 2021.

[17] A. Asadi, Q. Wang, and V. Mancuso, “A survey on device-to-device communication in cellular networks,” IEEE Commun. Surveys Tuts., vol. 16, no. 4, pp. 1801–1819, 4th Quart. 2014.

[18] P. Gandotra and R. K. Jha, “Device-to-device communication in cellular networks: A survey,” Elsevier J. Netw. Comput. Appl., vol. 71, pp. 99–117, Aug. 2016.

[19] Y. Li, K. Chi, H. Chen, Z. Wang, and Y. Zhu, “Narrowband Internet of things systems with opportunistic D2D communication,” IEEE Internet Things J., vol. 5, no. 3, pp. 1474–1484, Jun. 2018.

[20] X. Chen, D. W. K. Ng, W. Yu, E. G. Larsson, N. Al-Dhahir, and R. Schober, “Massive access for 5G and beyond,” IEEE J. Sel. Areas Commun., vol. 39, no. 3, pp. 615–637, Mar. 2021.

[21] A. Goldsmith, S. A. Jafar, M. I. Maric, and S. Srinivasa, “Breaking spectrum gridlock with cognitive radios: An information theoretic perspective,” Proc. IEEE, vol. 97, no. 5, pp. 894–914, May 2009.

[22] Y. Han, A. Pandharipande, and S. H. Ting, “Cooperative decode-and-forward relaying for secondary spectrum access,” IEEE Trans. Wireless Commun., vol. 8, no. 10, pp. 4945–4950, Oct. 2009.

[23] L. I. Albraheem, L. H. Alhadaithy, A. A. Aljaser, M. R. Alhdaifian, and G. M. Bahliwah, “Toward designing a Li-Fi-based hierarchical IoT architecture,” IEEE Access, vol. 6, pp. 40811–40825, 2018.

[24] J. Jin, J. Gubbi, S. Marusic, and M. Palaniswami, “An information framework for creating a smart city through Internet of Things,” IEEE Internet Things J., vol. 1, no. 2, pp. 112–121, Apr. 2014.

[25] C.-M. Kim and S.-J. Koh, “Device management and data transport in IoT networks based on visible light communication,” Sensors, vol. 18, no. 8, pp. 1–17, 2018.

[26] S. Zargari, M. Kolivand, S. A. Nezamalhosseini, B. Abolhassani, L. R. Chen, and M. H. Kakaie, “Resource allocation of hybrid VLC/RF Systems with light energy harvesting,” IEEE Trans. Green Commun. Netw., vol. 6, no. 1, pp. 600–612, Mar. 2022, doi: 10.1109/TGCOM.2021.3097051.

[27] L. Yin, W. O. Popoola, X. Wu, and H. Haas, “Performance evaluation of non-orthogonal multiple access in visible light communication,” IEEE Trans. Commun., vol. 64, no. 12, pp. 5162–5175, Dec. 2016.

[28] A. Gupta, P. Garg, and N. Sharma, “Hybrid LiFi-WiFi indoor broadcasting system,” in Proc. IEEE 28th Annu. Int. Symp. Personal Indoor Mobile Radio Commun. (PIMRC), Montreal, QC, Canada, Oct. 2017, pp. 1–6, doi: 10.1109/PIMRC.2017.8292476.

[29] I. S. Gradshteyn and I. M. Ryzhik, Table of Integrals, Series, and Products, 7th ed. Amsterdam, The Netherlands: Academic, 2007.

[30] S. Ghosh, T. Acharya, and S. P. Mailt, “Outage analysis in SWIPT enabled cooperative AF/DF relay assisted two-way spectrum sharing communication,” 2020, arxiv:2007.08599.