Energy- vs Spectral-Efficiency for Energy-Harvesting Hybrid RF/VLC Networks

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***Abstract*—We consider a hybrid radio frequency (RF) / visible light communications (VLC) scenario where the RF link is empowered by the energy harvested during the VLC transmission. We take into account the power consumption of the access point (AP), which is composed of light emitting diodes (LEDs), while it is communicating with a far user over a two-hop hybrid RF/VLC link. In particular, we consider the energy efficiency of the end-to-end network in enhancing the energy-harvesting performance by choosing the optimal direct current (DC) bias, which is overlooked in the existing literature. To this end, we model the energy consumption of the commercially available LEDs, and formulate a joint energy- and spectral-efficiency optimization problem. The extreme cases of optimizing energy and spectral efficiency individually underscores the importance of optimizing the DC bias for a given joint (multi-objective) optimization problem.**

***Index Terms*—DC bias, energy efficiency, hybrid RF/VLC, multi-objective optimization, spectral efficiency.**

I. Introduction

The VLC networks offer promising solution to the spectrum scarcity in the conventional RF spectrum [1]–[3]. The use of license-free spectrum at the visible light wavelengths of $380-750$ nm brings the opportunity of carrying out transmission at a very high data rate. The communication channels at this extremely high frequency regime, however, mainly rely on the availability of the optical line-of-sight (LoS) links [4]–[6]. The performance loss of the VLC links in real-life environments with many obstacles, which degrades the probability of having LoS sight, can be relieved through the hybrid use of RF and VLC links.

The hybrid RF/VLC communications have attracted a great attention recently from both the industry and academia in an attempt to establish robust and high-speed data transmission strategies [7]–[11]. In [7], a two-hop hybrid VLC/RF topology is considered to extend the coverage of the VLC link through an energy-harvesting relay node, which retransmits the received optical signal over the RF link. [8] proposes a cooperative non-orthogonal multiple access (NOMA) transmission in a hybrid VLC/RF network where each weak user is served either directly by the optical AP, or by the respective energy-harvesting strong user over the RF link. A hybrid VLC/RF indoor Internet-of-Things (IoT) system is considered in [9] where the energy-harvesting terminals are randomly deployed in the 3D space. In particular, while multiple LEDs are serving IoT terminals in the VLC downlink with both information and power, the uplink transmission occurs over the RF link through NOMA using the harvested energy at the terminals. [10] proposes an indoor hybrid VLC/RF downlink where an optical AP serves two randomly deployed users simultaneously through NOMA, and the performance of the far user is improved through near user carrying out RF relaying (i.e., the far user is served either by mixed RF/VLC or the direct VLC link). [11] considers a hybrid RF/VLC ultra-small network where multiple optical angle-diversity transmitters serve multiple users through simultaneous wireless information and power transfer (SWIPT), and a multiple-antenna AP also sends power to the users over the RF link to help improve the efficiency.

Despite all these recent works investigating various aspects of the hybrid RF/VLC scenarios, the *energy efficiency* of the end-to-end system with *realistic LED power consumption* is missing in the literature. In this work, we therefore formulate a joint energy- and spectral-efficiency optimization problem for a two-phase energy-harvesting hybrid RF/VLC scenario. In particular, we model the exact current-voltage (I-V) characteristics of several commercially available LEDs on the market, and compute the model variables numerically. Exploiting the power consumption of the LEDs as a function of the DC bias, we investigate the energy-efficiency performance of the end-to-end hybrid RF/VLC network in comparison to spectral efficiency performance. The numerical results reveal the fact that the spectral-efficiency and energy-efficiency behaviors of the overall network exhibit an exact opposite trend for varying DC bias (i.e., one feature is improving while the other is deteriorating, and vice versa).

The rest of the paper is organized as follows. Section II overviews the transmission scenario for the hybrid RF/VLC network under consideration. The end-to-end rate and energy efficiency are formulated in III along with the respective optimization problem. The numerical results are presented in Section IV, and the paper concludes with Section V.

II. System Model

We consider a hybrid RF/VLC communications scenario where an access point (AP) intends to communicate with a far user by means of a relay, as in the illustration in Fig. 1. We assume that the AP is composed of a cluster of N co-located LEDs, and the relay is equipped with a single photodetector (PD), energy-harvesting circuity, and a transmit antenna for RF

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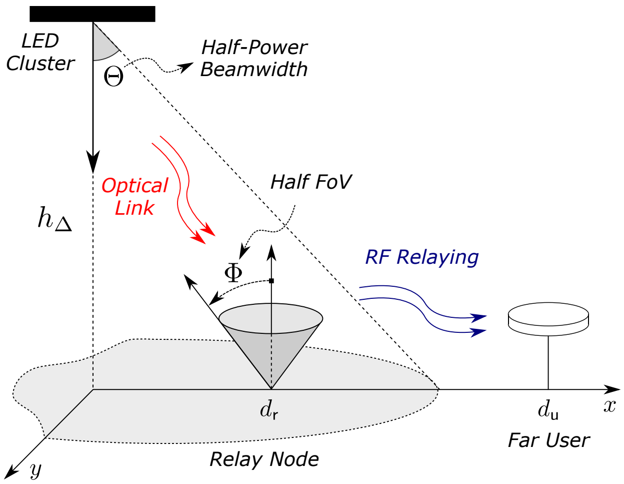

Fig. 1. System model for the RF/VLC transmission scenario.

communications. The overall transmission process completes in two consecutive phases. In the first phase, the AP is transmitting *both information* and *energy* towards the relay node through a VLC link. In the second phase, the relay node is conveying the information transmitted by the LEDs to the far user (possibly outside the coverage of the AP) over RF link using the energy harvested during the first phase.

The LEDs are assumed to add a DC-bias I_{b} to the information-bearing signal $m(t)$ to satisfy the non-negativity constraint. In addition, the overall bias current $I(t) = m(t) + I_{\mathsf{b}}$ should be both lower- and upper-limited such that $I(t) \in [I_{\mathsf{min}}, I_{\mathsf{max}}]$ where I_{min} and I_{max} are the minimum and maximum allowable bias currents for the LED under consideration. The bias current $I(t)$ therefore satisfies both the minimum illumination and human eye-safety requirements, and complies with the LED operation specifications. We assume that the information-bearing signal is zero-mean, and satisfies the peak-intensity constraint of the optical channel such that

$$A = \min\left(I_{\mathsf{max}} - I_{\mathsf{b}}, I_{\mathsf{b}} - I_{\mathsf{min}}\right), \tag{1}$$

and $m(t)$ is designed so that $A_{\mathsf{m}} = \max(|m(t)|) \le A$. In our particular setting, we assume that $A_{\mathsf{m}} = A$.

The received signal at the relaying node is split into two such that the DC part is forwarded to the energy-harvesting unit, and the alternating current (AC) part is transferred to the PD for detection. The relaying operation is, hence, of decode-and-forward (DaF) type. The normalized information rate associated with the optical link between the AP and relay node is given as follows

$$R_{\mathsf{VLC}} = \log_2\left(1 + \frac{e}{2\pi}\frac{\left(\rho_{\mathsf{eo}}\rho_{\mathsf{oe}} N h_{\mathsf{VLC}} A\right)^2}{\sigma^2}\right), \tag{2}$$

where ρ_{eo} and ρ_{oe} are the electrical-to-optical (E/O) and optical-to-electrical (O/E) conversion ratios, respectively, h_{VLC} is the optical DC channel gain, and σ^2 is the power of the shot noise at the PD which is given as

$$\sigma^2 = q_{\mathsf{e}} I_{\mathsf{i}}\,\mathsf{B}, \tag{3}$$

where q_{e} is the charge of an electron, I_{i} is the induced current due to the ambient light, and B is the double-sided signal bandwidth. In addition, the optical DC channel gain is

$$h_k = \frac{(m+1)A_{\mathsf{p}}}{2\pi(h_\Delta^2 + d_{\mathsf{r}}^2)}\cos^m(\phi_{\mathsf{r}})\cos(\theta_{\mathsf{r}})\,\Pi\left(|\theta_{\mathsf{r}}|, \Phi\right), \tag{4}$$

where h_Δ and d_{r} are the vertical and horizontal distances, respectively, between AP and the relay node, and ϕ_{r} and θ_{r} are the respective angle of irradiance and incidence, respectively. The Lambertian order is $m = -1/\log_2(\cos(\Theta))$ where Θ is the half-power beamwidth of each LED, and A_{p} and Φ are the detection area and half field-of-view (FoV) of the PD, respectively. The function $\Pi(x, y)$ is 1 whenever $x \le y$, and is 0 otherwise. We also assume that the relay node distance d_{r} follows a Uniform distribution with $\mathcal{U}\left[d_{\mathsf{r}}^{\mathsf{min}}, d_{\mathsf{r}}^{\mathsf{max}}\right]$, and that relay PD is looking directly upward.

The harvested energy at the relaying node is computed as

$$E_{\mathsf{h}} = 0.75\tau_{\mathsf{h}} I_{\mathsf{DC}} V_{\mathsf{t}} \ln\left(1 + \frac{I_{\mathsf{DC}}}{I_0}\right), \tag{5}$$

where τ_{h} is the duration of harvesting, V_{t} is the thermal voltage, I_0 is the dark saturation current, and I_{DC} is the DC part of the output current given as

$$I_{\mathsf{DC}} = \rho_{\mathsf{eo}}\rho_{\mathsf{oe}} N h_{\mathsf{VLC}} I_{\mathsf{b}}. \tag{6}$$

The harvested energy is then used to transmit the detected symbol at the relay node to the far user over an RF link. We assumed that the user is off the AP horizontally by a distance d_{u}, which follows a Uniform distribution with $\mathcal{U}\left[d_{\mathsf{u}}^{\mathsf{min}}, d_{\mathsf{u}}^{\mathsf{max}}\right]$. The respective normalized information rate (i.e., spectral efficiency) is given as follows

$$R_{\mathsf{RF}} = \log_2\left(1 + \frac{P_{\mathsf{h}}\, E_{\mathsf{m}}\, |h_{\mathsf{RF}}|^2}{N_0}\right), \tag{7}$$

where $P_{\mathsf{h}} = E_{\mathsf{h}}/\tau_{\mathsf{t}}$ is the transmit power with τ_{t} being the duration of transmission, ε is the average signal energy given as $E_{\mathsf{m}} = \mathsf{E}\{m(t)^2\}$, and h_{RF} is the flat-fading RF channel including the path loss. In addition, the noise power N_0 is is defined as follows

$$N_0 = \mathsf{P}_0 + 10\log_{10}(\mathsf{B}) + \mathsf{N}_{\mathsf{F}}, \tag{8}$$

where P_0 is the thermal noise power, and N_{F} is the noise figure. The overall normalized transmission rate from AP to the user (or, equivalently, spectral efficiency) is then given as

$$R_{\mathsf{SE}} = \min\left\{R_{\mathsf{VLC}}, R_{\mathsf{RF}}\right\}. \tag{9}$$

III. End-To-End Spectral and Energy Efficiency

The optical data rate given by (2) is primarily dominated by the peak optical intensity A, which is determined by the DC bias I_{b} through (1). Note that assuming $I_{\mathsf{b}} \ge (I_{\mathsf{min}} + I_{\mathsf{max}})/2$, small I_{b} values make A larger, and, hence, enhance the optical data rate in (2). On the other hand, the rate over RF link in (7) is driven by the DC bias I_{b} through the energy-harvesting operation described in (5), for which larger I_{b} values produce a greater RF data rate in (7). The value of the DC bias I_{b} is therefore a compromise between VLC and RF data rates.

While I_{b} is the main driving source of the rate performance, the cost of varying I_{b} manifests itself in the energy consumption of the LED cluster at AP. The average electrical power at any LED is given as follows

$$P_{\mathsf{LED}} = \mathsf{E}\left\{V(t)I(t)\right\}, \tag{10}$$

where $V(t)$ is the voltage across the LED and $I(t)$ is the overall bias current flowing through the LED. Note that $I(t)$ is determined by the information-bearing signal $m(t)$ and the DC bias I_{b}. The respective voltage $V(t)$ is determined through the I-V characteristic, which is unique to any LED. Theoretically, the I-V characteristic is generally modeled by Shockley equation, which relates the voltage across a p-n junction diode and the forward current as follows

$$V(t) = nV_{\mathsf{t}} \ln\left(1 + \frac{I(t)}{I_{\mathsf{s}}}\right), \tag{11}$$

where n is the ideality factor, and I_{s} is the reverse saturation current. Most of the commercial LEDs, however, have a linear I-V characteristic for sufficiently high forward current due to the parasitic resistances, which is given as follows

$$V(t) = V_0 + R_{\mathsf{s}} I(t), \tag{12}$$

where V_0 and R_{s} are model parameters (specific to any particular LED) representing the *cutoff voltage* and *serial parasitic resistance*, respectively. The respective average electrical power is therefore given as

$$\begin{aligned} P_{\mathsf{LED}} &= \mathsf{E}\left\{\left(V_0 + R_{\mathsf{s}}\left(m(t)+I_{\mathsf{b}}\right)\right)\left(m(t)+I_{\mathsf{b}}\right)\right\}, && (13)\\ &= \left(V_0 + R_{\mathsf{s}} I_{\mathsf{b}}\right) I_{\mathsf{b}} + E_{\mathsf{m}} R_{\mathsf{s}}, && (14)\end{aligned}$$

which uses the previous assumption of $m(t)$ being zero-mean (i.e., $\mathsf{E}\{m(t)\} = 0$).

Note that while maximizing end-to-end information rate (or, equivalently, spectral efficiency) is widely adopted as the objective function, energy efficiency is yet another related performance measure which is mostly overlooked in the related literature. In an attempt to incorporate the energy efficiency into the system design, we consider jointly optimizing the spectral and energy efficiency. The corresponding multi-objective optimization problem can be described in a scalar form as follows

$$\begin{aligned} \max_{I_{\mathsf{b}}} \quad & \beta\,\theta_{\mathsf{EE}} \frac{R_{\mathsf{SE}}}{P_{\mathsf{LED}}} + (1-\beta)\,\theta_{\mathsf{SE}} R_{\mathsf{SE}}, && (15)\\ \text{s.t.} \quad & I_{\min} \le I_{\mathsf{b}} \le I_{\max} && (15a)\end{aligned}$$

where $\beta \in [0,1]$ is the weight (priority) of the energy efficiency problem, and θ_{EE} and θ_{SE} are the normalization coefficients to make two objective functions spanning the same range of values. Note that $\beta = 0$ corresponds to the spectral-efficiency optimization problem while $\beta = 1$ results in the energy-efficiency optimization. Note also that both the overall spectral efficiency R_{SE} and the power consumption P_{LED} are functions of the DC bias I_{b}, and, hence, I_{b} needs to be optimized to produce the best tradeoff between the spectral and energy efficiency for a given priority β. As a final remark, practical values of the normalization coefficients θ_{EE} and θ_{SE} can be taken as the value of the unnormalized cost function of (15) at the optimum point for $\beta = 1$ and $\beta = 0$.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
User distance ($d_{\mathsf{u}}^{\min}$, $d_{\mathsf{u}}^{\max}$)	$(4, 10)$ m
Relay distance ($d_{\mathsf{r}}^{\min}$, $d_{\mathsf{r}}^{\max}$)	$(0, 4)$ m
Noise figure (N_F)	9 dB
Signal bandwidth (B)	10 MHz
Thermal noise (P_0)	-174 dBm/Hz
Frequency (f_{c})	2.4 GHz
Minimum DC bias ($I_{\min}$)	100 mA
Maximum DC bias ($I_{\max}$)	1 A
Number of LEDs (N)	5
E/O conversion ratio (ρ_{eo})	4 W/A
O/E conversion ratio (ρ_{oe})	0.53 A/W
Time ratio ($\tau_{\mathsf{h}}/\tau_{\mathsf{t}}$)	1
Thermal voltage (V_{t})	25 mV
Dark saturation current (I_0)	10^{-10} A
Half FOV (Φ)	60°
Half-power beamwidth (Θ)	60°
Electron charge (q_{e})	1.6×10^{-19}
Induced current (I_{i})	5840×10^{-6} A
PD detection area (A_{p})	10^{-4} m^2
AP relative height (h_{Δ})	2 m

Due to the ratio in the energy-efficiency maximization, (15) is in the class of fractional programming. Following the Dinkelbach approach, the objective function of (15) can transformed into non-fractional form as follows

$$\begin{aligned} f\left(I_{\mathsf{b}}, \lambda^{(k-1)}\right) = &\left[\beta\,\theta_{\mathsf{EE}} + (1-\beta)\,\theta_{\mathsf{SE}} P_{\mathsf{LED}}^{(k)}\right] R_{\mathsf{SE}}^{(k)} \\ &- \lambda^{(k-1)} P_{\mathsf{LED}}^{(k)}, \end{aligned} \tag{16}$$

where $\lambda^{(k-1)}$ is the maximum value of the objective function in (15) at the $(k-1)$-th iteration, and can be obtained through Dinkelbach algorithm for given $R^{(k-1)}$ and $P_{\mathsf{LED}}^{(k-1)}$. For a given $\lambda^{(k-1)}$, the equivalent objective function in (16) needs to be maximized over $I_{\mathsf{b}} \in [I_{\min}, I_{\max}]$ to compute the optimal $R_{\mathsf{SE}}^{(k)}$ and $P_{\mathsf{LED}}^{(k)}$. Note that (16) is a non-convex function of the DC bias I_{b}, and the techniques to obtain a convex equivalent form is not considered within the scope of this study. We, instead, consider the two extreme cases in the next section, and leave the complete solution as a future work.

IV. Numerical Results

In this section, we present numerical results considering two extreme cases with $\beta \in \{0, 1\}$, which correspond to solely spectral- and energy-efficiency maximization, respectively. We adopt the 3GPP channel model for indoor hotspot (InH) environment for the RF link between the relay node and user, which has the following path loss

$$\mathsf{PL}(x) = 32.4 + 17.3 \log_{10}(x) + 20 \log_{10}(f_{\mathrm{c}}), \tag{17}$$

where x is the LoS distance (between the relay node and user), and f_{c} is the carrier frequency [12]. We present the complete list of simulation parameters in Table I.

We consider three commercial LEDs available on the market: OSRAM Golden DRAGON® [13], CREE XLamp XR-E [14], and LUMILEDS LUXEON Rebel [15]. The exact

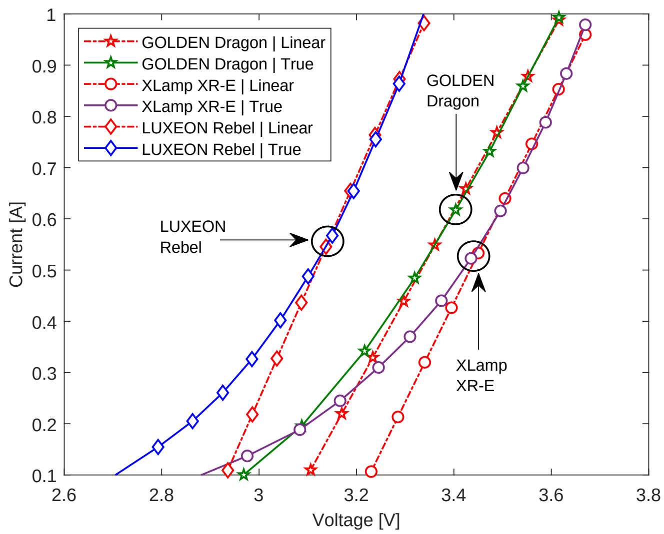

Fig. 2. Exact and approximated I-V characteristics of the LEDs.

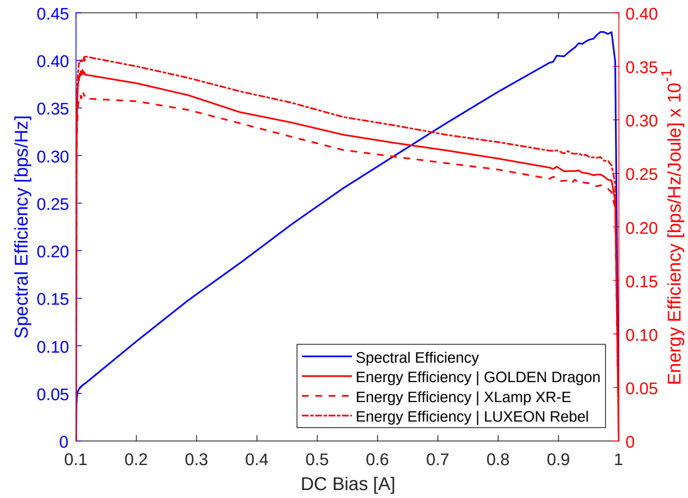

Fig. 3. Spectral- and energy-efficiency of the hybrid RF/VLC network.

I-V characteristics of these particular LEDs are depicted in Fig. 2. We also model these I-V curves through the linear approximation of (12) using the cutoff voltage V_0 and serial parasitic resistance R_s. The respective model parameters are computed by numerical methods as given in Table II, and corresponding performance curves are depicted in Fig. 2. We observe that although the parasitic resistance of the LEDs are similar, cutoff voltages are different which results in the I-V curves shifted horizontally (i.e., along the voltage axis). Note also that all three I-V characteristic curves become sufficiently linear after the voltage values greater than $3.1 - 3.45$ V.

TABLE II
I-V MODEL PARAMETERS FOR LEDS

LED	V_0 (V)	R_s (Ω)
OSRAM Golden DRAGON	3	0.58
CREE XLamp XR-E	3.2	0.52
LUMILEDS LUXEON Rebel	2.9	0.46

We present the greedy-based spectral and energy efficiency results in Fig. 3 for varying DC bias. We observe that the spectral- and energy-efficiency performance of all these three LEDs are exactly opposite to each other along with varying DC bias (i.e., one is increasing while the other is decreasing, and vice versa). This observation points out the fact that the DC bias should be optimized to achieve the best spectral and energy efficiency tradeoff for a given weight β (priority) in the optimization of (15). We also observe how the energy-efficiency performance changes with the LED choice. In particular, LUXEON Rebel turns out to be more energy efficient under the given simulation environment, which is consistent with its I-V curve in Fig 2 being at the leftmost side. As the I-V operation region Fig 2 shifts right, which ends up with higher voltages for similar DC bias values, the energy consumption increases, and GOLDEN Dragon and XLamp XR-E accordingly become less energy efficient.

V. CONCLUSION

We considered a hybrid RF/VLC communications scenario in which a VLC AP communications with a far user by means of a relay node equipped with energy-harvesting circuitry. We model the energy consumption of various LEDs available on the market, and investigate the end-to-end spectral- and energy-efficiency performance. The results underscore the importance of optimizing the DC bias in obtaining the best tradeoff between spectral and energy efficiency for a given priority.

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