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On the Design of Rate Adaptation for Relay-Assisted Satellite Hybrid FSO/RF Systems

Thang V. Nguyen, *Student Member, IEEE*, Hoang D. Le, *Member, IEEE*, Ngoc T. Dang, *Member, IEEE* and Anh T. Pham, *Senior Member, IEEE*

Abstract—This paper addresses the design of hybrid free-space optical/radio frequency (FSO/RF) systems for a high-altitude platform (HAP)-aided relaying satellite communication for mobile networks supported by unmanned aerial vehicle (UAV). While prior work primarily focused on fixed-rate design, which frequently switches between FSO and RF lead reduced the system performance, we propose a rate adaptation design that gradually adjusts the data rate in each link when its channel state fluctuates, under a target bit error rate (BER) constraint. The proposed design's downlink performance is analyzed, taking into account many challenging issues, including beam spreading loss, cloud attenuation, statistical behaviors of the atmospheric turbulence in the dual-hop channel, and pointing misalignment due to the UAV hovering. Different performance metrics are analytically derived based on channel modelings, including outage probability, average transmission rate, and achievable spectrum efficiency. In addition, the average system BER, which satisfies the design constraint, is also numerically obtained. The results quantitatively confirm the effectiveness of our proposed system under the impact of UAV hovering misalignment and atmospheric-related issues like clouds and turbulence. Finally, Monte-Carlo simulations validate the accuracy of theoretical results.

Index Terms—Satellite communications, High-altitude platform (HAP), unmanned aerial vehicles (UAVs), Adaptive rate, Hybrid FSO/RF systems.

I. INTRODUCTION

According to the International Telecommunication Union (ITU) report in 2019, half of the world population did not have regular Internet access [1]. The main barriers come from a lack of infrastructure and affordability. Satellite communications have recently emerged as a complementary solution to bridge the gap by offering Internet connectivity at a reasonable cost, and ubiquitous coverage [2]. For example, Starlink presently offers Internet access from space with a fee of 99 USD per month (unlimited data); download speed varies from 50 to 150 Mbps depending on the location [3].

As satellite communication is susceptible to weather-related issues (e.g., clouds, rain, atmospheric turbulence), it is still challenging to increase the data rate and the coverage area. A promising solution is to use a high-altitude platform (HAP),

Fig. 1. HAP-assisted satellite network with UAVs.

which is a quasi-stationary vehicle located at a cloud-free atmospheric altitude from 17 to 25 km above the earth's surface [4]. Thanks to unique properties, such as quick deployment, low maintenance cost, and broader coverage, the development of HAP-assisted satellite can further improve the scalability of the 5G network and beyond [5]–[7]. In a HAP-assisted satellite network, a swarm of HAP can be deployed to cover a vast area, e.g., approximately 100 km as expected by Softbank [8]. Besides, HAP can be a stand-alone system to provide a stable connection to a remote area, temporary link to emergencies situations, such as a natural disaster, as described in Fig. 1. Furthermore, unmanned aerial vehicles (UAVs) as mobile base stations can further enhance the Internet connectivity provision as they can flexibly adjust their positions based on the demand on the ground. The UAV-mounted mobile base station solution has gained significant interest in both academic, and industry [9], [10]. In case of natural disaster, UAVs can promptly give warnings, rapidly assist rescue and temporarily recover the operation of damaged communication networks [9].

In the considered network, HAP functions as a relay station between the satellite and UAVs. The system, therefore, consists of two links: (1) a satellite-to-HAP and (2) HAP-to-UAV links. As the HAP situates in the stratosphere, which is less susceptible to atmospheric turbulence and clouds, we employ a free-space optical (FSO) link from satellite to HAP for a high-speed connection. In the second hop between HAP and UAVs, the FSO link may face weather-related issues such as clouds, snow, haze, rain, atmospheric turbulence, etc., which reduce link availability and limit the link distance [11]. In addition,

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Thang V. Nguyen, Hoang D. Le, and Anh T. Pham are with the Computer Communications Laboratory, the University of Aizu, Aizuwakamatsu 965-8580, Japan (e-mail: nguyenvanthang2404@gmail.com, hoang-bkset@gmail.com, pham@u-aizu.ac.jp).

Ngoc T. Dang is with the Posts and Telecommunications Institute of Technology, Hanoi 100000, Vietnam (e-mail: ngocdt@ptit.edu.vn).

multiple UAVs can be supported by one HAP; UAVs' locations are therefore not necessarily in the center of the optical beam. Also, UAVs can be in mobility; the optical link outage may occur because of the combined effect of beam misalignment and UAV hovering. Therefore, a hybrid RF/FSO system is proposed, in which the FSO link is prioritized higher. The RF is used as a backup link when the optical channel condition is insufficient to maintain the high data rate.

As a matter of fact, the dual-hop relay-assisted FSO and hybrid FSO/RF communications have been well studied for terrestrial networks [12]–[14]. In the satellite networks, the current state-of-the-art of hybrid FSO/RF systems for relay-assisted satellite communication focuses on fixed users [15]–[19]. In particular, in [15], the authors studied the downlink satellite-HAP-ground with the assumption of gamma-gamma turbulence channel model for FSO link and Rician distribution for RF link. The impact of pointing error and atmospheric attenuation was not included in the study. The hybrid FSO/RF for uplink ground-HAP-satellite scenarios was considered in [16], in which the RF channel was also modeled by Rician distribution. The combined channel model for the FSO link was taken into account free space loss, atmospheric turbulence, and beam wander induced pointing error. In both [15], [16], the single-threshold-based scheme was used to switch between RF and FSO links. The adaptive-combining-based switching scheme was used for integrated satellite-HAP-ground with hybrid FSO/RF system in both cases of uplink and downlink [17], [18]. The maximal-ratio-combining of FSO and RF links was implemented at the receiver when the RF link was transmitted simultaneously with the FSO link. Nevertheless, all previous work did not consider the case of mobile users, such as UAV-mounted mobile base stations, which are being considered for irregular, unexpected events, including sports events, natural disasters, and emergencies. In addition, the adaptive rate hybrid FSO/RF system was recently applied for the downlink satellite-HAP-ground [19]. With the help of the rate adaptation, the hybrid FSO/RF system can avoid frequently switching between FSO link and RF link, leading to enhancing the system performance.

In this paper, we, therefore, attempt to provide a comprehensive design and an insightful evaluation of dual-hop satellite-HAP-UAV hybrid FSO/RF systems with rate adaptation for mobile users, which can be summarized as follows:

- *Firstly*, we propose a multi-rate design for the integrated downlink satellite-HAP-UAV with the help of hybrid FSO/RF systems to counteract the effect of transmission media. As the role of the relay node, the amplified and forward scheme is implemented at HAP thanks to its cost-effectiveness and simple hardware requirements.
- *Secondly*, a number of performance metrics, including the end-to-end outage probability, average transmission rate, and achievable spectrum efficiency, have been derived considering various atmospheric-related issues. Specifically, the Rician distribution is used to model the RF channel. The FSO channel is modeled by taking into account the atmospheric turbulence, which is modeled by Gamma-Gamma distribution, cloud attenuation, beam spreading loss, and UAV hovering misalignment. The

Monte-Carlo simulation verifies the accuracy of the theoretical model.

- *Finally*, from the perspective of practical design, the insightful numerical results are discussed to quantify the effect of transmission media on the dual-hop satellite-HAP-UAV hybrid FSO/RF system. To this end, we have demonstrated the effectiveness of the proposed system compared with the conventional ones.

The rest of the paper is organized as followed. The relay-assisted satellite hybrid FSO/RF communication system description is shown in Section II. In Section III, the FSO and RF channel models are investigated. Next, Section IV presents rate adaptation and analyzes the system performance concerning the average transmission rate, achievable spectrum efficiency, outage probability, and average bit error rate. The discussion on the numerical results is expressed in Section V. Finally, the critical points of our work are concluded in Section VI.

II. SYSTEM DESCRIPTIONS

Figure 2 describes a block diagram of dual-hop satellite-HAP-UAV with an FSO system at first hop and hybrid FSO/RF system at the second hop. In the considered system, the satellite is a source node. The HAP is a relay node that amplifies the received signal from the satellite then forwards it to the destination. The UAV-mounted base station is a destination node. At the transmitter, the data is modulated by a quadrature amplitude modulation (QAM) modulator, and the output signal can be expressed as

$$s_n(t) = A_{nI}g(t) \cos(2\pi f_r t) - A_{nQ}g(t) \sin(2\pi f_r t), \quad (1)$$

where $g(t)$ is the pulse shaping function, f_r is the sub-carrier frequency, $0 \leq t \leq T$ with T is the interval time of the QAM symbol, $A_{nI} = \{2n - 1 - I\}_{n=1}^I$ and $A_{nQ} = \{2n - 1 - Q\}_{n=1}^Q$ are the amplitude of the information signal belong to in-phase and quadrature, respectively. Then, the electrical QAM signal is used to modulate the intensity of optical beam to generate the SC-QAM optical signal, which can be shown as

$$s(t) = P_t [1 + m s_n(t)], \quad (2)$$

where P_t is the transmitted power at the satellite, m is the modulation index. At the HAP, i.e., relay node, the optical aperture collects the optical signals then forwards them to an optical switch. Based on channel state information (CSI), the signal is decided to transmit RF or FSO link in the next state. If the RF link is selected, the optical signal is converted to the electrical signal by photodiode then amplify before transmitting to the destination node. If the FSO link is chosen, the optical signal is amplified and directly forward to the ground station. The representative of the output signal of the relay node can be expressed as

For RF link:

$$r_r(t) = G_{RF} [\eta h_{SR} P_t m s_n(t) + \eta n_{b1} + n_{re_hap}], \quad (3)$$

For FSO link:

$$r_f(t) = G_F [h_{SR} s(t) + n_{b1}], \quad (4)$$

Fig. 2. The dual-hop satellite-HAP-UAV hybrid FSO-FSO/RF systems including challenge issues (left side) and block diagram (right side).

where η is the optical-to-electrical coefficient, h_{SR} is the beam spreading loss at the first hop, n_{b1} is the background noise, and n_{re_hap} is the receiver noise, G_{RF} is the electrical amplifier gain, G_F is the optical amplifier gain. Based on CSI, the FSO link will be activated if the channel quality is good. Otherwise, the RF link will be applied if the channel condition is poor. The received signal at the ground station can be expressed as

For RF link:

$$y_r(t) = h_{RF}G_{RF}\eta h_{SR}P_t m_s(t) + h_{RF}G_{RF}\eta n_{b1} + h_{RF}G_{RF}n_{re_hap} + n_{re}. \quad (5)$$

For FSO link:

$$y_f(t) = h_{FSO}\eta G_F h_{SR}P_t m_s(t) + \eta h_{FSO}G_F n_{b1} + \eta n_{b2} + n_{rec}, \quad (6)$$

where h_{RF} and h_{FSO} are the channel coefficient of the RF link and the FSO link, respectively. n_{re} and n_{rec} are receiver noise. For convenient, $G_{RF}^2 = \frac{1}{(P_t m h_{SR})^2 + (\sigma_{b1})^2}$ and $G_F^2 = \frac{1}{(P_t m h_{SR})^2 + (\sigma_{b1})^2}$, the SNR at the destination node, denoted as γ_f^{e2e} for FSO-FSO link and γ_r^{e2e} for FSO-RF link, can be given as

For FSO-RF link:

$$\gamma_r^{e2e} = \frac{(h_{RF}G_{RF}\eta h_{SR}P_t m)^2}{(h_{RF}G_{RF}\eta \sigma_{b1})^2 + (h_{RF}G_{RF}\sigma_{re_hap})^2 + (\sigma_{re})^2}, \quad (7)$$

$$= \frac{\gamma_1 \gamma_{2,RF}}{\gamma_1 + \gamma_{2,RF} + 1}.$$

For FSO-FSO link:

$$\gamma_f^{e2e} = \frac{(h_{FSO}\eta G_F h_{SR}P_t m)^2}{(h_{FSO}\eta G_F \sigma_{b1})^2 + (\eta \sigma_{b2})^2 + (\sigma_{rec})^2}, \quad (8)$$

$$= \frac{\gamma_1 \gamma_{2,FSO}}{\gamma_1 + \gamma_{2,FSO} + 1}.$$

where $\gamma_1 = \frac{(P_t m h_{SR})^2}{(\sigma_{b1})^2}$ is the SNR of FSO link at the first hop. In the second hop, $\gamma_{2,RF} = \frac{(\eta h_{RF})^2}{(h_{RF}G_{RF}\sigma_{re_hap})^2 + (\sigma_{re})^2}$ is the SNR of the RF link. And, $\gamma_{2,FSO} = \frac{(\eta h_{FSO})^2}{(\eta \sigma_{b2})^2 + (\sigma_{rec})^2}$ is the SNR of FSO link at the second hop.

III. CHANNEL MODELING

The integrated satellite-HAP-UAV system considered in this paper contains two hops: (1) satellite-to-HAP using FSO links, and (2) HAP-to-UAV using hybrid FSO/RF links. This section investigates the challenging factors for each hop separately.

A. Satellite-to-HAP FSO link

Due to the relative motion between satellite and HAP, unfortunately, the Doppler effect may affect received signals. Nevertheless, the existing receiver design for optical satellite communication is able to deal with the Doppler frequency shift as reported in [20], [21]. Hence, the effect of Doppler can be negligible in our work. On the other hand, the impact of clouds and atmospheric turbulence on laser beam can be ignore since HAP situates at cloud-free altitude (i.e., 17-25 km) as described above. Besides, an optical Gaussian beam is diverged by some amount over the path from the satellite to HAP. The divergence loss is computed as the ratio between the fraction of collected power of HAP's aperture and the area of beam footprint. For a single beam, the divergence loss can be approximately calculated as

$$L_{geo} \approx A_0 \exp\left(-\frac{2\rho^2}{w_{deq}^2}\right), \quad (9)$$

where $w_{deq}^2 = w_d^2 \frac{\sqrt{\pi} \operatorname{erf}(v)}{2v \exp(-v^2)}$ is the equivalent beam waist, in which $w_d = w_0 \sqrt{1 + \varepsilon \left(\frac{\lambda d_1}{\pi w_0^2}\right)^2}$ is the beam waist at the distance d_1 , which is given by $d_1 = (H_s - H_p)/\cos(\xi_s)$ in which H_s is the altitude of the satellite, H_p is the height of the HAP, and ξ_s is the zenith angle of the satellite, $w_0 = (2\lambda)/(\pi\theta_s)$ is the beam waist at $d_1 = 0$ with θ_s is the divergence angle of the satellite, $\varepsilon = \left(1 + 2\frac{w_0^2}{\rho_0^2(d_1)}\right)$, and $\rho_0(d_1) = (0.55C_n^2 k_w^2 d_1)^{-3/5}$ is the coherence length [22]. In this study, we assume that active tracking between the satellite and the HAP is perfect, then the detector of HAP is located at the center of beam footprint (i.e., $\rho = 0$). Hence, $A_0 = [\operatorname{erf}(v)]^2$ corresponds to the fraction of the collected power at $\rho = 0$ with $v = \frac{a\sqrt{\pi}}{w_d\sqrt{2}}$ is the ratio between aperture radius and beam-width, in which a is the radius of detector.

B. HAP-to-UAV hybrid FSO/RF link

1) *RF channel*: The Rician distribution is used to model the RF channel due to line-of-sight (LOS) transmission between HAP and UAV. The channel coefficient of the RF link can be given as $h_{RF} = g_1 h_r$, where g_1 and h_r denote the average power gain and fading gain of the RF link, respectively. The power gain of the RF link can be expressed as

$$g_1 (\text{dB}) = G_T + G_R - L_F - L_A - L_c, \quad (10)$$

where G_T and G_R are the transmit and receive antenna gains, respectively. L_A denotes the gaseous atmosphere loss [16]. $L_F = 20\log_{10}\left(\frac{4\pi d_2}{f_r}\right)$ is the free space loss from the HAP to UAV, in which f_r is the frequency for RF link, and $d_2 = (H_p - H_u)/\cos(\xi_p)$ is the transmission distance from HAP to UAV with HAP's zenith angle of ξ_p , and H_u is the altitude of UAVs.

Cloud effects: As introduced by ITU-P840 [23], the cloud attenuation model is based on Rayleigh scattering suitable for frequencies up to 200 GHz, and it is expressed as

$$L_c = d_c \alpha_1, \quad (11)$$

Fig. 3. An example of the visibility for several cloud types.

where L_c is the attenuation due to effect of cloud, in which $d_c = d_z/\cos\xi_p$ is the signal path propagation in clouds, in which d_z is the considered length of clouds. $\alpha_1 = K_c M_c$ is the specific attenuation within clouds in which K_c ((dB/km)/(g/m³)) is the specific attenuation coefficient, M_c (g/m³) is the cloud liquid water content [23].

Rician fading model: Due to LOS between HAP and UAV, and following [24], [25], the fading gain is then modeled by Rician distribution with the probability density function (PDF) and cumulative density function (CDF) of the SNR received at the destination can be given respectively by

$$f_{\gamma_{2,RF}}(\gamma_{2,RF}) = \frac{K+1}{\bar{\gamma}_{RF}} I_0 \left(2\sqrt{\frac{K(K+1)}{\bar{\gamma}_{RF}}} \gamma_{2,RF} \right) \times \exp \left[-\frac{(K+1)\gamma_{2,RF}}{\bar{\gamma}_{RF}} - K \right], \quad (12)$$

$$F_{\gamma_{2,RF}} = 1 - Q_1 \left(\sqrt{2K}, \sqrt{\frac{2(K+1)}{\bar{\gamma}_{RF}}} \gamma_{2,RF} \right), \quad (13)$$

where $Q_1(\cdot, \cdot)$ is the Marcum Q_1 -function, K is the Rician factor which reflects the relative strength of the direct LOS path component of fading coefficient. $\bar{\gamma}_{RF}$ is the average SNR of the RF link.

2) *FSO channel*: For the downlink from HAP to UAV, the mathematical model of channel coefficient is expressed as $h_{FSO} = h_c h_a h_p$ in which h_c is the cloud attenuation, h_a is turbulence-induced fading, and h_p is UAV hovering-induced fading.

Cloud effects: In the optical downlink, atmospheric attenuation is severe due to scattering, which is caused by clouds [26]–[29]. Clouds result from the condensation of water vapors above the earth's surface and may occasionally disrupt the signal or completely block the optical signal from HAP to UAV. Besides, optical wavelength, which operates in THz band corresponds to the range of wavelength from 0.8 to 2 μm , is about the same particle size of water vapors. Hence, the scattering phenomenon occurs on the beam propagation, leading to decrease visibility significantly and signal power [28], [29]. In this model, the visibility can be determined based on cloud droplet number concentration N_c and cloud liquid

water content M_c as followed [30]

$$V = \frac{1.002}{(N_c \times M_c)^{0.6473}}. \quad (14)$$

The cloud effects on the visibility is illustrated in Fig. 3 for various cloud types such as stratus ($N_c = 250 \text{ cm}^{-3}$), altostratus ($N_c = 400 \text{ cm}^{-3}$), and nimbostratus ($N_c = 200 \text{ cm}^{-3}$). The figure reveals that visibility decreases rapidly when the CLWC grows up. Following the Beer-Lambert law, the cloud attenuation can be expressed [28]

$$h_c = \exp(-\alpha_2 d_c), \quad (15)$$

where d_c is the distance regarding scattering phenomena happen. α_l is the attenuation coefficient and can be expressed as

$$\alpha_2 = \frac{3.91}{V [km]} \left(\frac{\lambda [nm]}{550} \right)^{-q}, \quad (16)$$

where q is the coefficient, which is given by Kim's model [28].

Turbulence-induced fading: The Gamma-Gamma distribution is used for modeling the turbulence from weak regime to strong regime. The PDF of the turbulence coefficient can be expressed

$$f_{h_a}(h_a) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h_a^{\frac{\alpha+\beta}{2}} K_{\alpha-\beta} \left(2\sqrt{\alpha\beta} h_a \right), \quad (17)$$

where $\Gamma(\cdot)$ is the gamma function and $K_v(\cdot)$ is the v -th order modified Bessel function of the second kind. In addition, α and β can be found in [26], which is the function of Rytov variance, σ_R^2 , and for the plane wave, σ_R^2 can be given as

$$\sigma_R^2 = 2.25 k_w^{7/6} \sec^{11/6}(\xi_p) \int_{H_u}^{H_p} C_n^2(h) (h - H_u)^{5/6} dh, \quad (18)$$

where $k_w = 2\pi/\lambda$ is the optical wave number. Based on Hufnagel-Valley model [26], the variation of refractive index structure parameter $C_n^2(h)$ according to the altitude h can be written as

$$C_n^2(h) = 0.00594 \left(\frac{v_{wind}}{27} \right)^2 (10^{-5}h) \exp\left(-\frac{h}{1000}\right) + 2.7 \times 10^{-16} \exp\left(-\frac{h}{1500}\right) + C_n^2(0) \exp\left(-\frac{h}{100}\right), \quad (19)$$

where $C_n^2(0)$ is the ground turbulence level varying in the range of $10^{-17} \text{ m}^{-2/3}$ (weak turbulence regime) to $10^{-13} \text{ m}^{-2/3}$ (strong turbulence regime), and v_{wind} (m/s) is the root mean squared wind speed with typical value of 21 m/s [26].

UAV hovering misalignment model: Pointing error is mainly caused by the wind pushing the UAV around its operating position shown in Fig. 4. The HAP, on the contrary, is assumed to remain stable as it is located at a much higher altitude where there is little wind. The hovering results in a change of position of the UAV aperture. Note that the UAV's position is not necessarily in the center of the beam footprint for the purpose of serving multiple UAVs at the same time. Let r be

Fig. 4. UAV hovering misalignment model.

the radial vector from the beam center to the UAV's initial position. Due to the wind, UAV hovers around r_h radial to another position. Consequently, the actual position can be a r_{pe} radial distance from the beam footprint, and it can be expressed in the coordinate plane as followed

$$r_{pe}(x_{r_{pe}}, y_{r_{pe}}) = \begin{cases} x_{r_{pe}} = r_x + x_{r_h} = \|r\| \sin(\varphi) + x_{r_h}, \\ y_{r_{pe}} = r_y + y_{r_h} = \|r\| \cos(\varphi) + y_{r_h}, \end{cases} \quad (20)$$

where $\|\cdot\|$ is the norm of a vector, x_{r_h} and y_{r_h} are zero-mean Gaussian random variables (RVs) with variance σ_p^2 . Besides, $x_{r_{pe}}$ and $y_{r_{pe}}$ are two statistically independent Gaussian RVs as $x_{r_{pe}} \sim \mathcal{N}(r_x, \sigma_p^2)$ and $y_{r_{pe}} \sim \mathcal{N}(r_y, \sigma_p^2)$. As reported in [31], the variance of $x_{r_{pe}}$ and $y_{r_{pe}}$ are the same and equal σ_p^2 , the PDF of radial displacement r_{pe} follows Rician distribution

$$f_{r_{pe}}(r_{pe}) = \frac{r_{pe}}{\sigma_p^2} \exp\left[-\frac{(r_{pe}^2 + r^2)}{2\sigma_p^2}\right] I_0\left(\frac{r_{pe}r}{\sigma_p^2}\right), \quad (21)$$

where $I_0(\cdot)$ is the modified Bessel function of the first kind with order zero, σ_{pe}^2 is the jitter variance. By considering the Gaussian beam, the UAV hovering misalignment coefficient can be expressed as

$$h_{pe} = B_0 \exp\left(-\frac{2r_{pe}^2}{w_{zeq}^2}\right), \quad (22)$$

where $B_0 = [\text{erf}(v_2)]^2$ is the fraction of the collected power by UAV's detector at $r_{pe} = 0$. $w_{zeq}^2 = \frac{\sqrt{\pi} \text{erf}(v_2)}{2v_2 \exp(-v_2^2)} w_z^2$ is the equivalent beam-width, $v_2 = \frac{a_2 \sqrt{\pi}}{w_z \sqrt{2}}$ in which a_2 is the radius of detector, $w_z \approx w_{z0} \sqrt{1 + \varepsilon_2 \left(\frac{\lambda d_2}{\pi w_{z0}^2} \right)^2}$ is the beam waist at the distance d_2 , w_{z0} is the beam waist at $d_2 = 0$, $\varepsilon_2 = \left(1 + 2 \frac{w_{z0}^2}{\rho_{z0}^2(d_2)} \right)$, and $\rho_{z0}(d_2) = (0.55 C_n^2 k_w^2 d_2)^{-3/5}$ is

the coherence length. As derived in [31], [32], the PDF of pointing error h_{pe} can be expressed as

$$f_{h_p}(h_p) = \frac{w_{deq}^2}{4A_0\sigma_p^2} \exp\left(-\frac{r^2}{2\sigma_p^2}\right) \left(\frac{h_p}{A_0}\right)^{\frac{w_{deq}^2}{4\sigma_p^2}} \times I_0\left(\frac{r}{\sigma_p^2} \sqrt{-\frac{w_{deq}^2}{2} \ln\left(\frac{h_p}{A_0}\right)}\right), \quad (23)$$

Joint PDF and CDF of combined channel: After mathematical manipulation, the joint distribution of the channel coefficient h_{FSO} can be expressed as

$$f_{h_{FSO}}(h_{FSO}) = \sum_{i=1}^n 4x_i w_i \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} \exp\left(-\frac{r^2}{4\sigma_p^2}\right) \times \left(\frac{1}{A_0 h_c}\right)^{\frac{\alpha+\beta}{2}} \exp\left[\frac{4x_i^2 \sigma_p^2 (\alpha+\beta)}{w_{zeq}^2}\right] I_0\left(\frac{rx_i}{\sigma_p}\right) \times K_{\alpha-\beta} \left(2\sqrt{\frac{\alpha\beta h_{FSO}}{A_0 h_c}} \exp\left(\frac{8x_i^2 \sigma_p^2}{w_{zeq}^2}\right)\right) h_{FSO}^{\frac{\alpha+\beta}{2}-1}. \quad (24)$$

where x_i and w_i are the weights and the zeros of the Hermite polynomial, respectively. As reported in [31], the PDF of received SNR of FSO channel from HAP to UAV can be expressed

$$f_{\gamma_{2,FSO}}(\gamma_{2,FSO}) = \sum_{i=1}^n 2x_i w_i \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} \exp\left(-\frac{r^2}{2\sigma_p^2}\right) k_{pe}^{\frac{\alpha+\beta}{2}} \times \exp\left[\frac{2x_i^2 \sigma_p^2 (\alpha+\beta)}{w_{Leq}^2}\right] I_0\left(\frac{r\sqrt{2}x_i}{\sigma_p}\right) \left(\frac{1}{\gamma_{2,FSO}}\right)^{\frac{\alpha+\beta}{4}} \times K_{\alpha-\beta} \left(2\sqrt{\alpha\beta k_{pe} \gamma_{2,FSO}} \exp\left(\frac{4x_i^2 \sigma_p^2}{w_{Leq}^2}\right)\right) \gamma_{2,FSO}^{\frac{\alpha+\beta}{4}-1}. \quad (25)$$

By applying [33, Eq.(8.4.23)], [34, Eq. (26)], and after several mathematical manipulations, the CDF of the SNR of FSO link can be shown as in Eq. (26), in which the value of k_{pe} can be found in [31].

IV. RATE ADAPTATION DESIGN

This section focuses on the design of rate adaptation for our proposed systems. Several performance metrics are then derived in our analysis, including outage probability, average transmission rate, achievable spectrum efficiency, and average bit error rate.

A. Adaptive Transmission Schemes

The purpose of the adaptive multi-rate scheme is to maximize the data rate over the wireless channels while satisfying a predefined quality of service (QoS). To support the data-rate selection, a channel estimator is designed at the destination (i.e., UAVs) to estimate the channel state information (CSI) for both FSO and RF links, as illustrated in Fig. 2. The CSI reflects the information regarding the selection of both transmission rates and links based on the estimated received SNRs. In our study, for the sake of simplicity in the analysis, the feedback

channel carrying CSI information is assumed to be reliable¹. In addition, the temporal coherence times of considered FSO [36] and RF [37] links, i.e., in the order of tens of milliseconds, are relatively long in comparison with the time slot duration, including the data transmission and feedback time (order of several milliseconds). Due to the slowly time-varying nature of fading channels, CSIs are still up-to-date information when arriving at the HAP and satellite. Based on the available CSIs, the selection of data rate and link for transmissions are controlled by the satellite's rate-adaptive controller and HAP's switching controller, respectively.

In our system design, the high-speed FSO link is considered as a primary link, while the RF link is used as a backup when the quality of the FSO link becomes unacceptable, e.g., due to the strong turbulence or cloud coverage. The design of rate adaptation is applied for both FSO and RF links to increase the data rate while satisfying a pre-defined QoS, i.e., a targeted bit error rate (denoted as BER₀). We adopt the subcarrier M -array quadrature amplitude modulation (M -QAM) scheme with a fixed symbol rate of R_f for m possible transmission modes of the FSO link. Similarly, the N -QAM scheme is also applied to the RF link with a fixed symbol rate of R_r for n possible transmission modes. To facilitate the data transmission using rate adaptation, the channel is modeled by multiple states defined by a range of received signal-to-noise ratio (SNR). In particular, the range of received SNRs over FSO transmission is partitioned into $m+1$ set of non-overlapping intervals: $\{(-\infty, \gamma_{e2e}^{f(1)}), [\gamma_{e2e}^{f(1)}, \gamma_{e2e}^{f(2)}), \dots, [\gamma_{e2e}^{f(m)}, +\infty)\}$, in which the transmission mode i -th is selected for FSO link if the instantaneous SNR $\gamma_{e2e}^f \in [\gamma_{e2e}^{f(i)}, \gamma_{e2e}^{f(i+1)})$ with $i \in \{1, 2, \dots, m\}$. To avoid a high error rate, no FSO transmission is allowed when $\gamma_{e2e}^f < \gamma_{e2e}^{f(1)}$. In this case, the RF link using n transmission modes is activated.² The range of received SNRs over RF transmission is divided into $n+1$ set of non-overlapping intervals: $\{(-\infty, \gamma_{e2e}^{r(1)}), [\gamma_{e2e}^{r(1)}, \gamma_{e2e}^{r(2)}), \dots, [\gamma_{e2e}^{r(n)}, +\infty)\}$, in which the transmission mode j -th is selected for RF link if the instantaneous SNR $\gamma_{e2e}^r \in [\gamma_{e2e}^{r(j)}, \gamma_{e2e}^{r(j+1)})$ with $j \in \{1, 2, \dots, n\}$; no RF transmission is allowed to avoid high error rate when $\gamma_{e2e}^r < \gamma_{e2e}^{r(1)}$. If both the FSO and RF links happen to be in standby mode (i.e., $\gamma_{e2e}^f < \gamma_{e2e}^{f(1)}$ and $\gamma_{e2e}^r < \gamma_{e2e}^{r(1)}$), the hybrid FSO/RF system goes into outage. In summary, the data bit rate for each link changes for every transmission mode and is given as

$$R = \begin{cases} R_f \log_2 M, & \text{if } \gamma_{e2e}^f \leq \gamma_f < \gamma_{e2e}^{f(i+1)}, & \text{FSO link,} \\ R_r \log_2 N, & \text{if } \gamma_{e2e}^r \leq \gamma_r < \gamma_{e2e}^{r(j+1)}, & \text{RF link,} \\ 0, & \text{if } \gamma_{e2e}^f < \gamma_{e2e}^{f(1)}; \gamma_{e2e}^r < \gamma_{e2e}^{r(1)}, & \text{Outage,} \end{cases}$$

where $M = 2^i$ with $i \in \{1, 2, \dots, m\}$ and $N = 2^j$ with $j \in \{1, 2, \dots, n\}$. What remains now is to determine the SNR threshold levels for both FSO and RF transmissions. These threshold levels are obtained based on the fact that the BER for each transmission mode satisfies the targeted

¹In practice, a strong error correction code can be used in the feedback channel [35].

²Whenever the quality of the FSO link becomes acceptable, the system switches back to this link, and the RF link is put on the standby mode.

$$F_{\gamma_{2,FSO}}(\gamma_{2,FSO}) = \sum_{i=1}^n 2x_i w_i \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} \exp\left(-\frac{r^2}{2\sigma_p^2}\right) k_{pe}^{\frac{\alpha+\beta}{2}} \exp\left[\frac{2x_i^2 \sigma_p^2 (\alpha+\beta)}{w_{Leq}^2}\right] I_0\left(\frac{r\sqrt{2}x_i}{\sigma_p}\right) \left(\frac{\gamma_{2,FSO}}{\bar{\gamma}_{2,FSO}}\right)^{\frac{\alpha+\beta}{4}} \\ \times G_{1,3}^{2,1} \left[\alpha \beta k_{pe} \exp\left(\frac{4x_i^2 \sigma_p^2}{w_{Leq}^2}\right) \sqrt{\frac{\gamma_{2,FSO}}{\bar{\gamma}_{2,FSO}}} \mid \frac{\alpha-\beta}{2}, \frac{-\alpha+\beta}{2}, -\frac{\alpha+\beta}{2} \right]. \quad (26)$$

BER₀. Specifically, for a link using $\mathcal{K}$ -QAM modulation, it is formulated as [38]

$$\text{BER}(\mathcal{K}, \gamma) \cong 0.2 \exp\left[-\frac{3\gamma}{2(\mathcal{K}-1)}\right] \triangleq \text{BER}_0, \quad (27)$$

where $\mathcal{K} = M$ and $\gamma = \gamma_{e2e}^{f(i)}$ for the FSO link, while $\mathcal{K} = N$ and $\gamma = \gamma_{e2e}^{r(j)}$ for the RF link. From (27), the SNR threshold levels for FSO and RF links can be obtained as

$$\gamma = \frac{-2(\mathcal{K}-1)}{3} \ln(5\text{BER}_0). \quad (28)$$

An example of rate adaptation design for hybrid FSO/RF system is illustrated in Table I, in which $m = n = 3$ transmission modes for FSO and RF links.

B. Performance Analysis

1) *Outage probability*: The outage occurs when the system moves to the zero-rate mode, in which no data is transmitted to avoid the high error rate. The outage probability is then defined as [12]

$$P_{\text{out}} = \int_0^{\gamma_{e2e}^{f(1)}} f_{\gamma_{e2e}^f}(\gamma_{e2e}^f) d\gamma_{e2e}^f \int_0^{\gamma_{e2e}^{r(1)}} f_{\gamma_{e2e}^r}(\gamma_{e2e}^r) d\gamma_{e2e}^r \\ = F_{\gamma_{e2e}^f}(\gamma_{e2e}^{f(1)}) F_{\gamma_{e2e}^r}(\gamma_{e2e}^{r(1)}), \quad (29)$$

where $\gamma_{e2e}^{f(1)}$ and $\gamma_{e2e}^{r(1)}$ are the outage thresholds for corresponding FSO and RF links, adopted in Table I by the SNR thresholds of lowest transmission modes for such links. $F_{\gamma_{e2e}^r}(\gamma_{e2e}^r)$ and $F_{\gamma_{e2e}^f}(\gamma_{e2e}^f)$ are respectively the CDFs of end-to-end for the dual-hop of FSO-RF and FSO-FSO, which are expressed as

For FSO-RF link:

$$F_{\gamma_{e2e}^r}(\gamma_{e2e}^r) = \Pr\left(\frac{\gamma_1 \gamma_{2,\text{RF}}}{\gamma_{2,\text{RF}} + 1} < \gamma_{e2e}^r\right) = F_{\gamma_{2,\text{RF}}}\left(\frac{\gamma_{e2e}^r}{\gamma_1 - \gamma_{e2e}^r}\right). \quad (30)$$

For FSO-FSO link:

$$F_{\gamma_{e2e}^f}(\gamma_{e2e}^f) = \Pr\left(\frac{\gamma_1 \gamma_{2,\text{FSO}}}{\gamma_{2,\text{FSO}} + 1} < \gamma_{e2e}^f\right) = F_{\gamma_{2,\text{FSO}}}\left(\frac{\gamma_{e2e}^f}{\gamma_1 - \gamma_{e2e}^f}\right). \quad (31)$$

2) *Average transmission rate*: The average transmission rate, which is an essential parameter in adaptive multi-rate systems, can be determined as

$$\bar{R} = \sum_{k=1}^N p_k R_k, \quad (32)$$

where N is the total modes. Since the transmission rate of each link is fixed, the link switching threshold is designed based on targeted BER, then the fixed M -QAM is used. Mode probability is defined as the probability that k -th mode is selected; then it can be calculated as

For FSO-RF link

$$p_k^{RF} = \int_0^{\gamma_{e2e}^{f(1)}} f_{\gamma_{e2e}^f}(\gamma_{e2e}^f) d\gamma_{e2e}^f \int_{\gamma_{e2e}^{r(j)}}^{\gamma_{e2e}^{r(j+1)}} f_{\gamma_{e2e}^r}(\gamma_{e2e}^r) d\gamma_{e2e}^r \\ = \left[1 - F_{\gamma_{e2e}^f}(\gamma_{e2e}^{f(1)})\right] \left[F_{\gamma_{e2e}^r}(\gamma_{e2e}^{r(j+1)}) - F_{\gamma_{e2e}^r}(\gamma_{e2e}^{r(j)})\right]. \quad (33)$$

For FSO-FSO link

$$p_k^{FSO} = \int_{\gamma_{e2e}^{f(i)}}^{\gamma_{e2e}^{f(i+1)}} f_{\gamma_{e2e}^f}(\gamma_{e2e}^f) d\gamma_{e2e}^f \\ = F_{\gamma_{e2e}^f}(\gamma_{e2e}^{f(i+1)}) - F_{\gamma_{e2e}^f}(\gamma_{e2e}^{f(i)}). \quad (34)$$

3) *Spectrum efficiency*: As the system is in the state k -th, each transmitted symbol carries R_k information bits. We suppose that a Nyquist pulse shaping filter with the bandwidth $B = 1/R_0$. Then, the achievable spectral efficiency, defined as the data rate per unit bandwidth, is given by

$$S_{\text{eff}} = \frac{1}{R_0} \sum_{k=1}^N p_k R_k. \quad (35)$$

4) *Average bit error rate (ABER)*: The ABER is defined as the ratio of the average number of erroneously received bits over the total average number of transmitted bits, which is expressed by

$$\text{ABER} = \frac{\text{Total erroneous bits}}{\text{Total transmitted bits}} = \frac{\sum_{k=1}^N R_k p_k \text{BER}_k}{\sum_{k=1}^N R_k p_k}, \quad (36)$$

where R_k is the transmission rate at state k -th, BER_k is the bit error rate of selecting mode k -th over fading channel, which can be determined as

For FSO-FSO link

$$\text{BER}_{fso} = \frac{1}{p_k^{FSO}} \int_{\gamma_{e2e}^{f(k)}}^{\gamma_{e2e}^{f(k+1)}} \text{BER}(M, \gamma_{e2e}^f) f_{\gamma_{e2e}^f}(\gamma_{e2e}^f) d\gamma_{e2e}^f. \quad (37)$$

TABLE I
AN EXAMPLE OF RATE ADAPTATION DESIGN FOR HYBRID FSO/RF SYSTEMS.

		System Outage	RF (active): Backup Link			FSO (active): Primary Link		
Transmission Mode			1	2	3	1	2	3
Modulation			BPSK	QPSK	8-QAM	BPSK	QPSK	8-QAM
Data Rate		0	$2R_r$	$3R_r$	$4R_r$	$2R_f$	$3R_f$	$4R_f$
Thresholds (dB)	FSO	Outage of FSO $(-\infty, \gamma_{e2e}^{f(1)})$				$[\gamma_{e2e}^{f(1)}, \gamma_{e2e}^{f(2)})$	$[\gamma_{e2e}^{f(2)}, \gamma_{e2e}^{f(3)})$	$[\gamma_{e2e}^{f(3)}, +\infty)$
	RF	Outage of RF $(-\infty, \gamma_{e2e}^{r(1)})$	$[\gamma_{e2e}^{r(1)}, \gamma_{e2e}^{r(2)})$	$[\gamma_{e2e}^{r(2)}, \gamma_{e2e}^{r(3)})$	$[\gamma_{e2e}^{r(3)}, +\infty)$

Fig. 5. Outage performance versus satellite's transmitted power for different CLWCs at the UAV's position of 20 m.

For FSO-RF link

$$\text{BER}_{rf} = \frac{1}{p_{rf}^{RF}} \int_{\gamma_{e2e}^{f(k)}}^{\gamma_{e2e}^{f(k+1)}} \text{BER}(N, \gamma_{e2e}^r) f_{\gamma_{e2e}^r}(\gamma_{e2e}^r) d\gamma_{e2e}^r. \quad (38)$$

C. Conventional Hybrid FSO/RF Design

In conventional hybrid FSO/RF systems, the transmission rate of each link is fixed, where the link switching mechanism is based on a predefined $\text{BER}_0(M, \gamma)$. In other words, the system works on two modes: FSO and RF ones. It is supposed that a fixed M -QAM and N -QAM are used for FSO and RF modes, respectively. The SNR thresholds for such FSO and RF links obtained from (28) are, then, expressed as $\gamma_{e2e}^{f(i)}$ and $\gamma_{e2e}^{r(j)}$, where $i = \log_2(M)$ and $j = \log_2(N)$.

The primary FSO link is selected when $\gamma_{e2e}^f \in [\gamma_{e2e}^{f(i)}, \infty)$; otherwise the system switches to operate on the backup RF link with $\gamma_{e2e}^r \in [\gamma_{e2e}^{r(j)}, \infty)$. Therefore, the average transmission rate for such systems can be written as

$$\bar{R}_{\text{fix}} = p^{FSO} R_f + p^{RF} R_r, \quad (39)$$

where R_f and R_r are respectively the data bit rate of FSO and RF modes. In addition, the FSO and RF mode probabilities,

denoted by p^{FSO} and p^{RF} , are defined as

$$\begin{cases} p^{FSO} = \int_{\gamma_{e2e}^{f(i)}}^{\infty} f_{\gamma_{e2e}^f}(\gamma_{e2e}^f) d\gamma_{e2e}^f = F_{\gamma_{e2e}^f}(\gamma_{e2e}^{f(i)}), \\ p^{RF} = (1 - p^{FSO}) F_{\gamma_{e2e}^r}(\gamma_{e2e}^{r(j)}). \end{cases} \quad (40)$$

On the other hand, the average BER for conventional hybrid FSO/RF systems is expressed as

$$\text{ABER}_{\text{fix}} = \frac{R_f p^{FSO} \text{BER}_{fso} + R_r p^{RF} \text{BER}_{rf}}{R_f p^{FSO} + R_r p^{RF}}, \quad (41)$$

where BER_{fso} and BER_{rf} are defined as

$$\begin{cases} \text{BER}_{fso} = \int_{\gamma_{e2e}^{f(i)}}^{\infty} \text{BER}(M, \gamma_{e2e}^f) f_{\gamma_{e2e}^f}(\gamma_{e2e}^f) d\gamma_{e2e}^f, \\ \text{BER}_{rf} = \int_{\gamma_{e2e}^{r(j)}}^{\infty} \text{BER}(N, \gamma_{e2e}^r) f_{\gamma_{e2e}^r}(\gamma_{e2e}^r) d\gamma_{e2e}^r. \end{cases} \quad (42)$$

V. NUMERICAL RESULTS

In this section, we present selected numerical results to demonstrate the advantages of our proposed adaptive hybrid FSO/RF design in the scenario of space-air-ground networks. Notably, we highlight the effectiveness of our proposed systems by comparing performance metrics analyzed in Section IV with those of conventional systems, i.e., adaptive dual-hop FSO-FSO, adaptive dual-hop FSO-RF, and fixed-rate dual-hop FSO-hybrid FSO/RF designs. To this purpose, the sets of transmission modes using M -QAM modulation

with $M \in \{2, 4, 8, 16, 32, 64, 128\}$ for FSO links and N -QAM modulation with $N \in \{2, 4, 8, 16, 32\}$ for RF links³ are adopted for the adaptive multi-rate design. For the sake of comparison, 32-QAM modulation is given for RF links, while different M -QAM modulations are considered for FSO links in the conventional fixed-rate systems. The parameters used in the analysis, unless otherwise noted, are given in Table II.

Monte Carlo simulations using MATLAB are also provided to validate the analytical results. Using the system parameters outlined in Table II, the simulation is done by using a discrete-event simulator. The details of simulation process are described as follows. *Regarding the FSO transmission*, with a given value of $C_n^2(0)$, we generate 10^6 independent coefficients of h_a , which have the Gamma-Gamma distribution as given in (17). In addition, for a given UAV's hovering jitter variance σ_p^2 , we generate 10^6 independent RVs $x_{r_{pe}}$ and $y_{r_{pe}}$. Then, using generated RVs $x_{r_{pe}}$ and $y_{r_{pe}}$, we generate 10^6 independent coefficients of h_p from (23). Since the path loss (h_c) is deterministic, it is generated using relations in (15). We then obtain 10^6 independent values of UAV-based FSO channel coefficient (h_{FSO}) from $h_{FSO} = h_c h_a h_p$ used to derive the FSO channel SNR $\gamma_{2,FSO}$ as well as γ_{e2e}^f from (8). *As for the RF transmission*, given the Rician factor K , we generate 10^6 independent channel SNR $\gamma_{2,RF}$ based on (12), which is used to derive γ_{e2e}^f from (7). Finally, using the obtained 10^6 independent values of γ_{e2e}^f and γ_{e2e}^r , the performance metrics based on Monte Carlo simulation can be found.

We first analyze the effectiveness of our proposed dual-hop FSO-hybrid FSO/RF adaptive systems by comparing with the conventional adaptive ones, including dual-hop FSO-FSO and dual-hop FSO-RF, in terms of outage performance, over a range of satellite's transmitted power in Fig. 5. Here, in addition to the uncoded dual-hop FSO-FSO system, we consider an additional transmission mode using BPSK with a coding rate of 1/2 as the lowest mode [39], which results in a lower outage threshold, for such a system. Also, different cloud conditions, i.e., CLWC = 6 mg/m³, CLWC = 8 mg/m³, and CLWC = 10 mg/m³, which are the critical concerns, especially for FSO links, are investigated.

There are two remarkable observations here. *Firstly*, when the CLWC increases, the outage performance of dual-hop FSO-FSO systems is significantly deteriorated, even with the one using the strong coding scheme. While a minimal change is witnessed for dual-hop FSO-RF ones. The reason is that the impact of clouds is much more severe in FSO systems as the optical wavelength is smaller than the typical cloud droplet size values [20]. Contrary to optical bands, the wavelengths of RF ones are often larger than the size of cloud droplets, resulting in a very low attenuation caused by clouds on such links [23]. In addition, with high values of the satellite's transmitted power, the dual-hop FSO-FSO systems, however, can maintain a better performance than dual-hop FSO-RF ones in less severe cloud conditions, e.g., CLWC = 6 mg/m³ and CLWC = 8

TABLE II
SYSTEM PARAMETERS

Name	Symbol	Value
LEO Satellite		
LEO satellite altitude	H_s	530 km
Divergence angle	θ_{sat}	15 μ rad
Optical wavelength	λ	1550 nm
RF frequency	f_r	2 GHz
FSO symbol rate	R_f	500 Msps
RF symbol rate	R_r	100 Msps
High Altitude Platform (HAP)		
HAP altitude	H_p	20 km
HAP aperture radius	r_{hap}	10 cm
Zenith angle	ξ_p	60°
Divergence angle	θ_{hap}	1.5 mrad
Unnamed Aerial Vehicle (UAV)		
UAV altitude	H_u	100 m
Hovering jitter variance	σ_p^2	0.9 m
UAV aperture radius	r_{uav}	5 cm
Detector responsivity	$\mathcal{R}$	0.9
Noise standard deviation	σ_n	10^{-7} A/Hz
Gaseous atmosphere losses	L_A	5.4×10^{-3} dB/km
Receiver noise bandwidth	BW	74.8 dBHz
System noise temperature	T_N	17.6 dBK
Noise figure	N_F	2 dB
Other Parameters		
Targeted BER	BER_0	10^{-5}
Number of cloud concentrations	N_c	250 cm ⁻³
Considered length of clouds	d_z	2 km
Turbulence at ground level	$C_n^2(0)$	10^{-13} m ^{-2/3}
Rician factor	K	6 dB

mg/m³. *Secondly*, as is expected, our proposed dual-hop FSO-hybrid FSO/RF systems can provide a significant performance improvement over the conventional ones in different cloud conditions, thanks to inheriting both FSO and RF benefits. Also, in this figure, the analytical results closely follow the simulated ones, which confirms the correctness of the model and analysis.

In Fig. 6, we investigate the outage performance in terms of beam footprint size provided by the HAP-based relaying node, when CLWC = 6 mg/m³. Also, different satellite's transmitted powers, i.e., $P_t = 7$ dBm, 8 dBm, and 9 dBm, and HAP's divergence angles, i.e., $\theta_{HAP} = 1.5$ mrad, 2 mrad, and 2.5 mrad, are taken into account. This is a vital performance metric to determine the system operational coverage area. For instance, when $\theta_{HAP} = 1.5$ mrad, to retain a target outage performance level of below 10^{-4} , the operational area of UAVs should be within 15 m, 19 m, 24 m, for $P_t = 7$ dBm, 8 dBm, and 9 dBm, respectively. In addition, the highly directional beam is obtained for smaller HAP's divergence angles, resulting in a better outage performance. Such smaller HAP's divergence angles, nevertheless, restrict the system operational areas, leading to the high outage probability at the edge of the beam footprint. As a result, there exists a tradeoff between the operational areas and system performance in the selection of HAP's divergence angles.

Next, we further analyze the advantages of our proposed adaptive multi-rate design compared to the conventional systems with fixed-rate schemes. Specifically, Fig. 7 investigates the achievable data rate over a range of CLWCs, when $P_t = 15$ dBm. Obviously, compared to the fixed-rate scheme, the adaptive multi-rate design could offer considerably better

³It is worth noting that more transmission modes result in better performance while the system complexity is increased. As FSO is the primary link, the number of RF modes is, therefore, selected to be less than the FSO ones.

Fig. 6. Outage probability versus satellite transmit power and distance from center of Gaussian beam to UAV position with CLWC of 6 mg/m^3 .

Fig. 7. The impact of cloud to average transmission rate of adaptive rate system and fixed rate system.

Fig. 8. The achievable spectrum efficiency versus satellite transmit power in the case of adaptive rate system and fixed rate system.

performance under the impact of cloud coverage. This fact can be explained from two remarkable points: (i) the systems with high modulation order could maintain a high maximum achievable data rate in less severe cloud conditions; (ii) the performance of such systems using high modulation order is significantly degraded in more severe cloud conditions, in which low modulation order is preferable in this situation, leading to the limitation of maximum achievable data rate. As a result, systems using a fixed-rate scheme may not be efficient in time-varying channels, and adaptive multi-rate design would be the promising solution. For example, when $\text{CLWC} = 6 \text{ mg/m}^3$, our proposed adaptive system can achieve 2.45 Gbps of data rate, while the fixed-rate one could only retain the data rate of 1.77 Gbps, 1.45 Gbps, 1.37 Gbps, 0.99 Gbps, and 0.5 Gbps with 32-QAM, 8-QAM, 64-QAM, 128-QAM,

2-QAM modulations used for the FSO links, respectively. The outperformance of the proposed adaptive multi-rate design over the conventional fixed-rate one can also be observed in Fig. 8 in which variations in achievable spectrum efficiency performance with different values of the satellite's transmitted power when $\text{CLWC} = 6 \text{ mg/m}^3$. For instance, when $P_t = 20 \text{ dBm}$, our proposed design can achieve the spectrum efficiency of 6.8 bits/symbol, while they are only 6.2 bits/symbol, 5.8 bits/symbol, 4.9 bits/symbol, 4 bits/symbol, 3 bits/symbol, 2 bits/symbol, 1 bits/symbol for respectively 128-QAM, 64-QAM, 32-QAM, 16-QAM, 8-QAM, 4-QAM, 2-QAM with the fixed-rate one.

Finally, we highlight the effectiveness of our proposed adaptive design by comparing the average BER performance with that of conventional fixed-rate one, over a range of beam

Fig. 9. Average BER and average transmission rate versus UAV's position for different values of HAP's divergence angle.

footprint sizes, as illustrated in Fig. 9. Also, $P_t = 20$ dBm, $CLWC = 6$ mg/m³, and different HAP's divergence angles, i.e., $\theta_{HAP} = 1.5$ mrad, 2 mrad, and 2.5 mrad, are considered. It is noted that the obtained results of BER are based on their exact-form expressions found in (36) and (41) for respectively the proposed and conventional designs. As expected, our proposed design offers a lower average BER performance compared to the conventional one, even with higher achievable data-rate transmissions. This phenomenon is due to the fact that the objective of adaptive multi-rate design is to maximize the data rate over the time-varying turbulence-induced fading channels while satisfying a pre-defined Quality of Service (QoS), i.e., a targeted BER. Moreover, using this figure, we can decide the operational range of UAVs to maintain a targeted BER performance by selecting a proper HAP's divergence angle parameter, which is an especially essential parameter for mobile users. For example, to retain a level of BER performance of below 10^{-7} , the operational area of UAVs should be within 24 m, 22 m, and 17 m for $\theta_{HAP} = 1.5$ mrad, 2 mrad, and 2.5 mrad, respectively.

VI. CONCLUDING REMARKS AND FUTURE WORK

We have proposed the adaptive hybrid FSO/RF design and a comprehensive analytical framework for the performance of HAP-aided relaying satellite communications for mobile networks supported by UAVs. For hybrid FSO/RF channels, the Rician distribution was adopted for RF links. At the same time, several factors were taken into account on FSO links, including atmospheric turbulence modeled by the Gamma-Gamma distribution, the cloud coverage, and the UAV hovering-induced pointing misalignment. Several system performance metrics, including outage probability, average transmission rate, and achievable spectrum efficiency, were analytically derived.

Through the numerical results, there are several concluding remarks: (i) Our proposed system could offer a significant performance improvement compared to the existing designs in the scenario of integrated downlink satellite-HAP-ground/vehicles, i.e., adaptive design (dual-hop FSO-FSO and

dual-hop RF-RF) and fixed-rate design (dual-hop FSO-hybrid FSO/RF); (ii) Our results could support the proper parameter selection for practical mobile users, i.e., beam size provided by HAP and satellite's transmitted power; and (iii) the correctness of our analytical model was confirmed by the Monte Carlo simulations, in which the excellent agreement between theoretical results and simulated ones was validated.

Our study could be a generalized framework for relay-based satellite-assisted vehicular networks, with UAVs and other vehicles, e.g., high-speed trains and autonomous cars. Future work would be interesting to investigate other adaptive schemes, i.e., power adaptation, which is especially essential to save energy consumption in the domain of satellite and/or vehicular networks.

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