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Performance Analysis of Satellite-Vehicle Networks With a Non-Terrestrial Vehicle

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***Abstract*—In this work, we propose a non-terrestrial vehicle communication network where the communication between the satellite and the terrestrial source is assisted by a unmanned aerial vehicle (UAV) used as a relay. In particular, a reconfigurable intelligent surface (RIS) is used in the RF channel to reflect the signals of the terrestrial user to the relay with a fixed amplification gain, while free-space optical (FSO) is applied to the relay-satellite link to obtain a high speed transmission. For such a dual-hop system, assuming that the FSO channel experiences $\mathcal{M}$-distributed fading with pointing errors, the expressions for the outage probability (OP) and average bit error rate (ABER) are evaluated in closed-forms. In addition, the high signal-to-noise ratio (SNR) analyses for the OP and ABER are developed and the lower and upper bounds on the average channel capacity (ACC) are calculated to obtain further insights. Results show that the diversity order of the proposed system is $\min\{k_w, m_w\}$, where these two parameters are related to the Nakagami-*m* distribution parameters and the number of RIS elements. Finally, we take the shadowing effects into consideration, and it can be seen that the shadowing effects significantly degrade the system performance.**

***Index Terms*—Amplified-and-forward, satellite-vehicle networks, free-space optical, RIS, unmanned aerial vehicle (UAV).**

I. Introduction

With the evolution of communication technologies, Internet of Vehicles (IoV) network will be an important application scenario. IoV utilizes wireless communication technology to achieve network connectivity between vehicles and different terminals (i.e. vehicles, service platforms, people), and provides intelligent and efficient transportation services. Generally, the communication connections between the vehicles and the cloud platforms can be implemented by the conventional mobile cellular systems or the satellite wireless communication. Therefore, owing to its wide coverage and enormous potential to serve countless flights and ground users to meet the explosive growth of global mobile data demand, space-air-ground integrated vehicle network (SAGIVN) has been considered in [1]-[3].

Recently, reconfigurable intelligent surface (RIS) demonstrates the potential to achieve high network energy efficiency requirements [4]. Due to its unique structural characteristics, the RIS can effectively improve the wireless communication environment of the IoV, thereby improving the communication quality of IoV networks. More recently, applying RISs to IoV has received extensive researches [5]-[7]. In [5], the authors studied the RIS-aided unmanned aerial vehicle (UAV) vehicular communication systems with infinite and finite block length codes. In [6], the rate-splitting multiple access scheme for RIS-aided UAV multi-user vehicular communication network with co-channel interference was investigated. In [7], the authors investigated the optimization problem of millimeter-wave communication with link blockages with the help of RISs in IoV. In addition, due to their flexibility, UAVs including drones, balloons, high altitude platform (HAP), low altitude platform (LAP), and quadcopters are extensively used in current wireless communication systems [8]. The UAV+RIS topic also has received extensive attention. For instance, in [9], the authors proposed an RIS-assisted UAV framework, which uses an RIS set on walls to reflect signals to the UAV serving as a relay to retransmit the messages to the destination. In [10], the authors considered applying a buoy serving as a relay to build the communication connection between the UAV and the underwater node.

In the deep space communication environment, RF links are affected by the solar scintillation [11], which results in severe signal fading. Also, the conventional radio frequency (RF) communication is affected by the limited capacity, spectrum congestion, low bandwidth, and regulatory constraints. However, free-space optical (FSO) links are almost immune to the solar scintillation, and has rich spectrum resources, high throughput, low power consumption, and other advantages. Due to its significant advantages, the FSO has been widely applied to the free-space communication, such as the satellite-terrestrial and satellite-satellite communication [12]. However, due to the existence of obstacles such as buildings and trees on the ground, the line-of-sight (LoS) links of FSO com-

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munication may be blocked in some urban environments. To address this issue, one can apply the so-called mixed RF/FSO structure where the UAV has a relay on it, the ground user-UAV link is the RF link, while the UAV-satellite link is a FSO link. In [13], the authors considered the mixed FSO-RF communication between the ground and satellites with and without HAP stations. In [14], the performance of a terahertz (THz)/FSO hybrid wireless transmission system was studied, taking into account the joint effects of channel fading and pointing errors on the THz and FSO links.

To the authors' knowledge, the performance analysis of the RIS-aided SAGIVN has not been thoroughly studied. Thus, a cooperative satellite-vehicle communication network with the help of a UAV is proposed. For practical considerations, here the UAV can be a LAP or HAP. To further improve the communication quality of the ground vehicle-relay link and expand the coverage, an RIS is used in the first RF link. Specifically, the vehicle source on the ground sends signals to the RIS fixed on the buildings and the RIS reflects the signals to the relay. Then, the relay converts its received electric signals to the optical signals with help of an electric-to-optical (E2O) conversion device. After that, the optical signals are amplified by using a fixed-gain amplifier and retransmitted to the satellite by way of the FSO link, where pointing errors exist in the FSO link. In this work, the main contributions can be summarized as follows:

- A cooperative satellite-vehicle RF/FSO relaying network with the help of a UAV and an RIS is proposed, where the RF and FSO links are modeled using K_G distribution and $\mathcal{M}$-distribution, respectively.
- New formulas for the statistical distributions of the $\mathcal{M}$-distribution are derived.
- The exact expressions of the cumulative distribution function (CDF) and the probability density function (PDF) of the system signal-to-noise ratio (SNR) are derived. Based on these, the exact expressions for the outage probability (OP) and average bit error rate (ABER) are evaluated.
- To obtain more meaningful conclusions, asymptotic analyses of OP and ABER are also presented. In addition, the upper and lower bounds on the average channel capacity (ACC) are calculated to obtain some more useful conclusions.
- The shadowing effects in the RF channels are considered, and the analytical results for the OP and ABER are developed.

A. Organization

The remainder of this paper is organized as follows. The system and channel models are presented in Section II. In Section III, the performance indicators of the system are calculated, including OP, ABER and the upper and lower bounds on ACC. In Section IV, the OP and ABER of the proposed system with the shadowing effects in the RF channels are derived. Numerical evaluated results are presented and discussed in Section V. Finally, in Section VI, the conclusions can be found.

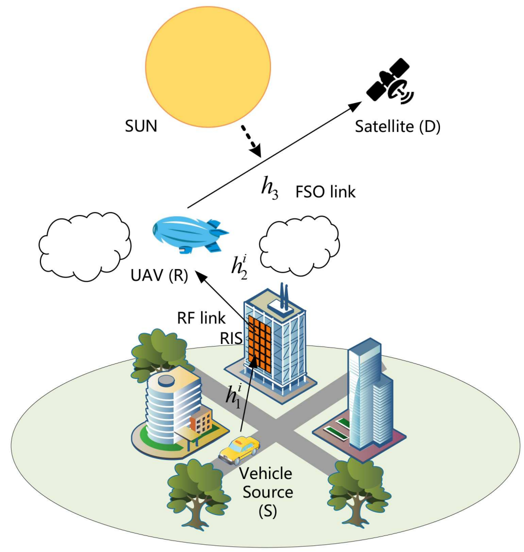

Fig 1. System model.

II. System and Channel Models

As depicted in Fig. 1, we study a UAV-aided cooperative satellite-vehicle network, which consists of a vehicle source (S), an RIS employed on a building with N reflective elements, a relay (R) operating under a fixed gain amplify-and-forward (AF) protocol located on a UAV, and a satellite (D). To ensure that the R-D link is relatively static, the UAV can be a LAP or HAP. Further, we assume that all the communication nodes are only deployed with one antenna, and no direct links exist between S and R, and D. The entire signal transmission requires two time slots. In the first stage, the RF signal is sent from S to R with the aid of the RIS. In the second one, after the E2O conversion at R, the optical signal amplified by a fixed gain amplifier is transmitted to D by way of the FSO link. Since S is located on the ground and the signals transmitted from S are easily affected by the rich scatters, such as buildings and trees, we suppose that the S-RIS link follows Rayleigh fading. Besides, owing to the high position of R in the air, we assume that the RIS-R link follows the Nakagami-m fading. Moreover, we focus on the small-scale fading for the RF link, and the angle-of-arrival fluctuation of the UAV and atmospheric attenuation are ignored for the FSO link. In addition, due to the fact that shadowing effect is a log-normal distribution, the system performance evaluation becomes very difficult. Thus, we ignore the shadowed fading for the RF link in this work. This is a reasonable assumption since the RIS and UAV are placed in higher positions and blockage from objects in the signal path seldom happens.

A. RF link

In the first time slot, S transmits signals to the UAV with the assistance of the RIS and the resulting signal at R is

$$y_1 = \sqrt{L_S L_R}\left[\sum_{i=1}^{N} h_1^i e^{j\phi_i} h_2^i\right] x + n_1. \tag{1}$$

where $h_1^i=\epsilon_i e^{-j\xi_i}$ and $h_2^i=b_i e^{-j\delta_i}$ are the channel gains of the cascaded channels ($i=1,2,...,N$), and ϵ_i and b_i are the channel amplitudes of h_1^i and h_2^i, ξ_i and δ_i represent the phases of h_1^i and h_2^i, respectively. ϵ_i follows a Rayleigh distribution with variance $(4-\pi)/4$ and mean $\sqrt{\pi}/2$, and b_i obeys a Nakagami-*m* distribution with the fading parameter $m\geq 1/2$. And $n_1\sim\mathcal{CN}(0,N_1)$ is the additive white Gaussian noise (AWGN). In (1), $L_S=10^{g_S/10}/r_S^{\mu_S}$ and $L_R=10^{g_R/10}/r_R^{\mu_R}$ are the large-scale (local average) behaviors of h_1^i and h_2^i [15], respectively, where g_S and g_R are system dependent constants, μ_S and μ_R are the path loss exponents, r_S and r_R are the distance between S and RIS, RIS and R, respectively.

Then, setting $\phi_i=\xi_i+\delta_i$ $(i=1,2,...,N)$, we obtain the SNR at the UAV as

$$\gamma_1=\frac{L_SL_RE_S\left(\sum_{i=1}^N\epsilon_ib_i\right)^2}{N_1}=Z^2\bar{\gamma}_1, \tag{2}$$

where $Z=\sum_{i=1}^N\epsilon_ib_i$, E_S is the average power of the signal and $\bar{\gamma}_1=L_SL_RE_S/N_1=10^{(g_S+g_R)/10}E_S/N_1r_S^{\mu_S}r_R^{\mu_R}$ is the average SNR of the S-R link. From [9], we apply the K_G distribution to model the statistical distribution of γ_1. Thus, the PDF and CDF of γ_1 are obtained as

$$f_{\gamma_1}(\gamma_1)\approx\frac{2\Xi^{k_w+m_w}\gamma_1^{(\frac{k_w+m_w}{2}-1)}}{\bar{\gamma}_1^{\frac{k_w+m_w}{2}}\Gamma(k_w)\Gamma(m_w)}K_{k_w-m_w}\left(2\Xi\sqrt{\frac{\gamma_1}{\bar{\gamma}_1}}\right), \tag{3}$$

$$F_{\gamma_1}(\gamma_1)\approx\frac{1}{\Gamma(k_w)\Gamma(m_w)}\mathrm{G}_{1,3}^{2,1}\left(\frac{\Xi^2\gamma_1}{\bar{\gamma}_1}\middle|\begin{matrix}1\\k_w,m_w,0\end{matrix}\right), \tag{4}$$

where the definitions of the parameters $k_w=\frac{-b_w+\sqrt{b_w^2-4a_wc_w}}{2a_w}$, $m_w=\frac{-b_w-\sqrt{b_w^2-4a_wc_w}}{2a_w}$, a_w, b_w, and c_w can be found in [16]. $\Xi=\sqrt{\frac{k_wm_w}{\Omega_w}}$, and Ω_w is the mean power of Z. Moreover, $K_v(\cdot)$ is the modified v-order Bessel function of the second kind, $\Gamma(\cdot)$ is the gamma function, and $\mathrm{G}_{:,:}^{:,:}(\cdot|)$ is the Meijer G-function.

B. FSO link

Similar to [17], a subcarrier intensity modulation (SIM) mode is applied to implement the E2O conversion. For the FSO link, the M fading model is applied to model the turbulence. In addition, pointing errors are also taken into consideration. Then, from [17, Eq. (4)], we have

$$y_2=\sqrt{E_r}Gh_3(1+\eta y_1)+n_2, \tag{5}$$

where $n_2\sim\mathcal{CN}(0,N_2)$ is the AWGN of the FSO link, E_r is the transmit power of R, G is the amplification gain, and η is the E2O conversion coefficient. In addition, $h_3=h_ah_p$ is the FSO channel gain composed of two attenuation components due to the turbulence-induced fading and pointing errors. Finally, after filtering out the direct-current component, y_2 is rewritten as

$$y_2=\sqrt{E_r}Gh_3\eta y_1+n_2. \tag{6}$$

In [18], the PDF of the optical channel gain taking into account pointing errors has been given. However, for the convenience of subsequent calculation, we change Eq. (18) given in [18] to another form. By using [19, Eq. (2.6.20)], the Bessel-K function [18, Eq. (18)] can be rewritten as

$$\begin{aligned}K_{\alpha-k}(2\sqrt{\theta h_a})=&\frac{2^{\alpha+k-2}}{\pi}(\theta h_a)^{-\frac{\alpha+k}{2}}\\&\times\mathrm{G}_{0,4}^{4,0}\left(\frac{\theta^2h_a^2}{16}\middle|\begin{matrix}-\\\frac{\alpha}{2},\frac{\alpha+1}{2},\frac{k}{2},\frac{k+1}{2}\end{matrix}\right).\end{aligned} \tag{7}$$

Thus, by applying equations [20, Eq. (07.34.21.0085.01)] and [20, Eq. (07.34.21.0084.01)], the PDF and CDF of h_3 can be rewritten as

$$\begin{aligned}f_{h_3}(h)=&\sum_{k=1}^{\beta}\frac{2^{\alpha+k-3}g^2A}{\pi h}a_k\theta^{-\frac{\alpha+k}{2}}\\&\times\mathrm{G}_{2,6}^{6,0}\left(\frac{\theta^2h^2}{16A_0^2}\middle|\begin{matrix}\frac{g^2+1}{2},\frac{g^2}{2}+1\\\frac{g^2}{2},\frac{g^2+1}{2},\frac{\alpha}{2},\frac{\alpha+1}{2},\frac{k}{2},\frac{k+1}{2}\end{matrix}\right),\end{aligned} \tag{8}$$

$$\begin{aligned}F_{h_3}(h)=&\int_0^h f_h(h)dh=\sum_{k=1}^{\beta}\frac{2^{\alpha+k-4}g^2A}{\pi}a_k\theta^{-\frac{\alpha+k}{2}}\\&\times\mathrm{G}_{4,8}^{6,2}\left(\frac{\theta^2h^2}{16A_0^2}\middle|\begin{matrix}\frac{1}{2},1,\frac{g^2+1}{2},\frac{g^2}{2}+1\\\frac{g^2}{2},\frac{g^2+1}{2},\frac{\alpha}{2},\frac{\alpha+1}{2},\frac{k}{2},\frac{k+1}{2},0,\frac{1}{2}\end{matrix}\right),\end{aligned} \tag{9}$$

where $\theta=\alpha\beta/(\omega\beta+\Omega')$, $A=\frac{2\alpha^{\alpha/2}}{\omega^{\alpha/2+1}\Gamma(\alpha)}\left(\frac{\omega\beta}{\omega\beta+\Omega'}\right)^{\beta+\alpha/2}$, $a_k=\binom{\beta-1}{k-1}\frac{(\omega\beta+\Omega')^{1-k/2}}{(k-1)!}\left(\frac{\Omega'}{\omega}\right)^{k-1}\left(\frac{\alpha}{\beta}\right)^{k/2}$, α is a positive parameter related to the effective number of large-scale cells of the scattering process, $\beta=E^2[X]/Var[X]$ is the amount of fading parameter, where X is a variable that follows a gamma distribution, $E[X]$ is the mean and $Var[X]$ is the variance. Similar to [17], [18], we assume that β is an integer. Besides, $\omega=2b_0(1-\rho)$, $\Omega'=\Omega+\rho 2b_0+2\sqrt{2b_0\Omega\rho}\cos(\phi_A-\phi_B)$ denotes the average power of the coherent contributions, and the above parameters are all defined in [17]. Note that values of g represent the degree of influence of pointing errors and $g\to\infty$ corresponds to the non-pointing error case.

Then, we readily have

$$\gamma_2=h_3^2\bar{\gamma}_2. \tag{10}$$

where $\bar{\gamma}_2=E_r\eta^2/N_2$. Substituting (10) into (8) and (9), we obtain

$$\begin{aligned}f_{\gamma_2}(\gamma_2)=&\sum_{k=1}^{\beta}\frac{2^{\alpha+k-4}g^2A}{\pi\gamma_2}a_k\theta^{-\frac{\alpha+k}{2}}\\&\times\mathrm{G}_{2,6}^{6,0}\left(\frac{\theta^2\gamma_2}{16A_0^2\bar{\gamma}_2}\middle|\begin{matrix}\frac{g^2+1}{2},\frac{g^2}{2}+1\\\frac{g^2}{2},\frac{g^2+1}{2},\frac{\alpha}{2},\frac{\alpha+1}{2},\frac{k}{2},\frac{k+1}{2}\end{matrix}\right),\end{aligned} \tag{11}$$

$$\begin{aligned}F_{\gamma_2}(\gamma_2)=&\sum_{k=1}^{\beta}\frac{2^{\alpha+k-4}g^2A}{\pi}a_k\theta^{-\frac{\alpha+k}{2}}\\&\times\mathrm{G}_{4,8}^{6,2}\left(\frac{\theta^2\gamma_2}{16A_0^2\bar{\gamma}_2}\middle|\begin{matrix}\frac{1}{2},1,\frac{g^2+1}{2},\frac{g^2}{2}+1\\\frac{g^2}{2},\frac{g^2+1}{2},\frac{\alpha}{2},\frac{\alpha+1}{2},\frac{k}{2},\frac{k+1}{2},0,\frac{1}{2}\end{matrix}\right).\end{aligned} \tag{12}$$

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$$F_{\gamma_0}(\gamma)=\frac{1}{\Gamma(k_w)\Gamma(m_w)}\mathrm{G}_{1,3}^{2,1}\left(\frac{\Xi^2\gamma}{\bar{\gamma}_1}\middle|\begin{matrix}1\\k_w,m_w,0\end{matrix}\right)+\sum_{k=1}^{\beta}\frac{2^{\alpha+k-4}g^2Aa_k\theta^{-\frac{\alpha+k}{2}}}{\pi\Gamma(k_w)\Gamma(m_w)}\sum_{i=0}^{\infty}\frac{(-\Xi^2)^i}{i!\bar{\gamma}_1^i}\gamma^i\mathrm{G}_{5,11}^{9,2}\left(\frac{\Xi^2\theta^2C\gamma}{16A_0^2\bar{\gamma}_1\bar{\gamma}_2}\middle|\begin{matrix}\frac{1}{2},1,1-i,\frac{g^2+1}{2},\frac{g^2}{2}+1\\1,\frac{g^2}{2},\frac{g^2+1}{2},\frac{\alpha}{2},\frac{\alpha+1}{2},\frac{k}{2},\frac{k+1}{2},k_w-i,m_w-i,0,\frac{1}{2}\end{matrix}\right). \tag{15}$$

$$\bar{P}_e=\frac{q^p}{2\Gamma(p)}\int_0^{\infty}\gamma^{p-1}e^{-q\gamma}F_{\gamma_0}(\gamma)d\gamma=\frac{1}{2\Gamma(p)\Gamma(k_w)\Gamma(m_w)}\mathrm{G}_{2,3}^{2,2}\left(\frac{\Xi^2}{q\bar{\gamma}_1}\middle|\begin{matrix}1-p,1\\k_w,m_w,0\end{matrix}\right)+\sum_{k=1}^{\beta}\frac{2^{\alpha+k-5}g^2Aa_k\theta^{-\frac{\alpha+k}{2}}}{\pi\Gamma(p)\Gamma(k_w)\Gamma(m_w)}\sum_{i=1}^{\infty}\frac{(-\Xi^2)^i}{i!\bar{\gamma}_1^iq^i}\mathrm{G}_{6,11}^{9,3}\left(\frac{\Xi^2\theta^2C\gamma}{16A_0^2\bar{\gamma}_1\bar{\gamma}_2q}\middle|\begin{matrix}1-p-i,\frac{1}{2},1,1-i,\frac{g^2+1}{2},\frac{g^2}{2}+1\\1,\frac{g^2}{2},\frac{g^2+1}{2},\frac{\alpha}{2},\frac{\alpha+1}{2},\frac{k}{2},\frac{k+1}{2},k_w-i,m_w-i,0,\frac{1}{2}\end{matrix}\right). \tag{19}$$

C. End-to-End Statistical Distribution

Regarding the fixed-gain relaying mode, the SNR γ_0 of the whole system is written as

$$\gamma_0=\frac{\gamma_1\gamma_2}{\gamma_2+C}, \tag{13}$$

where C is a constant related to G. Then, the CDF of γ_0 can be expressed as [10], [21]

$$F_{\gamma_0}(\gamma)=F_{\gamma_1}(\gamma)+\underbrace{\int_0^{\infty}F_{\gamma_2}\left(\frac{C\gamma}{x}\right)f_{\gamma_1}(\gamma+x)dx}_{D_1}. \tag{14}$$

By substituting (3), (4) and (12) into (14) and applying the equations [20, Eq. (07.34.16.0002.01)] and [20, Eq. (07.34.21.0082.01)], the CDF of γ_0 is obtained and shown as (15) at the top of 3-rd page.

III. Performance Analysis

Next the exact expressions for the OP and ABER of our proposed system are derived. To obtain more insights, we develop the asymptotic representations of OP and ABER at high SNRs. Besides, the upper and lower bounds on the ACC are provided.

A. OP

1) *Exact Analysis:* OP is defined as the probability that the instantaneous SNR γ_0 falling to a given threshold γ_{th}. Thus, it is readily to obtain the OP expression as

$$P_{out}=\Pr(\gamma_0<\gamma_{th})=F_{\gamma_0}(\gamma_{th}). \tag{16}$$

2) *Asymptotic Analysis:* By letting $\bar{\gamma}_1=\bar{\gamma}_2=\bar{\gamma}\to\infty$, the asymptotic representation of the OP is obtained as

$$P_{out}^{\infty}\approx F_{\gamma_1}^{\infty}+D_1^{\infty}. \tag{17}$$

By using [20, Eq. (07.34.06.0040.01)], [20, Eq. (07.34.21.0086.01)] and [22, Eq. 3.381.4], P_{out}^{∞} can be written as

$$P_{out}^{\infty}\approx F_{\gamma_1}^{\infty}+D_1^{\infty}=\frac{\Gamma(|m_w-k_w|)(\Xi^2\gamma_{th})^v}{v\Gamma(k_w)\Gamma(m_w)\bar{\gamma}^v}+\frac{\Gamma(|m_w-k_w|)(\Xi^2\gamma_{th})^v}{\Gamma(k_w)\Gamma(m_w)}\sum_{k=1}^{\beta}\frac{2^{\alpha+k-4}g^2A}{\pi\Gamma(1-v)}a_k\theta^{-\frac{\alpha+k}{2}}\times\sum_{n=1}^{7}\frac{\prod_{j=1,j\neq n}^{7}\Gamma(d_j-d_n)\prod_{j=1}^{3}\Gamma(1-c_j+d_n)}{\prod_{j=4}^{5}\Gamma(c_j-d_n)\prod_{j=8}^{9}\Gamma(1-d_j+d_n)}\times\left(\frac{\theta^2C}{16A_0^2}\right)^{d_n}\left(\frac{1}{\bar{\gamma}}\right)^{v+d_n}, \tag{18}$$

where $[c_1,...,c_5]=[v+1,\frac{1}{2},1,\frac{g^2+1}{2},\frac{g^2}{2}+1]$, $[d_1,...,d_9]=[1,\frac{g^2}{2},\frac{g^2+1}{2},\frac{\alpha}{2},\frac{\alpha+1}{2},\frac{k}{2},\frac{k+1}{2},0,\frac{1}{2}]$ and $v=\min\{k_w,m_w\}$. From (18), since α, k and g are all positive numbers, we obtain the diversity order (DO) of our proposed system as $G_d=v=\min\{k_w,m_w\}$. As k_w and m_w are related to the values of N and m, one can see that the DO is only dependent on the RF link and this observation will be demonstrated in section IV.

B. ABER

1) *Exact Analysis:* By applying [20, Eq. (07.34.21.0088.01)], the ABER for different binary modulation schemes is expressed as (19) shown at the top of the 3-rd page, where p and q are the parameters depended on the modulation scheme.

2) *Asymptotic Analysis:* Letting $\bar{\gamma}_1=\bar{\gamma}_2=\bar{\gamma}\to\infty$, we have

$$\bar{P}_e^{\infty}=\frac{q^p}{2\Gamma(p)}\int_0^{\infty}\gamma^{p-1}e^{-q\gamma}F_{\gamma_0}^{\infty}(\gamma)d\gamma=\frac{\Gamma(|m_w-k_w|)\Gamma(v+p)\Xi^{2v}}{2v\Gamma(p)\Gamma(k_w)\Gamma(m_w)q^v\bar{\gamma}^v}+\frac{\Gamma(|m_w-k_w|)\Gamma(v+p)\Xi^{2v}}{\Gamma(p)\Gamma(k_w)\Gamma(m_w)q^v}\sum_{k=1}^{\beta}\frac{2^{\alpha+k-5}g^2A}{\pi\Gamma(1-v)}a_k\theta^{-\frac{\alpha+k}{2}}\times\sum_{n=1}^{7}\frac{\prod_{j=1,j\neq n}^{7}\Gamma(d_j-d_n)\prod_{j=1}^{3}\Gamma(1-c_j+d_n)}{\prod_{j=4}^{5}\Gamma(c_j-d_n)\prod_{j=8}^{9}\Gamma(1-d_j+d_n)}\times\left(\frac{\theta^2C}{16A_0^2}\right)^{d_n}\left(\frac{1}{\bar{\gamma}}\right)^{v+d_n}. \tag{20}$$

Again, the DO is $G_d = v = \min\{k_w, m_w\}$.

C. ACC

Unfortunately, the exact ACC analysis is very difficult. Therefore, we only provide upper and lower bounds analyses.

1) *Upper Bound:* With the help of [23, Eq. (23)], by utilizing the Jensen's inequality, an upper bound on the ACC is written as

$$\bar{C} = E[\log_2(1+\gamma_0)] \leq \log_2[1+E(\gamma_0)] = \bar{C}_{UB}. \quad (21)$$

Since γ_1 and γ_2 are independent random variables, $E(\gamma_0)$ can be rewritten as

$$E(\gamma_0) = E\left(\frac{\gamma_1\gamma_2}{\gamma_2+C}\right) = E(\gamma_1)E\left(\frac{\gamma_2}{\gamma_2+C}\right), \quad (22)$$

where $E(\gamma_1)$ and $E\left(\frac{\gamma_2}{\gamma_2+C}\right)$ can be derived with the help of [20, Eq. (03.04.21.0116.01)] and [20, Eq. (07.34.21.0086.01)]:

$$E(\gamma_1) = \int_0^\infty \gamma_1 f_{\gamma_1}(\gamma_1)d\gamma_1 = \frac{k_w m_w \bar{\gamma}_1}{\Xi^2}, \quad (23)$$

$$\begin{aligned} E\left(\frac{\gamma_2}{\gamma_2+C}\right) &= \sum_{k=1}^{\beta} \frac{2^{\alpha+k-4}g^2 A}{\pi} a_k \theta^{-\frac{\alpha+k}{2}} \\ &\times \mathrm{G}_{3,7}^{7,1}\left(\frac{\theta^2 C}{16A_0^2\bar{\gamma}_2}\middle| \begin{matrix} 0, \frac{g^2+1}{2}, \frac{g^2}{2}+1 \\ 0, \frac{g^2}{2}, \frac{g^2+1}{2}, \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{k}{2}, \frac{k+1}{2} \end{matrix}\right). \end{aligned} \quad (24)$$

Based on (19) and (20), $\bar{C}_{UB}$ can be obtained. For $\bar{\gamma}_1 = \bar{\gamma}_2 = \bar{\gamma} \to \infty$, applying [20, Eq. (07.34.06.0040.01)], we have

$$\begin{aligned} \bar{C}_{UB}^{\infty} &= \log_2(E(\gamma_1)) + \log_2(E(\gamma_2)) - \log_2(E(\gamma_2+C)) \\ &\to \log_2(\bar{\gamma}) - \log_2(\Xi^2) + \log_2(k_w) + \log_2(m_w) \\ &+ \log_2\left(\sum_{k=1}^{\beta} \frac{2^{\alpha+k-4}g^2A}{\pi} a_k\theta^{-\frac{\alpha+k}{2}}\right. \\ &\times \sum_{n=1}^{7} \frac{\prod_{j=1,j\neq n}^{7}\Gamma(q_j-q_n)\prod_{j=1}^{1}\Gamma(1-p_j+q_n)}{\prod_{j=2}^{3}\Gamma(p_j-q_n)} \\ &\times \left.\left(\frac{\theta^2 C}{16A_0^2}\right)^{q_n}\left(\frac{1}{\bar{\gamma}}\right)^{q_n}\right), \end{aligned} \quad (25)$$

where $[p_1, p_2, p_3] = [0, \frac{g^2+1}{2}, \frac{g^2}{2}+1]$, $[q_1, ..., q_7] = [0, \frac{g^2}{2}, \frac{g^2+1}{2}, \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{k}{2}, \frac{k+1}{2}]$.

2) *Lower Bound:* With the help of [24, Eq. (16)], a tight lower bound on the ACC is expressed as

$$\bar{C} \geq \log_2[1 + e^{E(\ln\gamma_1)+E(\ln\gamma_2)-E(\ln(\gamma_2+C))}] = \bar{C}_{LB}. \quad (26)$$

Using [25, Eq. (2.16.20.1)], we have $E(\ln\gamma_1) = \psi(k_w)\psi(m_w) - 2\ln(\Xi/\sqrt{\bar{\gamma}_1})$, where $\psi(\cdot)$ is the digamma function. Let $E(\ln\gamma_2) - E(\ln(\gamma_2+C)) = -E(\ln(1+C/\gamma_2)) = -\lambda$. By using [25, Eq. (8.4.6.5)], [20, Eq. (07.34.16.0002.01)], and [20, Eq. (07.34.21.0013.01)], λ can be obtained

$$\begin{aligned} \lambda &= E\left[\mathrm{G}_{2,2}^{2,1}\left(\frac{\gamma_2}{C}\middle| \begin{matrix} 0,1 \\ 0,0 \end{matrix}\right)\right] = \sum_{k=1}^{\beta} \frac{2^{\alpha+k-4}g^2A}{\pi} a_k\theta^{-\frac{\alpha+k}{2}} \\ &\times \mathrm{G}_{4,8}^{7,2}\left(\frac{\theta^2 C}{16A_0^2\bar{\gamma}_2}\middle| \begin{matrix} 1,1,\frac{g^2+1}{2},\frac{g^2}{2}+1 \\ \frac{g^2}{2},\frac{g^2+1}{2},\frac{\alpha}{2},\frac{\alpha+1}{2},\frac{k}{2},\frac{k+1}{2},1,0 \end{matrix}\right). \end{aligned} \quad (27)$$

For $\bar{\gamma}_1 = \bar{\gamma}_2 = \bar{\gamma} \to \infty$, by applying [20, Eq. (07.34.06.0040.01)], $\bar{C}_{LB}^{\infty}$ is obtained as

$$\begin{aligned} \bar{C}_{LB}^{\infty} &= \frac{E(\ln\gamma_1)+E(\ln\gamma_2)-E(\ln(\gamma_2+C))}{\ln 2} \\ &\to \log_2(\bar{\gamma}) - \log_2(\Xi^2) + \frac{\psi(k_w)+\psi(m_w)}{\ln 2} \\ &- \sum_{k=1}^{\beta} \frac{2^{\alpha+k-4}g^2A}{\pi\ln 2} a_k\theta^{-\frac{\alpha+k}{2}} \\ &\times \left(\sum_{n=1}^{7} \frac{\prod_{j=1,j\neq n}^{7}\Gamma(w_j-w_n)\prod_{j=1}^{2}\Gamma(1-u_j+w_n)}{\prod_{j=3}^{4}\Gamma(u_j-w_n)\prod_{j=8}^{8}\Gamma(1-w_j+w_n)}\right. \\ &\times \left.\left(\frac{\theta^2C}{16A_0^2}\right)^{w_n}\left(\frac{1}{\bar{\gamma}}\right)^{w_n}\right), \end{aligned} \quad (28)$$

where $[u_1, ..., u_4] = [1, 1, \frac{g^2+1}{2}, \frac{g^2}{2}+1]$, $[w_1, ..., w_8] = [\frac{g^2}{2}, \frac{g^2+1}{2}, \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{k}{2}, \frac{k+1}{2}, 1, 0]$.

From the above high SNR bound analysis, one can see that the system capacity more depends on the RF link. In addition, it can be seen that λ increases when g increases.

IV. Extension to the System with Shadowing Effects in the RF Channels

In this section, we take the shadowing effects into consideration. In practical scenarios, signals experience the shadowed fading during the propagation, which is a kind of the large-scale fluctuation caused by slow changes in local average power levels over long propagation distances due to terrain features, such as buildings and hills [26].

With the consideration of the shadowing effects, the SNR of the RF link can be rewritten as

$$\gamma_1^s = \frac{E_S\left(\sum_{i=1}^{N} s\epsilon_i b_i\right)^2}{r_S^{\mu_S} r_R^{\mu_R} N_1} = Z_1 Z_2 \bar{\gamma}_1^s, \quad (29)$$

where s denotes the shadowing effect, which is widely characterized by a lognormal distribution. Besides, $\bar{\gamma}_1^s = \frac{E_S}{r_S^{\mu_S} r_R^{\mu_R} N_1}$, $Z_1 = s^2$, $Z_2 = \left(\sum_{i=1}^{N}\epsilon_i b_i\right)^2$. Since $10\log_{10} s \sim \mathcal{N}(0, \sigma_1^2)$, the PDF of s can be obtained as [27]

$$f_s(s) = \frac{10e^{-\frac{(10\log_{10}s)^2}{2\sigma_1^2}}}{10\ln 10\sqrt{2\pi}\sigma_1 s}. \quad (30)$$

where σ_1 is the standard deviation of $10\log_{10} s$. Applying eq. (30) to evaluate the system performance is generally very difficult. Thus, for a tractable analysis, many works using the gamma distribution to approximate the lognormal distribution, like [18], [28], [29]. Then, the PDF of s can be represented as

$$f_s(s) = \frac{s^{v_1-1}}{\Gamma(v_1)\lambda_1^{v_1}} e^{\frac{x}{\lambda_1}}, \quad (31)$$

where $v_1 = \frac{1}{e^{\sigma_1^2}-1}$ inversely reflects the shadowing severity and $\lambda_1 = (e^{\sigma_1^2}-1)e^{\frac{\sigma_1^2}{2}}$ [29]. $\varsigma_1 = v_1\lambda_1$ is the gamma shadow area mean power. Meanwhile, according to the developed method in [30] and similar to the RIS-related works [31]-[33], we approximate $Z = \sum_{i=1}^{N}\epsilon_i b_i$ to a gamma distribution. Thus,

$$F_{\gamma_0^s}(\gamma) = \frac{2^{v_1+v_2-2}}{\pi\Gamma(v_1)\Gamma(v_2)} \mathrm{G}_{1,5}^{4,1}\left(\frac{\gamma}{16\lambda_1^2\lambda_2^2\bar{\gamma}_1^s}\middle|\begin{matrix}1\\ \frac{v_1}{2}, \frac{v_1+1}{2}, \frac{v_2}{2}, \frac{v_2+1}{2}, 0\end{matrix}\right) + \sum_{k=1}^{\beta}\frac{2^{\alpha+k+v_1+v_2-6}g^2 A a_k \theta^{-\frac{\alpha+k}{2}}}{\pi^2\Gamma(v_1)\Gamma(v_2)} \times \sum_{i=0}^{\infty}\frac{(-\gamma)^i}{i!(16\lambda_1^2\lambda_2^2\bar{\gamma}_1^s)^i}\mathrm{G}_{5,13}^{11,2}\left(\frac{\theta^2 C\gamma}{256A_0^2\lambda_1^2\lambda_2^2\bar{\gamma}_1^s\bar{\gamma}_2}\middle|\begin{matrix}\frac{1}{2}, 1, 1-i, \frac{g^2+1}{2}, \frac{g^2}{2}+1\\ 1, \frac{g^2}{2}, \frac{g^2+1}{2}, \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{k}{2}, \frac{k+1}{2}, \frac{v_1}{2}-i, \frac{v_1+1}{2}-i, \frac{v_2}{2}-i, \frac{v_2+1}{2}-i, 0, \frac{1}{2}\end{matrix}\right) \tag{38}$$

$$\bar{P}_e^s = \frac{q^p}{2\Gamma(p)}\int_0^{\infty}\gamma^{p-1}e^{-q\gamma}F_{\gamma_0^s}(\gamma)d\gamma = \frac{2^{v_1+v_2-3}}{\pi\Gamma(v_1)\Gamma(v_2)\Gamma(p)}\mathrm{G}_{2,5}^{4,2}\left(\frac{1}{16\lambda_1^2\lambda_2^2\bar{\gamma}_1^s}\middle|\begin{matrix}1-p, 1\\ \frac{v_1}{2}, \frac{v_1+1}{2}, \frac{v_2}{2}, \frac{v_2+1}{2}, 0\end{matrix}\right) + \sum_{k=1}^{\beta}\frac{2^{\alpha+k+v_1+v_2-7}g^2 A a_k\theta^{-\frac{\alpha+k}{2}}}{\pi^2\Gamma(v_1)\Gamma(v_2)\Gamma(p)}\sum_{i=0}^{\infty}\frac{(-1)^i}{i!(16\lambda_1^2\lambda_2^2\bar{\gamma}_1^s q)^i} \times \mathrm{G}_{6,13}^{11,3}\left(\frac{\theta^2 C}{256A_0^2\lambda_1^2\lambda_2^2\bar{\gamma}_1^s\bar{\gamma}_2 q}\middle|\begin{matrix}1-p-i, \frac{1}{2}, 1, 1-i, \frac{g^2+1}{2}, \frac{g^2}{2}+1\\ 1, \frac{g^2}{2}, \frac{g^2+1}{2}, \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{k}{2}, \frac{k+1}{2}, \frac{v_1}{2}-i, \frac{v_1+1}{2}-i, \frac{v_2}{2}-i, \frac{v_2+1}{2}-i, 0, \frac{1}{2}\end{matrix}\right) \tag{40}$$

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we can write the PDF expressions of $Z_1 = s^2$ and $Z_2 = Z^2$ as

$$f_{Z_n}(z_n) = \frac{z_n^{\frac{v_n}{2}-1}}{2\Gamma(v_n)\lambda_n^{v_n}}e^{-\frac{\sqrt{z_n}}{\lambda_n}}. \tag{32}$$

where n={1,2}, $v_2 = \frac{E(Z)^2}{VAR(Z)}$ and $\lambda_2 = \frac{VAR(Z)}{E(Z)}$. After some mathematical computation, $E(Z)$ and $VAR(Z)$ can be written as

$$E(Z) = N\frac{\sqrt{\pi}\Gamma\left(m+\frac{1}{2}\right)}{2\sqrt{m}\Gamma(m)}, \tag{33}$$

$$VAR(Z) = N\left[1 - \frac{\pi\Gamma\left(m+\frac{1}{2}\right)^2}{4m\Gamma(m)^2}\right]. \tag{34}$$

By using [18, Eq. (2.6.20)], [20, Eq. (07.34.16.0001.01)], [20, Eq. (07.34.21.0084.01)], and [22, Eq. (3.471.9)], the PDF and CDF of the SNR γ_1^s for the RF link in the presence of the shadowing effects can be rewritten as

$$f_{\gamma_1^s}(\gamma_1) = \int_0^{\infty}\frac{1}{z_1\bar{\gamma}_1^s}f_{Z_1}(z_1)f_{Z_2}\left(\frac{\gamma_1}{z_1\bar{\gamma}_1^s}\right)dz_1 = \frac{2^{v_1+v_2-2}}{16\pi\Gamma(v_1)\Gamma(v_2)\lambda_1^2\lambda_2^2\bar{\gamma}_1^s} \times \mathrm{G}_{0,4}^{4,0}\left(\frac{\gamma_1}{16\lambda_1^2\lambda_2^2\bar{\gamma}_1^s}\middle|\begin{matrix}-\\ \frac{v_1}{2}-1, \frac{v_1-1}{2}, \frac{v_2}{2}-1, \frac{v_2-1}{2}\end{matrix}\right), \tag{35}$$

$$F_{\gamma_1^s}(\gamma_1) = \int_0^{\gamma_1}f_{\gamma_1^s}(\gamma_1)d\gamma_1 = \frac{2^{v_1+v_2-2}}{\pi\Gamma(v_1)\Gamma(v_2)} \times \mathrm{G}_{1,5}^{4,1}\left(\frac{\gamma_1}{16\lambda_1^2\lambda_2^2\bar{\gamma}_1^s}\middle|\begin{matrix}1\\ \frac{v_1}{2}, \frac{v_1+1}{2}, \frac{v_2}{2}, \frac{v_2+1}{2}, 0\end{matrix}\right). \tag{36}$$

Then, the CDF of the e2e SNR γ_0^s can be expressed as

$$F_{\gamma_0^s}(\gamma) = F_{\gamma_1^s}(\gamma) + \int_0^{\infty}F_{\gamma_2}\left(\frac{C\gamma}{x}\right)f_{\gamma_1^s}(\gamma+x)dx. \tag{37}$$

By substituting (12), (35), and (36) into (37) and with the help of [20, Eq. (07.34.16.0002.01)], [20, Eq. (07.34.21.0082.01)], and [22, Eq. (3.381.4)], the CDF of γ_0 is obtained and shown as (38) at the top of this page.

From (38), the OP is $P_{out}^s = F_{\gamma_0^s}(\gamma_{th})$. Let $\bar{\gamma} = \bar{\gamma}_1 = \bar{\gamma}_2 \to \infty$, by applying [20, Eq. (07.34.06.0040.01)], the asymptotic expression for the OP can be obtained as

$$P_{out}^{s\infty} \approx \frac{2^{v_1+v_2-1}\Gamma\left(\frac{|v_2-v_1|}{2}\right)\Gamma\left(\frac{|v_2-v_1|+1}{2}\right)\gamma_{th}^{\frac{u}{2}}}{\sqrt{\pi}\Gamma(v_1)\Gamma(v_2)(16\lambda_1^2\lambda_2^2 q)^{\frac{u}{2}}u\bar{\gamma}^{\frac{u}{2}}} + \sum_{k=1}^{\beta}\frac{2^{\alpha+k+v_1+v_2-6}g^2 A\Gamma\left(\frac{|v_2-v_1|}{2}\right)\Gamma\left(\frac{|v_2-v_1|+1}{2}\right)\gamma_{th}^{\frac{u}{2}}}{\pi^{\frac{3}{2}}\Gamma(v_1)\Gamma(v_2)(16\lambda_1^2\lambda_2^2 q)^{\frac{u}{2}}\Gamma\left(1-\frac{u}{2}\right)} \times a_k\theta^{-\frac{\alpha+k}{2}}\left(\frac{\theta^2 C}{16A_0^2}\right)^{\varrho_n}\left(\frac{1}{\bar{\gamma}}\right)^{\frac{u}{2}+\varrho_n} \times \sum_{n=1}^{7}\frac{\prod_{j=1,j\neq n}^{7}\Gamma(\varrho_j-\varrho_n)\prod_{j=1}^{3}\Gamma(1-\varpi_j+\varrho_n)}{\prod_{j=4}^{5}\Gamma(\varpi_j-\varrho_n)\prod_{j=8}^{9}\Gamma(1-\varrho_j+\varrho_n)}, \tag{39}$$

where $[\varpi_1, ..., \varpi_5] = [\frac{u}{2}+1, \frac{1}{2}, 1, \frac{g^2+1}{2}, \frac{g^2}{2}+1]$, $[\varrho_1, ..., \varrho_9] = [1, \frac{g^2}{2}, \frac{g^2+1}{2}, \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{k}{2}, \frac{k+1}{2}, 0, \frac{1}{2}]$, $u = \min\{v_1, v_2\}$. Then, we can obtain the DO of the system as $G_d^s = \frac{u}{2} = \frac{1}{2}\min\{v_1, v_2\}$, where v_2 is related to the values of N and m. The same conclusion can be drawn that the DO is only dependent on the RF link.

Similarly, by applying [20, Eq. (07.34.21.0088.01)], the ABER for different binary modulation schemes is expressed as (40) shown at the top of this page. Again, when $\bar{\gamma} = \bar{\gamma}_1 = \bar{\gamma}_2 \to \infty$, the asymptotic expression for the ABER can be written as

$$\bar{P}_e^{s\infty} \approx \frac{2^{v_1+v_2-2}\Gamma\left(\frac{|v_2-v_1|}{2}\right)\Gamma\left(\frac{|v_2-v_1|+1}{2}\right)\Gamma\left(\frac{u}{2}+p\right)}{\sqrt{\pi}\Gamma(v_1)\Gamma(v_2)\Gamma(p)(16\lambda_1^2\lambda_2^2 q)^{\frac{u}{2}}u\bar{\gamma}^{\frac{u}{2}}} + \sum_{k=1}^{\beta}\frac{2^{\alpha+k+v_1+v_2-7}g^2 A\Gamma\left(\frac{|v_2-v_1|}{2}\right)\Gamma\left(\frac{|v_2-v_1|+1}{2}\right)\Gamma\left(\frac{u}{2}+p\right)}{\pi^{\frac{3}{2}}\Gamma(v_1)\Gamma(v_2)\Gamma(p)(16\lambda_1^2\lambda_2^2 q)^{\frac{u}{2}}\Gamma\left(1-\frac{u}{2}\right)} \times a_k\theta^{-\frac{\alpha+k}{2}}\left(\frac{\theta^2 C}{16A_0^2}\right)^{\varrho_n}\left(\frac{1}{\bar{\gamma}}\right)^{\frac{u}{2}+\varrho_n} \times \sum_{n=1}^{7}\frac{\prod_{j=1,j\neq n}^{7}\Gamma(\varrho_j-\varrho_n)\prod_{j=1}^{3}\Gamma(1-\varpi_j+\varrho_n)}{\prod_{j=4}^{5}\Gamma(\varpi_j-\varrho_n)\prod_{j=8}^{9}\Gamma(1-\varrho_j+\varrho_n)}. \tag{41}$$

As a double check, the DO is $G_d^s = \frac{u}{2} = \frac{1}{2}\min\{v_1, v_2\}$.

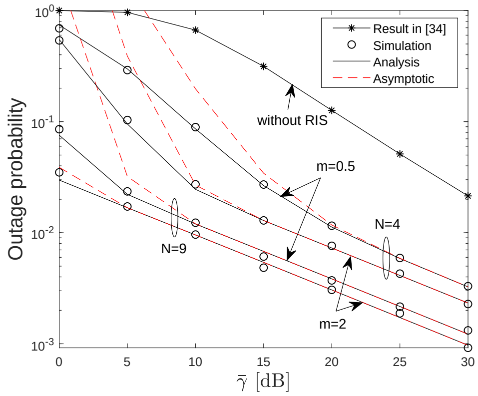

Fig 2. OP versus $\bar{\gamma}_1$ when $\alpha = 2$, $\beta = 5$, $g = 12$.

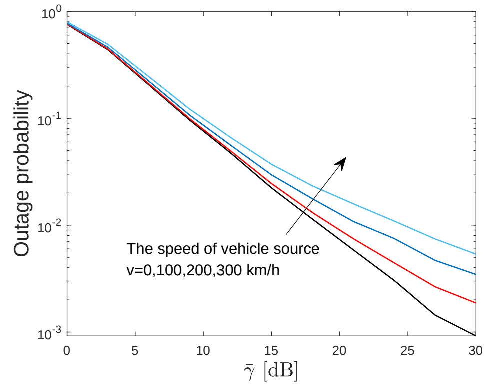

Fig 4. OP versus $\bar{\gamma}$ for different values of speed when $N = 4$, $m = 2$, $\alpha = 2$, $\beta = 5$ and $g = 12$.

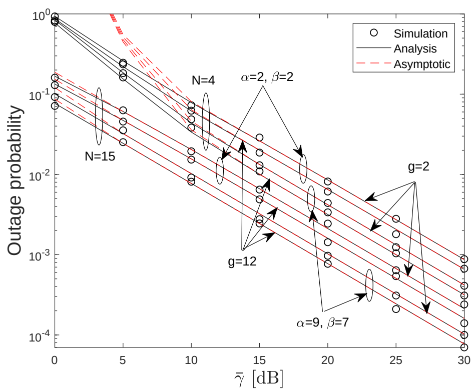

Fig 3. OP versus $\bar{\gamma}$ when $m = 2$.

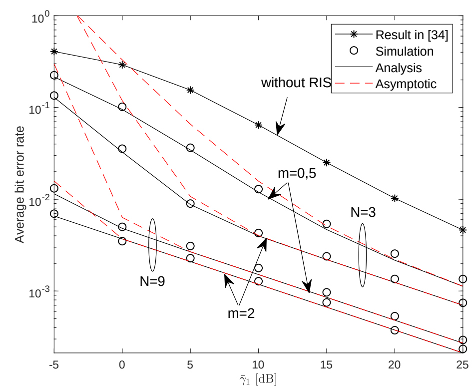

Fig 5. ABER versus $\bar{\gamma}_1$ when $\alpha = 2$, $\beta = 5$, $g = 12$.

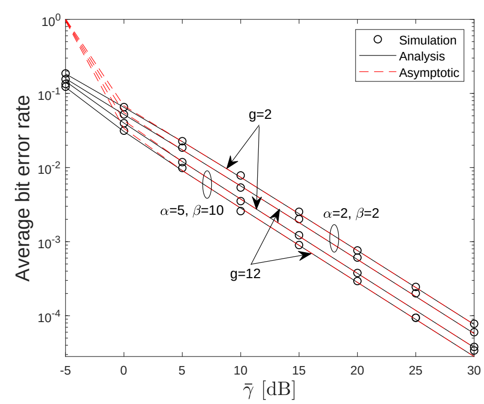

Fig 6. ABER versus $\bar{\gamma}$ when $N = 5$, $m = 2.5$.

V. Numerical Results

In this part, the OP, ABER, and ACC performance of our proposed system are presented by using the derived results along with their corresponding simulation ones. In general, we set $\gamma_{th} = 10$dB and $C = 1.5$. For the BER analysis, we employ the differential phase shift keying (DPSK) modulation scheme, namely, $p = 1$, $q = 1$. Further, the parameters of the FSO link are set to: $\phi_A = \pi/2$, $\phi_B = 0$, $\rho = 0.1$, $b_0 = 0.8$, and $\Omega = 1.5$.

In Fig. 2, the OP curves versus $\bar{\gamma}_1$ for our considered system when $\alpha = 2$, $\beta = 5$ and $g = 12$ are plotted, where $\bar{\gamma}_2$ is set to 20dB. It is clearly observed that the analytical results and simulation results are well fitted and the asymptotic results approach to the exact ones at high SNRs. As N increases, the system outage performance becomes better. The principal reason is that large N results in a higher SNR at the relay. Moreover, compared to the system without the RIS [34], the OP with RISs is clearly small. It indicates that the RIS can dramatically enhance the system performance. On the other hand, one can see that the system performance corresponding to $m = 2$ is better than that for $m = 0.5$. This is because m is the parameter of Nakagami-*m* distribution. Thus, the larger the value of m, the weaker the fading on the RF link.

In Fig. 3, the OP curves versus $\bar{\gamma}$ when $m = 2$ are plotted, where $\bar{\gamma} = \bar{\gamma}_1 = \bar{\gamma}_2$. Recall that the value of α affects the number of large-scale fluctuations, while β is related to the number of small-scale fluctuations. Therefore, both values of α and β affect the amount of the fading of the FSO channel. Again, the analytical results fit well with the simulation ones. It can be observed that increasing the values of α , β, and g are able to enhance the outage performance. Similar to the insights obtained in Fig. 2, according to the definition of β, $1/\alpha$ and $1/\beta$ are the amounts of fading to quantify the severity of the fading experienced by the FSO channel. Therefore, large values of α and β improve the system performance.

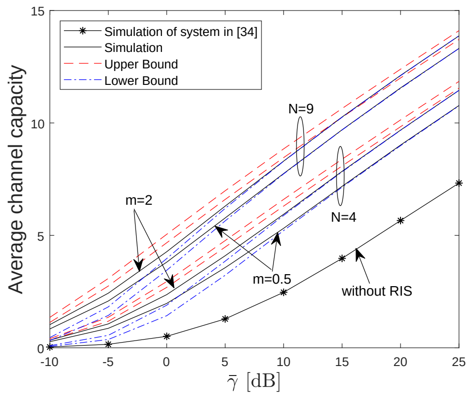

Fig 7. ACC versus $\bar{\gamma}$ when $\alpha = 2$, $\beta = 5$, $g = 12$.

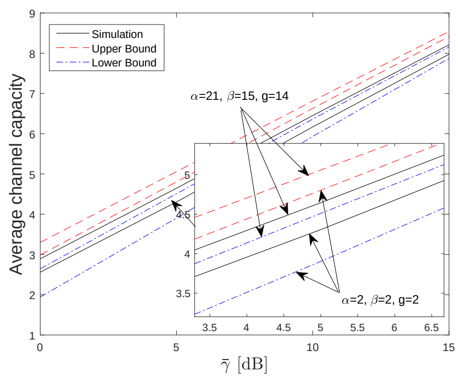

Fig 8. ACC versus $\bar{\gamma}$ when $N = 4$, $m = 2.5$.

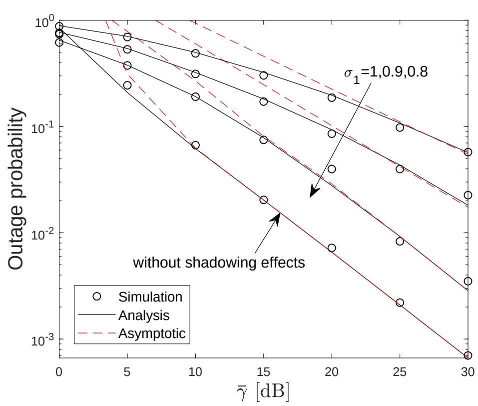

Fig 9. OP with and without shadowing effects versus $\bar{\gamma}$ when $N = 4$, $m = 2$, $\alpha = 2$, $\beta = 5$, $g = 12$.

Finally, one can see that the slopes of the curves are almost the same for different values of α, β, and g, which means that they have the same DOs and verifies the conclusion of the DO $G_d = \min\{k_w, m_w\}$. Thus, the achievable DO of our considered system is independent of the FSO link and only dependent on the RF link. As a double check, from both Fig. 2 and Fig. 3, we can find that the curves corresponding to small values of m and N have large slopes. The reason is that $G_d = \min\{k_w, m_w\}$, while m_w and k_w are related to N and m.

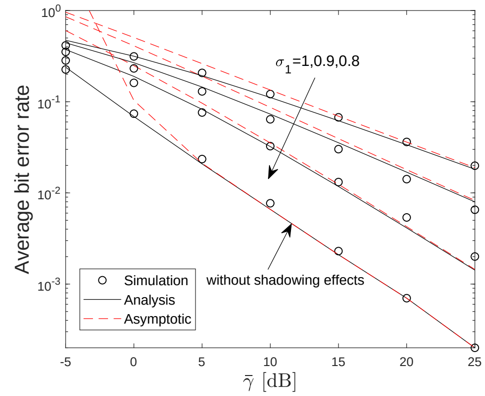

Fig 10. ABER with and without shadowing effects versus $\bar{\gamma}$ when $N = 4$, $m = 2$, $\alpha = 2$, $\beta = 5$, $g = 12$.

To observe the impact of mobility on system performance, the OP curves versus $\bar{\gamma}$ for different values of vehicle speed when $N = 4$, $m = 2$, $\alpha = 2$, $\beta = 5$ and $g = 12$ are plotted in Fig. 4, where $\bar{\gamma} = \bar{\gamma}_1 = \bar{\gamma}_2$. It can be seen that the larger the movement speed of ground vehicles, the higher the outage performance. This is because the mobility of the vehicle can cause Doppler frequency shift, thereby deteriorating system performance.

In Fig. 5, the BER curves versus $\bar{\gamma}_1$ when $\alpha = 2$, $\beta = 2$, $g = 12$ are plotted, while the BER performance when $\bar{\gamma} = \bar{\gamma}_1 = \bar{\gamma}_2$, $N = 5$ and $m = 2.5$ is plotted in Fig. 6. Again, the analytical results and simulation results are well matched and the asymptotic results are close to the analytical results at high SNRs. Similar to Fig. 2 and 3, it is revealed that increasing the values of N, m, α, β and g can improve the BER performance. Besides, similar conclusions as those gained in Fig. 2 and 3 can be attained.

In Fig. 7 and Fig. 8, the upper and lower bounds on the ACC when $\bar{\gamma}_1 = \bar{\gamma}_2 = \bar{\gamma}$ are plotted. As predicted, the upper and lower bounds are approach to the exact ones. Furthermore, at high SNRs, the lower bounds are very close to the simulation results. Similarly, using RIS and large values of N, m, α, β, and g can result in a large capacity.

In Fig. 9 and Fig. 10, the OP and ABER curves of the system with the shadowing effects in the RF channels are plotted when $N = 4$, $m = 2$, $\alpha = 2$, $\beta = 5$, $g = 12$, and $\bar{\gamma}_1 = \bar{\gamma}_2 = \bar{\gamma}$. Likewise, the analytical results and simulation results are well matched and the asymptotic results are close to the analytical results at high SNRs. As can be seen in the figures, as the value of the shadowing parameter σ_1 increases, the performance of the system deteriorates. This is because σ_1 is the quantity used to quantify the severity of the shadowing effects. The larger the value of σ_1, the more severe the shadowing effects experienced by the signal.

VI. Conclusion

In this work, a dual-hop satellite-vehicle network with the aid of a UAV was proposed. In fact, it is a mixed RF-FSO system. For such a scheme, we presented a comprehensive performance analysis including the OP, ABER, and ACC. Results showed that applying the RIS is able to significantly enhance the system performance. In addition, the shadowing effects can significantly degrade the system performance. Moreover, the DO of our considered system was only dependent on the RF link.

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