Outage Performance of NOMA-Based Hybrid Satellite-Terrestrial Relay Networks

Xiaojuan Yan, Hailin Xiao, *Member, IEEE*, Cheng-Xiang Wang, *Fellow, IEEE*, and Kang An

***Abstract*—In this letter, we investigate the outage probability (OP) of amplify-and-forward hybrid satellite-terrestrial relay networks with a nonorthogonal multiple access (NOMA) scheme. By assuming that a single antenna satellite communicates with multiple multiantenna users simultaneously through the help of a single antenna relay and the NOMA scheme, we first derive the closed-form OP expressions for each NOMA user. Then, asymptotic OP expressions at the high signal-to-noise ratio regime are also obtained to evaluate the achievable diversity order and coding gain. Finally, simulations are provided to the validity of theoretical results, the superiority of introducing the NOMA scheme in satellite-terrestrial relay networks, and the effect of key parameters on the performance of NOMA users.**

***Index Terms*—Hybrid satellite-terrestrial relay networks, non-orthogonal multiple access, outage probability.**

I. Introduction

HYBRID satellite-terrestrial relay networks (HSTRNs), in which a relaying technique is adopted to achieve the benefit of spatial diversity, has been proposed as an effective way to mitigate the masking effect and improve the reliability of satellite communications [1]. Many efforts have been devoted to investigate the key performance measures of HSTRNs, such as outage probability (OP), ergodic capacity, and bit error rate (BER) [2]–[6]. Although the performance of HSTRNs can be significantly enhanced, it should be noted that these enhancements via the deployment of additional relay node were achieved with more resource consumption, i.e., time and power. Moreover, the time division multiple access (TDMA) scheme, which was adopted in those aforementioned works, does restrict the improvement of resource utilization since only one user is served at any time slot. In future satellite communication systems, high information transmission quality to a large number of terrestrial users is required [2]. Under this situation, other multiple access schemes should be taken into account in future satellite communications.

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X. Yan is with the School of Information and Communication, Guilin University of Electronic Technology, Guilin 541004, China, and also with the Engineering Training Center, Qinzhou University, Qinzhou 535011, China (e-mail: yxj9609@163.com).

H. Xiao is with the College of Physics and Electronic Information Engineering, Wenzhou University, Wenzhou 325035, China, and also with the School of Information and Communication, Guilin University of Electronic Technology, Guilin 541004, China (e-mail: xhl_xiaohailin@163.com).

C.-X. Wang is with the Institute of Sensors, Signals, and Systems, School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, U.K. (e-mail: cheng-xiang.wang@hw.ac.uk).

K. An is with the National University of Defense Technology, Nanjing 210007, China (e-mail: ankang@nuaa.edu.cn).

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Having the ability to serve multiple users simultaneously and provide high resource efficiency, non-orthogonal multiple access (NOMA) scheme is attracting considerable interests and becoming a promising technology for the fifth generation (5G) networks [7]. Several works studied the superiority of introducing the NOMA scheme in terrestrial cellular networks [8]–[10]. In addition, applying the NOMA scheme to mmWave communications was studied in [11]. An extension of [11] to study NOMA-based mmWave massive multiple-input multiple-output (MIMO) systems was given in [12]. Recently, the work [13] incorporated the NOMA scheme into multibeam satellite networks to further improve the performance of the NOMA scheme. Yan *et al.* [14] integrated the NOMA scheme into cognitive satellite terrestrial networks, so that the ergodic capacity of a cognitive network can be increased. However, no results regarding the performance of NOMA-based HSTRNs have been reported thus far. To fill this gap, this letter studies the performance of NOMA-based amplify-and-forward (AF) HATRNs. Specifically, we first derive the end-to-end signal-to-interference-plus-noise ratios (SINRs) for each NOMA user. Then, the exact and asymptotic OP expressions are derived. Finally, simulation results are provided to show the validity of our theoretical analysis, the superiority of introducing the NOMA scheme in HSTRNs, and the effects of various parameters on the OP performance of each NOMA user.

II. System Model

In this letter, we consider downlink NOMA-based AF HSTRNs, where a land mobile satellite (S) communicates with M terrestrial users D_i ($i = 1, 2 \cdots M$) simultaneously through the help of a terrestrial relay (R) and the NOMA scheme. Each terrestrial user is equipped with N_{D_i} antennas, while S and R nodes are both equipped with a single antenna. It is assumed that all the direct links between S and D_i are not available due to raining, fog, or other masking effect [2]. Without loss of generality, we also assume these users are ordered based on their effective channel gains, i.e., $\|\mathbf{h}_{\mathrm{D}_1}\|_F^2 \le \|\mathbf{h}_{\mathrm{D}_2}\|_F^2 \le \cdots \le \|\mathbf{h}_{\mathrm{D}_M}\|_F^2$, where $\mathbf{h}_{\mathrm{D}_i}$ is the $N_{\mathrm{D}_i} \times 1$ channel vector of $\mathrm{R} \to \mathrm{D_i}$ link and $\|\cdot\|_F$ is the Frobenius norm of a matrix. For simplicity, we assume only the p^{th} and q^{th} users ($1 \le p < q \le M$) are selected to form a NOMA group. The overall communication takes place in two time phases. During the first phase, the S node broadcasts a superposing signal x ($x = \sqrt{\alpha P_s}x_p + \sqrt{(1-\alpha)P_s}x_q$) to R, and the received signal at the R node can be expressed as

$$y_{sr} = h_{sr}x + n_r \tag{1}$$

where h_{sr} and n_r ($E[|n_r|^2] = \delta_r^2$) are the channel coefficient and the additive white Gaussian noise (AWGN) of the S → R link, respectively, α ($0 \le \alpha \le 1$) is the power allocation coefficient at the p^{th} user, P_s denotes the transmit power at the S node, x_m ($m = p, q$) is the transmit signal of User D_m with $E[|x_m|^2] = 1$. During the second time phase, the R node first amplifies the received signal with a variable gain factor $G = \sqrt{1/(P_s|h_{sr}|^2 + \delta_r^2)}$ and then sends it to terrestrial users. By employing the maximal ratio combining (MRC) [1], the received signal at User D_m can be given by

$$y_{D_m} = \sqrt{P_r}G\mathbf{w}^H\mathbf{h}_{D_m}(h_{sr}x + n_r) + \mathbf{w}^H\mathbf{n}_{D_m} \tag{2}$$

where P_r is the transmit power at the R node, $\mathbf{w}^H = \frac{\mathbf{h}_{D_m}}{\|\mathbf{h}_{D_m}\|_F}$ denotes the receive beamforming (BF) weight vector, and $\mathbf{n}_{D_m}$ is the AWGN at User D_m with $E[\mathbf{n}_{D_m}\mathbf{n}_{D_m}^H] = \delta_d^2\mathrm{I}$.

In the NOMA downlink, the user with low effective channel gain decodes its signal directly. Thus, the end-to-end SINR of User D_p can be written as

$$\gamma_p = \frac{\alpha\overline{\gamma}_{sr}\rho_{sr}\overline{\gamma}_{rd}\rho_{rp}}{(1-\alpha)\overline{\gamma}_{sr}\rho_{sr}\overline{\gamma}_{rd}\rho_{rp} + \overline{\gamma}_{rd}\rho_{rp} + \overline{\gamma}_{sr}\rho_{sr+1}} \tag{3}$$

where $\overline{\gamma}_{sr} = P_s/\delta_r^2$, $\overline{\gamma}_{rd} = P_r/\delta_d^2$, $\rho_{sr} = |h_{sr}|^2$, and $\rho_{rp} = \|\mathbf{h}_{D_p}\|_F^2$. Meanwhile, before detecting its own signal, User D_q first decodes the signal of User D_p according to the principle of successive information cancellation (SIC) and the decoding SINR can be given by

$$\gamma_{q\to p} = \frac{\alpha\overline{\gamma}_{sr}\rho_{sr}\overline{\gamma}_{rd}\rho_{rq}}{(1-\alpha)\overline{\gamma}_{sr}\rho_{sr}\overline{\gamma}_{rd}\rho_{rq} + \overline{\gamma}_{rd}\rho_{rq} + \overline{\gamma}_{sr}\rho_{sr} + 1} \tag{4}$$

where $\rho_{rq} = \|\mathbf{h}_{D_q}\|_F^2$. We note that $\gamma_{q\to p} \ge \gamma_p$ since $\rho_{rq} \ge \rho_{rp}$, which means that User D_q can always correctly decode the signal of User D_p. In this regard, the signal from User D_p can be removed and the SINR of User D_q can be derived as

$$\gamma_q = \frac{(1-\alpha)\overline{\gamma}_{sr}\rho_{sr}\overline{\gamma}_{rd}\rho_{rq}}{\overline{\gamma}_{rd}\rho_{rq} + \overline{\gamma}_{sr}\rho_{sr} + 1}. \tag{5}$$

In this letter, we assume that the S → R link follows a shadowed-Rician fading distribution and the probability density function (PDF) of $\rho_{sr} = |h_{sr}|^2$ is given by [15]

$$f_{\rho_{sr}}(x) = \alpha_{sr}e_1^{-\beta_{sr}x}F_1(m_{sr}; 1; \delta_{sr}x) \tag{6}$$

where $\alpha_{sr} = 0.5(2b_{sr}m_{sr}/(2b_{sr}m_{sr} + \Omega_{sr}))^{m_{sr}}/b_{sr}$, $\beta_{sr} = 0.5/b_{sr}$, $\delta_{sr} = 0.5\Omega_{sr}/b_{sr}/(2b_{sr}m_{sr} + \Omega_{sr})$, $2b_{sr}$ and Ω_{sr} are the average power of the multipath and the line-of-sight (LoS) components, respectively, m_{sr} ($m_{sr} > 0$) denotes the Nakagami-m fading parameter, and ${}_1F_1(a; b; c)$ represents the confluent hypergeometric function [16, (9.100)].

The terrestrial links are modeled as independent and identically distributed (i.i.d.) Nakagami-m fading distributions. According to [2], the PDF of ρ_j ($j = rp, rq$) can be given as

$$f_{\rho_j}(y) = \frac{m_j^{m_jN_{D_m}}y^{m_jN_{D_m}-1}}{\Gamma(m_jN_{D_m})\Omega_j^{m_jN_{D_m}}}e^{-\frac{m_jy}{\Omega_j}} \tag{7}$$

where $\Gamma(\cdot)$ is the Gamma function, m_j is the fading severity parameter, and Ω_j denotes the average power of each link.

III. Outage Probability Analysis

The OP is defined as the probability that the instantaneous SINR γ_m falls below a predefined threshold γ_{thm}, i.e.,

$$P_{out}(\gamma_{thm}) = \Pr(\gamma_m \le \gamma_{thm}) = F_{\gamma_m}(\gamma_{thm}) \tag{8}$$

where $F_{\gamma_m}(\cdot)$ denotes the cumulative distribution function (CDF) of γ_m. Before evaluating the OP performance of each NOMA user, with the help of [16, (9.14.1), (3.381.1)], we first derive the CDF of (6) as

$$F_{\rho_{sr}}(u) = \alpha_{sr}\sum_{k=0}^{\infty}\frac{(m_{sr})_k\delta_{sr}^k}{(k!)^2\beta_{sr}^{k+1}}\gamma(k+1, \beta_{sr}u) \tag{9}$$

where $\gamma(a,x) = \int_0^x e^{-t}t^{a-1}dt$ denotes the incomplete Gamma function [16, (8.350.1)]. In the subsections, the exact as well as asymptotic expressions for OP are derived to evaluate the performance of NOMA-based HSTRNs.

A. The Exact OP Expressions for NOMA Users

1) User D_p: From (3), we can get

$$F_{\gamma_p}(\gamma_{thp}) = \int_0^{\Phi_p} f_{\rho_{rp}}(y)dy + \int_{\Phi_p}^{\infty} F_{\rho_{sr}}\left[\frac{\Phi_p(1+\overline{\gamma}_{rd}y)}{\overline{\gamma}_{sr}(y-\Phi_p)}\right]f_{\rho_{rp}}(y)dy$$
$$= \underbrace{\int_0^{\Phi_p} f_{\rho_{rp}}(y)dy}_{J_1} + \underbrace{\int_0^{\infty} F_{\rho_{sr}}\left[\frac{1+\overline{\gamma}_{rd}(y+\Phi_p)}{\Phi_p^{-1}\overline{\gamma}_{sr}y}\right]f_{\rho_{rp}}(y+\Phi_p)dy}_{J_2} \tag{10}$$

with

$$\Phi_p = \frac{\gamma_{thp}}{\overline{\gamma}_{rd}(\alpha + \gamma_{thp}(\alpha - 1))}. \tag{11}$$

Substituting (7) into (10) along with [16, (3.381.1)], we get

$$J_1 = \frac{\gamma(\Delta_p, \Phi_pm_{rp}/\Omega_{rp})}{\Gamma(\Delta_p)}. \tag{12}$$

In the derivation of J_2, we substitute (9) into (10), expand $\gamma(n+1,x) = n! - n!e^{-x}\sum_{m=0}^{n}\frac{x^m}{m!}$ according to [16, (8.352.1)], express $(a+x)^n$ in terms of binomial expression with [16, (1.111)], utilize [16, (3.382.4, 3.471.9)], and then obtain the expression of J_2 as (13) shown at the top of the next page with $\Delta_p{=}m_{rp}N_{D_p}$, $\Xi_{sr} = \alpha_{sr}\sum_{k=0}^{\infty}\frac{(m_{sr})_k\delta_{sr}^k}{k!\beta_{sr}^{k+1}}$, $\Xi_p = \beta_{sr}\overline{\gamma}_{rd}\Phi_p/\overline{\gamma}_{sr}$, $\Theta_p = \Phi_p + 1/\overline{\gamma}_{rd}$, and $K_v(\cdot)$ being the modified Bessel function [16, (8.432.6)].

To this end, inserting (12) and (13) into (10), the desired result for $F_{\gamma_p}(\gamma_{thp})$ can be obtained.

2) User D_q: From (5), we have

$$F_{\gamma_q}(\gamma_{thq}) = \Pr\left(\frac{(1-\alpha)\overline{\gamma}_{sr}\rho_{sr}\overline{\gamma}_{rd}\rho_{rq}}{\overline{\gamma}_{rd}\rho_{rq} + \overline{\gamma}_{sr}\rho_{sr} + 1} \le \gamma_{thq}\right)$$
$$= \int_0^{\Phi_q} f_{\rho_{rq}}(y)dy + \int_{\Phi_q}^{\infty} F_{\rho_{sr}}\left[\frac{\Phi_q(1+\overline{\gamma}_{rd}y)}{\overline{\gamma}_{sr}(y-\Phi_q)}\right]f_{\rho_{rq}}(y)dy \tag{14}$$

where $\Phi_q = \frac{\gamma_{thq}}{\overline{\gamma}_{rd}(1-\alpha)}$. Due to the fact that the PDFs of ρ_{rp} and ρ_{rq} have the same form, by following similar steps as in the derivation of (10), $F_{\gamma_q}(\gamma_{thq})$ can be obtained as (15), as shown at the top of the next page, with $\Delta_q{=}m_{rq}N_{D_q}$, $\Xi_q = \beta_{sr}\overline{\gamma}_{rd}\Phi_q/\overline{\gamma}_{sr}$, and $\Theta_q = \Phi_q + 1/\overline{\gamma}_{rd}$.

$$J_2 = \frac{\Xi_{\rm sr}\Gamma\left(\Delta_p, \Phi_p m_{\rm rp}/\Omega_{\rm rp}\right)}{\Gamma\left(\Delta_p\right)} - \frac{2\Xi_{\rm sr} m_{\rm rp}^{\Delta_p}}{\Gamma\left(\Delta_p\right)\Omega_{\rm rp}^{\Delta_p}} \sum_{v=0}^{k} \frac{\Xi_p^v}{v!} \sum_{n=0}^{v} \binom{v}{n} \overline{\gamma}_{\rm rd}^{n-v} e^{-\frac{m_{\rm rp}\Phi_p}{\Omega_{\rm rp}} - \Xi_p} \times \sum_{l=0}^{n+\Delta_p-1} \binom{n+\Delta_p-1}{l} \Phi_p^{n+\Delta_p-1-l} \left(\frac{\Omega_{\rm rp}\Xi_p\Theta_p}{m_{\rm rp}}\right)^{\frac{l-v}{2}} K_{1+l-n}\left(2\sqrt{\frac{\Xi_p\Theta_p m_{\rm rp}}{\Omega_{\rm rp}}}\right) \tag{13}$$

$$F_{\gamma_q}(\gamma_{\rm th}) = 1 + \frac{\Gamma\left(\Delta_q, \frac{m_{\rm rq}\Phi_q}{\Omega_{\rm rq}}\right)(\Xi_{\rm sr}-1)}{\Gamma\left(\Delta_q\right)} - \frac{2\Xi_{\rm sr} m_{\rm rq}^{\Delta_q}}{\Gamma\left(\Delta_q\right)\Omega_{\rm rq}^{\Delta_q}} \sum_{v=0}^{k} \frac{\Xi_q^v}{v!} \sum_{n=0}^{v} \binom{v}{n} \overline{\gamma}_{\rm rd}^{n-v} e^{-\frac{m_{\rm rq}\Phi_q}{\Omega_{\rm rq}} - \Xi_q} \times \sum_{l=0}^{n+\Delta_q-1} \binom{n+\Delta_q-1}{l} \left(\frac{\Omega_{\rm rq}\Xi_q\Theta_q}{m_{\rm rq}}\right)^{\frac{l-v}{2}} K_{1+l-n}\left(2\sqrt{\frac{\Xi_q\Theta_q m_{\rm rq}}{\Omega_{\rm rq}}}\right) \tag{15}$$

B. The Asymptotic OP Expressions for NOMA Users

To evaluate the achievable diversity orders and coding gains of each NOMA user in the considered downlink HSTRNs, we investigate the asymptotic OP performance at the high SINR in this subsection. To facilitate further work, we first evaluate the asymptotic CDF behavior for related links.

Satellite link: Using the series representation given by [16, (8.354.1)], $\gamma(k+1, \beta_{\rm sr}u)$ can be derived as

$$\gamma(k+1, \beta_{\rm sr}u) = \sum_{n=0}^{\infty} \frac{(-1)^n (u\beta_{\rm sr})^{k+1+n}}{n!(k+1+n)} \approx \frac{(\beta_{\rm sr}u)^{k+1}}{k+1}|_{u\to 0}. \tag{16}$$

Putting (16) into (9), the approximated CDF expression for the satellite link can be obtained as

$$F_{\rho_{\rm sr}}(u) \approx \alpha_{\rm sr} \sum_{k=0}^{\infty} \frac{(m_{\rm sr})_k \delta_{\rm sr}^k}{(k!)^2 \beta_{\rm sr}^{k+1}} \frac{\beta_{\rm sr}^{k+1} u^{k+1}}{k+1} \approx \alpha_{\rm sr} u. \tag{17}$$

Terrestrial links: Expressing the exponential function in (7) in terms of Maclaurin series, the approximated PDF of ρ_j can be given by

$$f_{\rho_j}(y) \approx \frac{m_j^{m_j N_{{\rm D}_m}} y^{m_j N_{{\rm D}_m}-1}}{\Gamma\left(m_j N_{{\rm D}_m}\right)\Omega_j^{m_j N_{{\rm D}_m}}}. \tag{18}$$

Then, the corresponding CDF can be expressed as

$$F_{\rho_j}(y) \approx \frac{m_j^{m_j N_{{\rm D}_m}} y^{m_j N_{{\rm D}_m}}}{\Gamma\left(m_j N_{{\rm D}_m}+1\right)\Omega_j^{m_j N_{{\rm D}_m}}}. \tag{19}$$

Based on (17) and (19), the asymptotic OP expressions for each NOMA user are obtained as follows.

1) User D_p*:* From (3), as $\overline{\gamma}_{\rm sr} \to \infty$ or $\overline{\gamma}_{\rm rd} \to \infty$, we can get the upper bound of γ_p as

$$\gamma_p^{\rm up} = \min\left(\frac{\alpha\overline{\gamma}_{\rm sr}\rho_{\rm sr}}{(1-\alpha)\overline{\gamma}_{\rm sr}\rho_{\rm sr}+1}, \frac{\alpha\overline{\gamma}_{\rm rd}\rho_{rp}}{(1-\alpha)\overline{\gamma}_{\rm rd}\rho_{rp}+1}\right). \tag{20}$$

Further, we get

$$F_{\gamma_{p^{\rm up}}^{\infty}}\left(\gamma_{{\rm th}p}\right) \approx \frac{\alpha_{\rm sr}\gamma_{{\rm th}p}}{\eta_1\overline{\gamma}\left(\alpha-(1-\alpha)\gamma_{{\rm th}p}\right)} + \frac{\left(\gamma_{{\rm th}p} m_{\rm rp}/\eta_2\overline{\gamma}\Omega_{\rm rp}\right)^{\Delta_p}}{\Gamma\left(\Delta_p+1\right)\left(\alpha-(1-\alpha)\gamma_{{\rm th}p}\right)^{\Delta_p}} \tag{21}$$

where $\overline{\gamma}_{\rm sr} = \eta_1\overline{\gamma}$ and $\overline{\gamma}_{\rm rd} = \eta_2\overline{\gamma}$. Then, we can express (21) as $F_{\gamma_p}^{\infty}(\gamma_{{\rm th}p}) \approx C_p(\gamma_{{\rm th}p}/\overline{\gamma})^{-min(1,\Delta_p)}$, with

$$C_p = \begin{cases} \alpha_{\rm sr}/\eta_1(\alpha-(1-\alpha)\gamma_{\rm th})\eta_1\left(\alpha-(1-\alpha)\gamma_{{\rm th}p}\right), & 1 < \Delta_p \\ \frac{\alpha_{\rm sr}/\eta_1 + m_{\rm r}p/\eta_2\Omega_{\rm rp}}{\alpha-(1-\alpha)\gamma_{{\rm th}p}}, & 1 = \Delta_p \\ \frac{\left(m_{\rm rp}/\eta_2\Omega_{\rm rp}\right)^{\Delta_p}}{\Gamma\left(\Delta_p+1\right)\left(\alpha-(1-\alpha)\gamma_{{\rm th}p}\right)^{\Delta_p}}, & 1 > \Delta_p. \end{cases} \tag{22}$$

We can get the diversity order and coding gain of User D_p as, $G_{\rm d} = min(1, \Delta_p)$ and $G_{\rm c} = \frac{C_p^{-1/G_{\rm d}}}{\gamma_{{\rm th}p}}$, respectively.

2) User D_q*:* From (5), as $\overline{\gamma}_{\rm sr} \to \infty$ or $\overline{\gamma}_{\rm rd} \to \infty$, we have

$$\gamma_q^{up} = (1-\alpha)\min\left(\overline{\gamma}_{\rm sr}\rho_{\rm sr}, \overline{\gamma}_{\rm rd}\rho_{\rm rq}\right). \tag{23}$$

After some simple computations, the asymptotic CDF of $\gamma_q^{\rm up}$ can be written as

$$F_{\gamma_{q^{\rm up}}^{\infty}}\left(\gamma_{{\rm th}q}\right) \approx \frac{\alpha_{\rm sr}\gamma_{{\rm th}q}}{\eta_1\overline{\gamma}(1-\alpha)} + \frac{\left(m_{\rm rq}\gamma_{{\rm th}q}/(1-\alpha)\eta_2\overline{\gamma}\right)^{\Delta_q}}{\Gamma\left(\Delta_q+1\right)\Omega_{\rm rq}^{\Delta_q}}. \tag{24}$$

Based on (24), one can straightforwardly finds out that the two performance metrics of User D_q as $G_{\rm d} = \min(1, \Delta_q)$ and $G_{\rm c} = \frac{C_q^{-1/G_{\rm d}}}{\gamma_{{\rm th}q}}$ with

$$C_q = \begin{cases} \alpha_{\rm sr}/\eta_1(1-\alpha), & 1 < \Delta_q \\ \frac{\alpha_{\rm sr}}{\eta_1(1-\alpha)} + \frac{m_{\rm rq}}{(1-\alpha)\eta_2\Omega_{\rm rq}}, & 1 = \Delta_q \\ \frac{\left(m_{\rm rq}/(1-\alpha)\eta_2\Omega_{\rm rq}(1-\alpha)\eta_2\Omega_{\rm rq}\right)^{\Delta_q}}{\Gamma\left(\Delta_q+1\right)}, & 1 > \Delta_q. \end{cases} \tag{25}$$

IV. Numerical Results

This section provides numerical results to validate the theoretical analysis and show the impact of various parameters on the performance of the proposed NOMA-based HSTRNs. In the simulations, we assume that the satellite link undergoes frequent heavy shadowing (FHS) with $(m_{\rm sr}, b_{\rm sr}, \Omega_{\rm sr}) = (0.739, 0.063, 8.97\times 10^{-4})$ or average shadowing (AS) with $(m_{\rm sr}, b_{\rm sr}, \Omega_{\rm sr}) = (10.1, 0.126, 0.835)$, $\Omega_{rp} = \Omega_{rq} = 1$, $\gamma_{{\rm th}p} = -3$ dB, and $\gamma_{{\rm th}q} = 3$ dB. Without loss of generality, we set $\eta_1 = \eta_2$, which means $\bar{\gamma}_{\rm sr} = \bar{\gamma}_{\rm rd}$. Moreover, according to the power allocation principle of the NOMA scheme, the user with worse channel gain can be allocated with more power resource. Thus, in this letter we consider $\alpha > 0.5$.

Fig. 1 shows the comparison of OP performance with NOMA and TDMA schemes for different power allocation

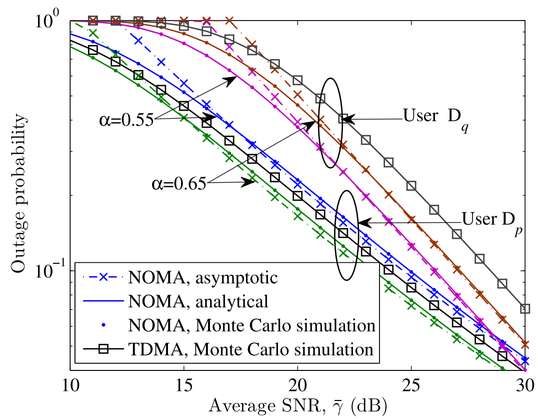
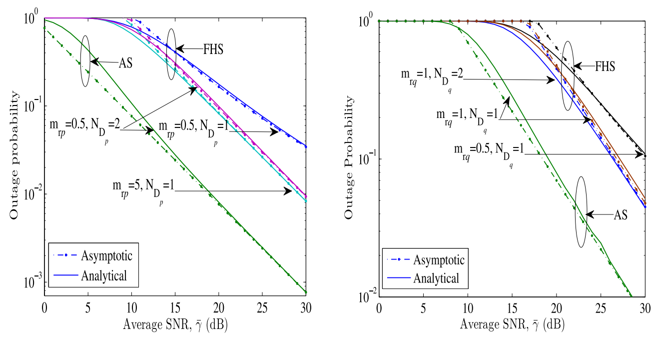


Fig. 1. Outage probability vs. $\bar{\gamma}$ for different power allocation factor α.



(a) (b)

Fig. 2. Outage probability vs. $\bar{\gamma}$ for various antenna numbers, terrestrial and satellite fading conditions: (a) User D_p and (b) User D_q.

factors α, where we consider $m_{rq} = 1$, $m_{rp} = 0.5$, $N_{D_q} = N_{D_p} = 1$, and the $S \rightarrow R$ link experiences FHS. As can be observed, analytical results computed by (10) and (15) agree well with the Monte Carlo simulations. Moreover, an increasing α obviously improves the OP performance of User D_p, but simultaneously degrades the OP performance of User D_q, which can be explained by the fact that γ_p derived by (3) increases, while γ_q derived by (5) decreases. It is worth noting that when the power allocation coefficient is reasonably chosen, i.e., $\alpha = 0.65$, the OP performance of both Users D_p and D_q outperform those with TDMA schemes. The reason is that the transmission slots needed by the TDMA scheme are twice of those needed by the NOMA scheme. This phenomenon implies that a higher resource utilization efficiency and transmission performance can be achieved by introducing the NOMA scheme in downlink HSTRNs.

Fig. 2 illustrates the effect of different channel conditions and antenna configurations on OP performance by considering $\alpha = 0.65$. As expected, the OP performance of User D_p and User D_q are improved when either the terrestrial or the satellite link quality gets better. In addition, by increasing the number of antennas at destination nodes, the OP performance of each NOMA user can be significantly improved, demonstrating the benefits of introducing multiple antennas in the HSTRNs. In particular, comparing those analytical and asymptotic OP curves in Figs. 1 and 2, we can see that asymptotic results excellently agree with analytical results across the entire average SNR range. Moreover, as analyzed in Section III, when $m_{rp}N_{D_p} > 1$ or $m_{rq}N_{D_q} > 1$, the achievable diversity order of User D_p or User D_q reduces to one. In this regard, improving channel parameters or increasing the number of antennas cannot improve the achievable diversity order, but can improve the OP performance in terms of coding gain.

V. Conclusion

In this letter, we have investigated the OP performance of downlink NOMA-based HSTRNs. In particular, we have derived exact as well as asymptotic OP expressions for each NOMA user. Simulation results have been provided to show the effect of different channel parameters, the power allocation factor, and the number of antennas on the OP performance. Our findings have demonstrated that an improved OP performance can be achieved with the NOMA scheme by employing a suitable power allocation factor.

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