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Performance analysis of multiuser dual-hop satellite relaying systems

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Abstract

In this study, we investigate the outage probability (OP) of a multiuser dual-hop satellite relaying system with decode-and-forward (DF) protocol, where both uplink and downlink experience Shadowed Rician (SR) fading. Specifically, by taking the effects of antenna pattern and path loss into account, we first establish a practical satellite channel model and obtain the end-to-end signal-to-noise ratio (SNR) expression for the considered system, where the uplink employs opportunistic scheduling (OS) scheme while the downlink adopts selection combining (SC) or maximal ratio combining (MRC) approaches. Then, we derive the closed-form OP expressions for the dual-hop satellite relaying with OS/SC and OS/MRC schemes, respectively. Furthermore, the asymptotic OP formulas at high SNR are also developed to gain further insights conveniently. Finally, numerical results confirm the validity of the theoretical formulas and reveal the representative parameters on the system performance.

Keywords: Dual-hop satellite relaying, Decode-and-forward, Outage probability, Selection combining, Maximal ratio combining

1 Introduction

Satellite communication (SatCom) has the potential of providing connectivity for fixed and mobile users especially in the areas where the terrestrial networks are challenging or infeasible to be deployed [1–4]. Meanwhile, it has been shown that relay technology is able to offer significant performance benefits, such as improving the system throughput via spatial diversity, extending signal coverage without consuming large transmitter power [5]. Therefore, the application of relay transmission in SatCom has been an active research topic both in academia and industry recently.

1.1 Previous works

In SatCom, the line-of-sight (LoS) link between the satellite and the terrestrial user is prone to be blocked, which makes the satellite services unavailable in some scenarios, thus a novel network architecture termed as the hybrid satellite-terrestrial network (HSTN), which utilizes the terrestrial relay to assist the satellite signal transmission, has received significant attention recently. Until now, substantial effort has been devoted to investigating the performance of HSTNs. For example, in [6] and [7], the authors investigated the performance of a HSTN with decode-and-forward (DF) protocol. The authors of [8] addressed the performance analysis problem of amplify-and-forward (AF)-based HSTN. Taking the interference power constraints imposed by satellite communications into account, the authors of [9] derived a closed-form expression for the outage probability (OP) of a HSTN system. In [10], a partial relay selection scheme was studied in which satellite selects a relay earth station (ES) among multiple relay ESs (situated on ground) on the basis of maximum instantaneous signal-to-noise ratio (SNR) in AF-based HSTN. Besides, the authors of [11] proposed a robust relay beamforming (BF) scheme for a HSTN, where a cognitive base station (BS) with multi-antenna is utilized not only as a BS of a cellular network but also as a relay to assist the satellite signal transmission. However, the main drawback of the aforementioned works is that they only consider the downlink transmission of satellite systems.

In a practical scenario, the satellite is often exploited as a relay on the sky, which receives signals from a source ES through uplink channel and forward them to the

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destination ES via downlink channel [12]. Consequently, in order to measure the performance of a satellite system more accurately, both uplink and downlink channels should be taken into account. For this reason, the authors of [13] derived the closed-form expressions of OP, ergodic capacity (EC), and average symbol error rate (ASER) for a dual-hop AF satellite relaying network. In [14] and [15], the authors conducted performance evaluation of a dual-hop AF system with satellite relaying. Although AF relaying protocol is a simple scheme, which is commonly employed in current bent-pipe satellite system, it is foreseeable that DF protocol will be widely utilized in the future due to its advantage of better performance and the rapid development of satellite on-board processing technology. In this content, the authors of [16] analyzed the performance of a dual-hop DF satellite relaying system over Shadowed Rician (SR) channels. However, it should be pointed out that all of the aforementioned works focus on the single-user scenario, which is not in line with practical application, since SatCom often provides various services to a large number of terrestrial users with high quality of service (QoS). Under this situation, the authors of [17] investigated the performance of a multiuser AF HSTN with opportunistic scheduling (OS) scheme and verified that the system performance can be improved via the multiuser diversity. This work was later extended to the case of imperfect channel state information (CSI) and co-channel interference (CCI) in [18]. Besides, considering the interference at the terrestrial relay, the authors of [19] studied a multi-antenna multiuser HSTN employing OS with outdated CSI and AF relaying with CCI. Furthermore, by making use of the complementary moment generating function (MGF) method, an accurate analytical expression for the EC of a HSTN with AF protocol was derived in [20], where the impacts of various system parameters on EC were also revealed. Nevertheless, to the best of our knowledge, the existing works conducting the performance of dual-hop satellite relaying system with multiple users remain very limited, making it still an open yet interesting research topic. These observations motivate the work presented in this paper.

1.2 Methods and contributions

In this paper, we consider a dual-hop satellite relaying network with multiple users, where both the uplinks and downlinks follow the SR fading. By applying OS scheme at the uplinks and selection combining (SC) or maximal ratio combining (MRC) schemes at the downlinks, the equivalent end-to-end output SNR of the system is first obtained, then analytical expressions of OP as well as asymptotic results are derived to evaluate the system performance. Finally, simulation results are provided to validate our theoretical formulas and show the impact of various parameters on the system performance.

The detailed contributions of this paper are outlined as follows:

- Considering the effects of antenna gain and path loss, we extend the channel model in [13] and [16] to a more practical one, and then obtain the end-to-end SNR expression of the multiuser dual-hop satellite relaying system with DF protocol, where the OS scheme is used in the uplink, while the SC and MRC schemes are used in the downlink, respectively.
- Assuming that both uplink and downlink experience SR fading, we derive the OP expressions of the multiuser dual-hop satellite relaying network with OS/SC and OS/MRC schemes, respectively. This is different from [13] and [16] focusing on the scenario of signal user, which do not coincide with the characteristics of SatCom, where a lot of terrestrial users are often served so that its benefits of wide coverage can be exploited.
- To gain further insights, we present the asymptotic OP formulas at high SNR for the considered system, which are utilized to reveal the diversity order and coding gain of the satellite relaying system conveniently. Thus, our work provides useful guidelines for the engineers to implement satellite system design.

The rest of the paper is organized as follows. Section 2 describes the system and channel model. Section 3 derives the closed-form OP expressions for the considered system with OS/SC and OS/MRC schemes, respectively. Section 4 presents the asymptotic OP expressions of the considered system. Moreover, based on these asymptotic OP expressions, the diversity order and coding gain expressions are also given. The numerical results and analyses are presented in Section 5, and the paper is concluded in Section 6.

Notation: $E[\cdot]$ denotes the expectation, $|\cdot|$ the absolute value, $\exp(\cdot)$ the exponential function, and $N_c\left(\mu,\sigma^2\right)$ the complex Gaussian distribution with mean μ and variance σ^2.

2 System and channel model

The system model considered in this paper is illustrated in Fig. 1, which consists of N source ESs termed as source (S), M destination ESs termed as destination (D) and a satellite relaying (R). Similar to the existing works [13, 16], we assume that both of the uplink (S-R) and downlink (R-D) channels undergo SR fading, and the direct links between the sources and the destinations are unavailable, due to the heavy shadowing of the radio propagation. In addition, it is assumed that S and D have a directional antenna, while the satellite is equipped with a multibeam antenna to serve the multiple ESs. Similar to the previous works, such as [3], we suppose that the satellite channels experience slow fading and perfect CSIs of satellite links are available.[1]

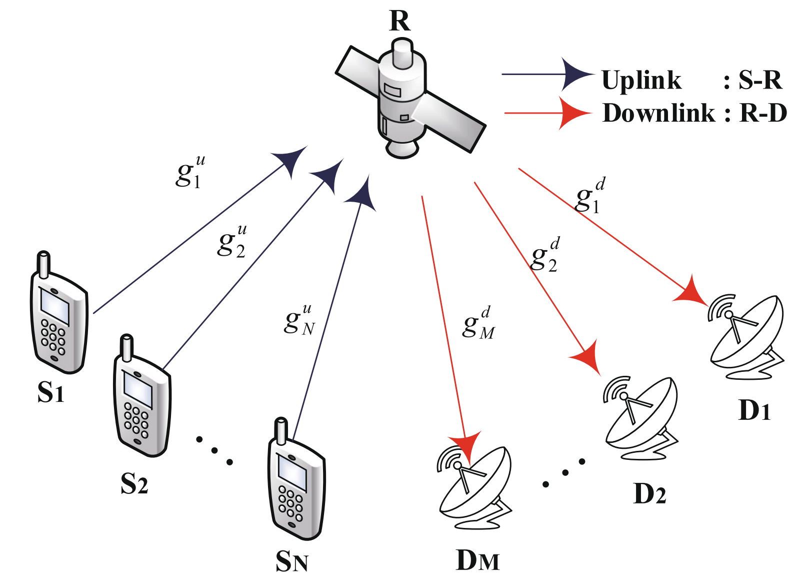

Fig. 1 System model of the multiuser dual-hop satellite relaying. The figure consists of *N* source ESs termed as source (S), *M* destination ESs termed as destination (D) and a satellite relaying (R)

2.1 Channel model

As shown in Fig. 1, we suppose that all of the ESs are within the coverage of satellite spot beam, and use g_i^u and g_j^d to denote the uplink channel response between the ith ES and R and downlink channel response between R and the jth ES, respectively. By taking the effects of practical parameters, such as antenna beam pattern, path loss, and channel fading into account, the satellite channel model of uplink and downlink can be uniformly expressed as

$$g_l = F_l h_l \tag{1}$$

where the coefficient F_l is given by

$$F_l = \frac{\lambda\sqrt{G_{s,l}G_{u,l}}}{4\pi d_l} \tag{2}$$

where λ denotes the wavelength, d_l the distance between the satellite and the lth user. Besides, $G_{s,l}$ and $G_{u,l}$ represent the satellite and terrestrial user antenna patterns, respectively. According to [21], $G_{s,l}$ can be written as

$$G_{s,l} = G_{s,l}^{\max}\left(\frac{J_1(u_l)}{2u_l} + 36\frac{J_3(u_l)}{u_l^3}\right)^2 \tag{3}$$

where $G_{s,l}^{\max}$ is the maximum satellite antenna gain, $J_1(x)$ and $J_3(x)$ the first-kind Bessel function of order 1 and 3, respectively, and $u_l = 2.07123\sin\phi_l / \sin\phi_{3\text{ dB}}$, where ϕ_l denotes the angle between the lth ES and the beam center with respect to the satellite, and $\phi_{3\text{ dB}}$ the 3 dB angle of the main beam. The normalized satellite antenna pattern is illustrated in Fig. 2.

In (2), the array gain in dB, namely, $\widehat{G}_{u,l}(\theta,\varphi) = 10log_{10}\left(G_{u,l}(\theta,\varphi)\right)$ can be modeled as [22]

$$\widehat{G}_{u,l}(\theta,\varphi) = G_{u,l}^{\max} - \min\left\{G_h(\varphi) + G_v(\theta), SLL\right\}. \tag{4}$$

where $G_{u,l}^{\max}$ is the maximum antenna gain of the lth ES and $G_h(\varphi)$ and $G_v(\theta)$ the radiation patterns in horizontal and vertical angle directions, which are, respectively, given by

$$\begin{aligned} G_h(\varphi) &= \min\left\{12\left(\frac{\varphi}{\varphi_{3\text{ dB}}}\right)^2, \text{SLL}\right\}, \\ G_v(\theta) &= \min\left\{12\left(\frac{\theta-\theta_{\text{tilt}}}{\theta_{3\text{ dB}}}\right)^2, \text{SLL}\right\} \end{aligned}$$

where $\varphi_{3\text{ dB}}$ and $\theta_{3\text{ dB}}$ are the 3 dB beamwidth of the horizontal and vertical patterns, respectively, θ_{tilt} the main beam tilting angle, SLL the side-lobe level of the antenna pattern.

In (1), h_l denotes the channel fading, which is often modeled as SR distribution described by $h_l = \overline{h}_l \exp(j\psi_l) + \widetilde{h}_l \exp(j\xi_l)$ [13, 16], where the LoS component $\overline{h}_l$ and the scattering component $\widetilde{h}_l$ satisfy Nakagami-m and Rayleigh fading distribution, respectively. ψ_l is the deterministic phase of the LoS component and ξ_l the static random phase vector satisfying the uniform distribution among $[0, 2\pi)$. Since the value of ψ_l does not affect the envelope characteristics, we assume $\psi_l = 0$ to simplify the notation. With this regard, the probability density function (PDF) of $|h_l|^2$ is given by [23]

$$f_{|h_l|^2}(x) = \alpha_l \exp(-\beta_l x)_1F_1(m_l; 1; \delta_l x) \tag{5}$$

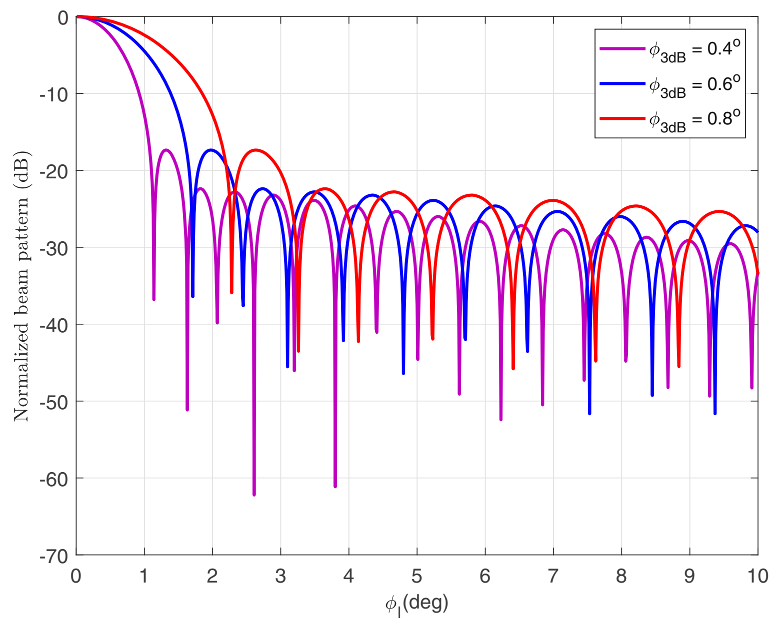

Fig. 2 Normalized beam pattern with different 3 dB angles. This figure presents normalized beam pattern when the 3 dB angles are 0.4°, 0.6°, and 0.8°, respectively

where $\alpha_l = \frac{1}{2b_l}\left(\frac{2b_l m_l}{2b_l m_l+\Omega_l}\right)^{m_l}$, $\beta_l = \frac{1}{2b_l}$, $\delta_l = \frac{\Omega_l}{2b_l(2b_l m_l+\Omega_l)}$, with Ω_l being the average power of LoS component, $2b_l$ the average power of the multipath component, and m_l the Nakagami parameter ranging from 0 to ∞. Meanwhile, the function ${}_1F_1(a;b;z)$ is the confluent hypergeometric function having the expression as [24]

$$ {}_1F_1(a;b;z) = \sum_{n=0}^{\infty} \frac{(a)_n z^n}{(b)_n n!} $$

where $(x)_n = x(x+1)\ldots(x+n-1)$.

2.2 Signal model

The total communication occurs in two time phases. During the first time phase, the ith S sends its signal $x(t)$ with $E[\,|x(t)|^2] = 1$ to R via the uplink channel g_i^u. Then, the received signal at R can be written as

$$ y_{s,i}(t) = \sqrt{P_{s,i}}g_i^u x(t) + n_i(t) \tag{6} $$

where $P_{s,i}$ denotes the transmitted power of the ith source, n_i the noise at R that is often modeled as additive white Gaussian noise (AWGN) with zero mean and variance $\sigma^2 = \kappa BT$, namely, $n_i \sim N_c\left(0,\sigma^2\right)$, where κ is the Boltzman constant, B the carrier bandwidth, and T the receiver noise temperature. By using (1) into (6), the output SNR at R can be expressed as

$$ \gamma_{s,i} = \bar{\gamma}_{s,i}\left|h_i^u\right|^2 \tag{7} $$

where $\bar{\gamma}_{s,i} = \frac{P_{s,i}F_i^2}{\sigma^2}$ is the average SNR of the ith S-R link and h_i^u the channel fading of the ith S-R link. Without loss of generality, we assume that the S-R links have the same average SNR, namely, $\bar{\gamma}_{s,i} = \bar{\gamma}_s (i = 1,2,\ldots N)$. By adopting the OS scheme to select the user with the best channel link at each scheduling time, so that multiuser diversity can be achieved to improve the system performance, one can obtain the output SNR at R as

$$ \gamma_1 = \max_{i=1,2\ldots N} \gamma_{s,i} = \bar{\gamma}_s \max_{i=1,2\ldots N}\left(\left|h_i^u\right|^2\right) \tag{8} $$

During the second time phase, since the DF relaying protocol is used, R decodes its received signal $y_{s,i}(t)$ at first. Then, the re-encoded signal is broadcasted to the destination within coverage. By supposing that the transmitted power at R is $P_{r,j}$, the received signal at the jth D can be written as

$$ z_{d,j}(t) = \sqrt{P_{r,j}}g_j^d x(t) + n_j(t) \tag{9} $$

Similarly, n_j is AWGN satisfying $n_j \sim CN\left(0,\sigma^2\right)$. As a result, According to (1) and (9), the received SNR at the jth D is given by

$$ \gamma_{d,j} = \bar{\gamma}_{d,j}\left|h_j^d\right|^2 \tag{10} $$

where $\bar{\gamma}_{d,j} = \frac{P_{r,j}F_j^2}{\sigma^2}$ is the average SNR of the jth R-D link and h_j^d the channel fading of the jth R-D link. Similar to the uplink, it is also supposed that $\bar{\gamma}_{d,j} = \bar{\gamma}_d (j = 1,2,\ldots M)$. In this paper, we exploit two methods, namely, SC and MRC schemes at D, yielding the final output SNR as

$$\gamma_2 = \begin{cases} \max_{j=1,2,\ldots,M} \gamma_{d,j}, & \text{for SC} \\ \sum_{j=1}^{M} \gamma_{d,j}, & \text{for MRC} \end{cases} \tag{11}$$

Consequently, the end-to-end SNR of multiuser dual-hop satellite relaying with DF protocol can be expressed as

$$\gamma = \min(\gamma_1, \gamma_2) \tag{12}$$

In the following section, we will derive the exact and asymptotic OP expressions to evaluate the considered satellite system, where the uplink exploits the OS scheme, while the downlink utilizes the SC and MRC schemes, respectively.

3 Performance analysis

Among all the performance measures, OP is one of the most important criterions to measure the wireless communication service quality [25, 26], which is defined as the probability that the output SNR γ is below a certain threshold x. Thus, following (12), the OP of the considered system can be expressed as

$$\begin{aligned} P_{\text{out}}(x) &= \Pr[\gamma < x] = \Pr[\min(\gamma_1, \gamma_2) < x] \\ &= 1 - \Pr[\gamma_1 \geq x, \gamma_2 \geq x] \\ &= 1 - [1 - F_{\gamma_1}(x)][1 - F_{\gamma_2}(x)]. \end{aligned} \tag{13}$$

where $F_{\gamma_1}(x)$ and $F_{\gamma_2}(x)$ denote the cumulative distribution function (CDF) of γ_1 and γ_2, respectively. Obviously, the OP performance depends on the scheduling scheme, which will be investigated in the following subsection.

3.1 OS/SC scheme

In order to obtain the closed-form OP expression of the considered system with OS/SC scheme, we will derive the analytical expressions of $F_{\gamma_1}(x)$ and $F_{\gamma_2}(x)$, respectively.

First of all, we focus on the closed-form expression of $F_{\gamma_1}(x)$. By considering that the OS scheme is adopted in the uplink, the CDF of γ_1 in (8) can be expressed as

$$\begin{aligned} F_{\gamma_1}(x) &= \Pr[\gamma_1 \leq x] = \Pr[\max_{i=1,2\ldots N}(\gamma_{s,i}) \leq x] \\ &= \Pr[\gamma_{s,1} \leq x, \ldots, \gamma_{s,N} \leq x] = \prod_{i=1}^{N} \Pr(\gamma_{s,i} \leq x) \\ &= \prod_{i=1}^{N} F_{\gamma_{s,i}}(x) \end{aligned} \tag{14}$$

In deriving (14), we have used the fact that $h_i^u (i = 1, 2, \ldots N)$ is independent identically distributed (i.i.d.). Meanwhile, by using (5) and (7), the PDF of $\gamma_{s,i}$ can be written as

$$\begin{aligned} f_{\gamma_{s,i}}(x) &= \frac{1}{\bar{\gamma}_s} f_{|h_i^u|^2}\left(\frac{x}{\bar{\gamma}_s}\right) \\ &= \frac{\alpha_s}{\bar{\gamma}_s} \exp\left(-\frac{\beta_s x}{\bar{\gamma}_s}\right) {}_1F_1\left(m_s; 1; \frac{\delta_s x}{\bar{\gamma}_s}\right) \end{aligned} \tag{15}$$

After expanding $exp(-x)$ with the Maclaurin series and utilizing the equation (2.01.1) in [24], the CDF of $\gamma_{s,i}$ can be written as

$$\begin{aligned} F_{\gamma_{s,i}}(x) &= \int_0^x f_{\gamma_{s,i}}(\tau) d\tau = A_s x {}_1F_1(m_s; 2; B_s x) \\ &+ \sum_{k=1}^{\infty} (-1)^k \frac{A_s x^{k+1}}{(k+1)!\,(2b_s\bar{\gamma}_s)^k} {}_2F_2(k+1, m_s; k+2, 1; B_s x) \end{aligned} \tag{16}$$

where

$$A_s = \frac{1}{2b_s\bar{\gamma}_s}\left(\frac{2b_s m_s}{2b_s m_s + \Omega_s}\right)^{m_s}, B_s = \frac{\Omega_s}{2b_s\bar{\gamma}_s\,(2b_s m_s + \Omega_s)}$$

and ${}_2F_2(a_1, a_2; b_1, b_2; z)$ is the confluent hypergeometric function, which is given by

$${}_2F_2(a_1, a_2; b_1, b_2; z) = \sum_{n=0}^{\infty} \frac{(a_1)_n (a_2)_n}{(b_1)_n (b_2)_n n!} z^n$$

By substituting (16) into (14), the CDF of γ_1 can be obtained as

$$\begin{aligned} F_{\gamma_1}(x) = \Bigg[& A_s x {}_1F_1(m_s; 2; B_s x) + \sum_{k=1}^{\infty} (-1)^k \\ & \times \frac{A_s x^{k+1}}{(k+1)!\,(2b_s\bar{\gamma}_s)^k} {}_2F_2(k+1, m_s; k+2, 1; B_s x) \Bigg]^N \end{aligned} \tag{17}$$

Next, when the SC scheme is used at D, only the ES with the maximal output SNR is selected [27], namely,

$$\gamma_2 = \bar{\gamma}_d \max_{j=1,2\ldots M}\left(\left|h_j^d\right|^2\right) \tag{18}$$

In a similar manner, by considering that $h_j^d (j = 1, 2, \ldots M)$ satisfies the condition of i.i.d., the CDF of $F_{\gamma_2}(x)$ can be written as

$$\begin{aligned} F_{\gamma_2}(x) = \Bigg[& A_d x {}_1F_1(m_d; 2; B_d x) + \sum_{k=1}^{\infty} (-1)^k \\ & \times \frac{A_d x^{k+1}}{(k+1)!\,(2b_d\bar{\gamma}_d)^k} {}_2F_2(k+1, m_d; k+2, 1; B_d x) \Bigg]^M \end{aligned} \tag{19}$$

By substituting (17) and (19) into (13), the OP of the dual-hop DF satellite relaying network with OS/SC scheme can be obtained as

$$P_{\text{out}}^{\text{SC}}(x) = 1 - \left\{1 - [A_s x_1F_1(m_s;2;B_s x) + \Xi(A_s,B_s,b_s,m_s,\bar{\gamma}_s,x)]^N\right\} \times \left\{1 - \left[A_d x_1F_1(m_d;2;B_d x) + \Xi\left(A_d,B_d,b_d,m_d,\bar{\gamma}_d,x\right)\right]^M\right\} \quad (20)$$

where $\Xi(A,B,b,m,\bar{\gamma},x)$ is given by

$$\Xi(A,B,b,m,\bar{\gamma},x) = \sum_{k=1}^{\infty}(-1)^k \frac{Ax^{k+1}}{(k+1)!\,(2b\bar{\gamma})^k}{}_2F_2(k+1,m;k+2,1;Bx) \quad (21)$$

3.2 OS/MRC scheme

Here, we focus on the OP of the considered system with OS/MRC scheme. Since the CDF of γ_1, namely, $F_{\gamma_1}(x)$, has already been obtained as in (17), here we aim at the closed-form expression of $F_{\gamma_2}(x)$ with the MRC scheme used in the downlink. To this end, we first express the output SNR as

$$\gamma_2 = \bar{\gamma}_d \sum_{j=1}^{M}\left|h_j^d\right|^2 \triangleq \bar{\gamma}_d \eta \quad (22)$$

where $\eta = \sum_{j=1}^{M}\left|h_j^d\right|^2$. According to [28], the MGF of $\left|h_j^d\right|^2$ can be written as

$$M_{\left|h_j^d\right|^2}(s) = E_{\left|h_j^d\right|^2}\left[e^{-s\left|h_j^d\right|^2}\right] = \int_0^{\infty} e^{-sx} f_{\left|h_j^d\right|^2}(x)\,dx \quad (23)$$

By substituting (5) into (23) and employing the equations (7.621.4) and (9.121.1) in [24], (23) can be expressed as

$$\begin{aligned} M_{\left|h_j^d\right|^2}(s) &= \frac{\alpha_{d,j}}{(s+\beta_{d,j})}{}_1F_1\left(m_j,1;1;\frac{\delta_{d,j}}{(s+\beta_{d,j})}\right) \\ &= \alpha_{d,j}\frac{\left(s+\beta_{d,j}\right)^{m_{d,j}-1}}{\left(s+\beta_{d,j}-\delta_{d,j}\right)^{m_{d,j}}} \end{aligned} \quad (24)$$

Considering that h_j^d $\left(j=1,2,\ldots M\right)$ is i.i.d., we can obtain the MGF of η as

$$M_\eta(s) = \prod_{j=1}^{M} M_{\left|h_j^d\right|^2}(s) = \alpha_d{}^M \frac{(s+\beta_d)^{M(m_d-1)}}{(s+\beta_d-\delta_d)^{Mm_d}} \quad (25)$$

Since m_d may be a decimal, the power $M(m_d-1)$ of the numerator can be written as

$$M(m_d-1) = c+\varepsilon \quad (26)$$

where

$$c = \max\{0, \lfloor M(m_d-1)\rfloor\}, \varepsilon = N(m_d-1) - c \quad (27)$$

In (27), $\lfloor z\rfloor$ means the largest integer that does not exceed z. In a similar manner, the power Mm_d of the denominator can be expressed as

$$Mm_d = d+\varepsilon \quad (28)$$

where

$$d = \max\{M, \lfloor Mm_d\rfloor\}, \varepsilon = Mm_d - d \quad (29)$$

Consequently, the MGF of η in (25) can be rewritten as

$$\begin{aligned} M_\eta(s) &= \alpha_d{}^M \frac{(s+\beta_d)^{c+\varepsilon}}{(s+\beta_d-\delta_d)^{d+\varepsilon}} \\ &= \alpha_d{}^M \frac{(s+\beta_d)^{c}}{(s+\beta_d-\delta_d)^{d}}\left(1+\frac{\delta_d}{s+\beta_d-\delta_d}\right)^{\varepsilon} \\ &= \alpha_d{}^M \sum_{l=0}^{c}\binom{c}{l}\beta_d{}^{c-l}\frac{s^l}{(s+\beta_d-\delta_d)^d} \\ &\quad \left(1+\frac{\delta_d}{s+\beta_d-\delta_d}\right)^{\varepsilon} \end{aligned} \quad (30)$$

when $\beta_d \gg \delta_d$, then $\frac{\delta_d}{s+\beta_d-\delta_d} \ll 1$, so we can get

$$\left(1+\frac{\delta_d}{s+\beta_d-\delta_d}\right)^{\varepsilon} \approx 1+\frac{\varepsilon\delta_d}{s+\beta_d-\delta_d} \quad (31)$$

By substituting (31) into (30), it follows that

$$M_\eta(s) \approx \alpha_d^M \sum_{l=0}^{c}\binom{c}{l}\beta_d{}^{c-l}\left(\frac{s^l}{(s+\beta_d-\delta_d)^d}+\frac{\varepsilon\delta_d s^l}{(s+\beta_d-\delta_d)^{d+1}}\right) \quad (32)$$

With the help of the inverse Laplace transform of (32), the PDF of γ_2 can be obtained as

$$f_{\gamma_2}(x) \approx \alpha_d^M \sum_{l=0}^{c}\binom{c}{l}\beta_d^{c-l}\left(\Theta(x,l,d,\bar{\gamma}_d) + \varepsilon\delta_2\Theta(x,l,d+1,\bar{\gamma}_d)\right) \quad (33)$$

where

$$\Theta(x,l,d,\bar{\gamma}_d) = \frac{(\beta_d-\delta_d)^{\frac{l-d}{2}}}{\bar{\gamma}_d^{(d-l)/2}\Gamma(d-l)}x^{\frac{l-d}{2}-1}e^{-\frac{(\beta_d-\delta_d)x}{\bar{\gamma}_d}} \times M_{\frac{d+l}{2},\frac{d-l-1}{2}}\left(\frac{(\beta_d-\delta_d)x}{\bar{\gamma}_d}\right) \quad (34)$$

In (34), $M_{\lambda,\mu}(z)$ represents the Whittaker function. Furthermore, the CDF of γ_2 is given by

$$F_{\gamma_2}(x) \approx \alpha_d^M \sum_{l=0}^{c}\binom{c}{l}\beta_d^{c-l}\left(\mathcal{G}(x,l,d,\bar{\gamma}_d) + \varepsilon\delta_d\mathcal{G}(x,l,d+1,\bar{\gamma}_d)\right) \quad (35)$$

where

$$\mathcal{G}(x,l,d,\bar{\gamma}) = \int_0^x \Theta(\tau,l,d,\bar{\gamma}_d)d\tau = \frac{(\beta_d-\delta_d)^{\frac{l-d-1}{2}}}{\bar{\gamma}_d^{\frac{d-l-1}{2}}\Gamma(d-l+1)} x^{\frac{d-l-1}{2}} \times \exp\left(-\frac{\beta_d-\delta_d}{2\bar{\gamma}_d}x\right) M_{\frac{d+l-1}{2},\frac{d-l}{2}}\left(\frac{\beta_d-\delta_d}{\bar{\gamma}_d}x\right) \quad (36)$$

By substituting (17) and (35) into (13), the OP of the dual-hop DF satellite relaying network with OS/MRC scheme can be expressed as

$$P_{\rm out}^{\rm MRC}(x) \approx 1-\left\{1-\left[A_s x {}_1F_1(m_s;2;B_s x)+\Xi(A_s,B_s,b_s,m_s,\bar{\gamma}_s,x)\right]^N\right\} \times\left\{1-\alpha_d^M\sum_{l=0}^{c}\binom{c}{l}\beta_d^{c-l}\left[\mathcal{G}(x,l,d,\bar{\gamma}_d)+\varepsilon\delta_d\mathcal{G}(x,l,d+1,\bar{\gamma}_d)\right]\right\} \quad (37)$$

Remark 1 *By taking the effects of antenna pattern and path loss into account, we have derived the closed-form expressions of OP for the considered dual-hop satellite relaying system with OS/SC and OS/MRC schemes, respectively. Therefore, we extend the existing works in [13] and [16] to a more practical scenario with multiple users.*

4 Asymptotic OP at high SNR

Although (20) and (37) are exact and valid for any given SNR, it is difficult to characterize the impact of key parameters on the system performance. To this end, we devote to investigating the asymptotic OP at high SNR to gain further insight. According to (13), the asymptotic OP of the considered system is given by

$$P_{\rm out}^{\infty}(x) = 1-\left[1-F_{\gamma_1}^{\infty}(x)\right]\left[1-F_{\gamma_2}^{\infty}(x)\right] \quad (38)$$

In this section, by supposing that $\bar{\gamma}_v \to \infty\,(v=s,d)$, we will derive the asymptotic OP expressions for the considered system, where the OS scheme is used in the uplink, while the SC and MRC schemes are used in the downlink, respectively.

4.1 OS/SC scheme

When OS/SC scheme is employed, the asymptotic OP behavior of the considered system is given by Theorem 1.

Theorem 1 *The asymptotic OP at high SNR for the system with OS/SC scheme can be expressed as*

$$\begin{aligned} P_{\rm out}^{\rm SC,\infty}(x) &= 1-\left[1-\left(\frac{\alpha_s}{\bar{\gamma}_s}x\right)^N\right]\left[1-\left(\frac{\alpha_d}{\bar{\gamma}_d}x\right)^M\right] \\ &= \left(\frac{\alpha_s}{\bar{\gamma}_s}x\right)^N+\left(\frac{\alpha_d}{\bar{\gamma}_d}x\right)^M - \left(\frac{\alpha_s}{\bar{\gamma}_s}x\right)^N\left(\frac{\alpha_d}{\bar{\gamma}_d}x\right)^M + O\left(\frac{1}{\bar{\gamma}_s^N}\right) \\ &= \begin{cases} \left(\frac{\alpha_s}{\bar{\gamma}_s}x\right)^N + O\left(\frac{1}{\bar{\gamma}_s^N}\right), & N<M \\ \left(\frac{\alpha_s}{\bar{\gamma}_s}x\right)^M + \left(\frac{\alpha_d}{\bar{\gamma}_d}x\right)^M + O\left(\frac{1}{\bar{\gamma}_d^M}\right), & N=M \\ \left(\frac{\alpha_d}{\bar{\gamma}_d}x\right)^M + O\left(\frac{1}{\bar{\gamma}_d^M}\right), & N>M \end{cases} \end{aligned} \quad (39)$$

Proof See Appendix 1. According to [29, 30], the OP of a wireless system at high SNR can be approximated as

$$p_{\rm out}^{\infty} \approx (G_c\bar{\gamma})^{-G_d} + O\left(\bar{\gamma}^{-G_d}\right) \quad (40)$$

where G_c represents the coding gain and G_d the diversity order, which is determined by the slope of the OP curve against average SNR at high SNR in a log-log scale. By comparing (39) with (40), the diversity order and coding gain of the system applying OS/SC scheme are given by

$$G_d = \min\{N,M\}$$
$$G_c = \begin{cases} \frac{1}{\alpha_s x}, & N<M \\ \frac{1}{\sqrt[M]{\alpha_s{}^M+\alpha_d{}^M}x}, & N=M \\ \frac{1}{\alpha_d x}, & N>M \end{cases} \quad (41)$$

□

4.2 OS/MRC scheme

As for the case of employing OS/MRC scheme, the asymptotic OP behavior of the considered system with OS/MRC scheme can be evaluated by Theorem 2.

Theorem 2 *The asymptotic OP at high SNR for the considered system with the OS/MRC scheme is given by*

$$\begin{aligned} P_{\rm out}^{\rm MRC,\infty}(x) &= 1-\left[1-\left(\frac{\alpha_s}{\bar{\gamma}_s}x_s\right)^N\right]\left[1-\frac{\alpha_d^M}{\bar{\gamma}_d^M\Gamma(M+1)}x^M\right] \\ &= \left(\frac{\alpha_s}{\bar{\gamma}_s}x\right)^N + \frac{\alpha_d^M}{\Gamma(M+1)}\left(\frac{x}{\bar{\gamma}_d}\right)^M - \left(\frac{\alpha_s}{\bar{\gamma}_s}x\right)^N \times\frac{\alpha_d^M}{\Gamma(M+1)}\left(\frac{x}{\bar{\gamma}_d}\right)^M + O\left(\frac{1}{\bar{\gamma}_s^N}\right) \\ &= \begin{cases} \left(\frac{\alpha_s}{\bar{\gamma}_s}x\right)^N + O\left(\frac{1}{\bar{\gamma}_s^N}\right), & N<M \\ \left(\frac{\alpha_s}{\bar{\gamma}_s}x\right)^M + \frac{\alpha_d^M}{\Gamma(M+1)}\left(\frac{x}{\bar{\gamma}_d}\right)^M + O\left(\frac{1}{\bar{\gamma}_d^M}\right), & N=M \\ \frac{\alpha_d^M}{\Gamma(M+1)}\left(\frac{x}{\bar{\gamma}_d}\right)^M + O\left(\frac{1}{\bar{\gamma}_d^M}\right), & N>M \end{cases} \end{aligned} \quad (42)$$

Proof See Appendix 2. Following the similar way, the diversity order and coding gain of the multiuser dual-hop satellite relaying system applying OS/MRC scheme can be expressed as

$$G_d = \min\{N, M\}$$
$$G_c = \begin{cases} \frac{1}{\alpha_s x}, & N < M \\ \frac{1}{\sqrt[M]{\alpha_s M + \frac{\alpha_d M}{\Gamma(M+1)}} x}, & N = M \\ \frac{\sqrt[M]{\Gamma(M+1)}}{\alpha_d x}, & N > M \end{cases} \quad (43)$$

□

Remark 2 *It is interesting to find that while the diversity order does not depend on the scheme used at D, the coding gain of the considered system with OS/MRC scheme is greater than that with OS/SC scheme in the case of $N > M$. Since the number of sources (e.g., mobile users) is often more than that of destinations (e.g., gateway), our results verify that it is better to exploit OS/MRC scheme in a practical satellite system.*

5 Results and dicussion

This section provides computer simulations to confirm the validity of our analytical results and investigates the impact of system parameters on the OP of the dual-hop satellite relaying network with DF protocol. The simulation parameters used are listed in Table 1. In the simulations, both uplink and downlink are subject to SR fading, which can be different shadowing severities, including the frequent heavy shadowing (FHS) $\{m, b, \Omega\} = \{0.739, 0.063, 8.97 \times 10^{-4}\}$ and average shadowing (AS) $\{m, b, \Omega\} = \{10.1, 0.126, 0.835\}$ [23]. In all the figures, it is assumed that $\bar{\gamma}_s = \bar{\gamma}_d = \bar{\gamma}$, and the threshold equals to 0 dB. In addition, the label (N, M) denotes the number of the sources and destinations, respectively, and all of the Monte Carlo simulations are obtained by performing 10^6 channel realizations.

By assuming that both uplink and downlink undergo FHS fading, we plot the exact and asymptotic OP versus $\bar{\gamma}$ with OS/SC and OS/MRC schemes in Figs. 3 and 4, respectively. Theoretical results were obtained by truncating the infinite series of (20) and (37) to 20 terms, i.e., $k = 20$. Just as we expect, the analytical results match well with Monte Carlo simulations, and the asymptotic curves sharply approach the corresponding analytical curves, verifying the effectiveness of the derived theoretical formulas.

Figure 5 illustrates the OP comparison between OS/SC scheme and OS/MRC schemes. As we see, the performance of OS/MRC scheme is better than that of OS/SC scheme, but the OP slope at high SNR of the consider system with downlink employing SC is similar with that employing MRC scheme, indicating that the diversity order only depends on the number of users. Furthermore, it is interesting to find that for the case of user combinations being $(N, M) = (2, 3)$ and $(N, M) = (3, 2)$, similar performance can be obtained when OS/SC scheme is used. However, when the relaying system employ OS/MRC scheme, the performance of $(N, M) = (3, 2)$ is better than that of $(N, M) = (2, 3)$. This is because the worst link dominates the performance in this dual-hop system.

Figure 6 shows the OP against $\bar{\gamma}$ with $(N, M) = (3, 3)$, where the S-R links experience FHS and AS, respectively. For the purpose of fair comparison, we assume that all R-D links follow FHS. Obviously, the OP of the considered system depends on the shadowing parameter of the link, namely, the system performance decreases with the increase of heavy shadowing, and vice versa.

6 Conclusions

In this paper, we have investigated the performance of a dual-hop satellite relaying system with multiple users. Specifically, based on a practical satellite channel, both the analytical and asymptotic OP expressions for the satellite relaying system with OS/SC and OS/MRC schemes have been derived. Our study reveals that OS/SC scheme and OS/MRC scheme have the same diversity gain and different coding gains, resulting in that the performance of OS/MRC scheme outperforms that of OS/SC scheme in the same condition. The validity of the theoretical analysis has been confirmed by comparison with Monte Carlo simulations. The obtained outage expressions and conclusions will provide valuable insight into the satellite relaying network.

Endnote

[1] It is assumed that these channels are quasi-static, and channel information can be obtained by employing the channel estimation method proposed in [31].

Table 1 Simulation parameters

Parameter	Value	Parameter	Value
Satellite orbit	GEO	Boltzman constant κ	1.38×10^{-23}
Frequency	2 GHz	Noise bandwidth B	5 MHz
3 dB angle $\varphi_{3\text{ dB}}$	0.8°	Maximum ES antenna gain $G_{u,l}^{\max}$	5 dB
Maximum satellite antenna gain $G_{s,l}^{\max}$	48 dB	Noise temperature T	300 K

By considering a more general case of multibeam satellite system, where many practical effects, such as satellite beam pattern and path loss, are taken into account, this table gives the detailed simulation parameters

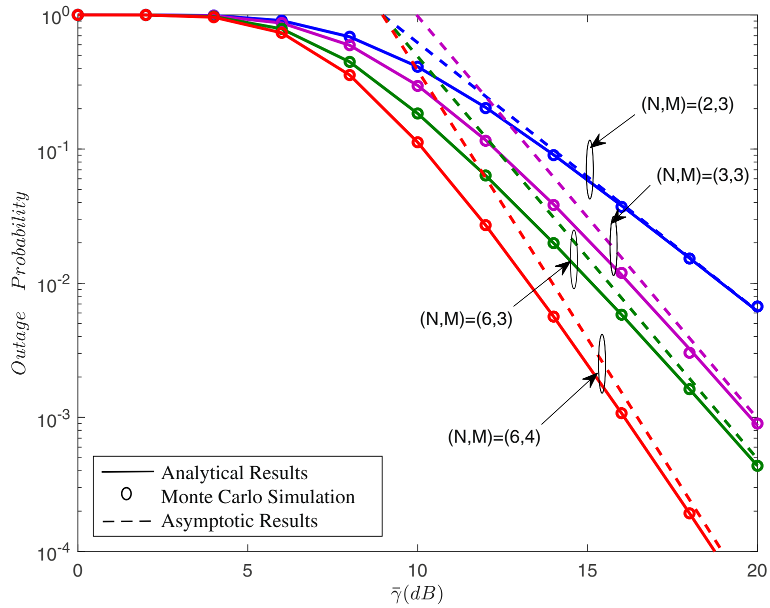

Fig. 3 Analytical and asymptotic OP with OS/SC scheme. This figure gives the exact and asymptotic OP versus $\bar{\gamma}$ with OS/SC scheme when both uplink and downlink undergo FHS fading. In addition, Monte Carlo simulations verify their correctness

Appendix 1

Proof of Theorem 1

Proof In order to obtain the asymptotic OP expression with OS/SC scheme, we will derive the expressions of $F^{\infty}_{\gamma_1}(x)$ and $F^{\infty}_{\gamma_2}(x)$, respectively.

As for the derivation of $F^{\infty}_{\gamma_1}(x)$, according to (14), we can get

$$F^{\infty}_{\gamma_1}(x) = \prod_{i=1}^{N} F^{\infty}_{\gamma_{s,i}}(x) \tag{44}$$

where $F^{\infty}_{\gamma_{s,i}}(x) = \int_0^x f^{\infty}_{\gamma_{s,i}}(\tau)d\tau$. Using (15) yields

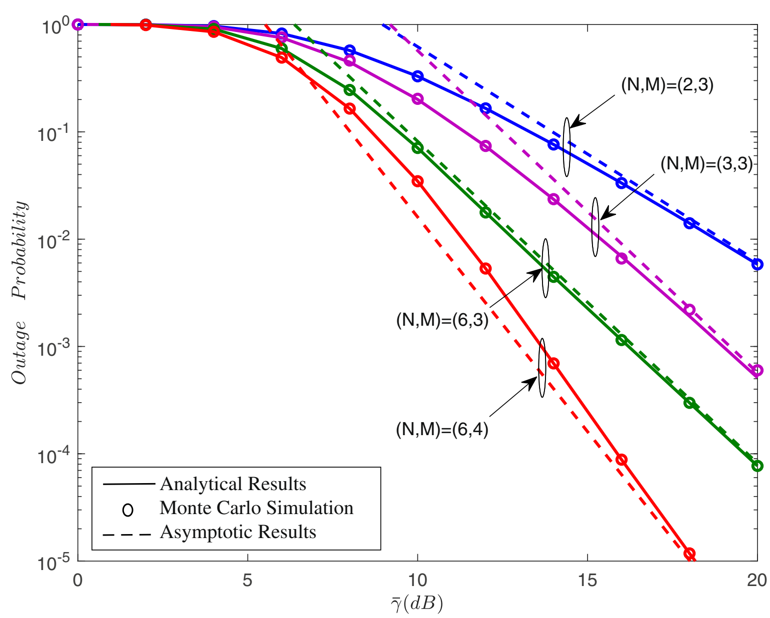

Fig. 4 Analytical and asymptotic OP with OS/MRC scheme. This figure gives the exact and asymptotic OP versus $\bar{\gamma}$ with OS/MRC scheme when both uplink and downlink undergo FHS fading. In addition, Monte Carlo simulations verify their correctness

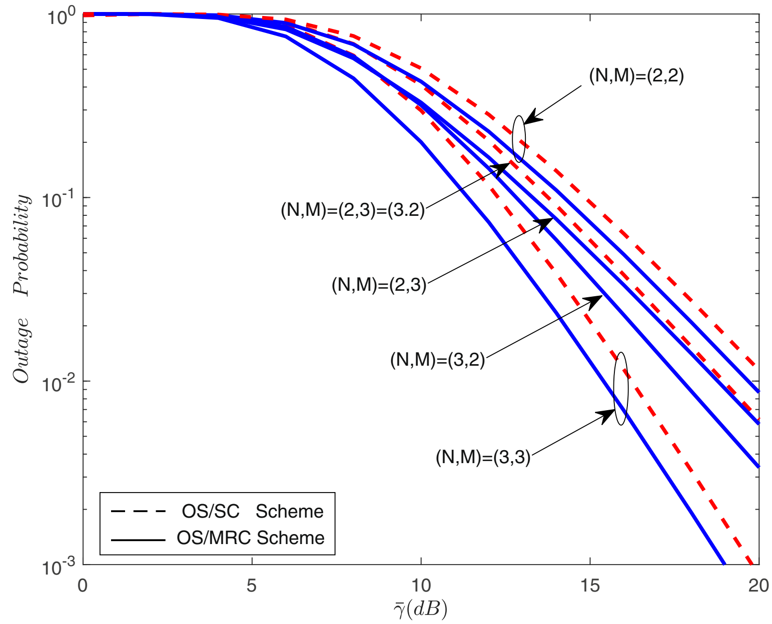

Fig. 5 OP comparison between OS/SC and OS/MRC schemes. This figure illustrates the OP comparison between OS/SC and OS/MRC schemes with different number of users

$$f_{\gamma_{s,i}}^{\infty}(x) = \lim_{\bar{\gamma}_s \to \infty} \frac{\alpha_s}{\bar{\gamma}_s} \exp\left(-\frac{\beta_s x}{\bar{\gamma}_s}\right) {}_1F_1\left(m_s; 1; \frac{\delta_s x}{\bar{\gamma}_s}\right) \quad (45)$$

when $x \to 0$, ${}_1F_1\,(;;)$ have the property ${}_1F_1\,(a; b; x) \to 1$. Besides, by applying the Maclaurin series representation of the exponential function, i.e., $e^{-x} = \sum_{n=0}^{\infty} \frac{(-1)^n}{n!} x^n$, when $x \to 0$, we have $e^{-x} = 1 - x + O\,(x)$. Hence, in the case of high SNR, i.e., $\bar{\gamma}_s \to \infty$, we have $\delta_s \frac{x}{\bar{\gamma}_s} \to 0$, then ${}_1F_1\left(m_s; 1; \frac{\delta_s x}{\bar{\gamma}_s}\right) \to 1$ and $e^{-\frac{\beta_s x}{\bar{\gamma}_s}} = 1 - \frac{\beta_s x}{\bar{\gamma}_s} + O\left(\frac{1}{\bar{\gamma}_s}\right)$.

Substituting the above properties to (45), the asymptotic PDF of $\gamma_{s,i}$ at high SNR can be denoted as

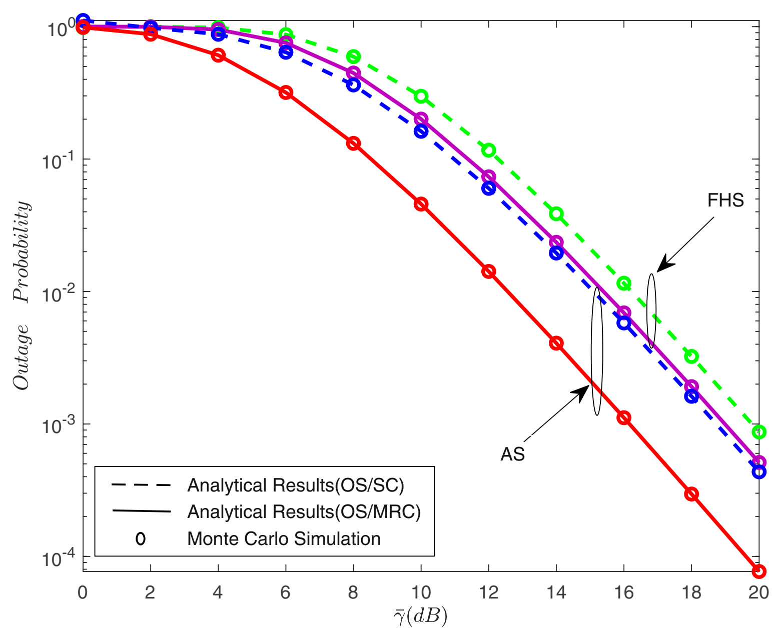

Fig. 6 OP against $\bar{\gamma}$ in different fading scenarios. This figure shows the OP against $\bar{\gamma}$ with $(N, M) = (3, 3)$, where all R-D links follow FHS, while the S-R links experience FHS and AS

$$f_{\gamma_{s,i}}^{\infty}(x) = \frac{\alpha_s}{\bar{\gamma}_s}\left[1 - \frac{\beta_s x}{\bar{\gamma}_s} + O\left(\frac{1}{\bar{\gamma}_s}\right)\right] \tag{46}$$

where $O(\cdot)$ stands for higher order terms. Since the asymptotic performance of $f_{\gamma_{s,i}}^{\infty}(x)$ is determined by the lowest order terms of $\bar{\gamma}_s$ at high SNR, we can further obtain

$$f_{\gamma_{s,i}}^{\infty}(x) = \frac{\alpha_s}{\bar{\gamma}_s} + O\left(\frac{1}{\bar{\gamma}_s}\right) \tag{47}$$

Then, the CDF of γ_s at high SNR can be obtained as

$$F_{\gamma_{s,i}}^{\infty}(x) = \int_0^x f_{\gamma_{s,i}}^{\infty}(\tau)\,d\tau = \int_0^x \frac{\alpha_s}{\bar{\gamma}_s}d\tau + O\left(\frac{1}{\bar{\gamma}_s}\right) = \frac{\alpha_s}{\bar{\gamma}_s}x + O\left(\frac{1}{\bar{\gamma}_s}\right) \tag{48}$$

By substituting (48) into (44), the CDF of γ_1 at high SNR can be obtained as

$$F_{\gamma_1}^{\infty}(x) = \left[\frac{\alpha_s}{\bar{\gamma}_s}x + O\left(\frac{1}{\bar{\gamma}_s}\right)\right]^N \tag{49}$$

In a similar manner, the CDF of γ_2 at high SNR can be obtained as

$$F_{\gamma_2}^{\infty}(x) = \left[\frac{\alpha_d}{\bar{\gamma}_d}x + O\left(\frac{1}{\bar{\gamma}_d}\right)\right]^M \tag{50}$$

By substituting (49) and (50) into (38), the asymptotic OP of the dual-hop DF satellite relaying network with OS/SC scheme can be obtained as in (39). □

Appendix 2

Proof of Theorem 2

Proof Since the CDF of γ_1 at high SNR, namely $F_{\gamma_1}^{\infty}(x)$, has already been obtained as (49), here we only focus on $F_{\gamma_2}^{\infty}(x)$ with OS/MRC scheme.

From (33), we can obtain

$$f_{\gamma_2}^{\infty}(x) = \lim_{\bar{\gamma}_d \to \infty} \alpha_d^M \sum_{l=0}^{c} \binom{c}{l} \beta_d^{c-l} \left(\Theta(x, l, d, \bar{\gamma}_d) + \varepsilon\delta_d \Theta(x, l, d+1, \bar{\gamma}_d)\right) \tag{51}$$

when $x \to 0$, ${}_1F_1(;;)$ have the property ${}_1F_1(a; b; x) \to 1$. Substituting the property to (51), the asymptotic PDF of γ_2 at high SNR can be denoted as

$$f_{\gamma_2}^{\infty}(x) = \alpha_d^M \sum_{l=0}^{c} \binom{c}{l} \beta_d^{c-l} \left(\frac{x^{d-l-1}}{\bar{\gamma}_d^{d-l}\Gamma(d-l)} + \frac{\varepsilon\delta_d x^{d-l}}{\bar{\gamma}_d^{d-l+1}\Gamma(d-l+1)}\right) \tag{52}$$

where $O(\cdot)$ stands for higher order terms. Since the asymptotic performance of $f_{\gamma_2}^{\infty}(x)$ is determined by the lowest order terms of $\bar{\gamma}_d$ at high SNR, we further obtain

$$f_{\gamma_2}^{\infty}(x) = \frac{\alpha_d^M}{\Gamma(M)} \frac{x^{M-1}}{\bar{\gamma}_d^M} + O\left(\frac{1}{\bar{\gamma}_d^M}\right) \tag{53}$$

Then, the CDF of γ_2 at high SNR can be obtained as

$$F_{\gamma_2}^{\infty}(x) = \int_0^x f_{\gamma_2}^{\infty}(\tau)\,d\tau = \frac{\alpha_d^M}{\bar{\gamma}_d^M \Gamma(M+1)} x^M + O\left(\frac{1}{\bar{\gamma}_d^M}\right) \tag{54}$$

By substituting (49) and (54) into (38), the asymptotic OP of the dual-hop DF satellite relaying network with OS/MRC scheme can be obtained as in (42). □

Abbreviations

AF: Amplify-and-forward; AS: Average shadowing; ASER: Average symbol error rate; AWGN: Additive white Guassian noise; BF: Beamforming; BS: Base station; CCI: Co-channel interference; CDF: Cumulative distribution function; CSI: Channel state information; DF: Decode-and-forward; EC: Ergodic capacity; ES: Earth station; FHS: Frequent heavy shadowing; HSTN: Hybrid satellite-terrestrial network; LoS: Line-of-sight; MGF: Moment generating function; MRC: Maximal ratio combining; OP: Outage probability; OS: Opportunistic scheduling; PDF: Probability density function; Qos: Quality of service; Satcom: Satellite communication; SC: Selection combining; SNR: Signal-to-noise ratio; SR: Shadowed Rician

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Availability of data and materials

The datasets generated and analyzed during the current study are not publicly available, but are available from the corresponding author on reasonable request.

Authors' contributions

XW derived the closed-form and asymptotic OP expressions for the multiuser dual-hop satellite relaying with OS/SC and OS/MRC schemes, respectively, and verified the correctness with Monte Carlo simulations. ML proposed an idea and provided the guidance for deriving these expressions. QH derived these expressions cooperatively. JO verified the correctness with Monte Carlo simulations cooperatively. ADP improved the presentation of the draft and provided valuable suggestions. All authors read and approved it.

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

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