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Outage Performance for Multiuser Threshold-Based DF Satellite Relaying

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ABSTRACT Satellite communication plays an important role in future seamless wireless network. In this paper, we investigate the system outage performance of a multiuser threshold-based decode-and-forward (DF) satellite relaying network, where the satellite employing spot beam technology is used as an aerial relay to assist the signal transmission between the terrestrial equipments with multi-antenna. Assuming that maximum ratio transmission (MRT) and maximum ratio combining (MRC) are utilized to achieve the optimal performance, we first obtain the equivalent output signal-to-noise ratio (SNR) expression of the considered system, where frequency division multiplexing access (FDMA) scheme is exploited in the uplink. Then, we derive the closed-form system outage probability (SOP) expression for the considered system, where both uplink and downlink are subject to shadowed-Rician (SR) fading with path loss and antenna gain being considered. The main advantage of our theoretical formula is that it can be used in the case of integer and rational Nakagami-*m* fading parameters. Furthermore, asymptotic SOP formula at high SNR is also presented to show the diversity order and coding gain of the considered system. Finally, simulation results are provided to verify the correctness of the exact and asymptotic SOP expressions and reveal the effects of representative parameters on the system outage performance of the satellite relaying system with threshold-based DF protocol.

INDEX TERMS Multiuser communication, satellite relaying, shadowed-Rician fading, system outage probability, threshold-based decode-and-forward.

I. INTRODUCTION

Satellite communication (SatCom) has received considerable attention due to its ability of seamless connectivity and high-speed broadband access for users all over the world. Especially in remote areas, where terrestrial networks are very difficult or uneconomic to be deployed, SatCom is an indispensable method to build wireless links [1]– [5]. Until now, many land mobile satellite (LMS) communication systems, such as Inmarsat, Globalstar, Thuraya, have already been put into operation at L or S bands to offer various services, such as voice, image and video communication for mobile users around the world.

A. PREVIOUS WORKS

More recently, a lot of works have begun to address the performance analysis of SatCom. For example, based on a simple infinite chi-squared series probability density function (PDF) form, the authors of [6] analyzed the performance of maximum ratio combining (MRC) over shadowed-Rician (SR) fading channels and novel analytical expressions for various performance criteria such as the outage probability (OP),

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the ergodic capacity (EC), and the bit error rate (BER) were developed. Considering the analytical results in [6] which are provided in the form of infinite power series and are not computationally efficient, approximate closed-form expressions of BER, OP, and capacity of the MRC scheme in SR fading LMS channels were derived in [7]. Further, the authors of [8] studied the transmission of orthogonal space-time block codes (OSTBCs) over a SR LMS link to achieve performance gain by utilizing the benefits of multiple-input multiple-output (MIMO) technology. Meanwhile, the performance of hybrid satellite-terrestrial relay network (HSTRN), where a terrestrial relay is employed to assist the satellite signal transmission, has also been thoroughly investigated in open literatures. In [9]– [12], the performance of HSTRN using amplify-and-forward (AF) relaying with single user has been investigated. Since the fifth-generation (5G) mobile systems need to provide services to a large number of terrestrial users, the HSTRN has been extended to a multiuser scenario. The authors of [13] derived the analytical approximated expression as well as the tight upper and lower bounds for the EC of an AF-based multiuser HSTRN with the opportunistic scheduling scheme. In [14], the authors employed a max–max user-relay selection scheme to minimize the OP of multiuser and multirelay AF-based HSTRNs. With dense frequency reuse in wireless networks, the HSTRN is prone to co-channel interference (CCI). Thus, the authors of [15] and [16] considered an AF HSTRN in the presence of CCI. Further, propagation conditions in wireless communications are not always ideal. In practice, the channel state information (CSI) may be outdated due to various reasons, such as feedback delay, mobility, etc. To this end, in [17]– [19], the authors investigated the performance based on AF relaying of HSTRN under the condition of imperfect channel gains. Although AF is an easy protocol commonly used in current bent-pipe satellite system, decode-and-forward (DF) protocol for the regenerative SatCom has become an important option of SatCom, which is suitable well for military and emergency services and will be widely employed for on-board processing satellites in the near future [20]. With this regard, the authors of [21] and [22] studied the performance of a DF HSTRN with multiple CCIs at the destination. In [23] and [24], the outage performance of a cooperative HSTRN configuration with DF protocol was analytically evaluated.

In addition to the performance analysis, since beamforming (BF) technology is an effective method to increase the intended signals while decrease the interference [25]– [27], the application of BF has also been widely studied in SatCom to improve the system performance. For example, the authors of [28] studied the robust secure BF issue of 5G cellular system operating at millimeter wave frequency and coexisting with a satellite network. In [29], a BF scheme to enhance wireless information and power transfer in terrestrial cellular networks coexisting with satellite networks was proposed. The authors of [26] proposed a joint optimization design for a non-orthogonal multiple access (NOMA) based on HSTRN. Further, a robust BF scheme to enhance the physical layer security (PLS) of a multibeam satellite system operating at Ka band was proposed in [30].

It should be pointed out that in the previous works, such as [6]– [19], [21]– [30], only the downlink transmission has been considered. In practice, satellite is usually employed as a relay to forward signals which are from the source to destination. Thus, both of downlink channels and uplink channels [31] should be considered to measure the performance of SatCom. Under this situation, the authors of [32] investigated a dual-hop satellite AF relaying scheme and provided a unified analysis for the CSI-assisted and fixed-gain relaying protocols when both hops are subject to independent and identically distribution (i.i.d.) SR fading channels. Besides, in [33], the authors derived the average BER of the DF satellite relaying system in closed form for i.i.d. SR fading channels and in terms of a power series for correlated SR fading channels. Furthermore, by assuming that the multibeam satellite suffers from hardware impairments and is perturbed by interference signals, the performance of a dual-hop DF relaying-aided LMS communication over SR fading channels was investigated in [34]. The authors of [35] derived the distribution of the product of two squared-SR random variables (RVs) and then made use of it to investigate the performance of the dual-hop satellite relaying system. In addition, considering that the perfect CSI is hard to know, detection of data was performed by replacing exact CSI by estimated CSI in decision metric and then the performance of multi-way satellite relaying was analyzed in [36]. However, it is worth-mentioning that all of the above works focus on the single user scenario, which is inconsistent with realistic application, since a multibeam SatCom network always serves multiple terrestrial users [31]. Our previous work [37] is the first in open technical literatures that studied the performance of multiuser dual-hop satellite relaying system with DF protocol. To the best of our knowledge, there has been no work so far in investigating the outage performance of multiuser satellite relaying system with threshold-based protocol, where all of the terrestrial equipments are equipped with multiple antennas while the satellite employs the spot beam technology. This observation motivates the work in this paper.

B. OUR CONTRIBUTIONS

In this paper, we investigate the system outage performance of a multiuser dual-hop satellite relaying with threshold-based DF protocol. Our main contributions of this paper are summarized as follows:

- Taking the effects of antenna gain, path loss and channel fading into account, and assuming that frequency division multiplexing access (FDMA) scheme is adopted in the uplink, we define an analytical framework for a multiuser dual-hop satellite relaying system, where the satellite employing spot beam technology is used as an aerial relay with threshold-based DF protocol to assist the signal transmission between the terrestrial equipments with multi-antenna. Compared with the existing works, such as [32]– [37], we consider a more practical scenario.

- By assuming that both uplink and downlink experience SR fading, and maximum ratio transmission (MRT) and MRC are exploited to achieve the optimal performance, we derive the closed-form system outage probability (SOP) expression for the considered satellite relaying system, which is a unified expression used in the cases of either integer or rational Nakagami parameter m. This is different from [32] where the expression is only valid for integer values of m, [33] where the expression is approximate for both integer and rational values of m, and [34] where the expressions for integer and rational values of m are independent. Based on the theoretical formula, the impacts of pitch angle on the system performance can be investigated.
- To gain further insight, an asymptotic expression for SOP at high signal-to-noise-ratio (SNR) is obtained, which shows the diversity order and coding gain of our considered system and reveals the impacts of some parameters on the system performance more conveniently.

The rest of the paper is organized as follows. Section II introduces the channel and signal models. Section III derives the exact and asymptotic expressions for SOP of the considered system. The results and discussion are presented in Section IV and this paper is concluded in Section V.

Notations: Vectors are represented by lowercase bold typeface letters. $(\cdot)^H$ stands for the Hermitian transpose. $\|\cdot\|$ represents the Euclidean norm of a vector. $E_x[\cdot]$ denotes the expectation over x. $|\cdot|$ is the absolute value. $\mathcal{CN}\left(\mu, \sigma^2\right)$ stands for the complex Gaussian distribution with mean μ and variance σ^2.

II. CHANNEL AND SIGNAL MODELS

As shown in Figure 1, we consider a multiuser satellite relaying system, where K mobile terminals (MTs), each of which is termed as source (S) equipped with N_t antennas, transmit signals to an earth station (ES), termed as destination (D) equipped with N_d antennas via a geostationary orbit (GEO) regenerative satellite relay (R). The model we consider can be used in Inmarsat SatCom System, where the MTs in remote areas communicate with the ES via the satellite relaying, then the ES is connected with public switched telephone network (PSTN) for further communication. Without loss of generality, it is assumed that the line-of-sight (LoS) link between S and D is unavailable due to the long distance and both uplink and downlink experience SR fading [8], [38]–[40]. It is worth-mentioning that the SR model proposed in [41] is a widely used channel fading model for SatCom, since it describes the satellite channel very accurately with a significantly reduced computational burden as compared with other satellite channel models and SR model is very tight fit for satellite links. Similar to the previous works, such as [27], [42], we assume that the satellite channels experience slow fading and perfect CSIs of satellite

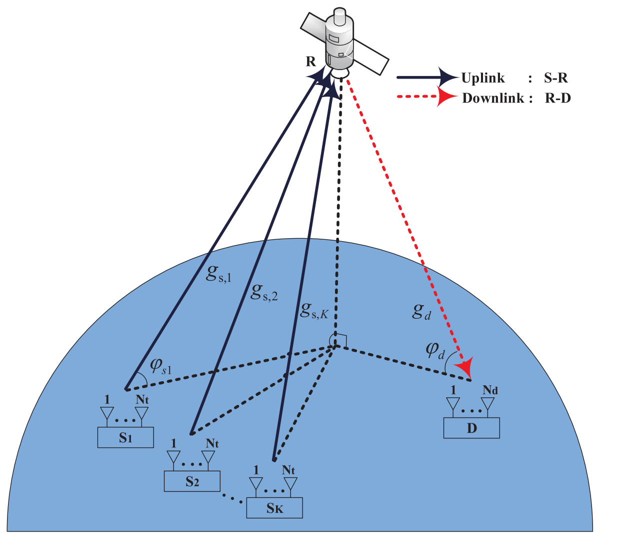

FIGURE 1. System model of the multiuser satellite relaying.

links are available. In addition, compared with other multiple access methods, FDMA is simple, reliable and easy to implement [20], [31], thus, we assume that FDMA scheme is employed, where total bandwidth is divided into many sub-bands with each sub-band being assigned to one of the users.

A. CHANNEL MODEL

One of the main differences between SatCom and terrestrial communications is the satellite channel characteristic. In practice, the effects of antenna pattern and path loss should be considered to accurately model the satellite channel. In this paper, we use $\mathbf{g}_v$ to denote the satellite channel response vector with $v = si$ for the uplink of the i-th ($i \in \{1, 2 \cdots, K\}$) user and $v = d$ for the downlink. With this regard, we have

$$\mathbf{g}_v = C_v \mathbf{h}_v, \tag{1}$$

where the coefficient C_v is given by

$$C_v = \frac{\lambda_v \sqrt{G_{s,v}}}{4\pi d_v}, \tag{2}$$

where λ_v denotes the wavelength for the v-th user, and d_v is the distance between the satellite and the v-th user. Meanwhile, $G_{s,v}$ represents the satellite antenna pattern. Following [26], $G_{s,v}$ can be written as

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

where $G_{s,v}^{\max}$ denotes the maximum satellite antenna gain, $J_n(x)$ is the first-kind Bessel function of order n, and $q_v = 2.07123\cos\varphi_v/\sin\varphi_{3dB}$ with φ_v being the angle of pitch between the v-th user and the satellite, φ_{3dB} is the 3 dB angle of the main beam.

In (1), we model the channel fading vector $\mathbf{h}_v = \left[h_{v,1}, h_{v,2} \ldots, h_{v,N}\right]^T$ as SR distribution, where $N \in \{N_t, N_d\}$. With this regard, according to [41], the PDF of

$\left|h_{v,j}\right|^2$ $(j \in \{1, 2 \cdots, N\})$ is given by

$$f_{\left|h_{v,j}\right|^2}(x) = \alpha_v e^{-\beta_v x}{}_1F_1(m_v; 1; \delta_v x), \tag{4}$$

where $\alpha_v = \frac{1}{2b_v}(\frac{2b_v m_v}{2b_v m_v+\Omega_v})^{m_v}$, $\beta_v = \frac{1}{2b_v}$, $\delta_v = \frac{\Omega_v}{2b_v(2b_v m_v+\Omega_v)}$, with Ω_v being the average power of LoS component, $2b_v$ the average power of the multipath component, and m_v the Nakagami parameter ranging from 0 to ∞. Meanwhile, the function ${}_1F_1(a; b; z)$ is the confluent hypergeometric function having the expression as [43]

$${}_1F_1(a; b; z) = \sum_{k=0}^{\infty} \frac{(a)_k (z)^k}{(b)_k k!}, \tag{5}$$

where $(x)_k = x(x+1)\ldots(x+k-1)$.

B. SIGNAL MODEL

As illustrated in Figure 1, since FDMA is used, all of the MTs try to simultaneously convey their signals to the ES with different sub-bands. In this context, during the period of uplink transmission, the i-th $(i \in \{1, 2 \cdots, K\})$ S sends its signal $x_{s,i}(t)$ with $E[|x_{s,i}(t)|^2] = 1$ to the satellite through the satellite channel $\mathbf{g}_{s,i}$, and the received signal at R can be written as

$$y_{si}(t) = \sqrt{P_{si}}\mathbf{g}_{si}^H \mathbf{w}_{si} x_{si}(t) + n_i(t), \tag{6}$$

where P_{si} denotes the transmit power of the i-th S, $\mathbf{g}_{si}$ is the $N_t \times 1$ channel response matrix from the i-th S to R, $\mathbf{w}_{si}$ is the $N_t \times 1$ transmit weight vector from the i-th S to R, $n_i \sim \mathcal{CN}\left(0, \sigma_i^2\right)$ represents the noise modeled as additive white Gaussian noise (AWGN) given by zero mean and variance $\sigma_i^2 = \kappa BT$ with $\kappa = 1.38 \times 10^{-23}$ being the Boltzman constant, B the carrier bandwidth, and T the noise temperature. Since MRT can lead to the largest SNR at the satellite [44], we utilize the same technique for the MTs. According to the principle of MRT, we choose the transmit weight vector $\mathbf{w}_{si} = \frac{\mathbf{g}_{si}}{\|\mathbf{g}_{si}\|}$. Then, by using (1) into (6), the received SNR at R can be written as

$$\gamma_{si} = \bar{\gamma}_{si}\left\|\mathbf{h}_{si}\right\|^2, \tag{7}$$

where $\bar{\gamma}_{si} = \frac{P_{si}C_{si}^2}{\sigma_i^2}$ denotes the average SNR of the i-th S to R link, $\mathbf{h}_{si}$ is the $N_t \times 1$ channel fading matrix from the i-th S to R.

During the period of downlink transmission, the threshold-based DF protocol is adopted, namely, if $\gamma_{si} \geq \Lambda_{th1}$ with Λ_{th1} being a predetermined threshold, R can correctly decode $x_{si}(t)$, and forward it to the destination. Otherwise, R fails to decode $x_{si}(t)$. Therefore, let D denote the decoding set where the sources transmit the signal that is correctly decoded by R, and it contains 2^K possible decoding subsets S, namely

$$D = \left\{\emptyset, S_1, S_2, \cdots, S_n, \cdots, S_{2^K-1}\right\}, \tag{8}$$

where $\emptyset$ is the null set with no eligible source and S_n the n-th non-empty subset of K sources. As is aforementioned, the decoding is perceived as correct if γ_{si} is higher than Λ_{th1}. Thus, we can define

$$\begin{aligned} &\text{if } \gamma_{si} < \Lambda_{th1}, i \in \{1, 2, \cdots, K\}, \text{ then } S = \emptyset, \\ &\text{if } \begin{cases} \gamma_{si} \geq \Lambda_{th1}, i \in S_n \\ \gamma_{sj} < \Lambda_{th1}, j \in \overline{S}_n \end{cases}, \text{ then } S = S_n, \end{aligned} \tag{9}$$

where $\overline{S}_n$ is the complementary set of S_n. Thus, the received signal at the destination can be written as

$$y_{di}(t) = \begin{cases} \sqrt{P_{ri}}\mathbf{w}_d^H \mathbf{g}_d x_{si}(t) + n_d(t), & i \in S_n, \\ 0, & i \in \bar{S}_n, \end{cases} \tag{10}$$

where P_{ri} denotes the transmit power of R for the i-th S, $\mathbf{g}_d$ is the $N_d \times 1$ channel response matrix from R to D, $\mathbf{w}_d$ is the $N_d \times 1$ receive weight vector at the destination, $n_d \sim \mathcal{CN}\left(0, \sigma_d^2\right)$ represents the AWGN. By employing MRC scheme, the higher SNR brought by array gain can lead to better performance [45]– [46]. According to the principle of MRC, we choose the receive weight vector $\mathbf{w}_d = \frac{\mathbf{g}_d}{\|\mathbf{g}_d\|}$. Thus, according to (1) and (10), the output end-to-end SNR at the destination can be written as

$$\gamma_{di} = \begin{cases} \bar{\gamma}_{di}\left\|\mathbf{h}_d\right\|^2, & i \in S_n, \\ 0, & i \in \bar{S}_n, \end{cases} \tag{11}$$

where $\bar{\gamma}_{di} = \frac{P_{ri}C_d^2}{\sigma_d^2}$ is the average SNR of the downlink for the i-th S, $\mathbf{h}_d$ the $N_d \times 1$ channel fading matrix from R to D.

III. PERFORMANCE ANALYSIS

In this section, we derive the exact SOP expression to measure the quality-of-service (QoS) of our considered system, and then examine the asymptotic behavior by deriving the asymptotic SOP expression.

A. EXACT SYSTEM OUTAGE PERFORMANCE

SOP is defined as the probability that the total received SNR at D falls below a predefined rate Λ_{th2}, which contains two cases in our considered system. One is that none of the transmit signal $x_{si}(t)$ can be decoded correctly at R. The other one is that the SNRs of the sources belonging to subset S_n fall below Λ_{th2}. Therefore, the SOP of the considered system can be calculated as

$$P_{sout}(\Lambda_{th1}, \Lambda_{th2}) = \Pr(S = \emptyset) + \sum_{n=1}^{2^K-1} \Pr(S = S_n)\,\Xi, \tag{12}$$

where $\Xi = \sum_{i \in S_n} p_i P_{out}^i$ with p_i being the access probability of the i-th soure and $P_{out}^i = \Pr(\gamma_{di} < \Lambda_{th2})$ the OP of the i-th source. Without loss of generality, we suppose that sources that satisfy the SNR threshold have the same probability to access the satellite, namely $p_i = \frac{1}{|S_n|}$, where $|S_n|$ is the cardinality of S_n.

Therefore, (12) can be further written as

$$P_{sout}(\Lambda_{th1},\Lambda_{th2}) = \Pr(S=\emptyset) + \sum_{n=1}^{2^K-1}\Pr(S=S_n)\frac{1}{|S_n|}\sum_{i\in S_n}\Pr(\gamma_{di}<\Lambda_{th2}). \quad (13)$$

According to (9), $\Pr(S=\emptyset)$ and $\Pr(S=S_n)$ are, respectively, given by

$$\Pr(S=\emptyset) = \prod_{i=1}^{K}\Pr(\gamma_{si}<\Lambda_{th1}) = \prod_{i=1}^{K}F_{\gamma_{si}}(\Lambda_{th1}), \quad (14a)$$

$$\Pr(S=S_n) = \prod_{i\in S_n}\left[1-F_{\gamma_{si}}(\Lambda_{th1})\right]\prod_{j\in\bar{S}_n}F_{\gamma_{sj}}(\Lambda_{th1}), \quad (14b)$$

and

$$\Pr(\gamma_{di}<\Lambda_{th2}) = F_{\gamma_{di}}(\Lambda_{th2}), \quad (15)$$

with $F_{\gamma_{si}}(\Lambda_{th1})$ and $F_{\gamma_{di}}(\Lambda_{th2})$ being the cumulative distribution function (CDF) of γ_{si} and γ_{di}, respectively. In order to obtain the SOP expression, we have to derive the CDF of γ_{si} and γ_{di} first. According to [7], the moment generating function (MGF) of $h_{si,j}$ $(j=1,2,\ldots,N_t)$ can be written as

$$M_{|h_{si,j}|^2}(s) = E_{|h_{si,j}|^2}\left[e^{-s|h_{si,j}|^2}\right] = \int_0^\infty e^{-sx}f_{|h_{si,j}|^2}(x)\,dx. \quad (16)$$

By substituting (4) into (16), and employing the equations (7.621.4) and (9.121.1) in [43], (16) can be expressed as

$$M_{|h_{si,j}|^2}(s) = \frac{\alpha_{si,j}}{(s+\beta_{si,j})}F\left(m_{si,j},1;1;\frac{\delta_{si,j}}{(s+\beta_{si,j})}\right) = \alpha_{si,j}\frac{(s+\beta_{si,j})^{m_{si,j}-1}}{(s+\beta_{si,j}-\delta_{si,j})^{m_{si,j}}}, \quad (17)$$

where $F(-n,\beta;\beta;-z) = (1+z)^n$ is the hypergeometric function [43]. In this paper, by assuming that RVs $h_{si,j}$ are i.i.d., we can obtain the MGF of $\|\mathbf{h}_{si}\|^2 = \sum_{j=1}^{N_t}|h_{si,j}|^2$ as

$$M_{\|\mathbf{h}_{si}\|^2}(s) = \prod_{j=1}^{N_t}M_{|h_{si,j}|^2}(s) = \alpha_{si}^{N_t}\frac{(s+\beta_{si})^{N_t(m_{si}-1)}}{(s+\beta_{si}-\delta_{si})^{N_t m_{si}}}. \quad (18)$$

Referring to [47], the PDF of $\|\mathbf{h}_{si}\|^2$ can be obtained by solving the inverse Laplace transform of (18) as

$$f_{\|\mathbf{h}_{si}\|^2}(x) = \frac{\alpha_{si}^{N_t}}{\Gamma(N_t)}x^{N_t-1}e^{-\beta_{si}x}{}_1F_1(N_t m_{si};N_t;\delta_{si}x), \quad (19)$$

where $\Gamma(\cdot)$ stands for the Gamma function [43]. With the help of (5), (19) can be further written as

$$f_{\|\mathbf{h}_{si}\|^2}(x) = \frac{\alpha_{si}^{N_t}}{\Gamma(N_t)}x^{N_t-1}e^{-\beta_{si}x}\sum_{k=0}^{\infty}\frac{(N_t m_{si})_k(\delta_{si}x)^k}{(N_t)_k k!}, \quad (20)$$

Then, the PDF of $\gamma_{si} = \bar{\gamma}_{si}\|\mathbf{h}_{si}\|^2$ can be obtained as

$$f_{\gamma_{si}}(x) = \frac{\alpha_{si}^{N_t}}{\Gamma(N_t)}e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}x}\sum_{k=0}^{\infty}\frac{(N_t m_{si})_k(\delta_{si})^k}{(N_t)_k k!\bar{\gamma}_{si}^{k+N_t}}x^{k+N_t-1}. \quad (21)$$

Thus, by employing the equation (3.351.1) in [43], the CDF of γ_{si} can be derived as

$$F_{\gamma_{si}}(x) = \int_0^x f_{\gamma_{si}}(\tau)d\tau = \frac{\alpha_{si}^{N_t}}{\Gamma(N_t)}\sum_{k=0}^{\infty}\frac{(N_t m_{si})_k(\delta_{si})^k}{(N_t)_k(\beta_{si})^{k+N_t}}\frac{(k+N_t-1)!}{k!}\times\left[1-e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}x}\sum_{n=0}^{k+N_t-1}\frac{1}{n!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}x\right)^n\right]. \quad (22)$$

In a similar manner, by assuming that RVs $h_{d,j}(j=1,2,\ldots,N_d)$ are i.i.d., we can obtain the CDF of $\gamma_{di} = \bar{\gamma}_{di}\|\mathbf{h}_d\|^2$ as

$$F_{\gamma_{di}}(x) = \frac{\alpha_d^{N_t}}{\Gamma(N_d)}\sum_{k=0}^{\infty}\frac{(\delta_d)^k}{(N_d)_k}\frac{(k+N_d-1)!}{k!}\times\frac{(N_d m_d)_k}{(\beta_d)^{k+N_d}}\left[1-e^{-\frac{\beta_d}{\bar{\gamma}_{di}}x}\sum_{n=0}^{k+N_d-1}\frac{1}{n!}\left(\frac{\beta_d}{\bar{\gamma}_{di}}x\right)^n\right]. \quad (23)$$

By substituting (22) and (23) into (14) and (15), respectively, we can obtain

$$\Pr(S=\emptyset) = \prod_{i=1}^{K}\frac{\alpha_{si}^{N_t}}{\Gamma(N_t)}\left\{\sum_{k=0}^{\infty}\frac{(N_t m_{si})_k(\delta_{si})^k}{(N_t)_k(\beta_{si})^{k+N_t}}\times\frac{(k+N_t-1)!}{k!}\left[1-e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}}\sum_{n=0}^{k+N_t-1}\frac{1}{n!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^n\right]\right\}, \quad (24a)$$

$$\Pr(S=S_n) = \prod_{i\in S_n}\left\{1-\left\{\sum_{k_1=0}^{\infty}\frac{(\delta_{si})^{k_1}}{(N_t)_{k_1}}\frac{(k_1+N_t-1)!}{k_1!}\times\frac{(N_t m_{si})_{k_1}}{(\beta_{si})^{k_1+N_t}}\left[1-e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}}\sum_{n_1=0}^{k_1+N_t-1}\frac{1}{n_1!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^{n_1}\right]\right\}\times\frac{\alpha_{si}^{N_t}}{\Gamma(N_t)}\right\}\prod_{j\in\bar{S}_n}\left\{\frac{\alpha_{sj}^{N_t}}{\Gamma(N_t)}\sum_{k_2=0}^{\infty}\frac{(\delta_{sj})^{k_2}}{(N_t)_{k_2}}\frac{(k_2+N_t-1)!}{k_2!}\times\frac{(N_t m_{sj})_{k_2}}{(\beta_{sj})^{k_2+N_t}}\left[1-e^{-\frac{\beta_{sj}}{\bar{\gamma}_{sj}}\Lambda_{th1}}\sum_{n_2=0}^{k_2+N_t-1}\frac{1}{n_2!}\left(\frac{\beta_{sj}}{\bar{\gamma}_{sj}}\Lambda_{th1}\right)^{n_2}\right]\right\}, \quad (24b)$$

and

$$\Pr\left(\gamma_{di} < \Lambda_{th2}\right) = \frac{\alpha_d^{N_t}}{\Gamma\left(N_d\right)} \sum_{k=0}^{\infty} \frac{\left(\delta_d\right)^k}{\left(N_d\right)_k} \frac{(k+N_d-1)!}{k!} \times \frac{\left(N_d m_d\right)_k}{\left(\beta_d\right)^{k+N_d}} \left[1 - e^{-\frac{\beta_d}{\bar{\gamma}_{di}}\Lambda_{th2}} \sum_{n=0}^{k+N_d-1} \frac{1}{n!}\left(\frac{\beta_d}{\bar{\gamma}_{di}}\Lambda_{th2}\right)^n\right]. \tag{25}$$

Therefore, by employing (24) and (25) into (13), the SOP expression of the considered system can be obtained as (26), shown at the bottom of this page.

Remark 1: We have derived the exact SOP expression for the considered satellite relaying system. The advantage of our theoretical formula is that it can be used in the cases of either integer or rational Nakagami-m of SR fading. Compared with [32] where the expression is only valid for integer values of m, [33] where the expression is approximate for both integer and rational values of m, and [34] where the expressions for integer and rational values of m are independent, it should be pointed out that our formula is more general and practical.

B. ASYMPTOTIC SYSTEM OUTAGE PERFORMANCE

Although (26) is 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 SOP at high SNR to gain further insight. To this end, we denote $\bar{\gamma}_{si} = \eta_s \bar{\gamma}$ and $\bar{\gamma}_{di} = \eta_d \bar{\gamma}$ with $\bar{\gamma}_{si}, \bar{\gamma}_{di} \to \infty$, where η_s and η_d are the scale factors of $\bar{\gamma}_{si}$ and $\bar{\gamma}_{di}$, respectively. According to (13), the asymptotic SOP of the considered system is given by

$$P_{sout}^{\infty}(\Lambda_{th1}, \Lambda_{th2}) = \Pr^{\infty}\left(S = \emptyset\right) + \sum_{n=1}^{2^K-1} \Pr^{\infty}\left(S = S_n\right) \frac{1}{|S_n|} \sum_{i \in S_n} \Pr^{\infty}\left(\gamma_{di} < \Lambda_{th2}\right), \tag{27}$$

where

$$\Pr^{\infty}\left(S = \emptyset\right) = \prod_{i=1}^{K} F_{\gamma_{si}}^{\infty}\left(\Lambda_{th1}\right), \tag{28a}$$

$$\Pr^{\infty}\left(S = S_n\right) = \prod_{i \in S_n}\left[1 - F_{\gamma_{si}}^{\infty}\left(\Lambda_{th1}\right)\right] \prod_{j \in \bar{S}_n} F_{\gamma_{sj}}^{\infty}\left(\Lambda_{th1}\right), \tag{28b}$$

and

$$\Pr^{\infty}\left(\gamma_{di} < \Lambda_{th2}\right) = F_{\gamma_{di}}^{\infty}\left(\Lambda_{th2}\right). \tag{29}$$

In order to obtain the asymptotic SOP expression, we have to derive the expressions of $F_{\gamma_{si}}^{\infty}\left(\Lambda_{th1}\right)$ and $F_{\gamma_{di}}^{\infty}\left(\Lambda_{th2}\right)$. According to (22), we can get

$$F_{\gamma_{si}}^{\infty}\left(\Lambda_{th1}\right) = \lim_{\bar{\gamma}_{si} \to \infty} \frac{\alpha_{si}^{N_t}}{\Gamma\left(N_t\right)} \sum_{k=0}^{\infty} \frac{\left(\delta_{si}\right)^k}{\left(N_t\right)_k} \frac{(k+N_t-1)!}{k!} \times \frac{\left(N_t m_{si}\right)_k}{\left(\beta_{si}\right)^{k+N_t}} \left[1 - e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}} \sum_{n=0}^{k+N_t-1} \frac{1}{n!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^n\right]. \tag{30}$$

By applying the Maclaurin series representation of the exponential function, we have

$$\begin{aligned} &e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}} \sum_{n=0}^{k+N_t-1} \frac{1}{n!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^n \\ &= e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}} \left[\sum_{n=0}^{\infty} \frac{1}{n!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^n - \sum_{n=k+N_t}^{\infty} \frac{1}{n!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^n\right] \\ &= e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}} \left[e^{\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}} - \sum_{n=k+N_t}^{\infty} \frac{1}{n!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^n\right] \\ &= 1 - e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}} \sum_{n=k+N_t}^{\infty} \frac{1}{n!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^n. \end{aligned} \tag{31}$$

$$\begin{aligned} &P_{sout}\left(\Lambda_{th1}, \Lambda_{th2}\right) \\ &= \prod_{i=1}^{K} \frac{\alpha_{si}^{N_t}}{\Gamma\left(N_t\right)} \left\{\sum_{k=0}^{\infty} \frac{\left(N_t m_{si}\right)_k \left(\delta_{si}\right)^k}{\left(N_t\right)_k \left(\beta_{si}\right)^{k+N_t}} \frac{(k+N_t-1)!}{k!} \left[1 - e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}} \sum_{n=0}^{k+N_t-1} \frac{1}{n!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^n\right]\right\} \\ &+ \sum_{n=1}^{2^K-1} \prod_{i \in S_n} \left\{1 - \left\{\frac{\alpha_{si}^{N_t}}{\Gamma\left(N_t\right)} \sum_{k_1=0}^{\infty} \frac{\left(\delta_{si}\right)^{k_1}}{\left(N_t\right)_{k_1}} \frac{(k_1+N_t-1)!}{k_1!} \frac{\left(N_t m_{si}\right)_{k_1}}{\left(\beta_{si}\right)^{k_1+N_t}} \left[1 - e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}} \sum_{n_1=0}^{k_1+N_t-1} \frac{1}{n_1!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^{n_1}\right]\right\}\right\} \\ &\times \prod_{j \in \bar{S}_n} \left\{\frac{\alpha_{sj}^{N_t}}{\Gamma\left(N_t\right)} \sum_{k_2=0}^{\infty} \frac{\left(\delta_{sj}\right)^{k_2}}{\left(N_t\right)_{k_2}} \frac{(k_2+N_t-1)!}{k_2!} \frac{\left(N_t m_{sj}\right)_{k_2}}{\left(\beta_{sj}\right)^{k_2+N_t}} \left[1 - e^{-\frac{\beta_{sj}}{\bar{\gamma}_{sj}}\Lambda_{th1}} \sum_{n_2=0}^{k_2+N_t-1} \frac{1}{n_2!}\left(\frac{\beta_{sj}}{\bar{\gamma}_{sj}}\Lambda_{th1}\right)^{n_2}\right]\right\} \\ &\times \frac{1}{|S_n|} \sum_{p \in S_n} \left\{\frac{\alpha_d^{N_t}}{\Gamma\left(N_d\right)} \sum_{k=0}^{\infty} \frac{\left(\delta_d\right)^k}{\left(N_d\right)_k} \frac{(k+N_d-1)!}{k!} \frac{\left(N_d m_d\right)_k}{\left(\beta_d\right)^{k+N_d}} \left[1 - e^{-\frac{\beta_d}{\bar{\gamma}_{dp}}\Lambda_{th2}} \sum_{n=0}^{k+N_d-1} \frac{1}{n!}\left(\frac{\beta_d}{\bar{\gamma}_{dp}}\Lambda_{th2}\right)^n\right]\right\}. \end{aligned} \tag{26}$$

Following (31), (30) can be further expressed as

$$F_{\gamma_{si}}^{\infty}(\Lambda_{th1}) = \lim_{\bar{\gamma}_{si}\to\infty} \frac{\alpha_{si}^{N_t}}{\Gamma(N_t)} \sum_{k=0}^{\infty} \frac{(\delta_{si})^k}{(N_t)_k} \frac{(k+N_t-1)!}{k!} \times \frac{(N_t m_{si})_k}{(\beta_{si})^{k+N_t}} e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}} \sum_{n=k+N_t}^{\infty} \frac{1}{n!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^n. \tag{32}$$

In the case of high SNR, i.e., $\bar{\gamma}_{si} \to \infty$, we have $e^{-\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}} = 1 - \frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1} + O\left(\frac{1}{\bar{\gamma}_{si}}\right)$, where $O(\cdot)$ stands for higher order terms. Substituting above property to (32), $F_{\gamma_{si}}^{\infty}(\Lambda_{th1})$ can be denoted as

$$F_{\gamma_{si}}^{\infty}(\Lambda_{th1}) = \lim_{\bar{\gamma}_{si}\to\infty} \frac{\alpha_{si}^{N_t}}{\Gamma(N_t)} \sum_{k=0}^{\infty} \frac{(\delta_{si})^k}{(N_t)_k} \frac{(k+N_t-1)!}{k!} \times \frac{(N_t m_{si})_k}{(\beta_{si})^{k+N_t}} \left(1 - \frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right) \sum_{n=k+N_t}^{\infty} \frac{1}{n!}\left(\frac{\beta_{si}}{\bar{\gamma}_{si}}\Lambda_{th1}\right)^n. \tag{33}$$

Since the asymptotic performance of $F_{\gamma_{si}}^{\infty}(\Lambda_{th1})$ is determined by the lowest order terms of $\bar{\gamma}_{si}$ at high SNR, we take $n = k + N_t$ with $k = 0$ in (33), i.e., $n = N_t$, then we can further obtain

$$F_{\gamma_{si}}^{\infty}(\Lambda_{th1}) \approx \frac{(\alpha_{si}\Lambda_{th1})^{N_t}}{N_t!\bar{\gamma}_{si}^{N_t}}. \tag{34}$$

In a similar manner, we can obtain $F_{\gamma_{di}}^{\infty}(\Lambda_{th2})$ as

$$F_{\gamma_{di}}^{\infty}(\Lambda_{th2}) \approx \frac{(\alpha_{d}\Lambda_{th2})^{N_d}}{N_d!\bar{\gamma}_{di}^{N_d}}. \tag{35}$$

Thus, by substituting (34) and (35) into (28) and (29), respectively, we can get

$$\Pr^{\infty}(S = \emptyset) \approx \prod_{i=1}^{K} \frac{(\alpha_{si}\Lambda_{th1})^{N_t}}{N_t!\bar{\gamma}_{si}^{N_t}}, \tag{36a}$$

$$\Pr^{\infty}(S = S_n) \approx \prod_{i\in S_n}\left[1 - \frac{(\alpha_{si}\Lambda_{th1})^{N_t}}{N_t!\bar{\gamma}_{si}^{N_t}}\right] \prod_{j\in \bar{S}_n} \frac{(\alpha_{sj}\Lambda_{th1})^{N_t}}{N_t!\bar{\gamma}_{sj}^{N_t}}, \tag{36b}$$

$$\Pr^{\infty}(\gamma_{di} < \Lambda_{th2}) \approx \frac{(\alpha_{d}\Lambda_{th2})^{N_d}}{N_d!\bar{\gamma}_{di}^{N_d}}. \tag{37}$$

Therefore, considering the lowest order terms at high SNR, by substituting (36) and (37) into (27), the asymptotic SOP expression of the considered system can be expressed as (38), shown at the bottom of this page.

According to [48], [49], the SOP of a wireless system at high SNR can be approximated as

$$p_{sout}^{\infty} \approx (G_c\bar{\gamma})^{-G_d}, \tag{39}$$

where G_c represents the system coding gain and G_d the system diversity order, which is determined by the slope of the SOP curve against average SNR at high SNR in a log-log scale. By comparing (38) with (39), the diversity order of the considered system is given by

$$G_d = \min(N_t K, N_d), \tag{40}$$

and the coding gain of the considered system can be obtained as (41), shown at the bottom of this page.

Remark 2: From the asymptotic SOP expression, it can be found that the diversity order is determined by the minimum value of $N_t K$ and N_d. Although the channel fading severity does not affect the diversity order, it does influence the overall performance through the system coding gain.

$$P_{out}^{\infty}(\Lambda_{th1}, \Lambda_{th2}) \approx \begin{cases} \frac{(\alpha_d \eta_d \Lambda_{th2})^{N_d}}{N_d!\bar{\gamma}^{N_d}}, & N_t K > N_d \\ \left[\prod_{i=1}^{K} \frac{(\alpha_{si}\eta_s\Lambda_{th1})^{N_t}}{N_t!} + \frac{(\alpha_d\eta_d\Lambda_{th2})^{N_d}}{N_d!}\right]\frac{1}{\bar{\gamma}^{N_d}}, & N_t K = N_d \\ \prod_{i=1}^{K} \frac{(\alpha_{si}\eta_s\Lambda_{th1})^{N_t}}{N_t!} \frac{1}{\bar{\gamma}^{N_t K}}, & N_t K < N_d \end{cases} \tag{38}$$

$$G_c = \begin{cases} \frac{\sqrt[N_d]{N_d!}}{\alpha_d \eta_d \Lambda_{th2}}, & N_t K > N_d \\ \left(\sqrt[N_d]{\prod_{i=1}^{K} \frac{(\alpha_{si}\eta_s\Lambda_{th1})^{N_t}}{N_t!} + \frac{(\alpha_d\eta_d\Lambda_{th2})^{N_d}}{N_d!}}\right)^{-1}, & N_t K = N_d \\ \left(\sqrt[N_t K]{\prod_{i=1}^{K} \frac{(\alpha_{si}\eta_s\Lambda_{th1})^{N_t}}{N_t!}}\right)^{-1}, & N_t K < N_d \end{cases} \tag{41}$$

TABLE 1. System parameters.

Parameter	Value
Orbit	GEO
Frequency for uplink	1535∼1542.5 MHz
Frequency for downlink	1636.5∼1644 MHz
3dB angle φ_{3dB}	0.4°
Carrier bandwidth B	5 MHz
Boltzman constant κ	1.38×10^{-23}
Maximum satellite antenna gain $G_{s,v}^{\max}$	53 dB
Noise temperature T	$300K$

IV. RESULTS AND DISCUSSION

In this section, the numerical results are provided to confirm the correctness of our analytical results and to highlight the impact of system parameters on the SOP of the multiuser satellite relaying network with the threshold-based DF protocol. The working frequency of the GEO satellite is in the L-band. The system parameters used are listed in Table 1. Theoretical results were obtained by truncating the infinite series of (26) to first 15 terms to achieve sufficient accuracy. Similar to most of the related works, we consider the average SNRs of the uplink and downlink satisfy $\bar{\gamma}_{s,i} = \bar{\gamma}_{d,i} = \bar{\gamma}$, namely, $\eta_s = \eta_d = 1$. In order to more intuitively describe the characteristics of satellite mobile communication channel parameters, according to the measured results given in [41], the relationship between the SR channel parameters $\{b_v, m_v, \Omega_v\}$ and the pitch angle φ_v between the user and the satellite can be expressed as

$$b_v(\varphi_v) \approx -4.7943 \times 10^{-8}\varphi_v^3 + 5.5784 \times 10^{-6}\varphi_v^2 - 2.1344 \times 10^{-4}\varphi_v + 3.2710 \times 10^{-2}, \quad (42a)$$

$$m_v(\varphi_v) \approx 6.3739 \times 10^{-5}\varphi_v^3 + 5.5784 \times 10^{-4}\varphi_v^2 - 1.5973 \times 10^{-1}\varphi_v + 3.5156, \quad (42b)$$

$$\Omega_v(\varphi_v) \approx 1.4428 \times 10^{-5}\varphi_v^3 - 2.3798 \times 10^{-3}\varphi_v^2 + 1.2702 \times 10^{-1}\varphi_v - 1.4864. \quad (42c)$$

According to the approximate parameter conversion formula, we can obtain a more intuitive method to analyze the influence of satellite channel parameters on the outage performance of our considered system. In all figures, we denote the uplink pitch angle $\varphi_{s1} = \varphi_{s2} = \cdots = \varphi_{sK} = \varphi_s$. Without loss of the generality, we set $\Lambda_{th1} = \Lambda_{th2} = 5$ in Figure 2-6, and all the simulations are obtained by performing 10^8 channel realizations.

By assuming that both the uplink and the downlink pitch angles are $\varphi_s = \varphi_d = 30°$, we plot the exact and asymptotic SOP versus $\bar{\gamma}$ with different source numbers when $(N_t, N_d) = (2, 4)$ in Figure 2. As we expect, the analytical results match well with Monte Carlo simulations, which verifies the correctness of the exact SOP expression. Also, the asymptotic curves sharply approach the corresponding exact curves, and it is easy to observe that the diversity order for $(KN_t, N_d) = (2, 4), (4, 4), (6, 4)$ is 2, 4, 4, confirming the derived asymptotic formulas. Furthermore, the greater source number can bring a better system performance, owing to the diversity order obtained from the multiple users.

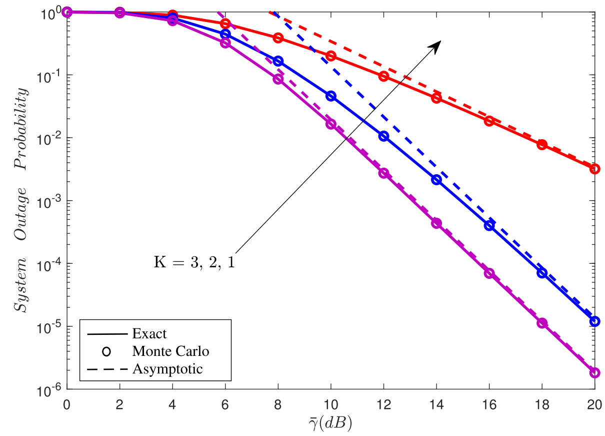

FIGURE 2. Exact and asymptotic SOP versus $\bar{\gamma}$ with different source numbers when $(N_t, N_d) = (2, 4)$, where both the uplink and the downlink pitch angles are $\varphi_s = \varphi_d = 30°$.

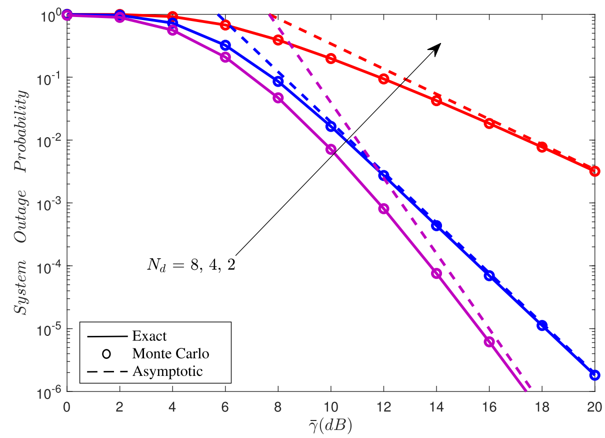

FIGURE 3. SOP versus $\bar{\gamma}$ with different numbers of antenna at D when $(N_t, K) = (2, 3)$, where both the uplink and the downlink pitch angles are $\varphi_s = \varphi_d = 30°$.

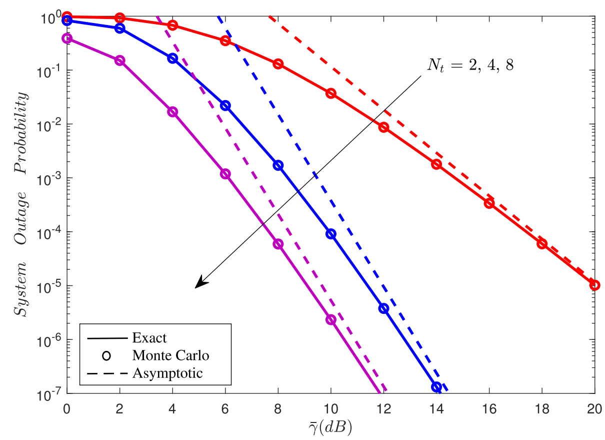

FIGURE 4. SOP versus $\bar{\gamma}$ with different numbers of antenna at S when $(K, N_d) = (2, 8)$, where both the uplink and the downlink pitch angles are $\varphi_s = \varphi_d = 30°$.

Figure 3 illustrates the impact of the number of antennas at D on SOP with $(N_t, K) = (2, 3)$, where both the uplink and the downlink pitch angles are $\varphi_s = \varphi_d = 30°$. It is easy to find that for antenna numbers $N_d = 2, 4, 8$ at D,

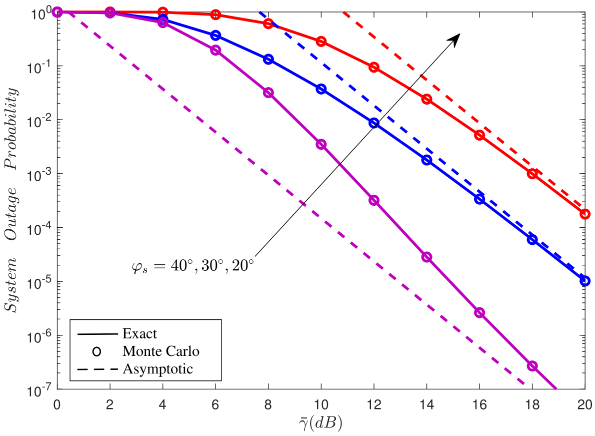

FIGURE 5. SOP versus $\bar{\gamma}$ with different uplink pitch angles when $(N_t, K, N_d) = (2, 2, 4)$, where the downlink pitch angle is $\varphi_d = 40°$.

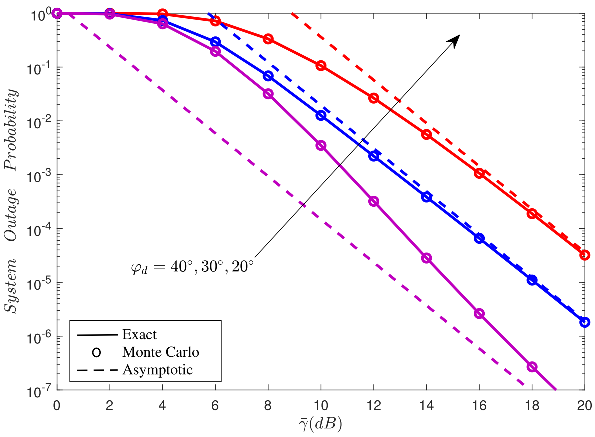

FIGURE 6. SOP versus $\bar{\gamma}$ with different downlink pitch angles when $(N_t, K, N_d) = (2, 2, 4)$, where the uplink pitch angle is $\varphi_s = 40°$.

the diversity orders for $(KN_t, N_d) = (6, 2), (6, 4), (6, 8)$ are 2, 4, 6, corresponding with the derived diversity order expression. In addition, we can obtain that increasing the number of antenna at D can improve the SOP performance, which results from the benefits of using multiple antennas and BF in our considered system.

Figure 4 depicts the impact of the number of antennas at S on SOP with $(K, N_d) = (2, 8)$, where both the uplink and the downlink pitch angles are $\varphi_s = \varphi_d = 30°$. It is easy to find that for antenna numbers $N_s = 2, 4, 8$ at S, the diversity orders for $(KN_t, N_d) = (4, 8), (8, 8), (16, 8)$ are 4, 8, 8. Although the diversity orders for $N_t = 4, 8$ are the same, which can be observed from the two parallel asymptotic curves in Figure 4, the SOP performance for $N_t = 8$ is better than $N_t = 4$. This is because that more antennas result in a greater system coding gain.

Figure 5 and Figure 6 show the effect of the uplink pitch angle φ_s and the downlink pitch angle φ_d on SOP with $(N_t, K, N_d) = (2, 2, 4)$, respectively. Obviously, as the pitch angle increases, the SOP gradually decreases, which owes to the gradual improvement of the channel quality of the satellite link. In addition, all the asymptotic curves are parallel, which means the same diversity order, verifying that the diversity order is independent of the pitch angle, i.e., the channel fading parameter. However, the pitch angle can influence the overall performance through the system coding gain. Thus, we can induce from Figure 5 and Figure 6 that the increase of the pitch angle can make the satellite channel quality better, which further improves the coding gain but has no effect on the diversity order of our considered system.

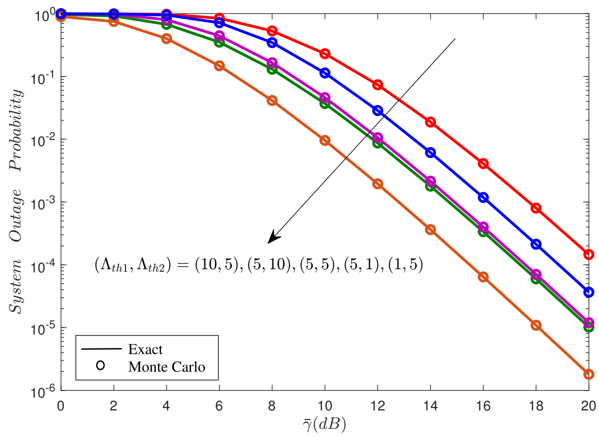

FIGURE 7. SOP versus $\bar{\gamma}$ with different thresholds when $(N_t, K, N_d) = (2, 2, 4)$, where both the uplink and the downlink pitch angles are $\varphi_s = \varphi_d = 30°$.

Figure 7 depicts the SOP versus $\bar{\gamma}$ with different thresholds when $(N_t, K, N_d) = (2, 2, 4)$, where both the uplink and the downlink pitch angles are $\varphi_s = \varphi_d = 30°$. As we can see, in the same condition, the smaller threshold, which means the lower quality requirement of the considered system, leads to a better SOP performance. Furthermore, it is interesting to find that the system outage performance of $(\Lambda_{th1}, \Lambda_{th2}) = (1, 5)$ and $(\Lambda_{th1}, \Lambda_{th2}) = (5, 10)$ are better than $(\Lambda_{th1}, \Lambda_{th2}) = (5, 1)$ and $(\Lambda_{th1}, \Lambda_{th2}) = (10, 5)$, respectively. This is because that the uplink dominates the system outage performance in our considered system.

V. CONCLUSION

In this paper, we have studied the system outage performance of a multiuser satellite relaying system with threshold-based DF protocol, where the multi-antenna sources communicate with the multi-antenna destination via the satellite relay who employs spot beam technology. Specifically, by taking the impacts of satellite beam pattern and path loss into account, we have first established a realistic model for the considered system. Then, by assuming that MRT and MRC are utilized at the transmitter and receiver, respectively, we derive the exact SOP expression of the considered system which is appropriate for both integer and rational Nakagami fading severity parameters m. Furthermore, the asymptotic expression at high SNR for SOP is also derived to show the diversity order and coding gain of the considered system. Finally, the validity of the theoretical analysis has been verified by simulation results.

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