Outage Performance of Intergrated Satellite-Terrestrial Multi-Antenna Relay Networks

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Abstract—This paper investigates the outage performance of an integrated satellite-terrestrial relay network (ISTRN), where the satellite links and the terrestrial links are assumed to experience Shadowed-Rician (SR) fading and Rayleigh fading, respectively. Here, the multi-antenna terrestrial relay with decode-and-forward (DF) protocol is adopted to assist the signal transmission from a satellite to a terrestrial destination. By supposing that the destination exploits the maximal ratio combining (MRC) scheme when the relay can decode the satellite signal successfully, we derive the closed-form expression of the outage probability (OP) for the considered ISTRN. Computer simulation results are provided to corroborate the analytical results and show the impact of the multi-antenna on the system.

Keywords—Intergrated satellite-terrestrial relay network (ISTRN), Decode-and-forward (DF), Maximal ratio combining (MRC), Outage probability (OP)

I. Introduction

Recently, researchers have paid more and more attention to the satellite communication (Satcom), since it can provide potential applications such as broadcasting, navigation and disaster relief for the users all over the world [1]. However, due to the obstacles between the satellite and terrestrial terminals, how to combat the masking effect is a challenging problem in this field. Under this situation, the concept of integrated satellite–terrestrial relay network (ISTRN) is proposed and studied. For example, by using the moment generating function (MGF), the authors of [2] and [3] derived the analytical expressions of the average symbol error rate (ASER) for an ISTRN with amplify-and-forward (AF) and decode-and-forward (DF) relaying, respectively. In [4], with the help of Meijer-G functions, the authors evaluated both of the outage probability (OP) and ASER for an ISTRN with single antenna relay employing AF protocol. Besides, the performance of ISTRN was analyzed in [5], [6].

This paper investigates the performance of an ISTRN with multi-antenna relay employing DF protocol. By assuming that the satellite links and the terrestrial links undergo Shadowed-Rician (SR) fading and Rayleigh fading, respectively, we derive the closed-form expression of OP for the considered system. The main difference between our work and the previous related works, such as [3] is that we consider the practical DF relay, and propose a selected maximal ratio combining (MRC) scheme at the destination. To the best of our knowledge, this is for the first time that such kind of expression has been derived.

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II. System Model

The system model is shown in Fig.1, which consists of a satellite source (S) having a single antenna, a terrestrial relay (R) equipped with N antennas, and a single-antenna destination (D). Both of S-D and S-R links are assumed to experience SR fading while R-D link undergoes Rayleigh fading. By utilizing DF at relay, the total communication occurs in two time slots. During the first time slot, the satellite broadcasts its signal $x(t)$ with $E\left[|x(t)|^2\right]=1$ to D and R. Meanwhile, R performs beamforming with weight vector $\boldsymbol{\omega}_1$ satisfying $\|\boldsymbol{\omega}_1\|_2^2=1$. As such, the received signal at D and R can be, respectively, written as

$$y_{sd}(t)=\sqrt{p_s}hx(t)+n_0 \tag{1a}$$

$$y_{sr}(t)=\boldsymbol{\omega}_1^{\mathbf{H}}\left(\sqrt{p_s}\mathbf{g}x(t)+\mathbf{n}_1\right) \tag{1b}$$

where P_s denotes the transmit power, h the channel coefficient of S-D link, $\mathbf{g}$ the N×1 channel vector of S-R link, and $\boldsymbol{\omega}_1$ the N×1 receive weight vector. Meanwhile, n_0 and $\mathbf{n}_1$ are additive white Gaussian noise (AWGN).

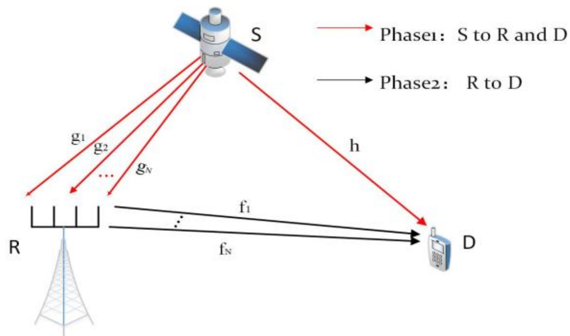

Fig.1 System model

Based on (1), the output SNR at D and R can be, respectively, expressed as

$$\gamma_1=\gamma_{sd}=P_s|h|^2/\sigma^2 \tag{2a}$$

$$\gamma_2=\gamma_{sr}=P_s\left|\boldsymbol{\omega}_1^{\mathbf{H}}\mathbf{g}\right|^2/\sigma^2=P_s\|\mathbf{g}\|_2^2/\sigma^2 \tag{2b}$$

In deriving (2b), we have employed the MRC scheme at R, meaning that $\boldsymbol{\omega}_1=\mathbf{g}/\|\mathbf{g}\|_2$. Thus, (1b) can be written as

$$y_{sr}(t)=\sqrt{p_s}\|\mathbf{g}\|_2x(t)+\boldsymbol{\omega}_1^H\mathbf{n}_1 \tag{3}$$

During the second time slot, R uses DF protocol to forward the signal at R. Only when its received SNR is higher than the given threshold γ_{th}. That is, when $\gamma_{sr} > \gamma_{th}$, R can decode the signal successfully, and send $x(t)$ to D using transmit beamforming with weight vector $\boldsymbol{\omega}_2$ satisfying $\|\boldsymbol{\omega}_2\|_2^2 = 1$. So, the received signal at D in the former case can be written as

$$y_{rd}(t) = \sqrt{p_r}\,\boldsymbol{\omega}_2^{\mathbf{H}}\mathbf{f}x(t) + n_2 \tag{4}$$

where p_r denotes the relay transmit power, $\mathbf{f}$ the N×1 channel vector, and $\mathbf{n}_2$ the AWGN.

Based on (4), the instantaneous output SNR at D can be expressed as

$$\gamma_3 = \gamma_{rd} = P_r\left|\boldsymbol{\omega}_2^{\mathbf{H}}\mathbf{f}\right|^2/\sigma^2 = P_r\|\mathbf{f}\|_2^2/\sigma^2 \tag{5}$$

In deriving (5), we have employed the maximal ratio transmission (MRT) scheme at R, meaning that $\boldsymbol{\omega}_2 = \mathbf{f}/\|\mathbf{f}\|_2$. Thus, (5) can be written as

$$y_{rd}(t) = \sqrt{p_r}\,\|\mathbf{f}\|_2\, x(t) + n_2 \tag{6}$$

By using MRC, the output SNR at D is given by

$$\gamma = \begin{cases}\gamma_1 & ,if \quad \gamma_2 < \gamma_{th}\\ \gamma_1 + \gamma_3, & if \quad \gamma_2 \ge \gamma_{th}\end{cases} \tag{7}$$

In what following, we will derive the closed-form OP expression of the considered system.

III. OUTAGE ANALYSIS

The outage probability is defined as the probability that the SNR falls below a certain threshold γ_{th}, namely,

$$P_{out}(\gamma_{th}) = \Pr\{\gamma \le \gamma_{th}\} = F_\gamma(\gamma_{th}) \tag{8}$$

where $F_\gamma(\mathrm{x})$ is the cumulative distribution function (CDF) of γ. By substituting (7) into (8), one can obtain [7]:

$$P_{out}(\gamma_{th}) = \begin{cases}\Pr\{\gamma_1 \le \gamma_{th}\} & ,if \quad \gamma_2 < \gamma_{th}\\ \Pr\{\gamma_1 + \gamma_3 \le \gamma_{th}\}, & if \quad \gamma_2 \ge \gamma_{th}\end{cases} \tag{9}$$

which can be rewritten as

$$F_\gamma(\gamma_{th}) = F_{\gamma_1}(\gamma_{th}) \times F_{\gamma_2}(\gamma_{th}) + F_{\gamma_4}(\gamma_{th}) \times \left(1\text{-}F_{\gamma_2}(\gamma_{th})\right) \tag{10}$$

The outage probability for the relay is $F_{\gamma_2}(\gamma_{th})$. Obviously, $1\text{-}F_{\gamma_2}(\gamma_{th})$ represents that the relay decodes correctly. $F_{\gamma_4}(\gamma_{th})$ is the CDF of $\gamma_4 = \gamma_1 + \gamma_3$ and $F_{\gamma_1}(\gamma_{th})$ is the CDF of γ_1. In what following, we will derive these closed-form expressions of $F_{\gamma_1}(\gamma_{th})$, $F_{\gamma_2}(\gamma_{th})$ and $F_{\gamma_4}(\gamma_{th})$.

Suppose that S-D link is subject to SR fading channel whose probability distribution function (PDF) is given by [8]

$$f_{|h|^2}(x) = \alpha_1 \exp(-\beta_1 x)\,{}_1F_1(m_{sd};1;\delta_1 x), x > 0 \tag{11}$$

$$\alpha_1 = \frac{1}{2b_{sd}}\left(\frac{2b_{sd}m_{sd}}{2b_{sd}m_{sd} + \Omega_{sd}}\right)^{m_{sd}}, \delta_1 = \frac{\Omega_{sd}}{2b_{sd}\left(2b_{sd}m_{sd} + \Omega_{sd}\right)}, \beta_1 = \frac{1}{2b_{sd}}.$$

where $2\mathrm{b}_{sd}$ denotes the average power of the multipath component, Ω_{sd} is the average power of the LOS component, and $0 \le m_{sd} \le \infty$ is the Nakagami parameter. For $m_{sd} = 0$, the envelope of h obeys the Rayleigh distribution; for $m_{sd} = \infty$, it follows the Rician distribution. Moreover, ${}_1F_1(m_{sd};1;\delta_1 x)$ denotes the confluent hypergeometric function [10,eq.(9.210.1)].

Based on (11), the PDF of γ_1 can be expressed as

$$f_{\gamma_1}(x) = \frac{\alpha_1}{\bar{\gamma}_{sd}}\exp(-\frac{\beta_1}{\bar{\gamma}_{sd}}x)\,{}_1F_1(m_{sd};1;\frac{\delta_1 x}{\bar{\gamma}_{sd}}) \tag{12}$$

where $\gamma_1 = \gamma_{sd} = |h|^2\bar{\gamma}_{sd}$ with $\bar{\gamma}_{sd} = P_s/\sigma^2$ being the average transmit SNR at S.

Based on (12), CDF can be derived by using Maclaurin series expansions of exp(-x) and the table of integrals [12], yielding

$$\begin{aligned}F_{\gamma_1}(\gamma_{th}) &= \frac{\alpha_1}{\bar{\gamma}_{sd}}\gamma_{th}\,{}_1F_1(m_{sd};2;\frac{\delta_1\gamma_{th}}{\bar{\gamma}_{sd}})\\ &+ \sum_{j=1}^{\infty}(-1)^j\frac{\alpha_1\beta_1\gamma_{th}{}^{j+1}}{(j+1)!\left(\bar{\gamma}_{sd}\right)^{j+1}}\,{}_2F_2\left(\mathrm{j}+1, m_{sd}; \mathrm{j}+2, 1; \frac{\delta_1\gamma_{th}}{\bar{\gamma}_{sd}}\right)\end{aligned} \tag{13}$$

where ${}_pF_q(a;b;z)$ denotes the general hypergometric function defined as [10,eq.(9.14.1)]

$${}_pF_q(a_1, a_2 \cdots a_{\mathrm{p}}; \mathrm{b}_1, \mathrm{b}_2 \cdots \mathrm{b}_{\mathrm{q}}; z) = \sum_{n=0}^{\infty}\frac{(a_1)_n (a_2)_n \cdots (a_p)_n}{(b_1)_n (b_2)_n \cdots (b_q)_n}\frac{z^n}{n!} \tag{14}$$

where $(x)_n = x(x+1)\cdots(x+n\text{-}1)$.

The S-R link is modeled as SR fading channels using MRC. Many of the existing analytical results are in the form of infinite power series, the authors of [9] approximate closed-form expressions of the CDF of the received SNR of the MRC scheme. Thus, the following approximate PDF of γ_2 is given by [9]

$$f_{\gamma_2}(x) = \alpha_2^N\sum_{l=0}^{c}\binom{c}{l}\beta_2^{c-l}\left(F\left(x,l,d,\bar{\gamma}_{sr}\right) + \varepsilon\delta_2 F\left(x,l,d+1,\bar{\gamma}_{sr}\right)\right) \tag{15}$$

where

$$F\left(x,l,d,\bar{\gamma}_{sr}\right) = \frac{\left(\beta_2-\delta_2\right)^{\frac{l-d}{2}}}{\bar{\gamma}_{sr}^{\frac{d-l}{2}}\Gamma(d-l)}x^{\frac{d-l}{2}-1}\exp\left(-\frac{\beta_2-\delta_2}{2\bar{\gamma}_{sr}}\mathrm{x}\right) \times M_{\frac{d+l}{2},\frac{d-l-1}{2}}\left(\frac{\beta_2-\delta_2}{\bar{\gamma}_{sr}}\mathrm{x}\right)$$

$$\alpha_2 = \frac{1}{2b_{sr}}\left(\frac{2b_{sr}m_{sr}}{2b_{sr}m_{sr} + \Omega_{sr}}\right)^{m_{sr}}, \delta_2 = \frac{\Omega_{sr}}{2b_{sr}\left(2b_{sr}m_{sr} + \Omega_{sr}\right)}, \beta_2 = \frac{1}{2b_{sr}}.$$

where $2b_{sr}$ denotes the average power of the multipath component, $d = \max\{N, \lfloor mN \rfloor\}$, $\lfloor n \rfloor$ represents the largest integer not greater than n; max{.,.} chooses greatest of the two positive integers. $c = (d-N)^+, \varepsilon = mN - d$, $(n)^+$ represents that if n<0, n=0, and $M_{\mu,\nu}$ denotes the Whittaker function[10,eq.(9.222)].

From (15) and [11,Eq.(2.19.5.3)], we derive the approximate CDF of γ_2.

$$F_{\gamma_2}(\gamma_{th}) = \alpha_2^N\sum_{l=0}^{c}\binom{c}{l}\beta_2^{c-l} \times \left(\mathrm{G}\left(\gamma_{th},l,d,\bar{\gamma}_{sr}\right) + \varepsilon\delta_2\left(G\left(\gamma_{th},l,d+1,\bar{\gamma}_{sr}\right)\right)\right) \tag{16}$$

where

$$\mathrm{G}\left(\gamma_{th},l,d,\bar{\gamma}_{sr}\right)=\int_0^x F(x,l,d,\bar{\gamma}_{sr})dx$$
$$=\frac{\left(\beta_2-\delta_2\right)^{\frac{l-d-1}{2}}}{\bar{\gamma}_{sr}^{\frac{d-l-1}{2}}\Gamma\left(d-l+1\right)}x^{\frac{d-l-1}{2}}\exp\left(-\frac{\beta_2-\delta_2}{2\bar{\gamma}_{sr}}\mathrm{x}\right)\times M_{\frac{d+l-1}{2},\frac{d-l}{2}}\left(\frac{\beta_2-\delta_2}{\bar{\gamma}_{sr}}\mathrm{x}\right)$$

Since the R-D link experience Rayleigh fading, γ_3 obeys the Central Chi-Square Distribution with 2N degrees of freedom, and its CDF can be expressed as [12]

$$F_{\gamma_3}(x)=1-\exp\left(-\frac{x}{\bar{\gamma}_{rd}}\right)\sum_{i=0}^{N-1}\frac{1}{i!}\left(\frac{x}{\bar{\gamma}_{rd}}\right)^i \tag{17}$$

where $\bar{\gamma}_{rd}=P_r/\sigma^2$ donates the average transmit SNR at R.

Finally, we derive the closed-form expression of γ_4.

When $\gamma_2 \ge \gamma_{th}$, Recall that $\gamma_4=\gamma_1+\gamma_3$,yielding

$$f_{\gamma_4}(x)\triangleq\int_0^x f_{\gamma_1}(\tau)f_{\gamma_3}(\gamma-\tau)d\tau \tag{18}$$

After some mathematical manipulations, $F_{\gamma_4}(x)$ can be expressed as

$$F_{\gamma_4}(x)\triangleq\int_0^x f_{\gamma_1}(\tau)F_{\gamma_3}(\gamma-\tau)d\tau \tag{19}$$

From (7) and (9) in $\gamma_2 \ge \gamma_{th}$, we get

$$F_{\gamma_4}(x)=\Pr\left\{\gamma_1+\gamma_3\le\gamma_{th}\right\}$$
$$=F_{\gamma_1}(x)-\sum_{i=0}^{N-1}\frac{1}{i!}\exp\left(-\frac{x}{\bar{\gamma}_{rd}}\right)\frac{\alpha_1}{\bar{\gamma}_{sd}}\left(\frac{1}{\bar{\gamma}_{rd}}\right)^i\sum_{j=0}^{\infty}\left(\left(\frac{1}{\bar{\gamma}_{rd}}-\frac{2}{2b_{sd}\bar{\gamma}_{sd}}\right)/j!\right) \tag{20}$$
$$\times\sum_{k=0}^{i}\binom{i}{k}(-1)^k\left(\frac{x^{i+j+1}}{j+k+1}\right){}_2F_2\left(j+k+1,m_{sd};j+k+2,1;\delta_1 x\right)$$

By inserting (13), (16) and (20) in (10), the closed-form expression of the outage probability can be directly calculated.

IV. SIMULATION RESULTS

In this section, we provide computer simulation to corroborate of the analytical results. Here, the Monte Carlo simulations are obtained by performing 10^6 channel realizations. In our numerical results, the SR fading parameters of the direct link and the S-R links are the same and considered as the average shadowing $(b,m,\Omega)=(0.063,0.739,8.97\times10^{-4})$. Let $\gamma_{th}=2^{2R}-1$, where R denotes the target spectral efficiency (in bits/s/Hz). In order to see the diversity order, we assume that the transmitted SNR per symbol of the direct link is equal to the R-D link ($\bar{\gamma}=\bar{\gamma}_{sd}=\bar{\gamma}_{rd}$). In addition, a data rate of R=0.5 bit/s/Hz is utilized.

Fig.2 shows the outage probability of the ISTRNs with different antenna numbers at the relay, where N denotes the case of the direct transmission only. The analytical results are calculated from (16). It can be observed from Fig.2 that the analytical results are matched well with the Monte Carlo simulations. We can also see that the outage probability of the system is significantly improved as the number of antenna increases. This is because of the array gain and diversity order from employing multiple antennas.

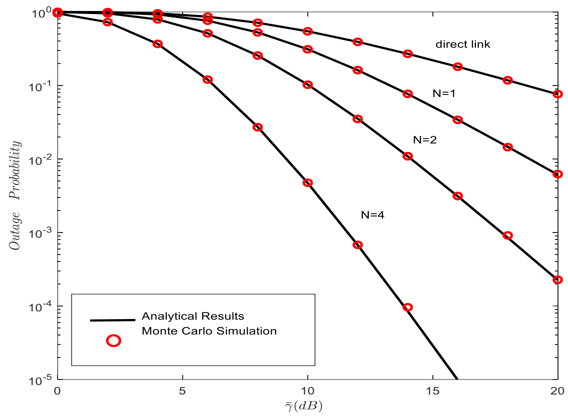

Fig.2 OP of the considered system

V. CONCLUSION

In this paper, we have studied the OP of the ISTRNs with a multi-antenna relay. Specifically, by assuming that the opportunistic selection DF protocol is applied to at relay, MRT and MRC is used at the relay and destination, we have derived the outage probability of the system. The Monte Carlo simulations have been presented to verify the accuracy of the proposed theoretical analysis.

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