Performance of Integrated Satellite-Terrestrial Relay Network With Relay Selection and Outdated CSI

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ABSTRACT Satellite communication plays an important role in future wireless network. In this article, we investigate the outage performance of the integrated satellite-terrestrial relay network (ISTRN) with relay selection based adaptive decode-and-forward (RSADF), where the relay selection is based on outdated channel state information (CSI), and the multiple-antenna relays conduct maximum-ratio receiving and transmitting for decoding and forwarding, respectively. Particularly, we first obtain a novel closed-form expression for the outage probability of the considered ISTRN with RSADF. Furthermore, to get further insights of the effect of key system parameters, e.g., the number of relays, the number of antennas, the CSI outdating level, and the channel fading characteristics, on the system performance, we conduct asymptotic analysis for three typical high average signal-to-noise-ratio (SNR) scenarios, i.e., 1) all satellite and terrestrial links are with high average SNR, 2) the satellite-to-relay link and the relay-to-user link are with high average SNR, and 3) only the relay-to-user link is with high average SNR. The derived high SNR approximations of outage probability explicitly reveal the impact of key system parameters in the form of diversity gain and coding gain. Finally, numerical simulations are presented to validate the analytical results.

INDEX TERMS Satellite communications, adaptive decode and forward, relay selection, outdated CSI.

I. INTRODUCTION

Satellite communication (SatCom) has received considerable attention due to its long-range coverage, abundant bandwidth for massive connectivity, and applicability for scenarios with rare access to cellular networks, e.g., rural, mountain, and sea areas [1], [2]. Typical land mobile satellite (LMS) communication systems, e.g., Inmarsat, Globalstar, Thuraya, have already been put into operation at L or S bands to offer various multimedia services for terrestrial mobile users.

The research on LMS communications dates back to early 1990s [3]. In [4], a shadowed-rician (SR) fading model was proposed for the LMS channels, which provides mathematically-tractable expressions for the fundamental channel statistics. Based on the SR fading model, the performance of LMS systems with maximal-ratio combining (MRC) at the multiple-antenna receiver was analyzed in [5]–[7], where some approximations are provided for the probability density function (PDF) and cumulative distribution function (CDF) of the receiving SNR. Under the similar system model and SR fading model, [8] further provided closed-form expressions for the PDF and CDF of receiving SNR.

In practical LMS systems, the link between the satellite and terrestrial users (denoted as S-D link) may experience non-negligible masking effect resulted from obstacles and shadowing. In this context, the integrated satellite-terrestrial relay network (ISTRN) [8], i.e., DVB-SH, has received significant attention, where terrestrial relays are employed to assist the transmission of satellite signals. Terrestrial relay
nodes can effectively improve the coverage of satellite signals and reduce the cost of user equipment. Since the amplify-and-forward (AF) and decode-and-forward (DF) relay protocols are easy to implement, they are widely used in ISTRN.

For ISTRN with the AF relaying scheme, authors in [9] studied the average symbol error rate (SER) under the $M$-ary phase shift keying constellation for a basic system, where a single satellite transmits data to a single terrestrial user, with the assistance of a single terrestrial relay. In [10], the basic system was extended to the one with multiple terrestrial users, and some analytical results were provided for the outage probability and ergodic capacity. In [11], the basic system was extended to the one with multiple single-antenna terrestrial relays. Via incorporating wireless caching and cooperative transmission into the ISTRN, the outage probability was studied for different cache placement schemes at the relays.

Three typical DF protocols are fixed DF, adaptive DF and incremental DF [12]. In fixed DF, the relay is used to decode and forward the messages to the destination. And the performance is limited by the link between the source and the relay (denoted as $S-R$ link). Via using a feedback link to notify the source whether or not the relay can decode the received signal, adaptive DF performs better with a suitable cooperation between source and relay. Incremental DF improves upon the spectral efficiency of both fixed and adaptive DF via relaying only when the $S-D$ link fails. In [13], the outage performance of non-orthogonal multiple access (NOMA) was studied for the ISTRN with fixed DF where one satellite serves two terrestrial users via the assistance of one single-antenna relay. In [14], the secrecy performance was studied for the ISTRN with multiple cooperative relays under adaptive DF protocols in the presence of multiple eavesdroppers. Authors in [8] adopted the incremental DF protocol for the ISTRN with multiple terrestrial users and gave the outage probability analysis.

For scenarios with multiple relays, the relay selection becomes the key for achieving good tradeoff between system performance and system cost. Single and several relays providing best received SNRs perform the transmission in non-cooperative and cooperative modes, respectively. Relay selection under non-cooperative mode was considered for the ISTRN in [14]. And in [15] the outage and SER performance were studied for the ISTRN with relay selection under cooperative mode. On the other hand, the channel state information (CSI) determines the performance gain of relay selection. Several researches studied the effect of CSI outdating on relay selection for conventional terrestrial wireless networks [16], [17]. For the ISTRN, authors in [10] studied the performance of antenna selection in multiple-antenna relay systems with outdated CSI.

Motivated by the related work, this article addresses the outage performance analysis of the ISTRN where one satellite serves one terrestrial user with some nearby multiple-antenna relays. We consider that the satellite channels and terrestrial channels are subject to SR fading and Nakagami-$m$ fading [18], respectively. And the channels of the $S-R$ link, $S-D$ link and the link between the relay and the user (denoted as $R-D$ link) experience different degrees of fading. One of the nearby relays is selected to assist the communication of $S-D$ link based on outdated CSIs. The selected multiple-antenna relay conduct MRC and maximum-ratio transmitting (MRT) in the first and second slot, respectively. Our major contributions are summarized as follows.

1) System Model: For the considered ISTRN, we adopt the adaptive DF relay protocol. Specifically, the relay notifies the satellite whether or not it can decode the received messages in the first slot. Then in the second slot, the messages are repetitively sent via either only the $S-D$ link or the cooperation of $S-D$ link and $R-D$ link. Meanwhile, the relay selection under non-cooperative mode is conducted based on outdated CSIs. This is because that the system cost may be unaffordable to acquire real-time channel realizations of all $R-D$ links, especially for a large number of relays and relay antennas. And the processing for relay selection itself may be time-consuming as well.

2) Performance Analysis: We first derive the necessary exact statistics and approximate statistics for the analysis of outage probability and its asymptotic behavior for high average link SNR. The derived exact closed-form expression of outage probability facilitates an efficient and fast evaluation of the outage performance. Moreover, we conduct asymptotic analysis of outage performance for three typical scenarios, i.e., 1) all the $S-R$ link, $S-D$ link and $R-D$ are with high average SNR, 2) both the $S-R$ link and $R-D$ link are with high average SNR, and 3) only the $R-D$ link is with high average SNR. The derived approximate expressions of outage probability provide explicit characterization of the impact of key system parameters, e.g., the number of relays and relay antennas, the severity of CSI outdating, and channel fading parameters on outage performance in the form of diversity gain and coding gain.

3) Performance Evaluation: To examine the outage performance of the ISTRN with relay selection and adaptive DF and the impacts of key system parameters, we present a volume of numerical results under various interested system setups. Both analytical and simulation results show that, for scenario 1, the high-SNR slope of outage probability, i.e., diversity gain, is equal to 1 plus the product of relay number and antenna number, when relay selection is based on perfect CSI. When outdated CSI is used for relay selection, the high-SNR slope decreases to the product of antenna number and Nakagami-$m$ parameter of the $R-D$ link, only if $m$ is less than the relay number, i.e., relatively severe channel fading. Meanwhile, the high-SNR offset, i.e., coding gain, decreases for more severe fading of satellite and terrestrial links and more severe CSI outdating for relay selection. In scenario 2, the high-SNR slope decreases by 1 compared to that of scenario 1. In scenario 3, the outage performance is limited by the satellite links, i.e., increasing the average SNR of $R-D$ link can not provide better outage performance.

The rest of the paper is organized as follows. Section II introduces the channel and signal models. Section III
introduces the transmission framework and performance metric. In section IV, we derive the exact and asymptotic expressions for outage probability of the considered system. Numerical results are presented in Section V and this article is concluded in Section VI.

In this article, bold upper case letters and bold lower case letters are used to denote matrices and vectors, respectively. \(a_i\) denotes the i-th entry of \(a\). \(\mathcal{CN} (\mu, \Sigma)\) denotes circularly symmetric complex Gaussian distribution with mean \(\mu\) and covariance matrix \(\Sigma\). \(I_N\) denotes the \(N\)-dimensional identity matrix. \(|A|\) denotes the size of the set \(A\). \(J_n (\cdot)\) and \(I_n (\cdot)\) denote the first-kind Bessel function and modified Bessel function of order \(n\), respectively. \(\Gamma (\cdot)\) is the confluent hypergeometric function \([19]\). \((a)^p = a(a + 1) \cdots (a + p - 1)\) is the rising factorial. \(\Gamma (\cdot)\) is the complete gamma function.

II. CHANNEL AND SIGNAL MODEL

As shown in Fig. 1, we consider the downlink of the ISTRN where one satellite \(S\) serves one target terrestrial user \(D\) in one time-frequency resource block. The direct \(S-D\) link experiences a certain degree of obstruction. And \(K\) terrestrial relays \(R_k, k \in \{1, \ldots, K\}\) with \(N_R\) antennas near the user \(D\) are utilized to assist the communication.

**FIGURE 1.** System model of the considered network.

A. CHANNEL MODEL

In this subsection, we provide the channel models for both the satellite and terrestrial links. To realistically model the channels of \(S-R\) and \(S-D\) link, we take the antenna gain of the satellite, path loss and fast fading into account. The channel from the satellite to the relay \(R_k, h_{Sk} \in \mathbb{C}^{N_R \times 1}, k \in \{1, \ldots, K\}\) and the user \(D, h_{SD} \in \mathbb{C}\) can be represented as

\[h_{SI} = \eta_{SI} g_{SI}\]

for \(i \in \{1, \ldots, K, D\}\). \(\eta_{SI}\) denotes the propagation loss including the effects of path loss and the satellite beam pattern. And \(g_{SI}\) is the fast fading component. Denote the \(K\) relays and the user \(D\) as node \(i\), \(i \in \{1, \ldots, K, D\}\), respectively.

We model the propagation loss \(\eta_{SI}\) as

\[\eta_{SI} = \frac{\lambda}{4\pi} \sqrt{\frac{G_i}{d_i^{PL}}}, \tag{2}\]

where \(\lambda\) is the carrier wavelength and \(d_i\) is the distance between the satellite and node \(i\). \(\alpha_i^{PL}\) is the path loss factor. Since relays are generally placed at locations with negligible blockage with respect to the satellite, we have \(\alpha_i^{PL} = 2\) for \(i \in \{1, \ldots, K\}\) to model the free space propagation. Due to the possible small or large blockage in the \(S-D\) link, \(\alpha_i^{PL}\) should be no less than 2, e.g., \(\alpha_i^{PL} \in [2, 4]\). \(G_i\) denotes the satellite beam pattern at node \(i\) and can be modeled as \([20]\)

\[G_i = G_{max} \left( \frac{J_1 (u_i)}{2u_i} + 36 \frac{J_3 (u_i)}{u_i^3} \right)^2, \tag{3}\]

where \(G_{max}\) is the maximal gain of the satellite beam and \(u_i = 2.07123 \frac{\sin \phi_i}{\sin \phi_{SB}}\) with \(\phi_{SB}\) and \(\phi_i\) being the 3dB angle of the satellite beam and the angle between beam center and node \(i\) with respect to the satellite. Since the distance between the satellite and any relay \(R_i, i \in \{1, \ldots, K\}\) is much larger than that between different relays, these \(\alpha_i\)s are approximately at the same location from the sight of the satellite. Thus, we assume \(\eta_{SI} = \eta_{SR}\) for \(i \in \{1, \ldots, K\}\) in the following for tractable analysis.

For the fast fading components of the satellite channels, we adopt the SR model \([4], [21]\) which provides better tradeoff between the modeling accuracy and computational complexity, compared to others, e.g., Loo, Barts-Stutzman, and Karasawa et al. Specifically, \(g_{Si,j}'s\) for different \(j\) are independent and identically distributed (i.i.d.) with the PDF of \(|g_{Si,j}|^2\) being

\[f_{|g_{Si,j}|^2} (x) = \alpha_i e^{-\beta_i x} F_1 (m_{Si}; 1; \delta_i x), \tag{4}\]

where \(m_{Si} \geq 0\) is the severity parameter. Denote \(\Omega_i\) and \(2b_i\) as the average power of the LoS component and the average power of the scatter component, we have \(\beta_i = \frac{1}{2b_i}\), \(\alpha_i = \alpha_R\) where \(\alpha_R = \beta_R\) and \(\delta_i = \delta_R\) for \(i \in \{1, \ldots, K\}\), i.e., fast fadings of different \(S-R\) links are with the same statistics \([14]\).

To realistically model the channels of \(R-D\) link, we take the path loss and fast fading into account. The channel from the relay \(R_k\) to the user \(D, h_{LD} \in \mathbb{C}^{N_R \times 1}, k \in \{1, \ldots, K\}\) can be given as

\[h_{LD} = \eta_{LD} g_{LD}, \tag{5}\]

where \(\eta_{LD} = \frac{\lambda}{4\pi} \sqrt{\frac{1}{d_{LD}^{PL}}}\) with \(\alpha_i^{PL} \in [2, 4]\) being the terrestrial path loss factor and \(d_{LD}\) the distance between the relay \(R_k\) and the user \(D\). We assume that \(h_{LD}, k \in \{1, \ldots, K\}\) are i.i.d., i.e., \(\eta_{LD} = \eta_{RD}\) for \(k \in \{1, \ldots, K\}\), as in \([15]\) and \([14]\).
In general, relays with significantly different distance will not be selected to serve the same user. For the fast fading component $g_{kD}$, we assume that it undergoes Nakagami-$m$ fading [18]. Specifically, $N_R$ entries of $g_{kD}, k \in \{1, \ldots, K\}$ are i.i.d. random variables with Nakagami parameter $m_{RD} \geq 0$ and unit average power. In the following, we consider integer values of $m_{RD}$ for tractable analysis. Note that $m_{RD} = 1$ results in the widespread Rayleigh-fading model, while $m_{RD} > 1$ corresponds to fading less severe than Rayleigh fading.

Additionally, we model the time-varying behavior of $h_{kD}, k \in \{1, \ldots, K\}$ as follows. Let $a_{k,j}^{(t)}$ and $a_{k,j}^{(t-\tau)}$, $j = 1, \ldots, N_R$ as the amplitude of $j$-th entry of $h_{kD}(t)$ and $h_{kD}(t-\tau)$ which are respectively the realization samples of $h_{kD}$ at time $t$ and time $t-\tau$. Their relationship can be represented by the joint PDF [18], [22]

$$f_{a_{k,j}^{(t)}, a_{k,j}^{(t-\tau)}}(x, y) = \frac{4(\pi y)^{m_{RD}^R} m_{RD}^{m_{RD}^R+1}}{(1-\rho)^{\tau} \Gamma(m_{RD}^R) \Gamma(m_{RD}^R-1)\pi^2} \times I_{m_{RD}^R-1} \left( \frac{2m_{RD}^R \sqrt{xy}}{1-\rho} \right) e^{-\frac{(m_{RD}^R)^2 y^2}{2(1-\rho^2)}}.$$  

(6)

where $\rho \in [0, 1]$ denotes the power correlation between $h_{kD}(t)$ and $h_{kD}(t-\tau)$. One can model $\rho = J_0(2\pi f_D\tau)$ where $f_D$ is the channel Doppler bandwidth.

### III. TRANSMISSION FRAMEWORK AND PERFORMANCE METRIC

For the considered downlink of the ISTRN, the transmission scheme is operated in the following framework. One transmission interval $T$ is divided into two slots. And the satellite sends the same messages in these two slots. If $B$ bits are transmitted by the satellite in the interval, then the average data rate over the interval is $R = \frac{B}{T}$ while the instant data rate over each slot is $2R$.

In the first slot, the satellite sends message $x_S$ to both $K$ relays and the user $D$. The relay $R_k$ can successfully decode $x_S$ if $\gamma_{kD} > 2^{2R} - 1$. Assume that the relays $R_k, k \in D$ can successfully decode the message $x_S$. In the second slot, if $|D| = 0$, i.e., no relay can successfully decode $x_S$, the satellite is informed to simply continue its transmission to the user $D$, in the form of repetition or more powerful codes. If $|D| > 0$, one of these $|D|$ relays is selected to forward $x_S$ to the user $D$. The selection criteria is to maximize the effective SNR $\gamma_{kD}, k \in D$ for decoding $x_k$ at the user $D$ among these $|D|$ relays, i.e.,

$$k^* = \arg\max_{k \in D} \gamma_{kD}. \quad (11)$$

However, we consider that $\gamma_{k^*D}$ may be an outdated version of the achievable effective SNR for the user $D$ to decode $x_{k^*}$ in the second slot, denoted as $\tilde{\gamma}_{k^*D}$. Possible reasons for this outdated are listed as follows. Note that $\gamma_{kD}$ is calculated from $h_{kD}$. If one want to acquire real-time realizations of $h_{kD}, k \in D$ for relay selection, the pilot cost may be unaffordable, especially for large $|D|$ and $N_R$. Meanwhile, the centralized processing for relay selection itself may also be time-consuming.

We call the above transmission scheme the relay selection based adaptive decode-and-forward (RSADF). The effective achievable rate at the user $D$ over one interval can be readily shown to be

$$I_{RSADF} = \begin{cases} 
\frac{1}{2} \log_2 (1 + 2\gamma_{SD}), & |D| = 0 \\
\frac{1}{2} \log_2 (1 + (\gamma_{SD} + \tilde{\gamma}_{k^*D})), & |D| > 0.
\end{cases} \quad (12)$$

Therefore, the outage event for the rate threshold $R$ is given by $I_{RSADF} < R$ and is equivalent to the event

$$\left( \{ |D| = 0 \} \cap \left\{ \gamma_{SD} < \frac{2^{2R} - 1}{2} \right\} \right) \cup \left( \{ |D| > 0 \} \cap \left\{ \gamma_{SD} + \tilde{\gamma}_{k^*D} < \frac{2^{2R} - 1}{2} \right\} \right). \quad (13)$$

### IV. PERFORMANCE ANALYSIS

In this section we will analyze the outage performance of the ISTRN under the RSADF transmission. The asymptotic behavior of the outage performance will be also studied to gain more insights on the impact of system parameters.

#### A. PRELIMINARIES

Necessary statistics are derived for the following analysis of outage probability and its asymptotic behavior at first.
We start with the statistics of effective SNRs for decoding messages from the satellite at relays \( R_k, \ k \in \{1, \ldots, K\} \) and the user \( D \). From Eq. (1) and Eq. (8), we have \( \gamma_{SR} = P_S \eta_{SR}^2 \| g_{SR} \|^2 = P_S \eta_{SR}^2 \sum_{n=1}^{N_R} \| g_{SR,n} \|^2 \). Define \( \gamma_{SR} \equiv P_S \eta_{SR}^2 \) as the average SNR of the \( S-R \) link. The CDF of \( \gamma_{SR} \) can be represented as [8]

\[
F_{\gamma_{SR}}(x) = \sum_{n=0}^{N_R(m_{SR}-1)} \frac{\alpha_R}{n!} \frac{(N_R - N_{Rm_{SR}}) \alpha_R}{n!} \frac{(-\beta_R)^{N_R+n}}{\gamma_{SR}^{N_R+n}} \times \left(1 - e^{-\frac{\rho_{SR} - \beta_R}{\gamma_{SR}}} \frac{N_R+n+1}{l!} \left(\beta_R - \beta_R\right)^{l} \right)^{\gamma_{SR}^l},
\]

(14)

Similarly, via defining \( \gamma_{SD} = P_S \eta_{RD}^2 \) as the average SNR of the \( S-D \) link, the PDF and CDF of \( \gamma_{SD} \) can be given as

\[
f_{\gamma_{SD}}(x) = \alpha_D \sum_{n=0}^{m_{SD}-1} \frac{1}{n!} \frac{(1 - m_{SD}) \alpha_D}{n!} \frac{(-\beta_D)^{m_{SD}+1}}{\gamma_{SD}^{m_{SD}+1}} \times \left(1 - e^{-\frac{\rho_{SD} - \beta_D}{\gamma_{SD}}} \frac{m_{SD}+1}{l!} \left(\beta_D - \beta_D\right)^{l} \right)^{\gamma_{SD}^l},
\]

(15)

and

\[
F_{\gamma_{SD}}(x) = 1 - \alpha_D \sum_{n=0}^{m_{SD}-1} \frac{1}{n!} \frac{(1 - m_{SD}) \alpha_D}{n!} \frac{(-\beta_D)^{m_{SD}+1}}{\gamma_{SD}^{m_{SD}+1}} \times \sum_{l=0}^{n} \left(\beta_D - \beta_D\right)^{l} \frac{x^l}{l!} e^{-\frac{\rho_{SD} - \beta_D}{\gamma_{SD}}}.
\]

(16)

Then, we study the statistics of \( \gamma_{RD}, k \), i.e., the effective SNR at the user \( D \) for decoding messages from the selected relay. Define \( \gamma_{RD} = P_R \eta_{RD}^2 \) as the average SNR of the \( R-D \) link. The PDF and CDF of \( \gamma_{RD}, k, \ k \in \{1, \ldots, K\} \) can be represented as [23]

\[
f_{\gamma_{RD}}(x) = \frac{N_{Rm_{RD}}(N_{Rm_{RD}}-1) - \alpha_R \rho_{RD}}{\gamma_{RD}} e^{-\frac{\rho_{RD}}{\gamma_{RD}}}.
\]

(17)

and

\[
F_{\gamma_{RD}}(x) = 1 - e^{-\frac{\rho_{RD}}{\gamma_{RD}}} \sum_{n=0}^{N_{Rm_{RD}}-1} \frac{1}{n!} \left(\frac{\gamma_{RD}}{\gamma_{SR}}\right)^n.
\]

(18)

From the statistics of \( \gamma_{RD}, k, \ k \in \{1, \ldots, K\} \) and the joint PDF in Eq. (6), the CDF of \( \gamma_{RD} \) can be derived in the following.

**Lemma 1:** The CDF of \( \gamma_{RD} \) can be represented as

\[
F_{\gamma_{RD}}(x; |D|) = 1 - \sum_{u=0}^{|D|-1} \sum_{\nu=0}^{N_{Rm_{RD}}-1} \sum_{\rho=0}^{P_{Rm_{RD}}+1} \sum_{q=0}^{q} \Theta_{u,\nu,\rho, q} x^q e^{-\lambda_u x},
\]

(19)

where

\[
\Theta_{u,\nu,\rho, q} = \binom{|D| - 1}{u} \binom{|D|}{\nu} \binom{P_{Rm_{RD}}}{\rho},
\]

and

\[
F_{\gamma_{SD}^1}(x; |D|) \approx \frac{\gamma_{SD}^1}{|D| N_{Rm_{RD}}},
\]

(26)

\[
F_{\gamma_{RD}^1}(x; |D|) \approx \frac{\gamma_{RD}^1}{|D| N_{Rm_{RD}}},
\]

(25)

\[
F_{\gamma_{RD}^1}(x; |D|) \approx \frac{\gamma_{RD}^1}{|D| N_{Rm_{RD}}},
\]

(24)

\[
F_{\gamma_{RD}^1}(x; |D|) \approx \frac{\gamma_{RD}^1}{|D| N_{Rm_{RD}}},
\]

(23)

\[
\Theta_{u,\nu,\rho, q} = \binom{|D| - 1}{u} \binom{|D|}{\nu} \binom{P_{Rm_{RD}}}{\rho},
\]

(20)
where

\[ A_{1,|D|} = \frac{\gamma_{NRM_{RDP}}}{\Gamma(N_{RM_{RDP}} + 1)^{|D|}} \]  

and

\[ A_{2,|D|} = \frac{\gamma_{NRM_{RDP}}}{\Gamma(N_{RM_{RDP}} + 1)^{|D|}} \times \sum_{u=0}^{N_{RM_{RDP}}-1} \sum_{v=0}^{\min(u, |D|-1)} \left( \begin{array}{c} |D| - 1 \\ u \\ \end{array} \right) \\
\times \left( -1 \right)^u \gamma_{NRM_{RDP}} (N_{RM_{RDP}} + v) (1 - \rho)^v \\
\times \left[ 1 + u (1 - \rho) \right]^{N_{RM_{RDP}} + v}. \]  

These are obtained from utilizing the Taylor series expansion of the exponential function and retaining the first order item. From Eq. (25) and Eq. (26), the approximate CDF of \( \gamma_D \) for high average SNR can be derived in the following.

**Proposition 1:** When the S-D and R-D link are with high average SNR, i.e., \( \gamma_{SD} \gg 1 \) and \( \gamma_{RD} \gg 1 \), the CDF of \( \gamma_D \) can be written as

\[ F_{\gamma_D} (x; |D|) \\
\begin{cases} 
A_{1,|D|}^{\gamma_{NRM_{RDP}}} |D|^{N_{RM_{RDP}}+1} - x^{N_{RM_{RDP}}} \gamma_{SD}^{|D|-1} N_{RM_{RDP}} (1 - \rho)^v \\
A_{2,|D|}^{\gamma_{NRM_{RDP}}} |D|^{N_{RM_{RDP}}+1} - x^{N_{RM_{RDP}}} \gamma_{SD}^{|D|-1} N_{RM_{RDP}} (1 - \rho)^v 
\end{cases}, \quad \rho = 1, \nonumber\]  

and

\[ A_{1,|D|}^{\gamma_{NRM_{RDP}}} |D|^{N_{RM_{RDP}}+1} - x^{N_{RM_{RDP}}} \gamma_{SD}^{|D|-1} N_{RM_{RDP}} (1 - \rho)^v \\
\times \sum_{t=0}^{|D|-1} \left( \begin{array}{c} |D| - 1 \\ t \\ \end{array} \right) (1 - \rho)^v \\
\times \left[ 1 + u (1 - \rho) \right]^{N_{RM_{RDP}} + v}. \]  

**Proof:** The proof procedure is similar to that for Theorem 1.

### B. OUTAGE PROBABILITY AND ITS ASYMPTOTIC BEHAVIOR

1) **OUTAGE PROBABILITY**

According to the definition of the outage event in Eq. (13), the outage probability of the considered system with RSADF can be derived in the following.

**Lemma 2:** For the given threshold of data rate \( R \), the outage probability of the ISTRN with RSADF can be represented as

\[ P_{out} (R) = \left( F_{YSR} \left( 2^{2R} - 1 \right) \right)^K F_{YSR} \left( \frac{2^{2R} - 1}{2} \right) \times \sum_{m=1}^{K} \binom{K}{m} \left[ 1 - F_{YSR} \left( 2^{2R} - 1 \right) \right]^m \]  

**Proof:** From the definition of the outage event in Eq. (13), \( P_{out} (R) = \Pr \{ |D| = 0 \} F_{YSR} \left( \frac{2^{2R} - 1}{2} \right) + \sum_{m=1}^{K} \Pr \{ |D| = m \} F_{YSR} \left( 2^{2R} - 1, m \right) \). Then, Eq. (32) can be directly obtained from \( \Pr \{ |D| = 0 \} = \left[ F_{YSR} \left( 2^{2R} - 1 \right) \right]^K \) and

\[ \Pr \{ |D| = m \} = \binom{K}{m} \left[ 1 - F_{YSR} \left( 2^{2R} - 1 \right) \right]^m \times \left[ F_{YSR} \left( 2^{2R} - 1 \right) \right]^{K-m}. \]

By combining Eq. (14), Eq. (16) and Eq. (21), the exact closed-form expression of outage probability in Eq. (32) can be obtained, which provides an efficient and fast characterization of the impact of key system parameters such as number of relays \( K \), number of antennas in each relay \( N_R \) and parameters of channel path loss and fading on the outage performance.

2) **ASYMPTOTIC OUTAGE PERFORMANCE**

Although Eq. (32) is exact and valid for any given average SNR, it is difficult to gain explicit insights on the impact of key parameters on the outage performance. To this end, three typical scenarios are considered, i.e., 1) \( \gamma_{SR} \gg 1 \), 2) \( \gamma_{SD} \gg 1 \), 3) both the S-R link and the R-D link are with high average SNR. Then, the asymptotic outage performance is given in the following.

\[ C_{u,q,n,t} = \begin{cases} 
\left( \frac{\beta_d - \delta_d}{\gamma_{SD}} \right)^{q+1} x^{n+1} e^{-\lambda_u x} \frac{1}{\Gamma(t+n+1)} \left[ \begin{array}{c} \beta_d - \delta_d \\ \gamma_{SD} \\ \end{array} \right]^{t+n+1} e^{-\left( \frac{\beta_d - \delta_d}{\gamma_{SD}} \right)^q} x^{q+1} \sigma^{\beta_d - \delta_d} - \lambda_u x^{\sigma+1} - \lambda_u x^{\sigma+1} - \lambda_u x + \frac{\beta_d - \delta_d}{\gamma_{SD}} \\
\end{cases} \]

\[ \lambda_u = \frac{\beta_d - \delta_d}{\gamma_{SD}} \]
**Theorem 2:** For any given finite rate threshold $R$, the outage probability of the ISTRN with RSADF in scenario 1 can be approximated as

$$
P_{\text{out}}(R) = \begin{cases} 
A_{1}(1)\gamma^{-(N_{R}K+1)}, & \rho = 1, m_{RD} > 1 \\
(A_{1}^{(1)} + A_{2}^{(1)})\gamma^{-(N_{R}K+1)}, & \rho = 1, m_{RD} = 1 \\
A_{1}(1)\gamma^{-(N_{R}K+1)}, & \rho < 1, m_{RD} > K \\
A_{1}(1)\gamma^{-(N_{R}K+1)}, & \rho < 1, m_{RD} < K & K > 1.
\end{cases}
$$

(34)

where

$$
A_{1}^{(1)} = \alpha_{D}^{2}(N_{R}K)^{2} - 1)^{N_{R}K} N_{R}^{!} K^{m},
$$

(35)

$$
A_{2}^{(2)} = \sum_{m=1}^{K} \frac{K m}{N_{R}^{!} K^{m}} \times A_{1,m}^{(2)}(2R - 1)^{mN_{K}K+m+1} \gamma_{1} \gamma_{2}^{N_{R}(K-m)},
$$

(36)

and

$$
A_{3}^{(3)} = A_{2}^{(2)}(2R - 1)^{N_{K}K+m} \gamma_{1} \gamma_{2}^{N_{R}(K-m)}.
$$

(37)

**Proof:** See Appendix B.

It can be seen from Eq. (34) that the asymptotic outage probability can be further written in the form of $((\Phi\gamma) \sim \Delta)$ where $\Phi$ and $\Delta$ respectively denote the coding gain and diversity order, e.g., for the case of $\rho = 1$ and $m_{RD} > 1$, $\Phi = A_{1}(1)\gamma^{-N_{R}K}$ and $\Delta = N_{R}K + 1$. For $\gamma \gg 1$, $\Delta$ and $\Phi$ determine the slope and horizontal offset of the outage probability curve against average SNR $\gamma$, respectively.

For $\rho = 1$, the relay selection is based on perfect CSI. For $m_{RD} \geq 1$, $\Delta = N_{R}K + 1$ which linearly increases with the number of total available relay antennas $N_{R}K$. This shows the effectiveness of using multiple-antenna relays to assist the satellite communications. $\Phi$ decreases from $m_{RD} > 1$ to $m_{RD} = 1$, i.e., more severe fast fading results in smaller coding gain.

For $\rho < 1$, the relay selection is based on outdated CSI. For $m_{RD} \geq K$, the diversity gain $\Delta = N_{R}K + 1$ is the same as that for $\rho = 1$. For $m_{RD} < K$, the diversity gain decreases to $\Delta = N_{R}m_{RD} + 1$. This means that outdated CSI can result in smaller diversity gain. But this loss diminishes as the degree of channel fast fading decreases. Meanwhile, $\Phi$ decreases from $m_{RD} > K$ to $m_{RD} = K$. Similarly, more severe fast fading results in smaller coding gain.

For scenario 2 with $\gamma_{SR} \gg 1$, $\gamma_{RD} > 1$ and finite $\gamma_{SD}$, we define $\gamma_{RD} \sim \gamma_{SR} \sim \gamma_{SD} \sim \frac{1}{\gamma_{2}}$. The asymptotic outage performance is given in the following.

**Proposition 2:** For any given finite rate threshold $R$, the outage probability of the ISTRN with RSADF in scenario 2 can be approximated as

$$
P_{\text{out}}(R) = \begin{cases} 
A_{1}(4)\gamma^{-N_{R}K}, & \rho = 1, m_{RD} > 1 \\
(A_{1}^{(4)} + A_{2}^{(4)})\gamma^{-N_{R}K}, & \rho = 1, m_{RD} = 1 \\
A_{1}(4)\gamma^{-N_{R}K}, & \rho < 1, m_{RD} > K \\
A_{1}(4)\gamma^{-N_{R}K}, & \rho < 1, m_{RD} < K & K > 1.
\end{cases}
$$

(38)

where

$$
P_{\text{out}}(R) = \left[F_{\gamma_{SD}}(2R - 1)^{K} \gamma_{SD}^{-2} \right].
$$

(42)

It can be seen that compared to scenario 1, the diversity gain in scenario 2 for different cases of $(\rho, m_{RD}, K)$ values all decrease by 1. This is because the diversity gain from the S-D link becomes negligible when $\gamma_{RD} \gg \gamma_{SD}$.

For scenario 3 with $\gamma_{SR} \gg 1$ and finite $\gamma_{SD}$ and $\gamma_{SR}$, the asymptotic outage performance can easily obtained as

$$
P_{\text{out}}(R) \approx \left[F_{\gamma_{SD}}(2R - 1)^{K} \gamma_{SD}^{-2} \right].
$$

(42)

**V. SIMULATIONS**

In this section, we provide numerical simulations to demonstrate the validity of our analytical results. These simulations also explicitly reveal the effects of key parameter on the system performance. All the simulations are obtained by performing $10^{5}$ channel realizations. Some basic simulation parameters are listed in Table 1. And the receiver noise can be calculated as $k_{B}T_{n}$ with $k = 1.38 \times 10^{-23}$ being the Boltzmann constant. Without specific notation, we consider $(m_{S}, b_{i}, \Omega_{i}) = (5, 0.251, 0.279)$, $i \in \{1, \ldots, K\}$ and $m_{RD} = 1$ for the satellite links, i.e., S-R link and S-D link, and the terrestrial R-D link, respectively. The average SNRs of the R-D, S-D and S-R links are set to be $\gamma_{RD} = \gamma_{SR} = \gamma_{SD} = \gamma_{1}$, $\gamma_{SR} = \gamma_{2}$ with $\gamma_{1} = 0.5$ and $\gamma_{2} = 1$. These match the configuration of scenario 1 in Section IV-B2 for large $\gamma$. And the diversity order $\Delta$ is calculated according to Eq. (34) in Theorem 2. The rate threshold $R$ is set to be 3 bps/Hz.
TABLE 1. Basic simulation parameters.

| Parameter            | Value         |
|----------------------|---------------|
| Carrier frequency    | 2 GHz         |
| Carrier bandwidth $B_w$ | 10 MHz       |
| Maximal satellite beam gain $G_{\text{max}}$ | 53 dB |
| 3dB angle $\phi_{3dB}$ | 0.4          |
| Noise temperature $T_n$ | 300 K        |

In Fig. 2, we study the impact of relay number $K$ and antenna number in each relay $N_R$ on the outage performance. It can be seen that the exact analytical results of outage probability calculated by Eq. (32) match the simulated results well for the entire range of $\gamma$. The asymptotic results calculated by Eq. (34) approach the simulated results as $\gamma$ increases. For $K = 2$ and $N_R = 2$, the outage probability decreases as $N_R$ increases to 3 or $K$ increases to 3. And the decrement from $N_R = 2$ to $N_R = 3$ is more significant. This shows that the array gain is more benefit for the outage performance compared to the relay selection gain. Thus, deploying array with larger size at each relay may be more cost-efficient than introducing more relays for selection. Note that this conclusion may not work for scenarios with distinct path loss among different S-R links.

Fig. 3 shows the impact of CSI outdating on the outage performance for $K = 2$, $N_R = 2$ and $m_{RD} = 1$. Recall that $\rho = 1$ means CSI without outdating. And smaller $\rho$ means more severe outdating. It can be seen that the outage performance deteriorates for smaller $\rho$. Meanwhile, for high average SNR, the outage probability decreases with increasing $\gamma$ at the same rate for $\rho \in \{0, 0.3, 0.6, 0.9\}$. The decreasing rate of outage probability for $\rho = 1$ is significant higher. These match the calculated results, e.g., $\Delta = 3$ for $\rho \in \{0, 0.3, 0.6, 0.9\}$ and $\Delta = 5$ for $\rho = 1$.

Fig. 4 shows the impact of the satellite link fadings on the outage performance for $K = 2$, $N_R = 2$, $\rho = 0.6$ and $m_{RD} = 2$. The diversity gain can be calculated as $\Delta = 5$. The SR fading parameters for the satellite links are considered under heavy shadowing (HS) and average shadowing (AS) [27] as $(m_{si}, b_i, \Omega_i) = (2, 0.063, 0.0005)$ and $(m_{si}, b_i, \Omega_i) = (5, 0.251, 0.279)$ for $i \in \{R, D\}$. It can be seen that for $\gamma \geq 15$ dB, compared to the case where both the $S$-$R$ and $S$-$D$ link are with average shadowing, the outage performance deteriorates when either the $S$-$R$ link or the $S$-$D$ link experiences heavy shadowing. Additionally, the performance degradation due to the heavy shadowing of the $S$-$R$ link is more significant compared to that of the $S$-$D$ link. This shows the dominate effect of the $S$-$R$ link and the importance of relay placement in the considered ISTRN. All these curves have the same slope of 5 for high SNR interval, thus the satellite links only affect the offset of outage probability, i.e., coding gain.

Fig. 5 demonstrates the asymptotic tendency of outage probability for scenario 1 discussed in Theorem 2 with $N_R = 2$ and different $\{m_{RD}, K, \rho\}$'s. It can be seen that the slope of the curve for $\{1, 2, 0.6\}$ approach 3 as $\gamma$ increases.
The high SNR slopes of the curves for \(3, 2, 0.6\), \(1, 2, 1\) and \(2, 2, 1\) are all about 5. The high SNR slope of the curve for \(3, 3, 0.6\) is about 7. These simulation results match the theoretical results from Eq. (34). Additionally, for \(K = 2\), \(\rho = 1\) and high SNR, the outage probability for \(m_{RD} = 1\) experiences a constant average SNR loss in value of 0.7 dB compared to that of \(m_{RD} = 2\). The shows that larger \(m_{RD}\), i.e., less severe fading of the \(R-D\) link, means higher coding gain for the outage performance.

Fig. 6 demonstrates the asymptotic variation trend of outage probability for scenario 2 discussed in Proposition 2 with \(N_R = 2\). We consider \(\overline{\gamma}_{RD} = \overline{\gamma}_{SR} = \overline{\gamma}\) and \(\overline{\gamma}_{SD} = 5\) dB. The simulation and exact results verify the accuracy of the asymptotic results in Eq. (38). It can be seen that the relative relationship between different curves is the same as that for scenario 1. The major difference is that the high SNR slopes of all curves decreases by one compared those in Fig. 5. This is because that the diversity gain from the \(S-D\) link vanishes for finite fixed \(\overline{\gamma}_{SD}\) as \(\overline{\gamma}\) grows very large.

VI. CONCLUSION
In this article, the outage performance of the ISTRN with RSADF was investigated where the relay selection is based on outdated CSIs, and multiple-antenna relays conduct MRC and MRT for DF relaying. The closed-form expression of the outage probability was first derived for the considered system. Then, asymptotic analysis was conducted for three typical high average SNR scenarios, i.e., 1) high average SNR \(S-R, S-D\) and \(R-D\) links, 2) high average SNR \(S-R\) and \(R-D\) links, and 3) high average SNR \(R-D\) links. The derived high SNR approximations of outage probability explicitly reveal the impact of key system parameters, e.g., the number of relays, the number of antennas, the CSI outdating level, and the channel fadings in the form of diversity gain and coding gain. Finally, numerical results verified our analytical results.

APPENDIX A
PROOF OF THEOREM 1
According to the definition of CDF, we have
\[
\Pr (\gamma_{SD} + \tilde{\gamma}_{k+D} \leq x) = \int_{0}^{x} F_{\gamma_{SD}} (x - y; |D|) f_{\gamma_{SD}} (y) \, dy
\]
When $C. Zhang$
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