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Performance Analysis of NOMA-Based Cooperative Spectrum Sharing in Hybrid Satellite-Terrestrial Networks

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ABSTRACT In this paper, the performance of non-orthogonal multiple access (NOMA) based cooperative spectrum sharing in hybrid satellite-terrestrial networks (HSTNs) is investigated, where the primary satellite network recruits the secondary terrestrial network as a cooperative relay. To improve the fairness and spectrum utilization under cooperative spectrum sharing (i.e. overlay paradigm of cognitive radio), the NOMA power allocation profile is determined by instantaneous channel conditioning at the second temporal phase. The closed-form outage probability and approximated ergodic capacity expressions for the primary user (PU) and the secondary user (SU) are derived by decode-and-forward (DF) relay protocols, where the generalized Shadowed-Rician fading and Nakagami-m fading are considered for satellite links and terrestrial links, respectively. Simulation results are conducted for validation of the theoretical derivation and analysis of the impact of key parameters, and prove the superiority of NOMA comparing to conventional orthogonal multiple access (OMA) schemes on cooperative spectrum sharing in HSTNs. Besides, the fairness analysis between the PU and the SU is introduced by Jain's fairness index (JFI).

INDEX TERMS Non-orthogonal multiple access (NOMA), hybrid satellite-terrestrial networks (HSTNs), cooperative spectrum sharing, outage probability (OP), ergodic capacity.

I. INTRODUCTION

SATELLITE communication (SATCOM) has earned a lot of attention in the field of navigation, broadcasting and multicasting services because of the huge coverage area [1]. With the help of large coverage, SATCOM offers a possibility to prvide anytime and anywhere access to data communications via mobile devices [2], for example, video streaming and cloud-access services. However, one of the main challenges for SATCOM is the heavy shadowing or physical obstacles, which causes an unreliable line-of-sight (LOS) link between the satellite and terrestrial user. The use of larger transmit power on satellites is difficult to achieve in the space segment and does not meet the future of green communications requirement. To resolve this problem, hybrid satellite-terrestrial relay networks (HSTRNs) are proposed to enhance coverage and high data rate services by deploying terrestrial relays [3], [4]. However, the performance improvement of HSTRNs is built on the basis that the relay nodes consume additional power and time resources [5]. Furthermore, the existing research does not consider the way to further improve resource utilization based on the resources consumed by the relay nodes [6].

Actually, with the rapid growth of satellite mobile users, the problem of low spectrum resource utilization and high cost in the SATCOM has become prominent [7]. Spectrum sharing among satellite and terrestrial networks, as a concept of cognitive radio (CR) [8], [9], called hybrid satellite-terrestrial cognitive networks (HSTCNs), is the most promising approach. CR contains three paradigms, including the interweave, underlay and overlay paradigms [10]. The authors in [11] introduce the interweave paradigm for

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HSTCN, where the satellite share idle spectrum with terrestrial networks. It is shown that cognitive satellite networks can not only increase the spectrum utilization but also benefit their operational revenues. However, it is hard for the terrestrial networks to find out the realtime idle spectrum. Most of the researches about HSTCNs consider the underlay paradigm [12], [13], which, however, would cause unavoidable co-channel interference among primary users (PUs) and secondary users (SUs). Therefore, reliable coordination between satellite and terrestrial networks has become a key issue, which is an extremely difficult problem due to the unknown of channel state information (CSI) exchange. The work in [14] proposes a cooperative scheme to improve the wireless spectrum utilization and tackles unreliable satellite direct communication (DC) link, which can be seen as the overlay paradigm. However, one major assumption of the work is that PU's co-channel interference can be successfully canceled by using its copy received in the first temporal phase, which is extremely ideal in practice since the receiving capability of SU and dynamic channel conditions are not guaranteed. Another problem is that the inequitable power allocation of the secondary relay, which would lead to an adverse impact on cooperation. Furthermore, to enhance the spectral efficiency of HSTCNs, a key issue is to maintain a good balance in the profits of different participants, in particular, to improve the fairness among heterogeneous networks.

Non-orthogonal multiple access (NOMA) [5], [15]–[23] allows multiple users to share the same resource elements in the time, frequency, space, or code domain. Benefits of NOMA include massive connectivity, high spectral efficiency, etc. Another attractive attribute of NOMA is that the issue of fairness could be solved by proper power allocation profile [24]. There exists some works combine NOMA with HSTRNs and HSTCNs [25]–[28]. The author in [25] applies a user with better channel condition as a relay node and forwards information to other users, thus alleviating the masking effect of users with poor channel conditions in heavy shadowing. Reference [21] studies the scenario that a single antenna satellite communicates with multiple multi-antenna users simultaneously through the help of a single antenna relay and the NOMA scheme. The authors in [27] and [28] introduce NOMA to HSTCNs, which implements spectrum sharing in the manner of the underlay paradigm. Reference [25] and [27] consider NOMA based HSTRN/HSTCN from a collaborative perspective. Reference [26] and [28] extend previous works to the perspective of spectrum sharing. Allowing the secondary users and primary users operating simultaneously in a cognitive relay network, [29], [30] introduce NOMA into the overlay paradigm into terrestrial networks. However, they only considered the priority of primary user without considering the fairness between the primary network and the secondary network. To the best of our knowledge, there is no prior work combining the NOMA and cooperative spectrum sharing in HSTNs. Therefore, we propose to implement NOMA for cooperative spectrum sharing in HSTNs, which is an overlay paradigm in CR.

Inspired by the above observations, a NOMA-based on cooperative spectrum sharing scheme in HSTNs is proposed to improve the spectrum utilization and tackle the fairness issue by decode-and-forward (DF) relay protocols for dynamic power allocation by instantaneous channel conditions. The contributions of this work are manifold as follows:

- First of all, we propose an overlay cooperative spectrum sharing scheme in HSTNs, where the secondary terrestrial network acts as a relay for primary satellite simultaneously and the transmission duration is divided into two temporal phases. Besides, the NOMA is adopted in the second temporal phase.
- Secondly, considering the fairness of the overlay paradigm at the second temporal phase, the NOMA-based power allocation profile is determined by instantaneous channel conditions for both the PU and the SU.
- Thirdly, closed-form outage probability (OP) and approximated ergodic capacity expressions for both PU and SU are derived by considering the generalized Shadowed-Rician fading for satellite links [31]–[34], and Nakagami-m fading for terrestrial links [31], [32].
- Finally, the impact of key parameters of the NOMA system is analyzed, and the superiority of the NOMA scheme is proved to compare to conventional OMA in terms of performance in HSTNs. Also, the fairness analysis between the PU and the SU is introduced by Jain's fairness index (JFI).

The rest of this paper is organized as follows. Section II introduces the cooperative spectrum sharing HSTNs system model, reformulates signal to interference plus noise ratio (SINR), and gives channels model. In Section III, the exact OP and ergodic capacity expressions are derived. Section IV shows simulation results. Finally, conclusions are drawn in Section V.

II. PROBLEM STATEMENT

A. SYSTEM MODEL

We consider a cooperative spectrum sharing model in HSTNs as illustrated in Fig. 1, consisting of a primary satellite transmitter (S), a cooperative CR relay (R), a PU (D) and a SU (C), where each node is assumed to have a single antenna and works in half-duplex mode. It is easy to expend to multi user scenarios by employing different subchannels.

The channel coefficient between X and Y is denoted as H_{XY}, where X,Y can be S, R, D, and C, respectively. One of the assumptions is that reliable direct communication (DC) link is unavailable since the heavy shadowing and physical obstacles in the cases of urban, populated, etc. Hence, the R is recruited as a relay and is authorized spectrum access opportunities as payoffs in a cooperative way. To prevent the noise of the first temporal phase from further amplification, the cognitive relay chooses DF protocols to retransmit primary network message in this paper. Besides, to improve the spectrum utilization and tackle a dilemma of fairness for

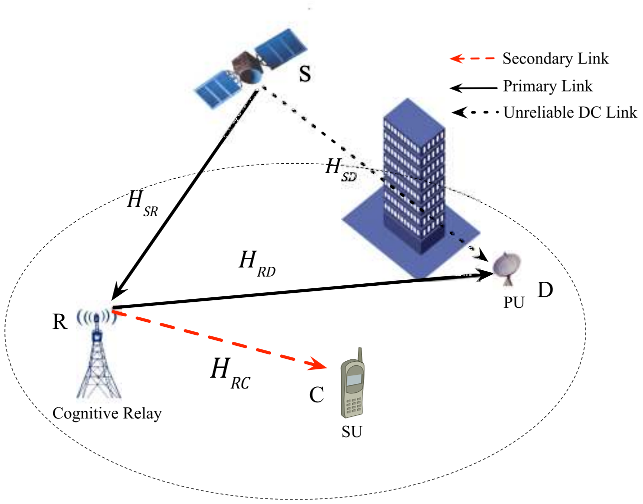

FIGURE 1. System model.

the relay in transmitting power allocation, a power domain NOMA scheme is adopted in the second temporal phase.

The overall communication frame divides into two temporal phases. The satellite broadcast the signal at the first temporal phase, and the relay transmits mixed signals by power domain NOMA scheme for both the PU and the SU in the second temporal phase.

Therefore, the signal of the first temporal phase, where the satellite sends the signal to the relay, is given by

$$y_{SR} = \sqrt{P_S} H_{SR} x_p + n_0, \tag{1}$$

where x_p denotes the signal of PU, $E\left[\left|x_p\right|^2\right] = 1$, and $E[\cdot]$ means the expectation operation, P_S is the transmitter power of satellite, and n_0 is the additive white Gaussian noise (AWGN) with mean zero and variance δ_1^2. In the second temporal phase, the relay transmits mixed signals of PU and SU by power domain NOMA scheme. For DF relay protocols for satellite signals, the received signals are denote as

$$y_{Rn} = \sqrt{\alpha P_R} H_{Rn} x_1 + \sqrt{(1-\alpha) P_R} H_{Rn} x_2 + n_{1,n}, \tag{2}$$

where $n \in \{D, C\}$, x_1, x_2 can be x_p, x_s respectively, x_s is the secondary signal, $E\left[|x_s|^2\right] = 1$, P_R is the transmitter power of the relay, the variance of mean zero AWGN $n_{1,n}$ is δ_2^2 or δ_3^2 for PU and SU, respectively, and α is the power allocation factor, ranging $(0.5, 1)$, which indicated that the user with poor channel condition (i.e. the weak user) would be allocated with more power.

We assume all channels undergo independent block fading. The average SNR of each channel is given as $\bar{\gamma}_{SR} = P_S/\delta_1^2$, $\bar{\gamma}_{RD} = P_R/\delta_2^2$ and $\bar{\gamma}_{RC} = P_R/\delta_3^2$, respectively. The average SNR can be seen as the large scale of fading. Therefore, the instantaneous SNR is $\bar{\gamma}_{XY}\rho_{XY}$, where ρ_{XY} is the channel gain, defined as $|H_{XY}|^2$. Due to time-varying block channel gains, signal detection with successive interference cancellation (SIC) should follow the order by instantaneous SNR. For DF relay protocols, the SINR of the weak user is given by

$$\gamma_{1,m} = \frac{\alpha \bar{\gamma}_{Rm}\rho_{Rm}}{(1-\alpha)\bar{\gamma}_{Rm}\rho_{Rm} + 1}, \tag{3}$$

where m is the weak user, which means $\bar{\gamma}_{Rn}\rho_{Rn} > \bar{\gamma}_{Rm}\rho_{Rm}$.

$$\gamma_{n\to m} = \frac{\alpha \bar{\gamma}_{Rn}\rho_{Rn}}{((1-\alpha)\bar{\gamma}_{Rn}\rho_{Rn} + 1)}. \tag{4}$$

Therefore, $\gamma_{n\to m} > \gamma_{1,m}$, which indicates SIC can be conducted properly. The SINR of the strong user is

$$\gamma_{2,n} = (1-\alpha)\bar{\gamma}_{Rn}\rho_{Rn}. \tag{5}$$

B. CHANNEL MODELS

There are various channel models to describe the satellite link, one of the most suitable channel statistic model is the Shadowed-Rician fading model [31]–[33], which has been widely used for mobile/fixed receiver operating in various propagation environment, including for S, Ku and Ka band. The probability density function (PDF) of $|H_{Si}|^2$ is shown as

$$f_{|H_{Si}|^2}(x) = \alpha_{Si}\exp(-\beta x)\,{}_1F_1(m, 1, \delta x), \tag{6}$$

where $i \in \{R, D\}$, ${}_1F_1(\cdot,\cdot,\cdot)$ is the confluent hypergeometric function, and $(\cdot)_k$ is the Pochhammer symbol. The other key parameters are defined as $\alpha_{Si} = (2bm)^m/\left[2b(2bm+\Omega)^m\right]$, $\delta = \Omega/[2b(2bm+\Omega)]$, and $\beta = 1/2b$, where $2b$ denotes the scatter component average power, Ω is the average power of the LOS, m represents the Nakagami fading parameter. We take m as integer values to simplify, and rewrite Shadowed-Rician fading PDF as

$$f_{|H_{Si}|^2}(x) = \alpha_{Si} e^{[(\delta-\beta)x]} \sum_{k=0}^{m-1} \frac{(-1)^k (1-m)_k (\delta x)^k}{(k!)^2}. \tag{7}$$

With the help of [36, eq. 9.210.1], the corresponding cumulative distribution function (CDF) can be obtained by

$$F_{|H_{Si}|^2}(x) = 1 - \alpha_{Si} e^{[(\delta-\beta)x]} \sum_{k=0}^{m-1} \frac{(-1)^k (1-m)_k}{k!} \times \sum_{p=0}^{k} \frac{(\delta-\beta)^{-(k+1-p)} x^p}{p!}. \tag{8}$$

where Pochhammer symbol is defined as

$$(x)_K = x(x+1)(x+2)\cdots(x-k+1) \tag{9}$$

For the terrestrial communication link, we employ Nakagami-m fading channels to analyze the performance of terrestrial users. The PDF of H_{Rj} is given as

$$f_{|H_{Rj}|^2}(x) = \left(\frac{m_{Rj}}{\Omega_{Rj}}\right)^{m_{Rj}} \frac{x^{m_{Rj}-1}}{\Gamma(m_{Rj})} e^{-\frac{m_{Rj}x}{\Omega_{Rj}}}, \tag{10}$$

where $j \in \{C, D\}$, m_{Rj} is fading severity, Ω_{Rj} is average power, $\Gamma(\cdot)$ denotes the complete gamma function. Therefore, the corresponding CDF can be given by

$$F_{|H_{Rj}|^2}(x) = \frac{1}{\Gamma(m_{Rj})} \Upsilon\left(m_{Rj}, \frac{m_{Rj}x}{\Omega_{Rj}}\right), \tag{11}$$

where $\Upsilon(\cdot)$ denotes the lower incomplete gamma function.

III. PERFORMANCE ANALYSIS

In this section, we conduct the performance analysis for HSTNs in the absence of a DC link between S and D.

A. OUTAGE PROBABILITY

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

$$P_{out}(\gamma_{th}) = \Pr(\gamma < \gamma_{th}) = F_{\gamma}(\gamma_{th}), \tag{12}$$

where $F_{\gamma}(\cdot)$ denotes the CDF of γ.

According to the attribute of NOMA scheme, the power allocation profile and SIC implementation are decision on the instantaneous channel conditions. Thus, the OP of DF protocols for the PU can be given as

$$P_{out\_SD}(\gamma_{th}) = 1 - [1 - F_{SR}(\gamma_{th})](1 - F_{RD}(\gamma_{th})), \tag{13}$$

where $F_{RD}(\gamma_{th})$ can be calculated by (14) and (15), as shown at the bottom of this page, where $u_1 = \gamma_{th}/(1-\alpha)\bar{\gamma}_{RD}$, $u_2 = \gamma_{th}/(\alpha\bar{\gamma}_{RD} - (1-\alpha)\gamma_{th}\bar{\gamma}_{RD})$, $v_C = m_{RC}/\Omega_{RC}$, $v_D = m_{RD}/\Omega_{RD}$, $v_1 = v_C t + v_D$, $t = \bar{\gamma}_{RD}/\bar{\gamma}_{RC}$, and $a_D = (m_{RD}/\Omega_{RD})^{m_{RD}}\Gamma(m_{RD})^{-1}$, and the detail derivation is sh.

In addition, the OP of the SU can be calculated by (16) and (17), as shown at the bottom of this page, where $v_2 = v_D/t + v_C$, $u'_1 = \gamma_{th}/(1-\alpha)\bar{\gamma}_{RC}$, $u'_2 = \gamma_{th}/(\alpha\bar{\gamma}_{RC} - (1-\alpha)\gamma_{th}\bar{\gamma}_{RC})$, and $a_C = (m_{RC}/\Omega_{RC})^{m_{RC}}\Gamma(m_{RC})^{-1}$.

B. APPROXIMATED ERGODIC CAPACITY

The ergodic capacity is defined as the expected value of the instantaneous end-to-end mutual information [5]. The ergodic capacity of the PU and the SU are given by (18) and (19), as shown at the bottom of this page, respectively.

$$\begin{aligned} P_{out\_RD}(\gamma_{th}) &= F_{RD}(\gamma_{th}) = \Pr\left(|\bar{\gamma}_{RD}\rho_{RD}| \le |\bar{\gamma}_{RC}\rho_{RC}|, \gamma_{1,D} < \gamma_{th}\right) + \Pr\left(|\bar{\gamma}_{RD}\rho_{RD}| > |\bar{\gamma}_{RC}\rho_{RC}|, \gamma_{2,D} < \gamma_{th}\right) \\ &= F_{strong} + F_{H_{RD}^2}(u_1) - a_D \sum_{n=0}^{m_{RC}-1} \frac{1}{n!} t^n v_1^{-n-m_{RD}} \Upsilon(n + m_{RD}, v_1 u_1) \end{aligned} \tag{14}$$

$$F_{strong} = \begin{cases} a_D \sum_{n=0}^{m_{RC}-1} \frac{1}{n!} t^n v_1^{-n-m_{RD}} \Gamma(n + m_{RD}) & \alpha - (1-\alpha)\gamma_{th} \le 0 \\ a_D \sum_{n=0}^{m_{RC}-1} \frac{1}{n!} t^n v_1^{-n-m_{RD}} \Upsilon(n + m_{RD}, v u_2) & \alpha - (1-\alpha)\gamma_{th} > 0 \end{cases} \tag{15}$$

$$\begin{aligned} P_{out\_RC}(\gamma_{th}) &= F_{RC}(\gamma_{th}) = \Pr\left(|\bar{\gamma}_{RD}\rho_{RD}| \le |\bar{\gamma}_{RC}\rho_{RC}|, \gamma_{2,C} < \gamma_{th}\right) + \Pr\left(|\bar{\gamma}_{RD}\rho_{RD}| > |\bar{\gamma}_{RC}\rho_{RC}|, \gamma_{1,C} < \gamma_{th}\right) \\ &= F_{H_{RC}^2}(u'_1) - a_C \sum_{n=0}^{m_{RD}-1} \frac{1}{n!} t^{-n} v_2^{-n-m_{RD}} \Upsilon\left(n + m_{RC}, v u'_1\right) + F_{weak} \end{aligned} \tag{16}$$

$$F_{weak} = \begin{cases} a_C \sum_{n=0}^{m_{RD}-1} \frac{1}{n!} t^{-n} v_2^{-n-m_{RD}} \Gamma(n + m_{RC}) & \alpha - (1-\alpha)\gamma_{th} \le 0 \\ a_C \sum_{n=0}^{m_{RD}-1} \frac{1}{n!} t^{-n} v_2^{-n-m_{RD}} \Upsilon\left(n + m_{RC}, v_2 u'_2\right) & \alpha - (1-\alpha)\gamma_{th} > 0 \end{cases} \tag{17}$$

$$\begin{aligned} C_{pri} &= \min\left(E\left[\log_2(1+\gamma_{RD})\right], E\left[\ln(1+\gamma_{SR})\right]\right) \\ &= \log_2(e) \min\left\{E\left[\ln\left(1+\gamma_{1,D}\right)\left|_{\bar{\gamma}_{RD}\rho_{RD} \le \bar{\gamma}_{RC}\rho_{RC}} + \ln\left(1+\gamma_{2,D}\right)\right|_{\bar{\gamma}_{RD}\rho_{RD} > \bar{\gamma}_{RC}\rho_{RC}}\right], E\left[\ln(1+\gamma_{SR})\right]\right\} \end{aligned} \tag{18}$$

$$C_{Sec} = E\left[\log_2(1+\gamma_{RC})\right] = E\left[\ln\left(1+\gamma_{2,C}\right)\left|_{\bar{\gamma}_{RD}\rho_{RD} \le \bar{\gamma}_{RC}\rho_{RC}} + \ln\left(1+\gamma_{1,C}\right)\right|_{\bar{\gamma}_{RD}\rho_{RD} > \bar{\gamma}_{RC}\rho_{RC}}\right] \tag{19}$$

$$E\left(\gamma_{1,D}^n\left|_{\bar{\gamma}_{RD}\rho_{RD} \le \bar{\gamma}_{RC}\rho_{RC}}\right.\right) = a_D\left(\frac{\alpha}{1-\alpha}\right)^n \sum_{i=0}^{m_{RC}-1} \frac{t^i}{i!} \sum_{k=0}^{+\infty} \frac{(-n-k+1)_k}{k!} u_3^{-k} v_1^{k-i-m_{RD}} \Gamma(m_{RD} + i - k) \tag{21}$$

$$E\left(\gamma_{2,C}^n\left|_{\bar{\gamma}_{RD}\rho_{RD} \le \bar{\gamma}_{RC}\rho_{RC}}\right.\right) = u_3^n v_C^{-n-m_{RC}} \Gamma(n + m_{RC}) - a_C u_3^n \sum_{i=0}^{m_{RD}-1} \frac{t^{-i}}{i!} v_2^{-n-i-m_{RD}} \Gamma(m_{RD} + i + n) \tag{22}$$

$$E\left(\gamma_{1,C}^n\left|_{\bar{\gamma}_{RD}\rho_{RD} > \bar{\gamma}_{RC}\rho_{RC}}\right.\right) = a_C\left(\frac{\alpha}{1-\alpha}\right)^n \sum_{i=0}^{m_{RD}-1} \frac{t^{-i}}{i!} \sum_{k=0}^{+\infty} \frac{(-n-k+1)_k}{k!} u_4^{-k} v_2^{k-i-m_{RC}} \Gamma(m_{RC} + i - k) \tag{23}$$

$$E\left(\gamma_{2,D}^n\left|_{\bar{\gamma}_{RD}\rho_{RD} > \bar{\gamma}_{RC}\rho_{RC}}\right.\right) = u_4^n v_D^{-n-m_{RD}} \Gamma(n + m_{RD}) - a_D u_4^n \sum_{i=0}^{m_{RD}-1} \frac{t^i}{i!} v_1^{-n-i-m_{RC}} \Gamma(m_{RC} + i + n) \tag{24}$$

TABLE 1. **Satellite channel parameters.**

Parameters	b	m	Ω
Frequent heavy shadowing	0.063	1	8.97×10^{-4}
Average shadowing	0.126	10	0.835
Infrequent light shadowing	0.158	20	1.29

The analytical approximation [20] of $E[\ln(1+x)]$ is expressed as

$$E[\ln(1+x)] \approx \ln(1+E(x)) - \frac{E(x^2) - E^2(x)}{2(1+E(x))^2}. \quad (20)$$

In order to get approximated ergodic capacity, the $n-th$ order moments of the SINR can be calculated by (21)-(24), as shown at the bottom of the previous page,

$$E\left(\gamma_{SR}^{n}\right) = \frac{\alpha_{SR}}{\Gamma(m_{SR})\beta_{SR}^{n+1}} G_{2,2}^{1,2}\left[\frac{-\delta_{SR}}{\beta_{SR}} \middle| \begin{matrix} -n, 1-m_{SR} \\ 0, 0 \end{matrix}\right], \quad (25)$$

where $n \in \{1, 2\}$, $u_3 = (1-\alpha)\bar{\gamma}_{RD}$, $u_4 = (1-\alpha)\bar{\gamma}_{RC}$, and $G_{2,2}^{1,2}[\cdot]$ is the Meijer-G functions [36, 7.813.1]. Substituting (21)-(24) into (17)-(18), the approximated ergodic capacity of the considered system can be obtained.

C. FAIRNESS COMPARISON

Here, we analyze the fairness by using JFI, which is defined by [36]

$$J = \frac{\left(\sum_{i=1}^{N} R_i\right)^2}{N\sum_{i=1}^{N}(R_i)^2}, \quad (26)$$

where R_i denotes the rate of user i. It is noted that JFI translates a resource allocation vector $\{R_1, R_2, \cdots, R_N\}$ into a score in the interval of $[1/N, 1]$. A higher JFI indicates a fairer resource allocation scheme.

IV. SIMULATION RESULTS

In this section, we apply the representative simulation to validate the theoretical results of the closed-form express on above and study the impact of some key parameters on the performance of cooperative spectrum sharing in HSTNs. Besides, all Monte Carlo simulation results are obtained with an average calculation of 10^5 blocks.

Fig. 2 shows the OP of the PU versus different average SNR, where $\bar{\gamma}_{SR} = \bar{\gamma}_{RD} = \bar{\gamma}$. The link among satellite and secondary relay undergoes infrequent light shadowing (ILS) ($b_{SR} = 0.158, m_{SR} = 20, \Omega_{SR} = 1.29$), the channel coefficients of terrestrial link are $m_{RC} = m_{RD} = 2$, $\Omega_{RC} = \Omega_{RD} = 1$ [8]. Furthermore, we assume the direct link undergoes frequent heavy shadowing (FHS) ($b_{SD} = 0.063, m_{SD} = 1, \Omega_{SD} = 8.97e-4$) for comparison. The decode threshold is set as $\gamma_{th} = 5dB$. The analytical curve can be calculated by the closed-form expression in this scenario. The Monte Carlo curves are calculated directly by the OP definition by the MATLAB software. Those Monte Carlo simulation OP curves excellently agree with analytical results across the entire average SNR range. Comparing with the scenario of heavy shadowing in the direct link, the OP of the PU is significantly reduced by adopting the NOMA-based cooperative spectrum sharing scheme. In addition, it is obvious that the smaller the power allocation factor α, ranging (0.5, 1), the lower the OP under the premise of satisfying the demodulation threshold γ_{th}.

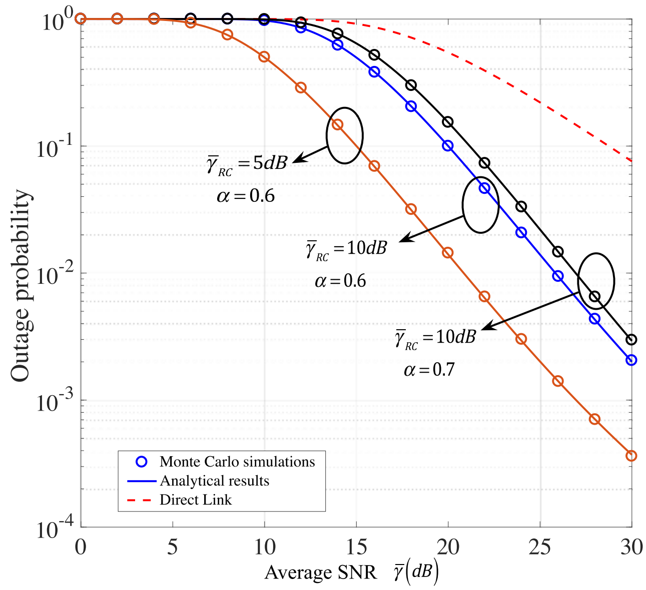

FIGURE 2. **The OP of the PU versus different average SNR.**

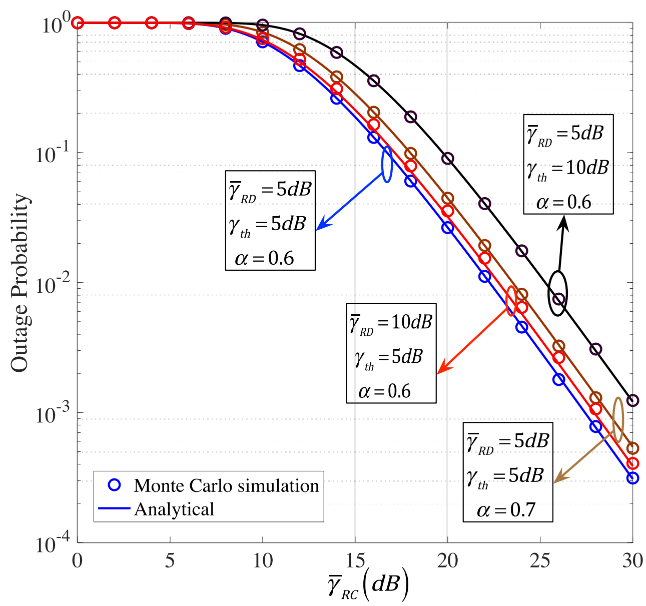

FIGURE 3. **The OP of the SU versus different average SNR.**

Fig. 3 illustrates the OP of the SU for different $\bar{\gamma}_{RC}$. It is obvious that the SNR of the second temporal phase and α of NOMA are related to the OP performance by contrast with Fig. 2 and Fig. 3. The higher the decision threshold γ_{th}, the worse the OP by giving the $\bar{\gamma}_{RC}$ and $\bar{\gamma}_{RD}$. Besides, the

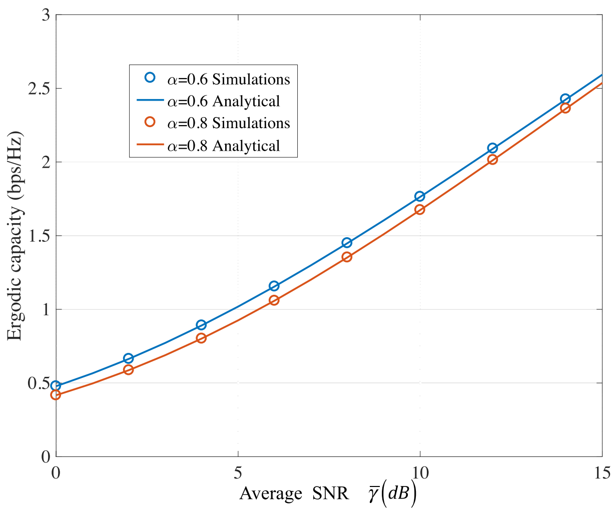

FIGURE 4. **The ergodic capacity of the PU on cooperative spectrum sharing in HSTNs.**

power allocation factor α influences the OP of the SU with the same trend as the PU.

Fig. 4 depicts ergodic capacity performance of the PU for the considered system by given the average SNR $\bar{\gamma}_{SR} = \bar{\gamma}_{RC} = \bar{\gamma}_{RD} = \bar{\gamma}$, where the small scale of channel fading coefficients are the same as OP simulations in Fig. 2. The Monte Carlo simulation ergodic capacity curves excellently agree with analytical results across the entire average SNR range. It can be seen that the smaller the power allocation factor α, the higher the ergodic capacity. The reason is that the strong user is allocated more power.

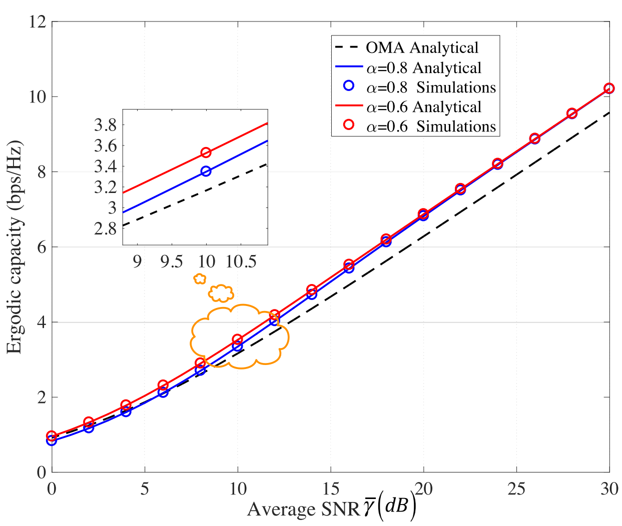

FIGURE 5. **The sum ergodic capacity of the PU and the SU on cooperative spectrum sharing in HSTNs.**

The sum ergodic capacity performance for NOMA and OMA are shown in Fig. 5. As we see, the sum ergodic capacity with the NOMA scheme is superior to those with the conventional OMA scheme, which proclaims that the NOMA scheme achieves higher ergodic capacity or resource utilization with the same amount of transmitting power. The NOMA power split factor α slightly influences the low SNR. Besides, the ergodic capacity of the PU and the SU is almost the same, which indicates the fairness of the NOMA scheme on cooperative spectrum sharing in HSTNs.

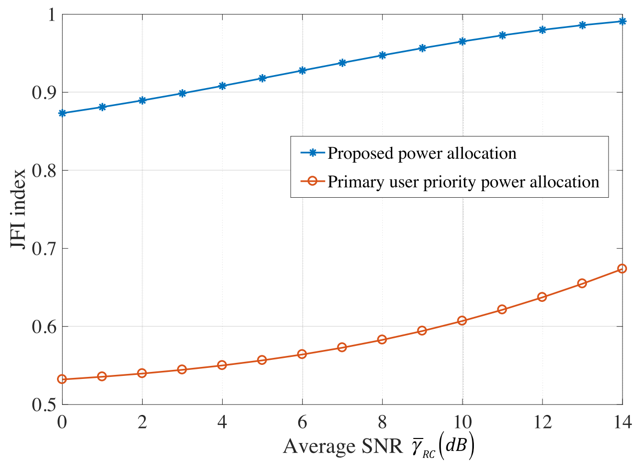

FIGURE 6. **The JFI of the PU and the SU on cooperative spectrum sharing in HSTNs.**

In order to quantify the user fairness, we apply JFI between the PU and the SU. The JFI for proposed power allocation and the PU prior power allocation scheme is shown in Fig. 6, where the $\bar{\gamma}_{RD} = \bar{\gamma}_{RC} + 3\,(dB)$. The small scale of fading coefficients are set the same parameters as Fig. 2. It is obvious that the proposed NOMA power allocation scheme obtains better fairness. After solving the problem of fairness, the primary network and the secondary network will have a stronger willingness to cooperate.

V. CONCLUSION

In this paper, a NOMA-based on cooperative spectrum sharing in HSTNs is proposed to improve the spectrum utilization and tackle the fairness issue. Specifically, DF relay protocols for the PU are first applied to prevent the noise of the first temporal phase from further amplification. Then, in the second temporal phase, the NOMA-based power allocation profile is determined by instantaneous channel conditions to avoid the fairness issue by overlay paradigm. Moreover, closed-form OP and approximated ergodic capacity expressions for both PU and SU are derived. The impact of key parameters on the NOMA system is analyzed. Simulation results show that the proposed NOMA scheme is superior to conventional OMA.

APPENDIXES

The detail derivation processes of outage probability of link between relay and PU $F_{RD}(\gamma_{th})$ is given by (27), as shown at the top of the next page, where derivation of J_1 and J_2 is given by (28) and (29), as shown at the top of the next page. The equation (15), (21)-(24) can be formulated similarly.

$$F_{RD}(\gamma_{th}) = \underbrace{\Pr\left(|\bar{\gamma}_{RD}\rho_{RD}| \le |\bar{\gamma}_{RC}\rho_{RC}|, \gamma_{1,D} < \gamma_{th}\right)}_{J_1} + \underbrace{\Pr\left(|\bar{\gamma}_{RD}\rho_{RD}| > |\bar{\gamma}_{RC}\rho_{RC}|, \gamma_{2,D} < \gamma_{th}\right)}_{J_2} \tag{27}$$

$$\begin{aligned}
J_1 &= \begin{cases} \int_0^{\gamma_{th}} \int_0^{\frac{\bar{\gamma}_{RD}\rho_{RD}}{\bar{\gamma}_{RC}}} f_{H_{RD}^2}(\rho_{RD}) f_{H_{RC}^2}(\rho_{RC})\, d\rho_{RC}\, d\rho_{RD} & \alpha - (1-\alpha)\gamma_{th} \le 0 \\ \int_0^{\frac{\gamma_{th}}{[\alpha-(1-\alpha)\gamma_{th}]\bar{\gamma}_{RD}}} \int_0^{\frac{\bar{\gamma}_{RD}\rho_{RD}}{\bar{\gamma}_{RC}}} f_{H_{RD}^2}(\rho_{RD}) f_{H_{RC}^2}(\rho_{RC})\, d\rho_{RC}\, d\rho_{RD} & \alpha - (1-\alpha)\gamma_{th} > 0 \end{cases} \\
&= \begin{cases} \int_0^{\gamma_{th}} F_{H_{RC}^2}\left(\frac{\bar{\gamma}_{RD}\rho_{RD}}{\bar{\gamma}_{RC}}\right) f_{H_{RD}^2}(\rho_{RD})\, d\rho_{RD} & \alpha - (1-\alpha)\gamma_{th} \le 0 \\ \int_0^{\frac{\gamma_{th}}{[\alpha-(1-\alpha)\gamma_{th}]\bar{\gamma}_{RD}}} F_{H_{RC}^2}\left(\frac{\bar{\gamma}_{RD}\rho_{RD}}{\bar{\gamma}_{RC}}\right) f_{H_{RD}^2}(\rho_{RD})\, d\rho_{RD} & \alpha - (1-\alpha)\gamma_{th} > 0 \end{cases} \\
&= \begin{cases} a_D \sum_{n=0}^{m_{RC}-1} \frac{1}{n!} t^n v_1^{-n-m_{RD}} \Gamma(n+m_{RD}) & \alpha - (1-\alpha)\gamma_{th} \le 0 \\ a_D \sum_{n=0}^{m_{RC}-1} \frac{1}{n!} t^n v_1^{-n-m_{RD}} \Gamma(n+m_{RD}, vu_2) & \alpha - (1-\alpha)\gamma_{th} > 0 \end{cases}
\end{aligned} \tag{28}$$

$$\begin{aligned}
J_2 &= \int_0^{\frac{\gamma_{th}}{(1-\alpha)\bar{\gamma}_{RD}}} \int_{\frac{\bar{\gamma}_{RD}\rho_{RD}}{\bar{\gamma}_{RC}}}^{+\infty} f_{H_{RD}^2}(\rho_{RD}) f_{H_{RC}^2}(\rho_{RC})\, d\rho_{RC}\, d\rho_{RD} = \int_0^{\frac{\gamma_{th}}{(1-\alpha)\bar{\gamma}_{RD}}} \left[1 - F_{H_{RC}^2}\left(\frac{\bar{\gamma}_{RD}\rho_{RD}}{\bar{\gamma}_{RC}}\right)\right] f_{H_{RD}^2}(\rho_{RD})\, d\rho_{RD} \\
&= F_{H_{RD}^2}(u_1) - a_D \sum_{n=0}^{m_{RC}-1} \frac{1}{n!} t^n v_1^{-n-m_{RD}} \Gamma(n+m_{RD}, v_1 u_1)
\end{aligned} \tag{29}$$

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