The Performance of Cooperative-NOMA in Cognitive Hybrid Satellite Networks

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***Abstract*—Integrating cognitive radio (CR) technology into satellite communication represents an effective approach to enhance the throughput of satellite systems. However, the use of orthogonal multiple access (OMA) in traditional satellite-based CR systems has posed limitations on satellite system development. This paper focuses on power-domain non-orthogonal multiple access (NOMA for simplicity), which has the potential to increase the number of access users and improve user communication capacity within the cognitive network. The integration of NOMA into CR networks holds immense potential for improving spectral efficiency and accommodating a larger user base. Notably, NOMA leverages successive interference cancellation (SIC) to decode information from the far user (FU) by the near user (NU), enabling the NU to potentially relay data and assist the FU. To fully harness this characteristic, we propose the utilization of cooperative NOMA (C-NOMA) to enhance system performance while ensuring the quality of service (QoS) for the FU. In evaluating the performance of the proposed system, we conduct an analysis of the outage probability and bit error rate (BER). This analysis provides valuable insights into the effectiveness of integrating CR and C-NOMA to enhance the reliability and quality of satellite communication.**

Keywords—Cooperative non-orthogonal multiple access(C-NOMA), Hybrid satellite networks, underlay Cognitive Radio(CR), Outage Probability, BER

I. Introduction

Satellite networks are gaining significant attention as a complement to 5G communication. The rise of multimedia services in satellite communication has given rise to a new trend known as hybrid satellite communication. Various satellites in different orbits can now provide a diverse range of services. For instance, Geostationary Earth Orbit (GEO) satellites excel at delivering seamless services, while Low Earth Orbit (LEO) satellites are better suited for applications that require low latency. [1][2].

Nevertheless, the scarcity of available frequency resources presents a challenge when it comes to accommodating an increasing number of users within the limited bandwidth. Moreover, effectively managing interference between users and satellites in hybrid satellite networks becomes a critical consideration as the number of terminals continues to grow. Cognitive radio (CR) has emerged as a solution that empowers secondary networks to access the licensed frequency bands of primary networks without causing harmful interference [3]. Incorporating cognitive radio into satellite communications can effectively mitigate interference [4].

In a hybrid cognitive satellite network, the LEO satellite functions as the secondary system, while the GEO satellite operates as the primary system. Historically, orthogonal multiple access (OMA) schemes have predominantly been employed in hybrid cognitive satellite networks [5]. However, OMA can only accommodate one user within a particular resource block, resulting in low spectrum utilization efficiency and restricting the number of users. This limitation has impeded the progress of satellite networks [6].

Recently, a novel multiple access scheme called power-domain non-orthogonal multiple access (NOMA) has been introduced in satellite networks [7]. NOMA allows multiple users to be simultaneously served within the same frequency/time/code resource block but at varying power levels, significantly enhancing spectrum efficiency. The NOMA system relies on two key operations for its functionality: superposition coding at the transmitter side and successive interference cancellation (SIC) at the receiver side. SIC is an iterative algorithm wherein data is decoded in decreasing power levels. The user with the highest power level has its data decoded first, followed by the user with the next highest power level. This implies that the user with lower power is granted access to the data of the user with higher power. We refer to the user with lower power as the near user (NU) and the user with higher power as the far user (FU). Consequently, the NU can potentially relay information to assist the FU, introducing the concept of cooperative NOMA (C-NOMA). C-NOMA provides diversity for the FU and reduces its outage probability. Several studies have already explored C-NOMA with cognitive aspects in hybrid satellite networks.

Existing literature has explored the application of the NOMA scheme in satellite networks to enhance spectral efficiency [8]. In [9], the authors introduced a C-NOMA scheme in the satellite downlink scenario and derived a closed-form expression for the outage probability to validate the effectiveness of the proposed system model. To further boost spectral efficiency, [10] investigated NOMA-based cognitive radio in terrestrial networks. Furthermore, in [11], the C-NOMA scheme was introduced in a two-layer GEO/LEO satellite network, and the performance of the proposed system was thoroughly analyzed. Numerous studies have concentrated on integrating C-NOMA with cognitive aspects in hybrid satellite networks.

Motivated by the aforementioned observations, we propose introducing the C-NOMA scheme in cognitive hybrid satellite networks and investigating its performance.

The remainder of this paper is organized as follows: Section II describes the system model. Section III analyzes the performance of C-NOMA with cognitive aspects in hybrid satellite networks, including outage probability (OP) and bit error rate (BER). Section IV presents and analyzes the simulation results. Finally, Section V concludes the paper.

II. System Model

As depicted in Fig. 1, our investigation focuses on a hybrid satellite system in the downlink direction, comprising a GEO satellite, a LEO satellite, and terrestrial users. The GEO satellite functions as the primary system, while the LEO satellite operates as the secondary system. To enhance performance of the system and guarantee the quality of service (QoS) of the FU, we employ the C-NOMA scheme in the LEO system. Simultaneously, the primary GEO system utilizes the Time Division Multiple Access (TDMA) technique to establish communication with terrestrial users. For the purpose of our analysis, we concentrate solely on the system within the coverage of a single beam emitted by the GEO satellite. It is worth noting that the terrestrial nodes are equipped with a single quasi-omni antenna, allowing them to communicate concurrently with both the satellite and other terrestrial nodes [12]. To simplify the evaluation process, we consider a scenario where two LEO users are selected to form a NOMA group. The NU is positioned at the center of the LEO's spot beam, benefiting from a stronger channel, while the FU is located at the edge of the spot beam, experiencing weaker channel conditions. Although we focus on a two-user scenario, it is crucial to emphasize that the proposed system can be extended to accommodate more than two users. It is worth mentioning that the computational complexity of the NOMA scheme increases exponentially as the number of users within a NOMA group grows. Therefore, to maintain simplicity, we limit our analysis to the case of two LEO users in a NOMA group. However, we recognize the potential for expanding this framework to encompass scenarios involving a greater number of users.

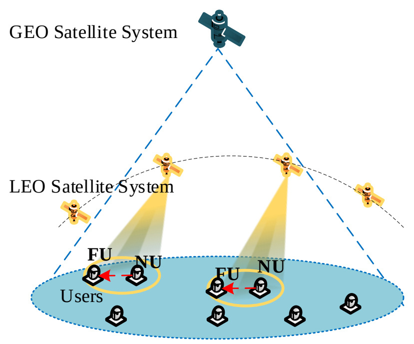

Fig. 1. System model of C-NOMA in CR hybrid satellite network

A. Channel Model

In this section, we will give the exact channel coefficient expression of the satellite-terrestrial link. The link between GEO and users is assumed to be quasi-static. And due to the high mobility of the LEO satellite, we have to consider the doppler shift effect in the channel model of LEO.

We denote L, G, k as the LEO satellite, the GEO satellite and the ground users, respectively. Then the channel coefficient can be expressed as

$$H_k^L(t) = h_k^L(t) \cdot e^{j2\pi f_d(t)t} \quad (1)$$

where $f_d(t)$ is the Doppler shift, and the $h_k^L(t)$ is the channel model which both considers the large scale fading and the small scale fading, the specific expression is shown as follows

$$h_k^L(t) = \sqrt{G_t G_{r,k} L_f(t)} a_k \quad (2)$$

in which G_t is the antenna gain for the transmitter, $G_{r,k}$ is the antenna gain for the k-th receiver, $L_f(t) = \frac{c}{4\pi f_c d_k(t)}$ is the path loss, and the a_k is the small scale fading model that obeys the Rician distribution, the probability of density (PDF) function of a_k is given by

$$f_{a_k}(x) = \frac{x}{\sigma^2} e^{\frac{x^2+c^2}{2\sigma^2}} I_0\left(\frac{xc}{\sigma^2}\right) \quad (3)$$

Referring to [13], the $d_k(t)$ in (2)can be expressed as

$$d_k(t) = \sqrt{r_E^2 + (r_E + h)^2 - 2r_E(r_E + h)\cos(\psi(t) - \psi(t_0))} \quad (4)$$

where r_E is the radius of the earth, h is the orbital altitude for the LEO satellite, and the $\psi(t) - \psi(t_0)$ is the anglebetween the line of the LEO satellite to the center of the earth and the line of the ground user to the center of the earth.

B. Transmission Model

There are two consecutive phases in C-NOMA. Let's call the first phase as direct transmission phase and the second phase as relaying phase.

1) Direct Transmission Phase

According to the NOMA scheme in a downlink, the LEO satellite directly sends signals intended for the NU and the FU. For simplicity, we donate the NU and the FU as user 1 and user 2, respectively. The transmitted signal at the LEO satellite is expressed as

$$\begin{aligned} x^L &= \sqrt{\alpha_1 P_L} x_1 + \sqrt{\alpha_2 P_L} x_2 \\ &= \sqrt{\varepsilon_1} x_1 + \sqrt{\varepsilon_2} x_2 \end{aligned} \quad (5)$$

where P_L is transmit power of the LEO satellite, according to the CR principle, the LEO satellite needs to be coordinated to avoid causing harmful interference to the GEO satellite, so the transmit power at the LEO satellite P_L should satisfy $P_L \le \frac{Q}{|g_i^L|^2}$ [14], which g_i^L is the interference from the LEO satellite to the GEO users, Q is the interference threshold of the GEO users, and α_1, α_2 are the power allocation factor of user 1 and user 2, respectively, with the constraint that $\alpha_1 + \alpha_2 = 1$. x_1 and x_2 are normalized modulated symbols for user 1 and user 2, respectively (e.g., $x_1, x_2 \in \{-1,1\}$ for BPSK modulation).

In existing literature, it is often assumed that all users utilize the same modulation mode, which is not practical since different users have varying QoS requirements. As highlighted in [15], user 1 may experience more challenging channel conditions compared to user 2, leading to the adoption of BPSK for user 2, while user 1 is assigned QPSK for the sake of simplicity in describing the detection and decision process.

By considering channel fading and Doppler shift [16], the observation of the LEO user m, $m=1,2$ can be stated as

$$\begin{aligned} y_m(t) &= h_m^L(t)\cdot e^{j2\pi f_d(t)t}\cdot x^L+\sqrt{P_G}g_m^G x^G+n_m \\ &= H_m^L(t)\cdot x^L+\sqrt{P_G}g_m^G x^G+n_m \end{aligned} \tag{6}$$

where $h_m^L(t)$ is the channel coefficient between the LEO satellite and LEO user m, $m=1,2$, $f_d(t)$ is the Doppler shift and t is the transmission time, P_G is transmit power of GEO satellite, g_m^G is the channel coefficient between the GEO satellite and LEO user m, x^G is the signal that the GEO satellite transmitted to the intended user, and n_m denotes the additive white Gaussian noise (AWGN) with $E\left[|n_m|^2\right]=N_0$.

In the direct transmission phase, user 2 just performs direct decoding. So, the signal-to-noise plus interference ratio (SINR) of user 2 can be expressed as

$$SINR_{2,1}(t)=\frac{\varepsilon_2\,|H_2^L(t)|^2}{\varepsilon_1\,|H_2^L(t)|^2+P_G\,|g_2^G|^2+N_0} \tag{7}$$

User 1 performs SIC to decode user 2's data first, and then proceeds to decode its own data. The SINR of user 1 to decode user 2 signal (before SIC) is

$$SINR_{1\to 2}(t)=\frac{\varepsilon_2\,|H_1^L(t)|^2}{\varepsilon_1\,|H_1^L(t)|^2+P_G\,|g_1^G|^2+N_0} \tag{8}$$

It's obvious that $SINR_{1\to 2}(t)\ge SINR_{2,1}(t)$ since the assumption that a better channel gain to interference plus ratio is required at user 1. In other words, the signal of user 2 can be removed successfully at user 1.

After the cancellation of user 2's signal using perfect SIC, the SINR of user 1 for decoding its own signal is

$$SINR_1(t)=\frac{\varepsilon_1\,|H_1^L(t)|^2}{P_G\,|g_1^G|^2+N_0} \tag{9}$$

Thus the achievable data rate at user 1 and user 2 are,

$$\begin{aligned} R_1(t) &= \frac{1}{2}\log_2(1+SINR_1(t)) \\ R_{2,1}(t) &= \frac{1}{2}\log_2(1+SINR_{2,1}(t)) \end{aligned} \tag{10}$$

2) Relaying Phase

As we saw, user 1 already has user 2's data because he decoded it in the previous phase. In the relaying phase, user 1 just transmits this data to user 2 adopting the DF protocol [17]. The achievable rate of user 2 is

$$SINR_{2,2}(t)=\frac{P\,|h_{1\to 2}|^2}{N_0} \tag{11}$$

Here, $h_{1\to 2}$ is the channel between user 1 and user 2. The terrestrial link is modeled as independent and identically distributed (i.i.d) Nakagami-m fading distribution [12]. Note that, the case $m=1$ is equivalent to the Rayleigh fading channel model.

At the end of the two phases, the FU has two copies of the same information received through two different channels. The FU can now use the diversity combining technique. In this article, we use selection combining to choose the copy which was received with high SNR. Thus, the achievable rate for user 2 would be,

$$R_2(t)=\frac{1}{2}\log_2(1+\max\{SINR_{2,1}(t),SINR_{2,2}(t)\}) \tag{12}$$

Thus, the sum rate of the two users can be written as

$$R_s(t)=R_1(t)+R_2(t) \tag{13}$$

III. The Performance Analysis

In this section, we will derive the analytical expressions for outage probability (OP) and BER of the proposed networks.

A. Outage Probability

The outage happens at the ground users when the received SINR falls below a predefined threshold, i.e. $SINR_i\le SINR_{th}$. Provided that the SINR threshold of user 1 and user 2 as $SINR_{th1}, SINR_{th2}$, respectively. Thus the OP can be expressed as [13]

$$P_{out}(SINR_{th})=\Pr\{SINR_i(t)\le SINR_{th}\} \tag{14}$$

For the sake of clarity in expression, let's define the target SINR for two users as $SINR_{thi}\overset{\Delta}{=}2^{R_i}-1$, where R_i represents the target rate of user i, $i=1,2$.

The outage for user 1 occurs when user 1 is unable to decode x1 in the first phase, whereas the outage for user 2 occurs when, in the second phase, user 2 cannot decode x2 from the combined signal. Based on this, we can proceed with the subsequent outage probability analysis:

(1) Outage Probability at user1

The outage probability for user 1 is:

$$\begin{aligned} P_{\text{out},1} &= \Pr\left(SINR_{1\to 2}<SINR_{th2}, SINR_1<SINR_{th_1}\right) \\ &\quad+\Pr\left(SINR_{1\to 2}\geqslant SINR_{th2}, SINR_1<SINR_{th_1}\right) \end{aligned} \tag{15}$$

(2) Outage Probability at user2

The outage probability for user 2 is:

$$\begin{aligned} P_{\text{out},2} &= \Pr\left(SINR_{1\to 2}<SINR_{th2}\right) \\ &\quad+\Pr\left(SINR_{1\to 2}\geqslant SINR_{th2}, SINR_1<SINR_{th_1}\right) \\ &\quad\times\Pr\left(SINR_2<SINR_{th2}\right) \end{aligned} \tag{16}$$

B. The Exact BER Expression

The received signal constellation at users is given in Fig.2. Referring from [15], we adopt the symmetric coding scheme for the low power user to get better performance. In Fig. 2, user 1 and user 2 symbols are shown in the form of $[x_{1,0}x_{1,1},x_2]$.

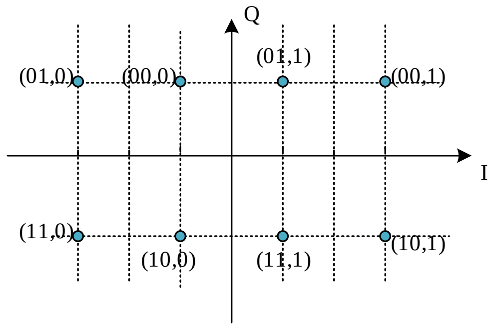

Fig. 2. Received signal of the NOMA users

We assume all symbols have equal prior probability, then the error probability at user 2 can be defined as

$$\begin{aligned} P_2(e) &= \frac{1}{4}\Bigg[P_r\left(n_I \ge \left(\sqrt{\frac{\varepsilon_1}{2}}+\sqrt{\varepsilon_2}\right)\left|H_2^L(t)\right|\right)+P_r\left(n_I \ge \left(-\sqrt{\frac{\varepsilon_1}{2}}+\sqrt{\varepsilon_2}\right)\left|H_2^L(t)\right|\right)+ \\ &\quad P_r\left(n_I \le \left(\sqrt{\frac{\varepsilon_1}{2}}-\sqrt{\varepsilon_2}\right)\left|H_2^L(t)\right|\right)+P_r\left(n_I \le -\left(\sqrt{\frac{\varepsilon_1}{2}}+\sqrt{\varepsilon_2}\right)\left|H_2^L(t)\right|\right)\Bigg] \\ &= \frac{1}{2}\Bigg[P_r\left(n_I \ge \left(\sqrt{\frac{\varepsilon_1}{2}}+\sqrt{\varepsilon_2}\right)\left|H_2^L(t)\right|\right)+P_r\left(n_I \ge \left(-\sqrt{\frac{\varepsilon_1}{2}}+\sqrt{\varepsilon_2}\right)\left|H_2^L(t)\right|\right)\Bigg] \end{aligned} \quad (17)$$

With the aid of [16], the error probability given in (14) can be redefined as

$$P_2(e)=\frac{1}{2}\left[Q\left(\frac{\left(\sqrt{\frac{\varepsilon_1}{2}}+\sqrt{\varepsilon_2}\right)\left|H_2^L(t)\right|}{\sqrt{N_0/2}}\right)+Q\left(\frac{\left(-\sqrt{\frac{\varepsilon_1}{2}}+\sqrt{\varepsilon_2}\right)\left|H_2^L(t)\right|}{\sqrt{N_0/2}}\right)\right] \quad (18)$$

For sake of mathematical simplicity, the expression of $Q(\cdot)$ in (18) can be defined as

$$\begin{aligned} \overline{\gamma_A} &= \frac{\left(\sqrt{\varepsilon_1}+\sqrt{2\varepsilon_2}\right)^2}{N_0}E\left[\left|H_2^L(t)\right|^2\right] \\ \overline{\gamma_B} &= \frac{\left(-\sqrt{\varepsilon_1}+\sqrt{2\varepsilon_2}\right)^2}{N_0}E\left[\left|H_2^L(t)\right|^2\right] \end{aligned} \quad (19)$$

And according to [15], the average error probability of user 2 becomes

$$\overline{P_2(e)}=\frac{1}{4}\left(2-\sqrt{\frac{\overline{\gamma_A}}{2+\overline{\gamma_A}}}-\sqrt{\frac{\overline{\gamma_B}}{2+\overline{\gamma_B}}}\right) \quad (20)$$

Because of the error propagation of SIC, the error probability of user 1 has to consider the two cases that user 1 is detected correctly and user 1 is detected erroneously. Thus, it can be written as

$$P_1(e)=P_1(e\,|\,\text{correct}_2)+P_1(e\,|\,\text{error}_2) \quad (21)$$

Similar to the calculation process of user 1 and to avoid making the paper difficult to follow, we directly give the final expression of average error probability for user 1, before that, let's define some parameters first,

$$\begin{aligned} &\overline{\gamma_C}=\frac{\varepsilon_1}{N_0}E\left[\left|H_1^L(t)\right|^2\right], \overline{\gamma_D}=\frac{\left(\sqrt{\varepsilon_1}+\sqrt{2\varepsilon_2}\right)^2}{N_0}E\left[\left|H_1^L(t)\right|^2\right] \\ &\overline{\gamma_E}=\frac{\left(-\sqrt{\varepsilon_1}-\sqrt{2\varepsilon_2}\right)^2}{N_0}E\left[\left|H_1^L(t)\right|^2\right], \\ &\overline{\gamma_F}=\frac{\left(\sqrt{\varepsilon_1}+2\sqrt{2\varepsilon_2}\right)^2}{N_0}E\left[\left|H_1^L(t)\right|^2\right], \\ &\overline{\gamma_G}=\frac{\left(-\sqrt{\varepsilon_1}+2\sqrt{2\varepsilon_2}\right)^2}{N_0}E\left[\left|H_1^L(t)\right|^2\right] \end{aligned} \quad (22)$$

Then, the average error probability for user 1 is

$$\overline{P_1(e)}=\frac{1}{2}\left(1-\sqrt{\frac{\overline{\gamma_C}}{2+\overline{\gamma_C}}}\right)+\frac{1}{8}\left[\sqrt{\frac{\overline{\gamma_D}}{2+\overline{\gamma_D}}}-\sqrt{\frac{\overline{\gamma_E}}{2+\overline{\gamma_E}}}+\sqrt{\frac{\overline{\gamma_F}}{2+\overline{\gamma_F}}}-\sqrt{\frac{\overline{\gamma_G}}{2+\overline{\gamma_G}}}\right] \quad (23)$$

IV. SIMULATION RESULTS

In this section, we present some computer simulations to validate the theoretical results and validate the superiority of C-NOMA in CR. Some parameters we used in the system are summarized in TABLE 1.

TABLE I. PARAMETERS USED IN THE HYBRID SATELLITE SYSTEM

PARAMETER	VALUE
Carrier Frequency	20GHz(Ka)
Bandwidth	500MHz
Height of GEO satellite	35786km
Height of LEO satellite	1500km
Maximum power of GEO satellite	300W
Maximum power of LEO satellite	10W
Maximum power of ground users	1W

In this paper, we consider the fixed power allocation, in which we set $\alpha_1 = 0.3, \alpha_2 = 0.7$, and target rates for users are $R_{th1} = R_{th2} = 0.2$BPCU (BPCU is the abbreviation for the bit per channel use). In the following figures, Monte-Carlo simulations are performed to validate the superiority of introducing the C-NOMA scheme in the cognitive network.

The effect of doppler shift in the dynamic LEO satellite communication system is shown in Fig. 3. From the figure, we can see that with the increase of the height of the LEO satellite, the ratio of the doppler shift curve decreases, and with the mobility of the LEO, the doppler shift changes. So, in the LEO satellite system, it's crucial to consider the doppler shift in the channel model.

The outage probability performance in the C-NOMA CR system is presented in Fig. 4 and Fig. 5, respectively. As shown in Fig. 4, although the NU is allocated more power than the FU, the NU receives heavy interference from the FU, thus, the OP for NU is worse than the OP for FU. And in Fig. 5, it's obviously that the OP performance for FU is better in C-NOMA than in the conventional NOMA and no matter what kinds of NOMA, the OP performance is better than the

OMA scheme. The reason is that in C-NOMA we have established two links to transmit the same message for FU. Even if one links is in outage, chances are the other link is good. The probability that both links simultaneously go into outage is very less compared to the probability that any one link fails. So, C-NOMA can improve the OP performance for FU.

As shown in Fig. 6, BER performances of OMA users are better than those of the C-NOMA scheme, because OMA users do not encounter any inter-user interferences.

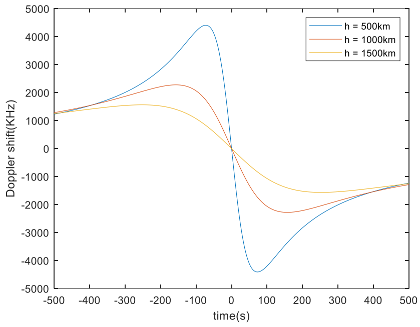

Fig. 3. Doppler shift characterization in the LEO satellite

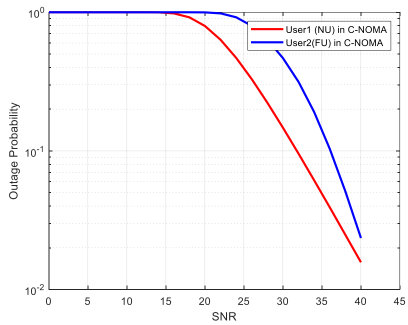

Fig. 4. Outage probability versus SNR for 2 NOMA users

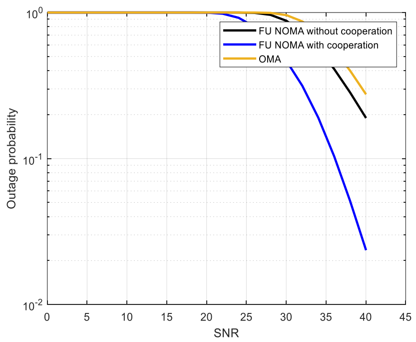

Fig. 5. Outage probability versus SNR in three different cases

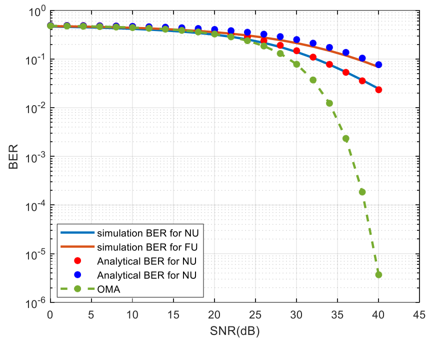

Fig. 6. BER versus SNR in C-NOMA in CR hybrid satellite system

V. CONCLUSION

In this paper, we proposed a C-NOMA with CR transmission scheme in which the LEO satellite is the secondary system using C-NOMA to communicate with its users, and the GEO satellite is the primary system using the OMA to communicate with its users. And due to the high mobility of the LEO, we consider the doppler shift in the channel model. Simulation results have demonstrated the superiority of C-NOMA with CR in hybrid satellite networks. A fixed power allocation scheme is adopted in this paper, and furthermore, we will study the optimal power allocation scheme in C-NOMA with CR in the system.

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