Outage Analysis of Coordinated NOMA Transmission for LEO Satellite Constellations

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ABSTRACT This work investigates the performance of a downlink non-orthogonal multiple access (NOMA) based coordinated low-earth orbit (LEO) satellite system. Two LEO satellites are assumed to coordinate their transmissions to serve three users simultaneously using NOMA protocol, where only one user lies in the intersection of the footprints of the two satellites. We investigate the reliability of the proposed architecture, which is expressed in terms of the outage probability (OP). We derive closed-form expressions of the users’ OPs taking into considerations different realistic losses effects on the link budget including receiver antenna gain, satellite antenna gain, antennas pointing errors, shadowing, small-scale fading, and large-scale free space path loss. The channels between satellites and the three users are assumed to follow shadowed-Rician (SR) fading. The mathematical analysis is verified by the extensive representative Monto-Carlo simulations. Finally, we demonstrate the impact of the system parameters on the considered system as well as the superiority of the NOMA scheme over conventional OMA system.

INDEX TERMS Coordinated transmission, low-earth orbit (LEO), non-orthogonal multiple access (NOMA), outage probability (OP), satellite communication, shadowed-Rician fading.

I. INTRODUCTION

RECENTLY, satellite communication (SatCom) networks have withdrawn an increasing interest in both academia and business specially with the initial deployment phases of low-earth orbit (LEO) satellite constellation networks. SatCom can provide multiple advantages over terrestrial networks including wide-coverage regions, supporting isolated geographical areas that where terrestrial networks can’t reach such as deserts, oceans, and forests. Moreover, SatCom can work as a key player in disaster situations, where the conventional terrestrial networks are compromised. Additionally, SatCom can support a fast range of applications including navigation, localization, weather prediction, television and radio broadcasting, Internet services, and satellite telephone systems [1]. On the other hand, it may suffer from propagation delay [2], and antenna pointing error angle caused by satellite and/or users mobility [3]. Additionally, the line-of-sight (LOS) path may be blocked by obstacles and/or heavy shadowing that reduces the coverage and performance of terrestrial users [4]. All these issues represent performance degradation in SatCom. To combat such issues, there are several researches that develop closed expressions for outage probability and ergodic capacity in different scenarios for enhancing the quality of services for the users. The authors in [5] derive exact expressions of outage probability for the p-th terrestrial user and provide the corresponding asymptotic analysis results.

The satellite systems in use today rotate in different types of orbits such as the geosynchronous orbit (GEO), medium earth orbit (MEO), low-earth orbit (LEO), and highly-elliptical orbit (HEO) [6]. It is observed that LEO satellites have the least propagation delay, the highest data rate and also the lower power consumption [7]. On the other hand, LEO satellites can serve users for limited periods of...
time due to the high rotation speed. To provide a global coverage for long times for LEO base systems, LEO satellite constellations have been proposed, where a large number of satellites are organized in different orbits and shells. Those constellations open new opportunities for global 24/7 coverage and coordinated access where multiple satellites can serve users simultaneously.

Non-orthogonal multiple access (NOMA) has drawn a lot of attention as an enabler of improving the spectrum efficiency of communication networks [8], [9], [10], [11], [12]. NOMA raises the number of concurrently serviced customers by serving numerous users at the same time and frequency resources [13], while the users can use different codes or different power levels in code-domain NOMA (CD-NOMA) and Power-domain NOMA (PD-NOMA), respectively. This work concentrates on PD-NOMA, where the multiple access is managed by assigning different power levels to different messages at the transmitter, while the receivers manage interference between users using successive interference cancellation (SIC) operation to separate the messages [10], [11], [14]. Different from conventional orthogonal multiple access (OMA) schemes, such as time-division multiple access (TDMA) and orthogonal frequency division multiple access (OFDMA), NOMA can support higher throughput, better reliability, low latency, and massive connectivity [3]. Several literature have investigated the performance of NOMA in both terrestrial [8], satellite [15], [16], underwater optical systems [17], [18], and hybrid terrestrial-satellite communication networks [19] in both half and full duplex transmissions [20]. In [15], the authors have investigated the performance of NOMA in a downlink land mobile satellite (LMS) network by deriving the users’ outage probabilities, ergodic capacities in addition to optimizing the power allocation coefficients to maximize the sum rate. The authors have considered a two-users system under shadowed-Rician fading channels. In [16], the authors investigated the performance of a downlink NOMA-based LEO satellite communication system under Doppler shift effect. They consider two users in one spot beam too, while the small-scale fading undergoes Rician distribution.

On the other hand, if the satellite to user links suffer from deep fading conditions, the authors in [21] and [19] have investigated using NOMA-based relays to assist the transmission, where the former uses an unmanned aerial vehicle (UAV) as a relay while the latter uses a terrestrial relay node. Similarly, the satellite itself can be used as a relay node to assist the terrestrial base stations to reach users in deep fading, where a NOMA-based coordinated direct and relay scheme is adopted [22].

Different from the mentioned literature, this work investigate the possibility to use NOMA-based coordinated transmission from two LEO satellites to benefit from the recently deployed LEO satellite constellation networks, where several users may lie in or share segments of the satellites’ footprints. The authors in [23] have discussed the challenges of multi-cluster coordination in industrial IoT to provide interference management. To the best of the authors knowledge, only the work in [24] has investigated the ergodic capacity of a similar architecture. However, the authors only considers the free-space path loss and ignores several critical losses for satellite-based communication. Additionally, the small-scale fading model is assumed to follow Rayleigh distribution, which is not the suitable model for such network. The main contributions of this paper can be summarized as follows:

- Different from the existing works in literature that addresses coordinated multiple access in terrestrial multi-cell systems, Satellite communication exhibits different features due to the different parameters that affects the link budget/channel gains between the satellite and ground users. Those parameters include the pointing error, the distance of the user from the center of the satellite beam in addition to the different small-scale fading. This work investigates coordinated LEO satellites NOMA-based transmission assuming a realistic satellite link budget.
- Derive the users’ OPs in closed-form expression.
- Finally, Monte-Carlo simulation results confirm our theoretical analysis. Furthermore, the impacts of critical parameters on the system performance are revealed by simulations, and the superiority of the NOMA scheme is highlighted compared with conventional OMA systems.

The remainder of this paper is laid out as follows: Section II discusses the system model, while Section III provides the derivation of outage probability for the downlink LEO coordinated NOMA system. Representative numerical results are shown in Section IV. Finally, Section V concludes our work.

II. SYSTEM AND CHANNEL MODELS

A. SYSTEM MODEL

In this work, we consider a downlink coordinated satellite system, where two LEO Satellites (LEO1 and LEO2) are coordinated to serve three terrestrial users1 (U1, U2, and Uf) using NOMA transmission, as shown in Fig. 1. Users U1 and Uf are covered by the footprint of LEO1, while U2 and Uf are covered by the footprint of LEO2. Consequently, U1 and U2 are considered as near users for LEO1 and LEO2, respectively, while Uf is a far user for both satellites. Without loosing generality, the two satellites are assumed to be on the same height (h) above the earth. All nodes are using a single antenna and half-duplex mode for communication.

A perfect channel state information (CSI) is assumed at the receivers. The channels between the satellites and all

1. Theoretically, NOMA can support any arbitrary number of users and the system analysis can be extended too. This work considers three terrestrial users that are distributed in two intersected footprints of two satellites. The three users are served using a single sub-carrier of an OFDMA system, where higher number of users can be paired on different sub-carriers. However, it is well established in literature that increasing the number of NOMA users induces complexity for NOMA detection due to successive interference cancellation (SIC) in addition to higher power consumption. Consequently, we limit our theoretical derivations to the three users scenario, which can be applicable in many real-world scenarios including direct satellite to IoT and low-power nodes.
users undergo both large and small-scale fading. The large-scale fading is characterized by free space loss for all links, while the small-scale fading is assumed to follow Shadowed Rician (SR) fading distribution. Moreover, we take into consideration the antenna gains of receiver and satellite, antenna pointing error, and shadowing as effective parameters on the performance. Therefore, the entire link budget of the satellite-to-user (S-U) link can be expressed as follows [3].

\[ L_{ij} = \frac{G_{ij}(\phi_s) G_{U_j}}{L_{ij}^f}, \]  

where \( L_{ij}^f \) is the free-space loss between \( U_i \) and the \( j^{th} \) LEO for \( i \in \{1, 2, f\} \), and \( j \in \{1, 2\} \). \( L_{ij}^f \) is the pointing-error loss which is expressed as \( L_{ij}^f = 2.7211 \times 10^{-20} f_s^2 D_s^2 \) with \( f_s \) being the carrier frequency, \( D_s \) is the antenna aperture’s diameter, and \( \theta_s \) is the pointing error angle between the user and the satellite. \( G_{ij}(\phi_s) \) is the beam gain expressed as \( G_{ij}(\phi_s) = G_s j_{11}(u_{ij}) + 36 (u_{ij})^2 \) with \( G_{U_i} \) denotes the antenna gain of \( U_i \), \( j(.) \) denotes the Bessel function, and \( u_{ij} = 2.07123 \frac{d_{ij}}{f_s^2} \). \( d_{ij} \) is the distance from the beam center of the \( j^{th} \) LEO to \( U_i \), and \( \phi_s \) denotes the angle between the user and the beam center with respect to satellite. The previously mentioned parameters have great impact on the channel gains of the satellites-users links and the effective signals-to-interference plus noise ratios (SINRs) [19], [25], which mandates taking them into consideration different from similar terrestrial coordinated multiple access (CoMP) transmissions. The results in [19] show that the pointing error and the distance from the center of the satellite beam have an impact on the downlink performance. The authors in [25] have investigated the effects of pointing errors on the ergodic capacity of uplink satellite users.

Based on NOMA protocol, LEO1 and LEO2 broadcast the following superimposed signals respectively

\[ x_{s1} = \sqrt{a_1} P_1 x_1 + \sqrt{a_f} P_1 x_f \]  
\[ x_{s2} = \sqrt{b_2} P_2 x_2 + \sqrt{b_f} P_2 x_f \]

where \( P_1, P_2 \) are the total power of the LEO1 and LEO2, respectively, \( a_1 + a_f = 1, b_2 + b_f = 1, a_f > a_1 \) and \( b_f > b_2 \) such that \( (a_1, a_f) \) denote the power allocation factors for \( U_1 \) and \( U_f \) from LEO1 respectively, while \( (b_2, b_f) \) denote the power allocation factors for \( U_2 \) and \( U_f \) from LEO2. Thus, the received signals at the three users can be expressed as follows:

\[ y_1 = h_{11} \sqrt{L_{B11}} x_{s1} + n_1, \]
\[ y_2 = h_{22} \sqrt{L_{B22}} x_{s2} + n_2, \]
\[ y_f = h_{f1} \sqrt{L_{B11}} x_{s1} + h_{f2} \sqrt{L_{B22}} x_{s2} + n_f \]

(4)

where \( n_j \sim \mathcal{CN}(0, \sigma^2) \) denotes the additive white Gaussian noise (AWGN) with zero mean and variance \( \sigma^2 \) of \( U_1 \) for \( j \in \{1, 2, f\} \). \( h_{ij} \) denotes the channel between the \( j^{th} \) LEO satellite and \( U_i \) assuming that the channels \( h_{21} \) and \( h_{12} \) are negligible since \( U_1/U_2 \) is out of the footprint of the LEO2/LEO1.

Following the principles of power domain NOMA, \( U_1 \) first decodes \( x_f \) then uses SIC to get its own signal \( x_1 \), where the signal to interference and noise ratio (SINR) at \( U_1 \) to decode \( x_f \) and \( x_1 \) are given respectively as follows

\[ \gamma_f^1 = \frac{a_f \rho_1 L_{B11} |h_{11}|^2}{a_1 \rho_1 L_{B11} |h_{11}|^2 + 1} \]
\[ \gamma_f^2 = \frac{b_f \rho_2 L_{B22} |h_{22}|^2}{b_2 \rho_2 L_{B22} |h_{22}|^2 + 1} \]

(5)

(6)

where \( \rho_1 = \frac{P_1}{\sigma^2} \) denotes the transmit SNR at LEO1. Similarly, \( U_2 \) detects \( x_f \) first then uses SIC to get \( x_1 \), where the SINRs are given as follows

\[ \gamma_f^2 = \frac{b_f \rho_2 L_{B22} |h_{22}|^2}{b_2 \rho_2 L_{B22} |h_{22}|^2 + 1} \]
\[ \gamma_f^1 = \frac{a_f \rho_1 L_{B11} |h_{11}|^2}{a_1 \rho_1 L_{B11} |h_{11}|^2 + 1} \]

(7)

(8)

where \( \rho_2 = \frac{P_2}{\sigma^2} \) denotes the transmit SNR at LEO2.

By substitute (2) and (3) into \( y_f \) (4), the received signal of \( U_f \) can be expressed as

\[ y_f = x_1 \left( \sqrt{L_{B11}} a_1 h_{11} \right) + x_f \left( \sqrt{L_{B12}} b_1 h_{12} \right) \]
\[ + x_f \left( \sqrt{L_{B21}} b_f h_{21} + \sqrt{L_{B22}} b_f h_{22} \right) + n_f \]

(9)

Since \( U_f \) receives two versions of \( x_f \) through the two satellites, it is capable of performing several forms of diversity combining techniques such as selective combining (SC) and maximum ratio combining (MRC). In this work, we investigate SC technique, where the effective SINR can be expressed respectively as follows

\[ \gamma_f^S = \max \left( \frac{a_f \rho_1 L_{B11} |h_{11}|^2}{a_1 \rho_1 L_{B11} |h_{11}|^2 + 1}, \frac{b_f \rho_2 L_{B22} |h_{22}|^2}{b_2 \rho_2 L_{B22} |h_{22}|^2 + 1} \right) \]

(10)

B. SR FADING CHANNELS STATISTICS

The channel gains of the link between the satellite and the users are subjected to SR fading, where the probability density function (PDF) of the \( |h_{ij}|^2 \) is given by [26] as

\[ f_{|h_{ij}|^2}(x) = \alpha_s \ e^{-\beta_s x} I_1(m_s; 1; \delta_s x), \]  

(11)

where \( \alpha_s \), \( \beta \), \( m_s \), and \( \delta_s \) are the scale factor, power loss, power loss index, and shadowing parameter respectively.
such that $s \in \{11, 22, f1, f2\}$, $\alpha_s = \frac{1}{2c_s} \frac{(\frac{2c_s m_s}{\Omega_s})^m_s}{\frac{2c_s m_s}{\Omega_s + 2c_s}}$, $\beta_s = \frac{1}{2c_s}$, and $\delta_s = \frac{\Omega_s}{2c_s (\frac{2c_s m_s}{\Omega_s + 2c_s})}$. $F_1(\cdot; \cdot; \cdot)$ is the first kind of confluent hypergeometric function [27, eq. (9.14.1)], $m_s$ is the severity parameter of the fading channel, $\Omega_s$ is line-of-sight (LOS) average power, and $2c_s$ is the multipath components. By using equations [28, (07.20.03. 0009.01)] and [29, (07.02.03.0014.01)], the hypergeometric function can be expressed as

$$I_F(\xi; 1; \delta, x) = e^{\delta x} \sum_{k=0}^{m_s-1} \frac{(-1)^k (1 - m_s)_{k}}{(k!)^2} (\delta, x)^k,$$

where $(\cdot)_n$ is the pochhammer symbol [27, p. xiii]. Let $\zeta(k) = \frac{(1 - m_s)_{k}}{(k!)^2}$. With the help of equation [27, (3.351.2)], the cumulative distribution function (CDF) of the $|h_{1i}|^2$ is expressed as

$$F_{|h_{1i}|^2}(\chi) = 1 - \alpha_s e^{-(\beta_s - \delta_s) x} \sum_{k=0}^{m_s-1} \sum_{l=0}^{k} \zeta(k) \times \frac{k!}{l!} \frac{x^l}{(\beta_s - \delta_s)^{(k-l+1)}}.$$

### III. PERFORMANCE ANALYSIS

In this section, we investigate the reliability of the considered coordinated NOMA-based transmission of LEO satellites in terms of the users OPs. The OP is defined as the probability that the effective SINR is less than a threshold value. In this section, we drive the OPs of the three users.

1) OUTAGE PROBABILITY OF $U_1$

The outage event of $U_1$ happens if $U_1$ can not correctly decodes $x_f$ or $x_1$. As a result, the OP of that event, $OP_1$, can be expressed as follows [30]

$$OP_1 = Pr\left(\gamma_f < \gamma_0 \text{ or } \gamma_1 < \gamma_0\right) = 1 - Pr\left(|h_{1i}|^2 > \tau_1, |h_{1i}|^2 > \tau_2\right) = 1 - Pr\left(|h_{1i}|^2 > \tau_3\right) \begin{cases} \frac{F_{|h_{1i}|^2}(\tau_3)}{\alpha_f > \alpha_1 \gamma_0} \\ \text{otherwise} \end{cases}$$

$$\begin{align} \frac{(a)}{\frac{(b)}} &= 1 - e^{-(\beta_{1i} - \delta_{1i}) \tau_1} \sum_{k=0}^{m_{1i}-1} \sum_{l=0}^{k} A_{1i}(k,l) \tau_1^l, \\ \frac{1}{2} + \gamma_0 &< \alpha_1 < \frac{1}{2} + \gamma_0 \end{align}$$

$$\begin{align} \frac{(c)}{\frac{(d)}} &= 1 - e^{-(\beta_{1i} - \delta_{1i}) \tau_2} \sum_{k=0}^{m_{1i}-1} \sum_{l=0}^{k} A_{1i}(k,l) \tau_2^l, \\ \alpha_1 &> 1 + \gamma_0 \end{align}$$

where $\gamma_0 = 2^{R_{th}/B} - 1$ is the threshold SINR of all satellite users, $R_{th}$ is the target threshold data rate, $B$ is the bandwidth, (a) stems from (12), $\tau_1 = \frac{\gamma_0}{\rho_1 L B_{1i} (\alpha_1 - a_1 \gamma_0)}$, $\tau_2 = \frac{\gamma_0}{\rho_1 L B_{1i}}$, $\tau_3 = \max(\tau_1, \tau_2)$, and $A_{1i}(k,l) = \frac{\alpha_{1i}(\frac{k!}{l!}) (\beta_{1i} - \delta_{1i})^{-(k-l+1)}}{\rho_1 L B_{1i}}$.

2) OUTAGE PROBABILITY OF $U_2$

The outage event of $U_2$ happens if $U_2$ can not correctly decodes $x_f$ or $x_2$. As a result, the OP of that event, $OP_2$, can be written as follows

$$OP_2 = Pr\left(\gamma_f < \gamma_0 \text{ or } \gamma_2 < \gamma_0\right) = 1 - Pr\left(|h_{2i}|^2 > \tau_4, |h_{2i}|^2 > \tau_5\right) = 1 - Pr\left(|h_{2i}|^2 > \tau_6\right) \begin{cases} \frac{1}{2} - e^{-(\beta_{2i} - \delta_{2i}) \tau_4} \sum_{k=0}^{m_{2i}-1} \sum_{l=0}^{k} A_{2i}(k,l) \tau_4^l, \\ \frac{1}{2} + \gamma_0 &< b_2 < \frac{1}{2} + \gamma_0 \end{cases}$$

$$\begin{align} \frac{(c)}{\frac{(d)}} &= 1 - e^{-(\beta_{2i} - \delta_{2i}) \tau_5} \sum_{k=0}^{m_{2i}-1} \sum_{l=0}^{k} A_{2i}(k,l) \tau_5^l, \\ b_2 &> \frac{1}{2} + \gamma_0 \end{align}$$

where $\tau_4 = \frac{\rho_2 L B_{2i} (\beta_2 - \delta_{2i})}{\rho_2 L B_{2i} \gamma_0}$, $\tau_5 = \frac{\rho_2 L B_{2i}}{\rho_2 L B_{2i} \gamma_0}$, and $A_{2i}(k,l) = \alpha_{2i}(\frac{k!}{l!}) (\beta_{2i} - \delta_{2i})^{-(k-l+1)}$.

3) OUTAGE PROBABILITY OF $U_F$

In the following, we derive the OP of $U_f$ assuming that $U_f$ uses SC diversity technique to detect $x_f$ as follows:

$$OP_f = Pr\left(\gamma_f (SC) < \gamma_0\right) = Pr\left(\max(\gamma_A, \gamma_B) < \gamma_0\right) = Pr\left(\gamma_A < \gamma_0, \gamma_B < \gamma_0\right) = Pr\left(|h_f1|^2 < \tau_7\right) Pr\left(|h_f2|^2 < \tau_8\right) \begin{cases} \frac{F_{|h_f1|^2}(\tau_7)}{\alpha_f > \alpha_1 \gamma_0, \alpha_f > \alpha_2 \gamma_0} \\ \frac{F_{|h_f2|^2}(\tau_8)}{\alpha_f > \alpha_1 \gamma_0, \alpha_f > \alpha_2 \gamma_0} \end{cases}$$

where (c) stems from the independence of $h_f1$ and $h_f2$, (d) stems from (12), $\tau_7 = \frac{\gamma_0}{\rho_1 L B_{f1} (a_f - \alpha_1 \gamma_0)}$, and $\tau_8 = \frac{\gamma_0}{\rho_2 L B_{f2} (a_f - \alpha_2 \gamma_0)}$.

### IV. RESULTS AND DISCUSSIONS

In this section, we use numerical results to evaluate the outage probabilities of the three satellite users and investigate the effects of different parameters on the performance. Monte-Carlo simulation is implemented to verify the accuracy of the theoretical analysis. All Monte Carlo simulation results are obtained with an average calculation of $10^6$ iterations. The links between satellite and the users undergo frequent heavy shadowing (FHS), where the channel coefficients of terrestrial links are $m_1 = m_2 = m_f = 1$, $\Omega_1 = \Omega_2 = \Omega_f = 0.0007$, and $c_1 = c_2 = c_f = 0.063$. For the numerical results, we use the settings in Table 1 [31], [32].

Figure 2 plots the OPs of the three users versus the transmit SNR ($\rho$) using both NOMA and OMA schemes, where $\gamma_0 = 0.5$, the power allocation factors for the users are $a_1 = 0.3, a_f = 0.7, b_2 = 0.4$, and $b_f = 0.6$. The curves
of theoretical analysis sufficiently coincide with the Monte Carlo simulations. It is noteworthy that the OPs for all users in both schemes improves with the increase of the transmit SNR values. The results show that using NOMA significantly enhances the outage performance at all users specially at $U_f$ where selection combining (NOMA-SC) is adopted.

Figure 3 highlights the effect of tweaking the power allocation factor of the common user ($U_f$) on the OPs of all users. The results show that increasing the power, assuming that $a_f = b_f$, enhances the OP of $U_f$. However, the OPs the two other users experience outage enhancement up to certain value ($0.65$ under the settings in Table 1, while $\rho = 10\,\text{dB}$), then the outage performance deteriorate with any further increase. In other word, the two curves show a convex behavior with an optimal power allocation value. The reason behind this behavior is that increasing $a_f$ in (5) and $b_f$ in (7) improve both SINRs ($\gamma_1^f$ and $\gamma_2^f$), which enhances the OP at first. However, if we increases the power allocation factor to higher values leads to the deterioration of $\gamma_1^f$ (6) and $\gamma_2^f$ in (8). It is noteworthy that $OP_1$ relies on both $\gamma_1^f$ and $\gamma_1^f$, while $OP_2$ relies on both $\gamma_2^f$ and $\gamma_2^f$ in (14) and (15), respectively.

Figure 4 shows the OP versus the pointing error angle with values from 0 to 7, while $\rho = 10\,\text{dB}$. The results shows that the OPs of all users deteriorate with the increase of the pointing error angle until a complete outage around $\theta_e = 5$. 

| Parameter name                      | Parameter value |
|-------------------------------------|-----------------|
| Height of LEO satellite             | 780 Km          |
| Carrier frequency at satellite (L Band) | 1.55 GHz        |
| Users antenna gain                  | 1 dB            |
| Satellite antenna gain              | 25 dB           |
| Diameters of satellites antennas aperture | 1 m             |
| Pointing error angle of satellite   | 1°              |
| The radius of a circle of the coverage area of spot-beam from the satellite (R) | 200 Km          |
| LEO1 beam center to $U_1$ distance  | 0.3*R           |
| LEO2 beam center to $U_2$ distance  | 0.3*R           |
| LEO1/LEO2 beam center to $U_f$ distance | 0.35*R         |
On the other hand, Figure 5 shows the variations of the system OP versus $\rho$ for three different values of the pointing error angle ($\theta_e \in \{0, 3, 5\}$). The perfect alignment angle case (i.e., $\theta_e = 0$) show a better outage performance compared to higher values of $\theta_e$.

The effect of distance of the edge user ($U_f$) from the beam center on the system OP is investigated in Figure 6 for 4 different values (0.1 R, 0.3 R, 0.5 R, and 0.7 R). The results show that the system OP deteriorates as $U_f$ move away from the center of the satellite beam.

As future research directions, we intend to derive closed-form or approximated expressions of the OPs if maximum ratio combining (MRC) is used at $U_f$ since it is expected to give better outage performance as shown in Figure 7, which is obtained using Monte-Carlo Simulations. Additionally, it is imperative to provide a resource allocation algorithm to find the optimal values of the power allocation factors to minimize the OP of the system or of a specific user. Moreover, it is interesting to consider the case where more than two satellites in the LEO constellation are coordinating their transmissions. In addition to exploiting machine-learning (ML) techniques to improve the performance of coordinated LEO satellite transmissions [33] including traditional ML and reinforcement learning (RL) techniques which are widely used in many communication networks [34], [35], [36], [37], [38], [39].

V. CONCLUSION

In this article, we have studied the reliability of coordinated NOMA-based transmission in LEO Satellite systems. The reliability is expressed in terms of the users outage probabilities. Closed-form expressions for the outage probabilities are derived and evaluated taking into consideration different losses. We show the impact of various parameters on the considered system such as the antenna-pointing angle, the power allocation factor, and combining technique. The numerical results show the superior of the NOMA over the OMA in the considered system.

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