# Performance Analysis of Simultaneous Non-Unique Decoding of Uplink NOMA in LEO Satellite Networks

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***Abstract*—We investigate simultaneous nonunique decoding (SND) for two-user uplink non-orthogonal multiple access (NOMA) in a low-earth-orbit (LEO) satellite spot beam. One tagged user equipment (UE) is fixed at a given ground distance from the beam center, whereas the other UE is located at an arbitrary or uniformly random position within the service area. Because the satellite beam gain and slant distance vary across the footprint, a co-user near the beam center is detrimental to treating interference as noise (IAN) but favorable to the joint-decoding branch of SND. The opposite behavior arises near the beam edge. We formulate the ground-distance-dependent outage events and show that SND combines these complementary spatial regimes. Simulation results with a representative S-band uplink budget and shadowed-Rician fading demonstrate a nonmonotonic SND outage with respect to the co-user distance.**

***Index Terms*—Low-earth-orbit (LEO) satellite, non-orthogonal multiple access (NOMA), simultaneous nonunique decoding (SND), outage probability, spot beam.**

## I. Introduction

Low-earth-orbit (LEO) satellite networks are expected to play an important role in future fifth-generation (5G) and sixth-generation (6G) communication systems by complementing terrestrial networks and extending connectivity to remote and underserved areas [1], [2]. In particular, the integration of satellites into non-terrestrial networks can support wide-area service coverage and massive Internet-of-Things (IoT) connectivity. However, satellite links exhibit distinctive propagation characteristics, including large free-space path loss, elevation-dependent link quality, and considerable received-power variation across a spot beam [3].

Non-orthogonal multiple access (NOMA) allows multiple user equipments (UEs) to share the same time-frequency resource and has been extensively investigated as a means of improving spectral efficiency and supporting massive connectivity [4], [5]. In uplink NOMA, the simultaneously received signals can be recovered usinwg successive interference cancellation (SIC) or joint decoding (JD). The outage performance of a two-user uplink land-mobile satellite system employing SIC and JD was analyzed under shadowed-Rician fading in [6]. Nevertheless, such fixed decoding strategies cannot fully exploit the different interference conditions that arise across a satellite spot beam.

Specifically, the received power of a terrestrial UE depends on both the satellite off-boresight antenna gain and the slant distance. A co-user close to the beam center generally produces a strong received signal. This signal severely degrades treating interference as noise (IAN), but can facilitate the joint-decoding branch. In contrast, a co-user near the beam edge produces weaker interference and is therefore more suitable for IAN, although its signal becomes difficult to exploit through joint decoding. Hence, the preferable decoding strategy can vary according to the ground locations of the UEs.

Simultaneous nonunique decoding (SND) combines the success regions of IAN and joint decoding and has recently been applied to improve the reliability of uplink non-orthogonal random access systems [7]. Motivated by this property, we investigate the ground-distance-dependent outage performance of SND for two-user uplink NOMA in a LEO satellite spot beam. We model the location-dependent beam gain and slant distance using spherical-Earth geometry and formulate the SND decoding conditions for a tagged UE. We then numerically evaluate its outage probability for different UE locations through Monte Carlo simulations. The location-averaged outage performance is also evaluated when the co-user is uniformly distributed over the spot-beam area. The results demonstrate that SND exploits the complementary spatial behaviors of IAN and the joint-decoding branch and improves the reliability of the tagged UE over a wide range of co-user locations.

## II. System Model

We consider a LEO satellite equipped with a single receive antenna and two single-antenna terrestrial UEs simultaneously transmitting over the same uplink resource, as shown in Fig. 1. Let $r_k$ denote the ground-surface radial distance from the beam center to UE $k \in \{1, 2\}$, and let $r_{\mathrm{b}}$ denote the spot-beam radius. All distances in the numerical results are expressed in kilometers. UE 1 is the tagged UE at a fixed $r_1$, whereas UE 2 is located at a given $r_2 \in [0, r_{\mathrm{b}}]$ or uniformly distributed over the spherical-cap service area.

Let $R_{\mathrm{E}}$ and $h_0$ denote the Earth radius and satellite altitude, respectively. The Earth-centered angle of UE $k$ is $\psi_k = r_k / R_{\mathrm{E}}$ in radians. Unless otherwise specified, all angular variables are expressed in radians. Its slant distance and off-boresight angle are

$$d_k = \sqrt{(R_{\mathrm{E}} + h_0)^2 + R_{\mathrm{E}}^2 - 2R_{\mathrm{E}}(R_{\mathrm{E}} + h_0) \cdot \cos(\psi_k)}, \quad (1)$$

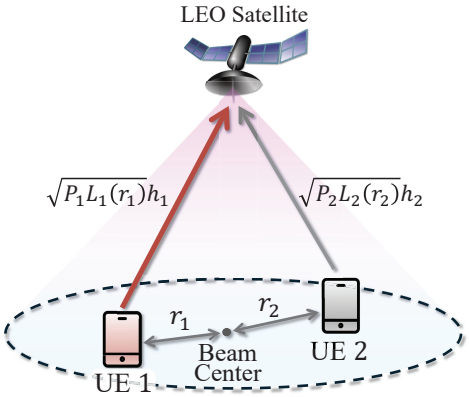


Fig. 1. Two-user uplink NOMA in a circular LEO satellite spot beam.

$$\phi_k = \sin^{-1}(R_{\mathrm{E}} \cdot \sin(\psi_k)/d_k)\,. \tag{2}$$

If the beam-edge elevation angle is $\theta_{\mathrm{E,b}}$, then

$$\phi_{\mathrm{b}} = \sin^{-1}\left(\frac{R_{\mathrm{E}} \cdot \cos(\theta_{\mathrm{E,b}})}{R_{\mathrm{E}} + h_0}\right),\ r_{\mathrm{b}} = R_{\mathrm{E}}\left(\frac{\pi}{2} - \theta_{\mathrm{E,b}} - \phi_{\mathrm{b}}\right). \tag{3}$$

For a uniformly distributed UE 2, its radial probability density function is

$$f_{R_2}(r) = \frac{\sin(r/R_{\mathrm{E}})}{R_{\mathrm{E}}[1 - \cos(r_{\mathrm{b}}/R_{\mathrm{E}})]},\quad 0 \le r \le r_{\mathrm{b}}. \tag{4}$$

The received signal at the satellite is

$$y = \sqrt{P_1L_1(r_1)}h_1x_1 + \sqrt{P_2L_2(r_2)}h_2x_2 + n, \tag{5}$$

where $P_k$, $x_k$, and $h_k$ are the transmit power, unit-power symbol, i.e., $\mathbb{E}[|x_k|^2]$, and small-scale fading coefficient of UE $k$, respectively, and $n \sim \mathcal{CN}(0, N_0)$. The link gain is

$$L_k(r_k) = G_{\mathrm{u}} \cdot G_{\mathrm{s,max}} \cdot b(\phi_k) \cdot 10^{-PL(d_k)/10}, \tag{6}$$

where $G_{\mathrm{u}}$ and $G_{\mathrm{s,max}}$ are the UE and maximum satellite antenna gains. We use $PL(d_k) = 32.45 + 20\log_{10} f_c + 20\log_{10} d_k$ in dB, where $f_c$ is in GHz and $d_k$ is in meters. Following the tapered-aperture model [8], [9],

$$b(\phi) = \left[\frac{J_1(u)}{2u} + 36\frac{J_3(u)}{u^3}\right]^2,\quad u = \frac{2.07123 \cdot \sin(\phi)}{\sin(\phi_{3\mathrm{dB}})}. \tag{7}$$

The channel is shadowed Rician,

$$h_k = \sqrt{\frac{\kappa}{\kappa+1}}h_{\mathrm{LoS},k} + \sqrt{\frac{1}{\kappa+1}}h_{\mathrm{NLoS},k}, \tag{8}$$

where $|h_{\mathrm{LoS},k}|$ is Nakagami-$m$ distributed and $h_{\mathrm{NLoS},k}$ is complex Gaussian. The instantaneous receive SNR is $\gamma_k = P_kL_k(r_k)|h_k|^2/N_0$.

## III. SND-Based Outage Probability

Let $R_k$ be the target rate of UE $k$, and define

$$\beta_k = 2^{R_k} - 1, \qquad \beta_{12} = 2^{R_1+R_2} - 1. \tag{9}$$

When UE 2 is treated as noise, UE 1 is successfully decoded if

$$\mathcal{I} = \{\gamma_1 \ge \beta_1(1 + \gamma_2)\}. \tag{10}$$

The joint-decoding branch of SND requires

$$\mathcal{J} = \{\gamma_1 \ge \beta_1,\ \gamma_1 + \gamma_2 \ge \beta_{12}\}. \tag{11}$$

The SND success event is $\mathcal{S} = \mathcal{I} \cup \mathcal{J}$. Equivalently, UE 1 succeeds if $\gamma_1 \ge T_{\mathrm{SND}}(\gamma_2)$, where

$$\begin{aligned} T_{\mathrm{SND}}(x) &= \min[\beta_1(1+x), \max\{\beta_1, \beta_{12} - x\}],\quad x \ge 0 \\ &= \begin{cases} \beta_1(1+x), & 0 \le x < \beta_2, \\ \beta_{12} - x, & \beta_2 \le x < \beta_2(1+\beta_1), \\ \beta_1, & x \ge \beta_2(1+\beta_1). \end{cases} \end{aligned} \tag{12}$$

Thus, IAN is favorable for a weak co-user, whereas the joint-decoding branch is favorable for a strong co-user.

For fixed positions, the UE 1 outage probability is

$$P_{\mathrm{out},1}^{\mathrm{SND}}(r_1, r_2) = 1 - \Pr(\mathcal{I} \cup \mathcal{J}). \tag{13}$$

Using (4), the outage averaged over a uniformly distributed UE 2 is

$$\bar{P}_{\mathrm{out},1}^{\mathrm{SND}}(r_1) = \int_0^{r_{\mathrm{b}}} P_{\mathrm{out},1}^{\mathrm{SND}}(r_1, r) f_{R_2}(r)\, dr, \tag{14}$$

where $r_{\mathrm{b}}$ denotes the ground spot-beam radius and $f_{R_2}(r)$ is the radial-distance distribution of UE 2.

## IV. Simulation Results

The LEO satellite altitude and the Earth radius are set to $h_0 = 780$ km and $R_{\mathrm{E}} = 6,371$ km, respectively. The minimum elevation angle at the spot-beam edge is $55°$, which results in a ground spot-beam radius of approximately $474.7$ km. The carrier frequency is $f_c = 2$ GHz, and the off-axis half-power angle of the satellite antenna is $\phi_{3\mathrm{dB}} = 22°$. The antenna gains of each UE and the satellite are set to 1 dBi and 17 dBi, respectively. Both UEs transmit with a power of 23 dBm over a shared uplink bandwidth of 15 kHz. The noise power spectral density and noise figure are set to $-174$ dBm/Hz and 3 dB, respectively. Clear-sky conditions are assumed, and the gaseous, scintillation, and building-entry losses are neglected. The target spectral efficiencies are set to $R_1 = 1$ bit/s/Hz and $R_2 = 2$ bit/s/Hz. The shadowed-Rician fading parameters are given by $\kappa = 10$ dB, $m = 10$, and $\Omega = 1$.

Fig. 2 shows the outage probability of UE 1 as the ground distance of UE 2 from the beam center varies from zero to the beam radius. UE 1 is fixed at $r_1 = 100$ km. When UE 2 is located near the beam center, its received signal power at the satellite is relatively high. Therefore, treating the UE 2 signal as noise results in severe interference and a high IAN outage probability. In contrast, the strong UE 2 signal helps satisfy the sum-rate condition of the joint-decoding branch. As UE 2 moves toward the beam edge, its received power decreases because of the reduction in the satellite beam gain and the increase in the slant distance. Consequently, the IAN outage probability gradually decreases because the interference from UE 2 becomes weaker. On the other hand, the outage probability of the joint-decoding branch increases to because the weakened UE 2 signal contributes less to the

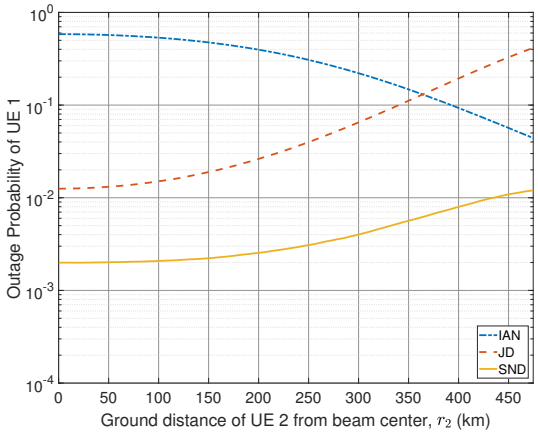


Fig. 2. Outage probability of tagged UE 1 versus the ground distance of UE 2 from the beam center when $r_1 = 100$ km.

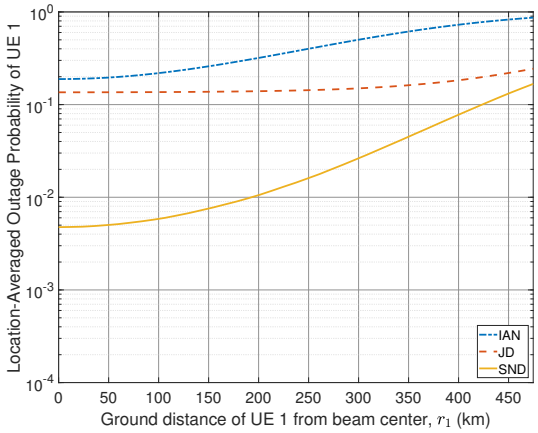


Fig. 3. Location-averaged outage probability of tagged UE1 versus the ground distance of tagged UE 1 from the beam center when UE 2 is uniformly distributed over the satellite spot beam.

sum-rate condition. These opposite tendencies show that the effect of UE 2 on the decoding of UE 1 strongly depends on its location within the satellite spot beam. SND declares UE 1 successfully decoded when either the IAN condition or the joint-decoding condition is satisfied. Therefore, its outage probability is lower than those of the two individual decoding branches over the entire spot beam. In the considered parameter setting, the joint-decoding branch remains more reliable than IAN, but SND provides an additional reliability improvement by including the IAN success region.

Fig. 3 shows the location-averaged outage probability as a function of the ground distance $r_1$ of tagged UE 1. For each position of UE 1, UE 2 is uniformly distributed over the spherical spot-beam area, and the outage probability is averaged over both the random location of UE 2. The outage probabilities of all decoding schemes increase as UE 1 moves toward the beam edge because the desired UE 1 signal experiences a reduction in beam gain and an increase in free-space path loss. Near the beam center, the location-averaged outage probabilities of IAN, the joint-decoding branch, and SND are approximately $2\times10^{-1}$, $8\times10^{-3}$, and $5\times10^{-3}$, respectively. Near the beam edge, they increase to approximately $9\times10^{-1}$, $2\times10^{-1}$, and $1.6\times10^{-1}$, respectively. These results confirm that the joint-decoding branch substantially improves the reliability of the tagged UE 1 compared with IAN, while SND achieves the lowest outage probability by exploiting the union of the two decoding regions.

## V. Conclusion

We investigated the outage performance of SND for two-user uplink NOMA in a LEO satellite spot beam using actual ground-surface distances and a spherical-Earth geometry. The location-dependent satellite antenna gain and slant distance cause the received power of each UE to vary considerably across the beam. Consequently, a strong co-user signal near the beam center favors the joint-decoding branch, whereas a weak co-user signal near the beam edge favors IAN. SND provides reliable decoding of the tagged UE over a wider range of co-user locations than either fixed decoding strategy. The simulation results demonstrated that the co-user distance has opposite effects on the outage probabilities of IAN and the joint-decoding branch. Moreover, SND achieved the lowest outage probability for fixed UE locations and a lower location-averaged outage when the co-user was uniformly distributed over the spot beam.

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## References

[1] O. Kodheli *et al.*, "Satellite communications in the new space era: A survey and future challenges," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 1, pp. 70–109, 2021.

[2] T. Darwish *et al.*, "LEO satellites in 5G and beyond networks: A review from a standardization perspective," *IEEE Access*, vol. 10, pp. 35 040–35 060, 2022.

[3] A. Guidotti *et al.*, "Architectures and key technical challenges for 5G systems incorporating satellites," *IEEE Trans. Veh. Technol.*, vol. 68, no. 3, pp. 2624–2639, Mar. 2019.

[4] S. M. R. Islam, N. Avazov, O. A. Dobre, and K. S. Kwak, "Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 721–742, 2017.

[5] Y. Liu, Z. Qin, M. Elkashlan, Z. Ding, A. Nallanathan, and L. Hanzo, "Non-orthogonal multiple access for 5G and beyond," *Proc. IEEE*, vol. 105, no. 12, pp. 2347–2381, Dec. 2017.

[6] S. A. Tegos *et al.*, "Outage performance of uplink NOMA in land mobile satellite communications," *IEEE Wireless Commun. Lett.*, vol. 9, no. 10, pp. 1710–1714, Oct. 2020.

[7] J. S. Yeom and B. C. Jung, "Opportunistic non-orthogonal random access with optimal decoder for 6G multi-channel IoT networks," *IEEE Wireless Commun. Lett.*, vol. 14, no. 7, pp. 2264–2268, Jul. 2025.

[8] J. Chu, X. Chen, C. Zhong, and Z. Zhang, "Robust design for NOMA-based multibeam LEO satellite internet of things," *IEEE Internet Things J.*, vol. 8, no. 3, pp. 1959–1970, Feb. 2021.

[9] J. S. Yeom, Y. Lee, and B. C. Jung, "MMSE-based MIMO receiver for cooperative downlink NOMA in LEO satellite networks," in *Proc. ICTC*, Oct. 2023, pp. 1650–1652.