

Link Budget Enhancement in HAP-RIS-Assisted LEO Direct-to-Cell Communications

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Abstract—Direct-to-Cell (D2C) communication through Low Earth Orbit (LEO) satellites is a promising approach for extending cellular coverage beyond terrestrial networks. However, the long propagation distance, limited transmit power of conventional user equipment, and time-varying satellite geometry make reliable D2C communication challenging. Hybrid Active–Passive Reconfigurable Intelligent Surfaces (HAP-RIS) can improve the link budget by combining passive phase control with amplification at a subset of active elements, although the additional noise introduced by these elements must also be considered.

In this paper, a combined STK–analytical end-to-end link-budget framework is developed for HAP-RIS-assisted D2C communications. STK is used to obtain the propagation, antenna, receiver, and satellite-dependent parameters of the UE–HAP-RIS and HAP-RIS–satellite links. These quantities are subsequently processed in Python, where the coherent response of the HAP-RIS, the active-element amplification constraint, the additional amplifier noise, and the final end-to-end received carrier power are evaluated analytically. The satellite receiver thermal noise and the independently generated noise contributions of the active RIS elements are combined in the linear domain to determine the total receiver noise. The resulting end-to-end C/N_0 , E_b/N_0 , and theoretical BER are then calculated.

The framework is evaluated using a 48-satellite Walker Delta constellation operating at 1.9925 GHz. The adopted HAP-RIS contains 1312 elements, comprising 732 active and 580 passive elements, with a maximum active-element gain of 40 dB. The fixed-UE scenario is evaluated statistically over the considered constellation, while user mobility is examined separately over a specific 143 s UE trajectory. The results show that the HAP-RIS-assisted link provides substantially higher C/N_0 and E_b/N_0 than the conventional direct UE-to-satellite link under the considered conditions, while the active-element noise is explicitly accounted for in the end-to-end calculation.

Index Terms—D2C communication, non-terrestrial networks, low Earth orbit satellites, hybrid reconfigurable intelligent surface, STK simulation, link budget analysis.

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I. INTRODUCTION

Providing reliable wireless connectivity remains a challenge in many rural areas, mountainous regions, highways, maritime environments, and sparsely populated locations where terrestrial cellular infrastructure is either limited or unavailable. In such scenarios, users are often located far from conventional base stations, while geographical barriers and low population density make network deployment difficult and economically unattractive. As a result, communication services outside urban areas frequently suffer from reduced coverage, lower reliability, and service interruptions [11]. Direct-to-Cell (D2C) communication through Non-Terrestrial Networks (NTNs) has emerged as a promising approach for extending cellular coverage beyond terrestrial networks by enabling conventional smartphones to communicate directly with Low Earth Orbit (LEO) satellites [2], [3], [4]. Reconfigurable Intelligent Surfaces (RISs) can improve wireless propagation through controllable phase adjustment, but fully passive RISs are limited by the cascaded attenuation of the two-hop satellite link. Hybrid active–passive RISs (HAP-RISs) address this limitation by introducing controlled amplification at a subset of elements in addition to passive phase control [13], [14]. Such architectures are therefore promising for improving the link budget of satellite-assisted communication systems [6]. Although RIS-assisted terrestrial and non-terrestrial communications have received considerable attention, end-to-end evaluation of HAP-RIS-assisted D2C links under realistic satellite orbital dynamics remains comparatively underexplored. Moreover, Ansys Systems Tool Kit (STK) does not natively represent the complete HAP-RIS processing chain, preventing direct end-to-end evaluation of the UE–HAP-RIS–satellite link. To address this limitation, this paper develops a combined STK–analytical framework for evaluating HAP-RIS-assisted D2C communications over LEO satellite networks. STK provides the time-varying satellite geometry, propagation, antenna, and receiver parameters, while the analytical model reconstructs the complete UE–HAP-RIS–satellite link, including coherent active–passive processing, active-element amplification and noise, and the resulting end-to-end communication metrics.

The proposed framework is evaluated for both fixed and

moving UE scenarios. The conventional direct and HAP-RIS-assisted links are compared in terms of C/N_0 , E_b/N_0 , and theoretical BER. In addition, passive, fully active, and HAP-RIS configurations are evaluated under the same propagation conditions and total number of elements to investigate the trade-off between active-element utilization and end-to-end link performance.

II. RELATED WORK AND RESEARCH MOTIVATION

NTNs have been widely investigated as a means of extending wireless connectivity beyond terrestrial cellular coverage [1], [15]. Within this context, D2C communication has gained increasing attention because it enables LEO satellites to provide connectivity to conventional cellular UEs using existing mobile devices and terrestrial spectrum [2]. Recent industrial developments, including the SpaceX–T-Mobile collaboration, further demonstrate the practical feasibility of this concept [2], [4].

RIS and HAP-RIS have attracted significant interest for improving wireless propagation conditions [5]. While passive RISs rely on phase control, their performance in long-distance satellite links is limited by the attenuation of the cascaded two-hop channel. Active RISs address this limitation through signal amplification in addition to phase control [13], [14], while HAP-RIS architectures reduce the number of required active elements while retaining amplification capability [6].

Although substantial progress has been achieved in RIS-assisted communications, most existing studies focus on terrestrial scenarios or simplified analytical channel models. In D2C satellite communications, previous work has mainly addressed coverage, connectivity, spectrum sharing, and system architecture [6]. Comparatively fewer studies have evaluated end-to-end HAP-RIS-assisted D2C links under realistic satellite orbital dynamics, where satellite motion, slant range, and elevation angle vary over time. Their combined impact on received carrier power, C/N_0 , E_b/N_0 , and BER therefore remains insufficiently investigated.

Existing active and hybrid RIS studies have investigated signal amplification, amplifier noise, power constraints, and active–passive element configurations, primarily in terrestrial communication scenarios. However, their integration into time-varying LEO D2C links remains comparatively less explored. In such links, the signal received at the HAP-RIS and the subsequent HAP-RIS-to-satellite propagation jointly determine end-to-end performance, requiring both propagation hops, the hybrid active–passive response, and active-element noise to be considered together.

To address this gap, this work combines STK-based satellite simulation with an analytical HAP-RIS model. STK captures the time-varying satellite link conditions, while the analytical model reconstructs the end-to-end HAP-RIS-assisted link, including the hybrid active–passive response and the additional noise introduced by the active elements.

III. PROPOSED END-TO-END HAP-RIS LINK-BUDGET FRAMEWORK

A. Communication Scenario

The communication scenario considered in this work is illustrated in Fig. 1. A conventional UE communicates with a LEO satellite operating at 1.9925 GHz within the PCS G Block S-band frequency range associated with emerging Supplemental Coverage from Space (SCS) systems [12]. The selected frequency band follows the spectrum-reuse concept adopted in recent D2C architectures, where existing terrestrial cellular spectrum is reused to enable communication between conventional smartphones and LEO satellites without requiring dedicated satellite terminals [4]. The selected operating frequency is also consistent with the reverse spectrum pairing concept considered in emerging SCS systems, in which terrestrial uplink and downlink bands are reused in reversed roles for satellite communications to improve NTN–TN coexistence [8]–[10].

Two communication scenarios are considered: a conventional direct UE-to-satellite D2C uplink and a HAP-RIS-assisted UE-HAP-RIS–satellite link. Because LEO satellites continuously move relative to the terrestrial UE and HAP-RIS, the communication geometry varies over time. In particular, changes in satellite elevation angle and slant range affect the propagation conditions and the received signal power. These time-varying geometric effects are explicitly captured by STK and propagated through the subsequent end-to-end link calculation.

The HAP-RIS combines passive elements for phase control with active elements that additionally amplify the incident signal, with a maximum active-element gain of 40 dB. The noise introduced by the active elements is included in the end-to-end model, as detailed in Sections III-E and III-F.

The time-varying link parameters are obtained from STK and subsequently processed in Python to reconstruct the complete end-to-end HAP-RIS-assisted link, as detailed in Section III-B.

For the multi-satellite analysis, the serving satellite is selected at each epoch according to the procedure described in Section III-B. Constellation-level performance is evaluated statistically using empirical cumulative distribution functions (CDFs) of the time-dependent end-to-end C/N_0 , E_b/N_0 , and BER metrics. Fig. 1 illustrates the direct and HAP-RIS-assisted communication paths together with the time-varying HAP-RIS–satellite geometry.

B. STK-Based Propagation Modeling

STK is used to model the satellite constellation, orbital motion, link visibility, propagation geometry, and antenna and receiver characteristics. The required link parameters are exported from STK and subsequently processed in Python to reconstruct the complete HAP-RIS-assisted communication link.

For the UE–HAP-RIS first hop, STK provides the received carrier power and the corresponding propagation conditions.

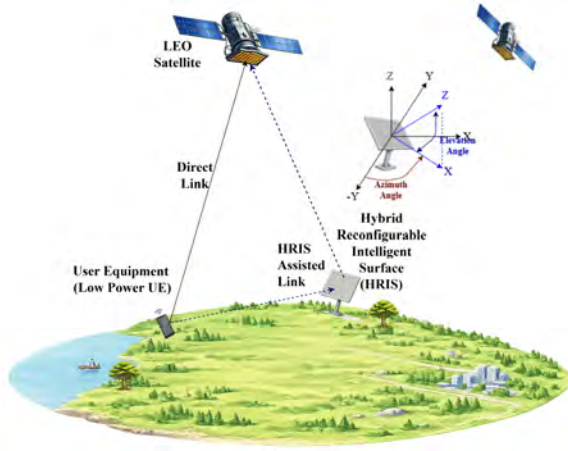


Fig. 1. Direct satellite link and HAP-RIS-assisted communication scenarios between a low-power UE and a LEO satellite.

For the HAP-RIS–satellite second hop, the required quantities include the carrier power at the satellite receiver input, HAP-RIS transmitter EIRP, satellite receive gain, receiver G/T , and the satellite strand associated with each sample.

When multiple satellites are simultaneously available, one satellite is selected at each simulation epoch. Let $\mathcal{S}(t)$ denote the set of satellites satisfying the visibility conditions at time t . The selected satellite is defined as

$$s^*(t) = \arg \max_{s \in \mathcal{S}(t)} \left(\frac{C}{N_0} \right)_{\text{STK},s}(t). \quad (1)$$

where $(C/N_0)_{\text{STK},s}(t)$ is the STK-reported carrier-to-noise density ratio for satellite s at time t .

Once $s^*(t)$ is selected, all second-hop quantities used in the analytical calculation, including the carrier power, EIRP, satellite receive gain, and G/T , are taken from the same satellite strand. This prevents parameters belonging to different satellite links from being combined in the end-to-end calculation.

The STK C/N_0 used in (1) serves only to select the satellite at each epoch and is not treated as the final HAP-RIS-assisted end-to-end C/N_0 . Instead, STK provides the physical propagation, antenna, and receiver parameters required by the analytical model. Python then applies the HAP-RIS processing and noise model to calculate the final received carrier power, C/N_0 , E_b/N_0 , and theoretical BER.

C. End-to-End Signal Model

The HAP-RIS-assisted communication link is evaluated by combining the STK-derived link parameters with an analytical model of the HAP-RIS. The complete communication path consists of two propagation hops: the UE–HAP-RIS link and the HAP-RIS–satellite link.

The signal transmitted by the UE first propagates to the HAP-RIS. The received signal is then processed coherently by the passive and active elements. The passive elements provide phase control, while the active elements additionally amplify the signal subject to their gain and power constraints. The

independent thermal noise generated by the active elements is also included in the model. A compact baseband representation of the received signal at the satellite is given by

$$y = \sqrt{P_{\text{UE}}} \mathbf{h}_2^H \Theta \mathbf{h}_1 x + \mathbf{h}_2^H \Theta_A \mathbf{n}_A + n_{\text{sat}}, \quad (2)$$

where P_{UE} is the UE transmit power, $\mathbf{h}_1$ and $\mathbf{h}_2$ represent the UE–HAP-RIS and HAP-RIS–satellite channels, respectively, Θ represents the HAP-RIS response, Θ_A contains the coefficients associated with the active elements, $\mathbf{n}_A$ represents the independently generated active-element noise, and n_{sat} denotes the satellite receiver thermal noise.

The first term in (2) represents the desired signal coherently processed by the HAP-RIS. The second term represents the noise introduced by the active elements and propagated through the second hop, while the final term represents the satellite receiver thermal noise.

The following subsections detail the first-hop reception, hybrid active–passive processing, second-hop propagation, and end-to-end calculation of C/N_0 , E_b/N_0 , and theoretical BER.

D. First-Hop Link Budget

The first stage of the end-to-end analysis represents the UE–HAP-RIS link. For the fixed-UE scenario, the carrier power at the HAP-RIS receiver input is obtained directly from the corresponding STK link. Therefore, the UE transmit power, first-hop propagation loss, and HAP-RIS receive gain are already included in this quantity and are not applied again during Python post-processing.

The incident carrier power is converted from dBW to linear power as $P_{\text{HAP-RIS,in}} = 10^{P_{\text{HAP-RIS,in}}^{\text{(dBW)}}/10}$, where $P_{\text{HAP-RIS,in}}^{\text{(dBW)}} = -39.392$ dBW for the fixed-UE case.

This value represents the total carrier power incident on the HAP-RIS and serves as the physical input to the subsequent hybrid active–passive processing. In the considered HAP-RIS architecture, signal reception from the UE is represented by the HAP-RIS receive aperture, modeled in STK with an equivalent phased-array receive gain of $G_{\text{Rx,array}} = 35$ dBi. This receive-array gain is already included in the STK-derived carrier power $P_{\text{HAP-RIS,in}}$ and is therefore not reapplied in the analytical reconstruction. It should be distinguished from both the coherent hybrid active–passive processing gain introduced in the following subsection and the independent HAP-RIS transmit-array gain used for the second hop.

For the element-level analytical model, $P_{\text{HAP-RIS,in}}$ is interpreted as the total carrier power collected by the HAP-RIS receive aperture, including the receive-array gain already accounted for in STK. This power is equally distributed across the N HAP-RIS elements as

$$P_{\text{sig,el}} = \frac{P_{\text{HAP-RIS,in}}}{N}, \quad N = 1312.$$

This normalization only partitions the total STK-derived aperture power among the element-level branches and does not introduce an additional receive-array gain.

The resulting element-level power is subsequently used to evaluate the active-element power constraint and noise contribution.

E. HAP-RIS Model

After reception of the UE signal, the HAP-RIS applies coherent phase control and amplification before the signal propagates toward the satellite. The surface consists of $N = N_A + N_P = 1312$ elements, with $N_A = 732$ active and $N_P = 580$ passive elements. The passive elements have unit reflection amplitude, whereas each active element provides an amplification coefficient α . For a maximum active-element power gain of $g_A = 40$ dB, the maximum amplitude coefficient, the power-limited coefficient, and the actual amplification coefficient are, respectively,

$$\alpha_{\max} = 10^{g_A/20} = 100, \quad \alpha_{\text{power}} = \sqrt{\frac{P_{\text{RIS,max}}}{N_A \xi_{\text{el}}}}, \quad (3)$$

$$\alpha = \min(\alpha_{\max}, \alpha_{\text{power}}).$$

where ξ_{el} is the total input power handled by one active element, including the incident signal and the amplifier input noise within the communication bandwidth. For the considered operating conditions, the power constraint does not reduce the active-element gain, resulting in $\alpha = 100$.

Assuming ideal phase alignment, the normalized coherent amplitude response and the corresponding coherent power gain of the hybrid surface are

$$A_{\text{coh}} = \frac{N_P + \alpha N_A}{N}, \quad (4)$$

$$G_{\text{coh}} = A_{\text{coh}}^2 = \left(\frac{N_P + \alpha N_A}{N} \right)^2.$$

It is important to distinguish G_{coh} from the HAP-RIS antenna-array gains. The former represents the coherent power gain produced by the hybrid active-passive processing and is not an antenna gain. For the considered configuration, $G_{\text{coh,dB}} \approx 35$ dB, whereas the HAP-RIS receive- and transmit-array gains are separate antenna quantities, each equal to 35 dBi.

F. Active-Element Noise Model

The active-element amplifier noise factor is $F_A = 10^{N_{FA}/10} = 1.2589$ for $N_{FA} = 1$ dB. The active-element noise power spectral density, noise power within bandwidth B , and total input power handled by one active element are, respectively,

$$N_{0,A} = kT_0(F_A - 1),$$

$$\sigma_A^2 = N_{0,A}B, \quad (5)$$

$$\xi_{\text{el}} = P_{\text{sig,el}} + \sigma_A^2,$$

where k is Boltzmann's constant and $T_0 = 290$ K is the reference temperature. The quantity ξ_{el} is used in the active-element power constraint introduced in Section III-E. Because the noise generated by different active elements is statistically independent, their noise powers are combined incoherently. Therefore, the aggregate active-element noise scales with $N_A \alpha^2 N_{0,A}$ rather than with $N_A^2 \alpha^2 N_{0,A}$. The

propagation of this noise through the HAP-RIS-satellite link and its contribution at the satellite receiver are included in the end-to-end noise calculation presented in Section III-H.

G. Second-Hop Link Budget and End-to-End Carrier Power

For the second hop, the channel transfer is obtained from the STK carrier power and EIRP corresponding to the satellite selected according to (1):

$$H_{(2,\text{dB})}(t) = P_{C,\text{STK2}}^{(\text{dBW})}(t) - \text{EIRP}_{\text{STK}}^{(\text{dBW})}(t). \quad (6)$$

The corresponding linear channel transfer is

$$H_2(t) = 10^{\frac{H_{(2,\text{dB})}(t)}{10}}. \quad (7)$$

This formulation extracts the second-hop transfer excluding the transmitter EIRP, thereby avoiding double counting of the HAP-RIS transmit antenna gain while retaining the STK-modeled propagation and receiver-side contributions. After hybrid processing, the signal is radiated toward the selected satellite through a dedicated phased-array transmit antenna, distinct from the receive array used on the UE-HAP-RIS hop. Both arrays provide 35 dBi gain in the considered configuration.

The HAP-RIS transmit-array gain is converted to linear scale as $G_{\text{Tx,array}} = 10^{G_{\text{Tx,array,dBi}}/10}$.

The final carrier power at the satellite receiver is then reconstructed as

$$C_{\text{sat}}(t) = P_{\text{HAP-RIS,in}}(t) G_{\text{coh}}(t) G_{\text{Tx,array}} H_2(t), \quad (8)$$

where $P_{\text{HAP-RIS,in}}$ is the carrier power at the HAP-RIS receiver input and G_{coh} is the coherent hybrid active-passive power gain defined in Section E.

The STK-reported second-hop carrier power is used only to extract $H_2(t)$; the final HAP-RIS carrier is reconstructed analytically according to (8).

H. End-to-End Noise and Performance Metrics

The total receiver noise includes the satellite receiver thermal noise and the active-element noise propagated through the second hop. The satellite system noise temperature is obtained from the STK receiver gain and G/T as

$$T_{\text{sys,sat}}(t) = 10^{\frac{G_{\text{Rx,sat}}(t) - (G/T)_{\text{sat}}(t)}{10}}. \quad (9)$$

where $G_{\text{Rx,sat}}(t)$ and $(G/T)_{\text{sat}}(t)$ are the receive antenna gain and G/T of the selected satellite receiver obtained from STK.

The corresponding satellite receiver noise power spectral density is $N_{0,\text{sat}}(t) = kT_{\text{sys,sat}}(t)$.

The effective second-hop transfer for the noise contribution of an individual active HAP-RIS element is

$$H_{(2,\text{el})}(t) = \frac{H_2(t) G_{\text{Tx,array}}}{N}. \quad (10)$$

The desired signal is coherently beamformed and therefore experiences the full transmit-array gain $G_{\text{Tx,array}}$, whereas

the statistically independent active-element noise contributions combine incoherently. Accordingly, $G_{Tx,array}/N$ is used as the equivalent per-element transmit gain for noise propagation.

$$N_{0,HAP-RIS}(t) = N_{0,A} N_A \alpha^2 H_{(2,el)}(t). \quad (11)$$

The total noise PSD is $N_{0,total}(t) = N_{0,sat}(t) + N_{0,HAP-RIS}(t)$.

Using the analytically reconstructed carrier power from (8), the final end-to-end C/N_0 is

$$\left(\frac{C}{N_0}\right)(t) = \frac{C_{sat}(t)}{N_{0,total}(t)}. \quad (12)$$

The link metrics are obtained from

$$\left(\frac{E_b}{N_0}\right)_{dB}(t) = \left(\frac{C}{N_0}\right)_{dB-Hz}(t) - 10 \log_{10}(R_b). \quad (13)$$

where $B = 180$ kHz and $R_b = 256$ kb/s. For Gray-coded QPSK, the BER is given by

$$P_b(t) = Q\left(\sqrt{2 \times 10^{(E_b/N_0)_{dB}(t)/10}}\right). \quad (14)$$

IV. SIMULATION SETUP

The proposed HAP-RIS-assisted D2C link is evaluated using a combined STK–Python simulation framework. The communication link operates at 1.9925 GHz within the PCS G Block S-band spectrum, with a bandwidth of 180 kHz and a bit rate of 256 kb/s. The adopted bandwidth corresponds to a single LTE/NR resource block consisting of 12 subcarriers with 15 kHz spacing and represents a narrowband D2C scenario suitable for low-rate NTN services [7]. QPSK modulation is considered, and the UE transmit power is set to -5 dBW.

The HAP-RIS parameters used in the simulation follow the model described in Section III.

The satellite constellation and propagation geometry are modeled in Ansys STK. The simulations are carried out for a Walker Delta LEO constellation consisting of 48 satellites distributed across 8 orbital planes, with 6 satellites in each plane. The satellites operate in circular orbits at an altitude of approximately 530 km and an inclination of 53° . The constellation is evaluated over a 24-hour observation period using a simulation step size of 60 s, resulting in 1440 observation epochs.

The simulations are performed for a terrestrial UE and a stationary HAP-RIS located in Pittsburgh, Pennsylvania, USA. For the fixed-user configuration considered in the final analysis, the UE-HAP-RIS separation is approximately 34.8 m. This geometry is used for the fixed-UE first-hop link, while the moving-user case is analyzed separately using the trajectory described in Section IV-D.

The analysis is first performed for an individual satellite pass to examine the effect of time-varying satellite geometry on link performance and is then extended to the complete constellation for statistical evaluation over the 24-hour observation period.

The satellite receiver is modeled using the STK Complex Receiver Model. The antenna noise temperature, antenna-to-LNA transmission-line temperature, LNA temperature, and LNA-to-receiver transmission-line temperature are set to 290 K, while the LNA noise figure is set to 1 dB. These STK receiver parameters are used to obtain the satellite receiver quantities required by the analytical noise model.

At each simulation epoch, the serving satellite and its corresponding second-hop parameters are selected according to the procedure described in Section III-B.

Empirical CDFs of C/N_0 , E_b/N_0 , and BER-related reliability metrics are used to compare the direct and HAP-RIS-assisted links.

A. Single-Satellite Direct-Link Analysis

The conventional D2C link is first examined during a representative LEO satellite pass. Fig. 2 shows the variation of the satellite elevation angle and slant range over the pass. As the satellite approaches the user location, the elevation angle increases and the slant range decreases. The shortest propagation distance occurs close to the maximum elevation angle, after which the satellite moves away and the slant range increases again.

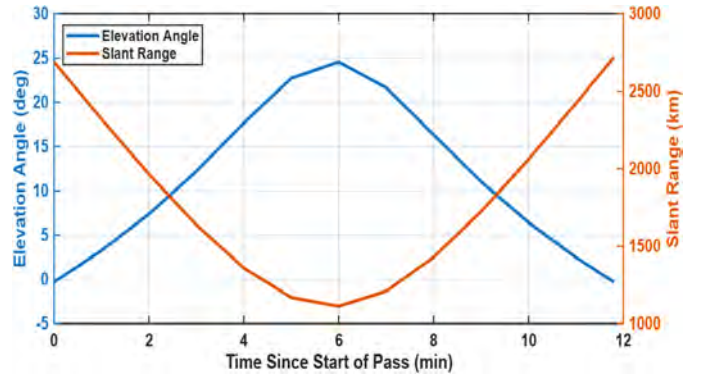


Fig. 2. Elevation angle and slant range variations during a representative visibility pass of the selected LEO satellite. The horizontal axis represents the elapsed time from the beginning of the pass.

The corresponding direct-link performance is shown in Fig. 3. The C/N_0 increases as the satellite approaches the user and reaches its maximum near the middle of the pass. It then decreases as the satellite moves away and the propagation distance increases. The BER follows the opposite trend, decreasing rapidly as the link improves and reaching its minimum near the maximum C/N_0 . Toward the end of the pass, the BER increases again as the C/N_0 decreases. These results illustrate the strong dependence of the direct D2C link on the time-varying satellite geometry.

B. Multi-Satellite Statistical Performance Analysis

The analysis is next extended to the complete 48-satellite Walker Delta constellation to evaluate the statistical performance of the direct and HAP-RIS-assisted links. At each epoch, the serving satellite and its corresponding second-hop

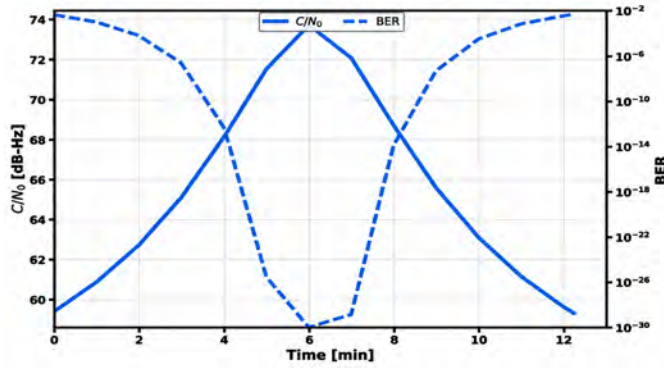


Fig. 3. Carrier-to-noise density ratio (C/N_0) and theoretical BER of the conventional direct UE-to-satellite link during a single LEO satellite pass.

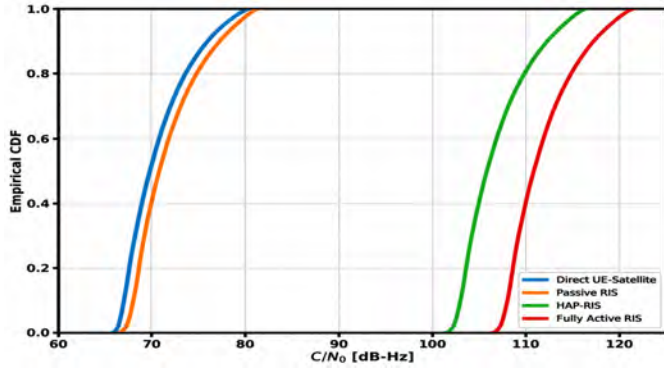


Fig. 4. Empirical CDFs of the end-to-end C/N_0 for the direct, passive RIS, HAP-RIS, and fully active RIS configurations in the fixed-user scenario.

parameters are selected according to the procedure described in Section III-B.

Before evaluating the communication performance, the availability of the constellation was analyzed. The corresponding results are summarized in Table I.

TABLE I
AVAILABILITY RESULTS FOR THE 48-SATELLITE HAP-RIS-ASSISTED D2C SCENARIO OVER A 24-HOUR OBSERVATION PERIOD

Metric	Value
Total time samples	1440
Samples with at least one valid satellite	1440
Samples with zero valid satellites	0
Availability	100%
Outage	0%
Outage time	0 min
Minimum valid satellites	2
Maximum valid satellites	6
Mean valid satellites	2.94

As shown in Table I, the constellation provides 100% availability with zero outage over the simulated day, with 2–6 simultaneously available satellites and an average of 2.94.

The statistical performance of the direct and HAP-RIS-assisted links is then compared in terms of C/N_0 , E_b/N_0 , and theoretical BER. As shown in Fig. 4, the HAP-RIS-assisted link provides consistently higher C/N_0 than the conventional

direct link. Among the RIS configurations, the fully active RIS provides the highest end-to-end C/N_0 , whereas the passive RIS provides the lowest performance. The proposed HAP-RIS operates between these two cases, providing a substantial improvement over the passive configuration while using fewer active elements than the fully active RIS. These results demonstrate the link-margin improvement provided by the HAP-RIS and illustrate the trade-off between active-element utilization and achievable end-to-end link quality.

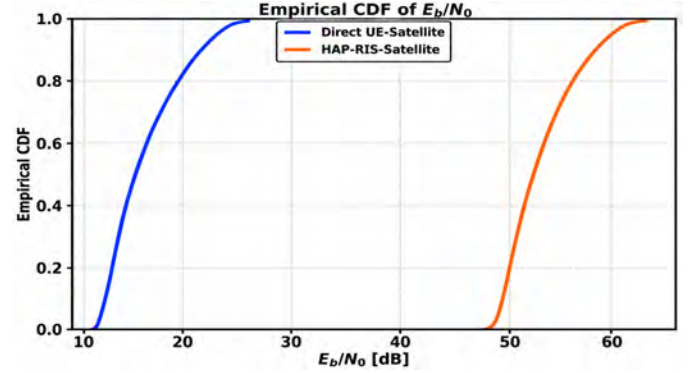


Fig. 5. CDFs of E_b/N_0 for the direct D2C and HAP-RIS-assisted UE-HAP-RIS-satellite communication links.

Figure 5 shows the corresponding E_b/N_0 distributions. As expected from the fixed bit rate, the E_b/N_0 results follow the same statistical trend as C/N_0 , while the HAP-RIS-assisted link maintains a substantially larger link margin than the direct link over the observation period.

The corresponding BER reliability is shown in Fig. 6 as the probability of achieving a BER below a specified threshold, enabling a direct comparison between the direct and HAP-RIS-assisted links.

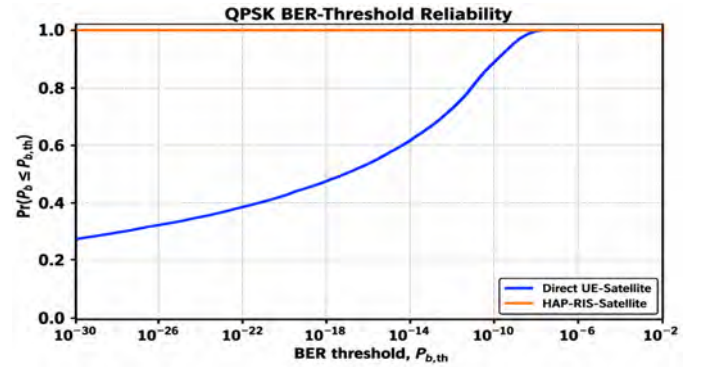


Fig. 6. Probability of achieving a theoretical BER below a specified threshold for the direct UE-to-satellite and HAP-RIS-assisted UE-HAP-RIS-satellite communication links.

As shown in Fig. 6, the HAP-RIS-assisted link provides a higher probability of satisfying stringent BER requirements than the direct link, consistent with the corresponding C/N_0 and E_b/N_0 improvements.

The final BER values are calculated from the analytically derived end-to-end E_b/N_0 rather than taken directly from

STK, whose BER output exhibits a numerical reporting floor at 10^{-30} . In the preliminary STK-based evaluation, 4397 out of 4398 HAP-RIS samples (99.98%) were reported at 10^{-30} , while only one sample (0.02%) had a larger value of 3.33×10^{-11} , indicating that 10^{-30} is a numerical reporting limit rather than a physical BER floor.

The final BER is therefore evaluated in the logarithmic domain to avoid this reporting limitation and numerical underflow at very small error probabilities. Accordingly, the lower BER threshold in Fig. 6 is a plotting limit rather than a physical BER floor.

C. RIS Architecture Comparison

The passive, hybrid active-passive, and fully active RIS architectures are compared under the same fixed-user scenario, each with $N = 1312$ elements. The passive RIS uses 1312 passive elements, the proposed HAP-RIS uses 732 active and 580 passive elements, and the fully active RIS uses 1312 active elements. The active configurations follow the amplification and noise model described in Section III.

D. Moving-User Performance Analysis

To investigate the effect of user mobility, a specific pedestrian trajectory was simulated over a 143 s observation interval. The UE follows a three-waypoint GreatArc trajectory at a constant speed of 1.4 m/s, covering approximately 200 m, while the HAP-RIS remains stationary. The trajectory extends from longitude -79.971481° to -79.969119° at a constant latitude of 40.461800° and an altitude of 1.7 m. Consequently, the UE-HAP-RIS distance and the corresponding first-hop propagation conditions vary throughout the trajectory.

The moving-user scenario uses the same communication and HAP-RIS parameters as the fixed-user case, and the results are specific to the considered trajectory rather than a general statistical characterization of user mobility.

Figure 7 compares the C/N_0 evolution for the fixed- and moving-UE cases. The direct-link curves remain nearly coincident, indicating that the considered UE movement has little effect on the direct link. In contrast, the HAP-RIS-assisted moving-UE link varies as the UE approaches and moves away from the HAP-RIS, with C/N_0 reaching its maximum near the minimum UE-HAP-RIS distance, as shown in Fig. 7(b).

This behavior is consistent with the first-hop received carrier power. The HAP-RIS input carrier power is approximately -39.392 dBW for the fixed UE, compared with a median of approximately -44.2 dBW for the moving UE. Since this power is the input to the HAP-RIS processing, its variation directly affects the end-to-end C/N_0 . As the same HAP-RIS-satellite second-hop conditions are used in both cases, the observed variation is primarily due to the time-varying UE-HAP-RIS first-hop conditions rather than UE speed alone.

Figure 8 shows the C/N_0 distributions and the corresponding E_b/N_0 distributions for the same trajectory, using the lower and upper horizontal axes, respectively. The HAP-RIS-assisted link shows a clear separation from the direct link, reflecting the time-varying UE-HAP-RIS first-hop conditions

observed in Fig. 7. The same separation is retained in E_b/N_0 , with the HAP-RIS-assisted link maintaining a higher link margin throughout the considered trajectory.

Figure 9 presents the corresponding BER-threshold reliability. For the HAP-RIS-assisted link, the analytically calculated BER remains below the minimum displayed threshold of 10^{-30} for the considered samples, whereas the direct link shows lower reliability over part of the threshold range.

V. CONCLUSION

This paper presented an end-to-end framework for evaluating HAP-RIS-assisted D2C communications in LEO non-terrestrial networks. The proposed approach combines STK-based satellite geometry, propagation conditions, and link parameters with an analytical model of the HAP-RIS. This allows the end-to-end carrier power, active-element noise contribution, C/N_0 , E_b/N_0 , and BER to be evaluated for the complete UE-HAP-RIS-satellite link.

The results show that the HAP-RIS-assisted link provides substantial improvements in C/N_0 and E_b/N_0 over the conventional direct UE-satellite link while explicitly accounting for the additional noise introduced by the active elements.

The comparison among passive, hybrid, and fully active RIS configurations shows that the fully active configuration provides the highest end-to-end C/N_0 , while the passive configuration provides the lowest. The proposed HAP-RIS achieves a clear improvement over the passive configuration using 732 active elements instead of a fully active 1312-element surface, illustrating the trade-off between active-element count and link performance.

The moving-user analysis further shows that, for the considered 143 s trajectory, the HAP-RIS-assisted link maintains higher C/N_0 , E_b/N_0 , and BER-threshold reliability than the direct link. Its larger variation is primarily associated with the time-varying UE-HAP-RIS first-hop conditions rather than UE speed alone. These results are specific to the considered trajectory and should not be interpreted as a general statistical characterization of user mobility.

The study also highlights a limitation of conventional STK-based evaluation: the standard communication chain does not directly represent the coherent active-passive RIS response together with active-element amplification and amplifier noise. The proposed STK-analytical approach addresses this limitation while retaining the realistic satellite geometry and propagation information provided by STK.

For very high E_b/N_0 , BER is evaluated in the logarithmic domain to avoid numerical underflow, and the minimum displayed BER thresholds should not be interpreted as physical BER floors.

Future work will extend the framework by considering practical hardware impairments, imperfect channel state information, power-allocation and beamforming optimization, and more extensive mobility scenarios. Longer observation periods and multiple UE trajectories will also be considered to obtain a broader statistical characterization of system performance under user mobility.

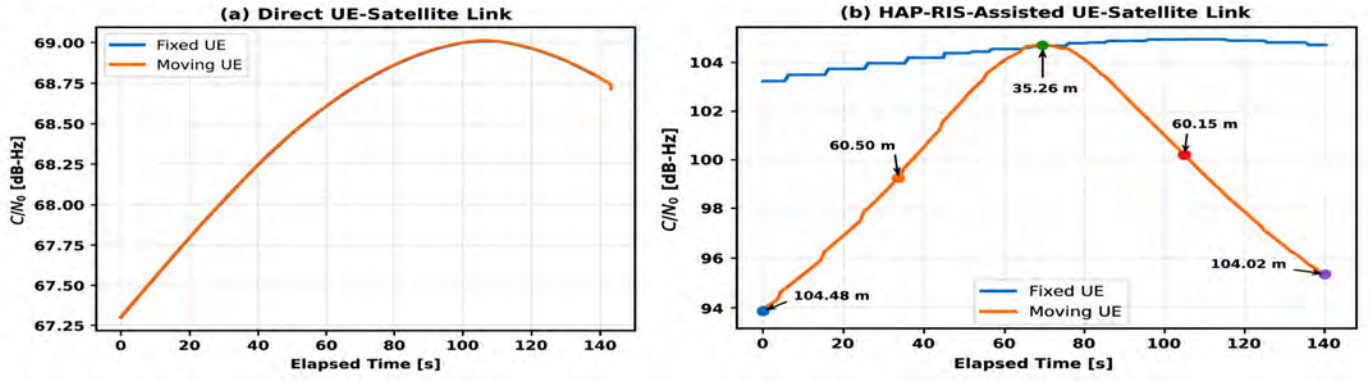


Fig. 7. C/N_0 comparison for the fixed and moving UE: (a) direct UE-satellite link and (b) HAP-RIS-assisted UE-satellite link. The annotated values in (b) indicate the UE-HAP-RIS distance at selected points along the moving-UE trajectory.

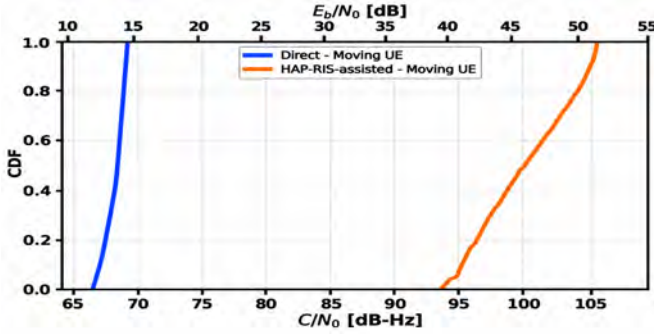


Fig. 8. Empirical CDFs of the moving-user direct and HAP-RIS-assisted links. The lower and upper horizontal axes show the equivalent C/N_0 and E_b/N_0 scales, respectively.

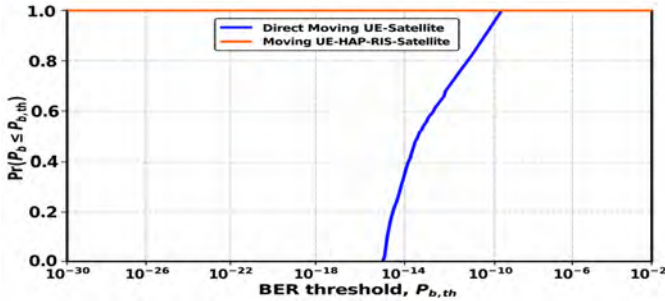


Fig. 9. QPSK BER-threshold reliability for the moving-user direct and HAP-RIS-assisted communication links.

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