Downlink and Uplink Low Earth Orbit Satellite Backhaul for Airborne Networks

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***Abstract*—Providing backhaul access for airborne networks ensures their seamless connectivity to other aerial or terrestrial users with sufficient data rate. The backhaul for aerial platforms (APs) has been mostly provided through geostationary Earth orbit satellites and the terrestrial base stations (BSs). However, the former limits the achievable throughput due to significant path loss and latency, and the latter is unable to provide full sky coverage due to existence of wide under-served regions on Earth. Therefore, the emerging low Earth orbit (LEO) Internet constellations have the potential to address this problem by providing a thorough coverage for APs with higher data rate and lower latency. In this paper, we analyze the coverage probability and data rate of a LEO backhaul network for an AP located at an arbitrary altitude above the ground. The satellites' locality is modeled as a nonhomogeneous Poisson point process which not only enables tractable analysis by utilizing the tools from stochastic geometry, but also considers the latitude-dependent density of satellites. To demonstrate a compromise on the backhaul network's selection for the airborne network, we also compare the aforementioned setup with a reference terrestrial backhaul network, where AP directly connects to the ground BSs. Based on the numerical results, we can conclude that, for low BS densities, LEO satellites provide a better backhaul connection, which improves by increasing the AP's altitude.**

I. Introduction

Connecting aerial platforms (APs), e.g., airplanes, unmanned aerial vehicles (UAVs), high altitude platforms (HAPs), etc. to the ground users or other APs is envisioned as a significant aspect in 6G airborne–terrestrial integration [1]. To satisfy the high demands of APs for data rate, a high quality backhaul connection is required to ensure the collection of data from/to the APs. One approach to provide backhaul for the airborne network is through geostationary satellites, which provide full sky coverage for most of the regions [2]–[4]. However, other than considerable delay caused by traveling the signal over a large distance, the received signal is subject to sever path loss which limits the achievable data rate significantly. Terrestrial base stations (BSs) can also serve as backhaul for the airborne network with considerably smaller path attenuation and latency [5]–[8]. The main drawback of the terrestrial network is the lack of full sky coverage due to huge under-served regions, e.g., oceans and deserts. Moreover, local operators may restrict the service for some global APs.

The emerging low Earth orbit (LEO) mega-constellation networks, with the primary intention to provide connectivity for remote and under-connected regions, have a great potential to serve as backhauls for the APs due to offering less path attenuation and delay w.r.t. satellites on the geostationary orbit, and a better sky coverage w.r.t. the terrestrial network.

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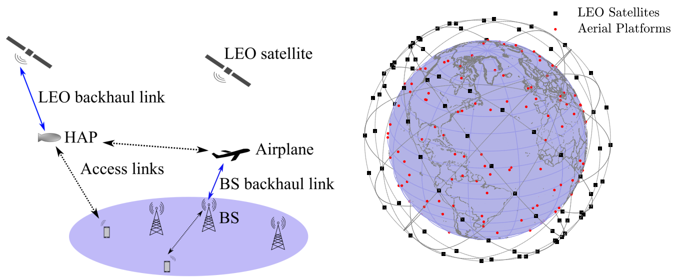
Along with rapid commercial progress of LEO mega-constellations, e.g., Starlink, Oneweb, Kuiper, and Telesat, their performance analysis when serving a ground gateway and/or user has attracted significant attention recently [9]–[15]. Stochastic geometry was deployed as the most promising tool for analytical understanding of such ultra-dense LEO networks. The first key step for stochastic geometry-based analysis is modeling the satellites' locality with a proper point process which not only facilitates the tractability of the derivations, but also captures the physical characteristics of the network. A Binomial point process (BPP) was used in [9], [10] to model a LEO constellation and derive the downlink coverage probability and data rate. Since the satellites' locations in actual constellations barely follow a uniform distribution, the inherent performance mismatch was adjusted numerically in [9], and analytically through finding the effective number of satellites for every user's latitude in [10].

To better address the uneven distribution of satellites on orbits, in [11] and [12], a nonhomogeneous Poisson point process (PPP) with a latitude-dependent intensity, was utilized to model the satellites' locations. In [13], [14], distance distributions and the coverage probability were formulated for a LEO network comprised of multiple concentric orbital shells, each of which has a known specific radius. The contact angle, i.e., the minimum angular distance between the satellites and the ground user, is characterized in [15] to evaluate the performance of a LEO network without considering the effect of shadowing attenuation. In [16], the distribution of conditional coverage probability was derived, given the nodes' positions, for a satellite–terrestrial relay network to evaluate the percentage of users that may reach a target SINR threshold. Estimation and characterization of Doppler shift is addressed in downlink LEO communication in [17].

Despite the significant utilization of stochastic geometry for UAV-to-ground communication analysis [5]–[8], its application on the study of LEO-backhauled APs has remained unrecognized. In [18], a LEO backhaul, by considering only a single orbit with few satellites at pre-determined positions, is studied for both terrestrial and aerial BSs. The throughput of both backhaul and access links is maximized jointly through radio resource management and UAV trajectory optimization. In [19], capacity and range of air-to-air and satellite networks



(a) Schematic of the system model. (b) A LEO constellation.

Fig. 1: An airborne network backhauled by either LEO or terrestrial network for uplink and/or downlink connections.

are evaluated as a backhaul for APs through simulations only. It was shown that integration of air-to-air communication and LEO satellites improves the data rate of APs significantly. Revenue maximization in LEO satellites in case of cooperation of LEO satellites and HAPs as data backhaul is studied in [20] for remote regions.

In this paper, we analyze the performance of a LEO satellite backhaul for an airborne network in terms of the coverage probability and the data rate. We model the satellites' locality as a nonhomogeneous PPP which leads to tractable analytical derivations as well as compensation for the latitude-dependent distribution of satellites over the spherical shell. Unlike the existing literature, the satellites are assumed to have directional antennas with their boresight radiating towards the AP. Moreover, we compare the performance of the described setup with the performance of the terrestrial backhaul which provides noteworthy criteria on the selection of the best backhaul for APs, depending on the constellation parameters, the density of ground BSs, and AP's location. Using the numerical results, we verify our derivations and illustrate the performance of both backhaul networks in terms of different system parameters.

II. System Model

Let us consider an airborne network, as in Fig. 1(a), which can be backhauled by either a LEO satellite network or the terrestrial BSs for both uplink and downlink directions. A high quality backhaul connection may facilitate the connectivity of APs in the airborne network to other APs or ground users via access links. Each AP is located at an arbitrary altitude and latitude, represented by a_{AP} and ϕ_{AP}, respectively, above the Earth's surface, which is assumed to be a perfect sphere with radius $r_\oplus \approx 6371$ km. Each AP may select the best backhaul connection, i.e, the one which provides better coverage and rate, between the LEO and the terrestrial network.

A LEO satellite backhaul to serve the airborne network is shown in Fig. 1(b). The satellite network comprises N satellites distributed uniformly on circular inclined orbits with altitude and inclination angle denoted by a_{s} and ι, respectively. Obviously, $a_{\mathrm{s}} > a_{\mathrm{AP}}$ or actually $a_{\mathrm{s}} \gg a_{\mathrm{AP}}$. The maximum distance at which an AP may communicate with a LEO satellite (that is when the signal is not blocked by Earth) is

$$r_{\max} = \sqrt{2r_\oplus a_{\mathrm{s}} + a_{\mathrm{s}}^2} + \sqrt{2r_\oplus a_{\mathrm{AP}} + a_{\mathrm{AP}}^2}. \tag{1}$$

The satellites and APs are equipped with directional antennas with their main beam radiating towards the transceiver. The satellites' and the AP's antenna gains are denoted by G_{s} and G_{AP}, respectively, and $G_{\mathrm{t}} = G_{\mathrm{AP}}G_{\mathrm{s}}$ is the overall antenna gain. For terrestrial backhaul, the BS's antenna gain is denoted by G_{BS}, and $G_{\mathrm{t}} = G_{\mathrm{AP}}G_{\mathrm{BS}}$. It is worth noting that the AP's antenna gain is different for LEO- and BS-backhauled connections. In this paper, we assume that APs connect to their nearest satellite/BS which will be referred to as the serving satellite/BS. As the network is equipped with directional antennas, the performance is assumed to be noise-limited. The signal-to-noise ratio (SNR) at the receiver can be expressed as

$$\mathrm{SNR} = \begin{cases} \dfrac{p_{\mathrm{s}} G_{\mathrm{t}} H_{\mathrm{s}} R_{\mathrm{s}}^{-\alpha}}{\sigma^2}, & R_{\mathrm{s}} \le u, \\ 0, & \text{otherwise}, \end{cases} \tag{2}$$

where p_{s} is the transmission power and R_{s} is the distance between the AP and the serving satellite or BS with H_{s} being its corresponding channel gain. The constant σ^2 is the additive noise power and α is a path loss exponent. The upper limit $u = r_{\max}$ for LEO backhaul and $u \to \infty$ for terrestrial backhaul.

To facilitate tractable performance analysis of the described LEO backhaul network, we model the satellites as a nonhomogeneous Poisson point process. Such model not only enables us to tractably analyze the performance of a LEO backhaul network, but also models the varying density of satellites across different latitudes in the actual physical network by setting the intensity of nonhomogeneous PPP, $\delta(\phi_{\mathrm{s}}, \lambda_{\mathrm{s}})$, to the actual distribution of satellites along different latitudes [11], [12]. When satellites are distributed uniformly on low Earth orbits, the intensity of nonhomogeneous PPP is a function the satellites' latitudinal element, ϕ_{s}, which is given as [11], [12]

$$\delta(\phi_{\mathrm{s}}, \lambda_{\mathrm{s}}) = \delta(\phi_{\mathrm{s}}) = \frac{N}{\sqrt{2}\pi^2 (a_{\mathrm{s}} + r_\oplus)^2 \sqrt{\cos(2\phi_{\mathrm{s}}) - \cos(2\iota)}}. \tag{3}$$

By the definition of a nonhomogeneous PPP, the number of points in a bounded region $\mathcal{A}$ of the orbital shell is a Poisson-distributed random variable denoted by $\mathcal{N}$. Therefore, the probability of existing n satellites in $\mathcal{A}$ is given by

$$\begin{aligned} P_n(\mathcal{A}) &\triangleq \mathbb{P}(\mathcal{N} = n) \\ &= \frac{1}{n!}\left(\iint_{\mathcal{A}} \delta(\phi_{\mathrm{s}}, \lambda_{\mathrm{s}}) (a_{\mathrm{s}} + r_\oplus)^2 \cos(\phi_{\mathrm{s}})\, d\phi_{\mathrm{s}} d\lambda_{\mathrm{s}}\right)^n \\ &\times \exp\left(-\iint_{\mathcal{A}} \delta(\phi_{\mathrm{s}}, \lambda_{\mathrm{s}}) (a_{\mathrm{s}} + r_\oplus)^2 \cos(\phi_{\mathrm{s}})\, d\phi_{\mathrm{s}} d\lambda_{\mathrm{s}}\right), \end{aligned} \tag{4}$$

where $\delta(\phi_{\mathrm{s}}, \lambda_{\mathrm{s}})$ is the intensity function of nonhomogeneous PPP at latitude ϕ_{s} and longitude λ_{s}.

Following the conventional approach for modeling the locations of terrestrial BSs [21], we assume that the BSs are distributed as a homogeneous PPP with constant intensity, given by δ_{BS}, on a flat plane.

III. Performance Analysis

In this section, we derive analytical expressions for the coverage probability and data rate of the backhaul network. The distribution of the shortest distance between AP and the backhaul server, in terms of its cumulative density function (CDF) and probability density function (PDF), is a key parameter to evaluate the SNR characteristics, which is expressed in the following subsections.

A. Distance to the Serving Satellite or Base Station

In the following lemmas, we will obtain the PDF of the shortest distance between an AP and a LEO satellite or a terrestrial BS.

Lemma 1. *The PDF of the nearest distance between an AP with $a_{\mathrm{AP}} < a_{\mathrm{s}}$ and a LEO satellite, when the satellites are distributed according to a nonhomogeneous PPP with intensity $\delta(\phi_{\mathrm{s}})$, is given by*

$$f_{R_{\mathrm{s}}}(r_{\mathrm{s}}) = \\ = 2r_{\mathrm{s}}\left(\frac{a_{\mathrm{s}}}{r_{\oplus}}+1\right)\exp(-\gamma(r_{\mathrm{s}}))\int_{\max(\phi_{\mathrm{AP}}-\phi_{\max},-\iota)}^{\min(\phi_{\mathrm{AP}}+\phi_{\max},\iota)}\delta(\phi_{\mathrm{s}}) \\ \times\frac{\cos(\phi_{\mathrm{s}})}{\sqrt{\cos^2(\phi_{\mathrm{s}}-\phi_{\mathrm{AP}})-\cos^2(\phi_{\max})}}d\phi_{\mathrm{s}}, \tag{5}$$

where

$$\gamma(r_{\mathrm{s}}) = 2(a_{\mathrm{s}}+r_{\oplus})^2 \\ \times\int_{\max(\phi_{\mathrm{AP}}-\phi_{\max},-\iota)}^{\min(\phi_{\mathrm{AP}}+\phi_{\max},\iota)}\delta(\phi_{\mathrm{s}})\cos(\phi_{\mathrm{s}})\cos^{-1}\!\left(\frac{\cos(\phi_{\max})}{\cos(\phi_{\mathrm{s}}-\phi_{\mathrm{AP}})}\right)d\phi_{\mathrm{s}}, \tag{6}$$

and $r_{\mathrm{s}} \in [a_{\mathrm{s}}-a_{\mathrm{AP}}, r_{\max}]$ while $f_{R_{\mathrm{s}}}(r_{\mathrm{s}}) = 0$ otherwise. The polar angle difference between the serving satellite and the AP is $\phi_{\max} = \cos^{-1}\left(\frac{(a_{\mathrm{s}}+r_{\oplus})^2+(a_{\mathrm{AP}}+r_{\oplus})^2-r_{\mathrm{s}}^2}{2(a_{\mathrm{s}}+r_{\oplus})(a_{\mathrm{AP}}+r_{\oplus})}\right)$.

Proof. For a nonhomogeneous PPP, the CDF of R_{s} can be written as

$$F_{R_{\mathrm{s}}}(r_{\mathrm{s}}) \triangleq 1-\mathbb{P}(R_{\mathrm{s}} > r_{\mathrm{s}}) = 1-\mathbb{P}(\mathcal{N}=0),$$

where $\mathbb{P}(\mathcal{N}=0)$ is the void probability of PPP in $\mathcal{A}(r_{\mathrm{s}})$ that can be obtained from (4) by setting $n=0$. Thus,

$$F_{R_{\mathrm{s}}}(r_{\mathrm{s}}) = \\ 1-\exp\!\left(-\int_{\max(\phi_{\mathrm{AP}}-\phi_{\max},-\iota)}^{\min(\phi_{\mathrm{AP}}+\phi_{\max},\iota)}\beta(\phi_{\mathrm{s}})\delta(\phi_{\mathrm{s}})(a_{\mathrm{s}}+r_{\oplus})^2\cos(\phi_{\mathrm{s}})d\phi_{\mathrm{s}}\right) \\ =1-\exp\!\left(-2\left(a_{\mathrm{s}}+r_{\oplus}\right)^2\int_{\max(\phi_{\mathrm{AP}}-\phi_{\max},-\iota)}^{\min(\phi_{\mathrm{AP}}+\phi_{\max},\iota)}\delta(\phi_{\mathrm{s}})\cos(\phi_{\mathrm{s}}) \right. \\ \left. \times\cos^{-1}\left(\frac{\cos(\phi_{\max})}{\cos(\phi_{\mathrm{s}}-\phi_{\mathrm{AP}})}\right)d\phi_{\mathrm{s}}\right), \tag{7}$$

where $\beta(\phi_{\mathrm{s}})$ is the longitude range inside the spherical cap above AP at latitude ϕ_{s}. The latter equality follows from substitution of $\beta(\phi_{\mathrm{s}})$ using the basic geometry. Taking the derivative of (7) with respect to r_{s} completes the proof. Note that for $\phi_{\max} \leq |\phi_{\mathrm{AP}}|-\iota$ the CDF given in (7) is zero since the spherical cap formed by polar angle $\phi_{\max}$ above the latitude ϕ_{AP} is much farther from the constellation's borders to contain any satellite. □

Let us then derive the serving distance distribution of a reference setup, where an AP is served by the nearest terrestrial BS. The scenario corresponds to the case when there is a sufficient availability of BSs that can provide a high quality backhaul connection for APs. The following lemma represents the distribution of the shortest distance between an AP and a ground BS. Similar approach was used to obtain the nearest distance distribution for terrestrial networks [21] and UAV networks [5].

Lemma 2. *The PDF of the nearest distance between an AP and a ground BS, when the BSs are distributed according to a homogeneous PPP with constant intensity δ_{BS}, is given by*

$$f_{R_{\mathrm{s}}}(r_{\mathrm{s}}) = 2\pi\delta_{\mathrm{BS}}r_{\mathrm{s}}\exp\left(-\pi\delta_{\mathrm{BS}}\left(r_{\mathrm{s}}^2-a_{\mathrm{AP}}^2\right)\right). \tag{8}$$

Proof. Assuming $a_{\mathrm{AP}} \ll r_{\oplus}$, Earth is approximately seen as a flat plane from AP's point of view. Thus, using the definition of CDF and basic geometry, we have

$$F_{R_{\mathrm{s}}}(r_{\mathrm{s}}) \triangleq \mathbb{P}(R_{\mathrm{s}} < r_{\mathrm{s}}) = \mathbb{P}\left(\sqrt{a_{\mathrm{AP}}^2+D_{\mathrm{s}}^2} < r_{\mathrm{s}}\right) \\ = F_{D_{\mathrm{s}}}\left(\sqrt{r_{\mathrm{s}}^2-a_{\mathrm{AP}}^2}\right), \tag{9}$$

where D_{s} is the distance from the serving BS to the projection of AP onto the ground plane. The complementary CDF of D_{s} at $\sqrt{r_{\mathrm{s}}^2-a_{\mathrm{AP}}^2}$ equals the null probability of the homogeneous PPP on a circle with radius $\sqrt{r_{\mathrm{s}}^2-a_{\mathrm{AP}}^2}$, i.e., $F_{R_{\mathrm{s}}}(r_{\mathrm{s}}) = 1-\exp\left(-\pi\delta_{\mathrm{BS}}\left(r_{\mathrm{s}}^2-a_{\mathrm{AP}}^2\right)\right)$. Taking the derivation with respect to r_{s} returns the PDF expression given in the lemma. □

In the following subsections, we utilize the distribution of the serving distance given in Lemmas 1 and 2 to obtain analytical derivations for the probability of coverage and the data rate of a LEO- or BS-backhauled airborne network.

B. Coverage Probability

The probability of SNR at the receiver being above a certain threshold value, $T > 0$, is named as coverage probability in telecommunication systems. Thus, whenever the received SNR is greater than the threshold level, the data can be transmitted successfully with error control coding.

Proposition 1. *The probability of network coverage for an arbitrarily located AP at an altitude, such that $a_{\mathrm{AP}} < a_{\mathrm{s}}$, under generally distributed fading is*

$$P_{\mathrm{c}}(T) \triangleq \mathbb{P}(\mathrm{SNR} > T) \\ = \int_l^u\left(1-F_{H_{\mathrm{s}}}\left(\frac{Tr_{\mathrm{s}}^{\alpha}G_{\mathrm{t}}^{-1}\sigma^2}{p_{\mathrm{s}}}\right)\right)f_{R_{\mathrm{s}}}(r_{\mathrm{s}})dr_{\mathrm{s}}, \tag{10}$$

where $F_{H_{\mathrm{s}}}(\cdot)$ is the CDF of the serving channel gain H_{s}. For LEO-backhauled AP, $f_{R_{\mathrm{s}}}(r_{\mathrm{s}})$ is given in Lemma 1, $u = r_{\max}$

TABLE I: Simulation Parameters

Parameters	Values
Path loss exponent, α	2
Rician factor for LEO-backhauled channel, K	20
Rician factor for BS-backhauled channel, K	5
Transmit power for LEO-backhauled connection, p_{s}	50 dBm
Transmit power for BS-backhauled connection, p_{s}	40 dBm
Noise power, σ^2	-120 dBm
Carrier frequency for LEO-backhauled connection	13.5 GHz
Carrier frequency for BS-backhauled connection	2 GHz
AP altitude	10 km

and $l = a_{\mathrm{s}} - a_{\mathrm{AP}}$, while for BS-backhauled AP, $f_{R_{\mathrm{s}}}(r_{\mathrm{s}})$ is given in Lemma 2, $u = \infty$ and $l = a_{\mathrm{AP}}$.

Proof. To obtain (10), we start with the definition of coverage probability:

$$\begin{aligned} P_{\mathrm{c}}(T) &= \mathbb{E}_{R_{\mathrm{s}}}\left[\mathbb{P}\left(\mathrm{SNR} > T \mid R_{\mathrm{s}}\right)\right] \\ &= \int_l^u \mathbb{P}\left(\mathrm{SNR} > T \mid R_{\mathrm{s}} = r_{\mathrm{s}}\right) f_{R_{\mathrm{s}}}(r_{\mathrm{s}})\, dr_{\mathrm{s}} \\ &= \int_l^u \mathbb{P}\left(H_{\mathrm{s}} > \frac{T r_{\mathrm{s}}^{\alpha} G_{\mathrm{t}}^{-1} \sigma^2}{p_{\mathrm{s}}}\right) f_{R_{\mathrm{s}}}(r_{\mathrm{s}})\, dr_{\mathrm{s}}, \end{aligned} \tag{11}$$

The proof is completed by substituting the complementary CDF of H_{s}. □

C. Average Data Rate

In the following proposition, we will derive the average achievable data rate (in bits per channel use) which is defined as the ergodic capacity derived from the Shannon–Hartley theorem over a fading communication link normalized to unit bandwidth, i.e., $\bar{C} \triangleq \mathbb{E}\left[\log_2(1+\mathrm{SNR})\right]$.

Proposition 2. *The average rate (in bits/s/Hz) of an arbitrarily located AP at an altitude, such that $a_{\mathrm{AP}} < a_{\mathrm{s}}$, under generally distributed fading is*

$$\bar{C} = \int_l^u \int_0^\infty \log_2\left(1 + \frac{p_{\mathrm{s}} G_{\mathrm{t}} h_{\mathrm{s}} r_{\mathrm{s}}^{-\alpha}}{\sigma^2}\right) f_{H_{\mathrm{s}}}(h_{\mathrm{s}}) f_{R_{\mathrm{s}}}(r_{\mathrm{s}})\, dh_{\mathrm{s}}\, dr_{\mathrm{s}}, \tag{12}$$

where $f_{H_{\mathrm{s}}}(h_{\mathrm{s}})$ represents the PDF of the serving channel gain H_{s}. For LEO-backhauled AP, $f_{R_{\mathrm{s}}}(r_{\mathrm{s}})$ is given in Lemma 1, $u = r_{\mathrm{max}}$ and $l = a_{\mathrm{s}} - a_{\mathrm{AP}}$, while for BS-backhauled AP, $f_{R_{\mathrm{s}}}(r_{\mathrm{s}})$ is given in Lemma 2, $u = \infty$ and $l = a_{\mathrm{AP}}$.

Proof. Taking the expectation over the serving distance and the channel gain, we have

$$\begin{aligned} \bar{C} &= \mathbb{E}_{H_{\mathrm{s}}, R_{\mathrm{s}}}\left[\log_2(1+\mathrm{SNR})\right] \\ &= \int_l^u \mathbb{E}_{H_{\mathrm{s}}}\left[\log_2\left(1 + \frac{p_{\mathrm{s}} G_{\mathrm{t}} H_{\mathrm{s}} r_{\mathrm{s}}^{-\alpha}}{\sigma^2}\right)\right] f_{R_{\mathrm{s}}}(r_{\mathrm{s}})\, dr_{\mathrm{s}}, \end{aligned} \tag{13}$$

and the expectation renders the inner integration in (12). □

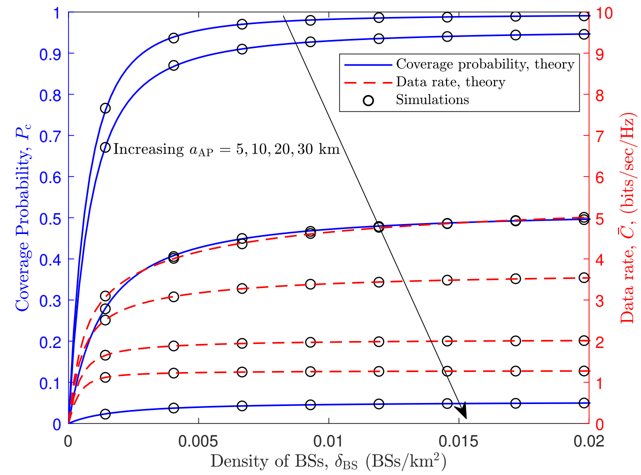


Fig. 2: Coverage probability and data rate provided by a terrestrial backhaul for some aerial platforms at different altitudes.

IV. Numerical Results and Discussion

In this section, we provide numerical results to study the effect of different network parameters on coverage probability and average data rate of the LEO and terrestrial backhaul networks for APs, using the analytical expressions obtained in Section III. Furthermore, we verify all the analytical derivations through Monte Carlo simulations in Matlab.

We consider the large-scale attenuation with path loss exponent $\alpha = 2$, and the small-scale fading is assumed to be Rician with parameter K. Thus, the CDF and the PDF of H_{s}, required to evaluate Propositions 1 and 2, are $F_{H_{\mathrm{s}}}(h_{\mathrm{s}}) = 1 - Q_1\left(\sqrt{2K}, \sqrt{h_{\mathrm{s}}}\right)$ and $f_{H_{\mathrm{s}}}(h_{\mathrm{s}}) = \frac{1}{2} e^{-\frac{h_{\mathrm{s}}+2K}{2}} I_0\left(\sqrt{2K h_{\mathrm{s}}}\right)$, respectively, where $Q_1(\cdot,\cdot)$ denotes the Marcum Q-function and $I_0(\cdot)$ is the modified Bessel function of the first kind.

The altitude of AP is set to 10 km, unless stated otherwise. The satellites' antenna gains within their beamwidth are approximated by a constant gain of 34 dBi. For LEO-backhauled connection, APs are equipped with antennas which radiate towards the sky with constant gain of 3 dBi, while for BS-backhauled communication, both AP and BS are assumed to have unity gain antennas.

The transmit power is set to 40 dBm and 50 dBm for terrestrial and satellite backhauls, respectively, and their corresponding operating frequency is assumed to be 2 GHz and 13.5 GHz. The noise power is set to -120 dBm. For the reference simulations, satellites are placed uniformly on orbits centered at Earth's center with radius $r_{\oplus} + a_{\mathrm{s}}$. The simulation parameters are summarized in Table I.

Figure 2 illustrates the coverage probability and data rate provided by the terrestrial backhaul for APs at different altitudes. The BSs are assumed to be distributed according to a homogeneous PPP on a disc with radius 30 km. As can be seen, for higher density of BSs and lower APs' altitudes, the terrestrial backhaul provides better probability of coverage and data rate. However, for very low densities, which correspond to

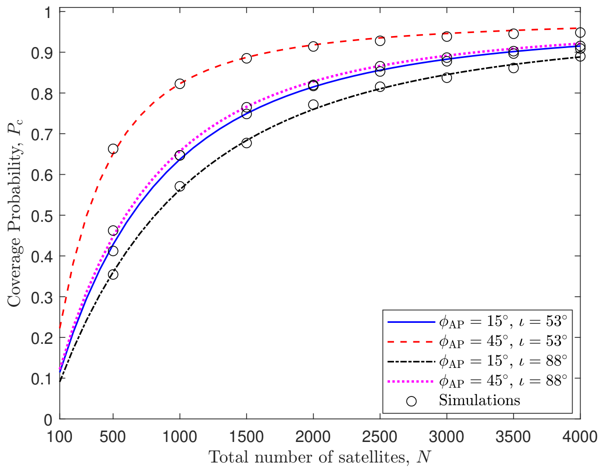


Fig. 3: Coverage probability versus the total number of satellites when $a_s = 500$ km, $a_{AP} = 10$ km, and $T = 5$ dB.

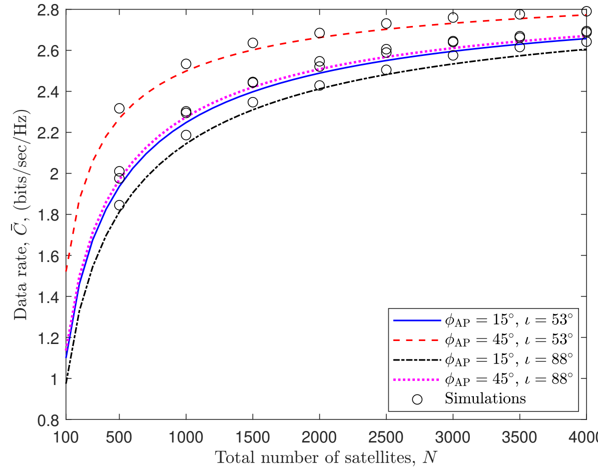


Fig. 4: Data rate versus the total number of satellites when a_s and a_{AP} are 500 km and 10 km, respectively.

under-served regions, as well as for high altitudes of APs, the performance of the terrestrial network degrades considerably, especially in terms of the coverage probability.

The effect of the total number of satellites on the coverage probability and data rate of a LEO-backhauled AP are illustrated in Figs. 3 and 4, respectively. The performance is depicted for different AP's latitudes and constellation inclination angles. A better visibility is provided by increasing the constellation size which leads to more promising performance in terms of both metrics. For higher AP's latitude the performance is better due to higher density of satellites at those latitudes and, consequently, the availability of closer satellites to serve the AP. As shown in the figures, lower inclination angles also provide higher rate and coverage due to higher density for those constellations, i.e., the same amount of satellites are distributed on a smaller region of the spherical shell. Since $a_s \gg a_{AP}$, the performance is only slightly affected by varying the altitude of AP.

The probability of coverage and the data rate of a LEO backhaul network versus the altitude of the constellation are depicted in Figs. 5 and 6, respectively. As can be seen in the figures, the smallest inclination angle and the highest AP's latitude provide better performance in terms of both performance metrics due to the availability of more visible satellites to the AP. Since the signal is exposed to more severe path loss when traveling over a larger distance, the performance degrades accordingly by increasing the constellation altitude.

The effect of AP's altitude on the data rate of both terrestrial and LEO backhauls are shown in Fig. 7. Despite the terrestrial backhaul, the data rate for LEO backhaul slightly improves by rising the AP's altitude due to the increase in visibility and the decrease in the serving distance, which results in smaller path loss. However, since the altitude of AP is notably smaller than the constellation altitude, the variation in the data rate is not significant. The altitude range over which the LEO backhaul outperforms the terrestrial backhaul is highly affected by the density of BSs.

Based on the numerical results, it can be interpreted that both terrestrial and LEO networks have the potential to serve as the backhaul for the airborne network. Selecting the best backhaul depends on several factors such as the LEO constellation parameters, the BS density, and AP's location. For instance, terrestrial backhaul can provide higher data rate than the LEO satellites, when the BS density is large or when the AP is located at very high latitudes, out of the constellation inclination limits. On the other hand, the AP is better to be LEO-backhauled if the density of BS is extremely low or the AP's altitude is excessively high. It is also worth noting that in highly dense urban areas where the transmission from the BSs is subject to severe blockage due to the surrounding obstacles, a LEO backhaul can provide better connectivity to the AP due to having a higher probability of line-of-sight.

V. Conclusions

In this paper, we studied the performance of LEO mega-constellation as a backhaul for an airborne network. Modeling the satellites locality as a nonhomogeneous Poisson point process enabled us to tractably analyze the performance of a LEO backhaul network, while precisely capturing the characteristics of the actual physical network by setting the intensity of PPP to the actual density of satellites along different latitudes. For sake of comparison, we also evaluated the performance when APs are backhauled by terrestrial networks. From the numerical results, other than verification of our derivations, we presented the coverage probability and the data rate in terms of different system parameters, e.g., constellation altitude, total number of satellites, inclination angle, and AP's location. Based on the results, it is concluded that a LEO backhaul can provide more promising performance in terms of both coverage probability and data rate when the terrestrial BSs' density is low and/or APs' altitude is significantly high.

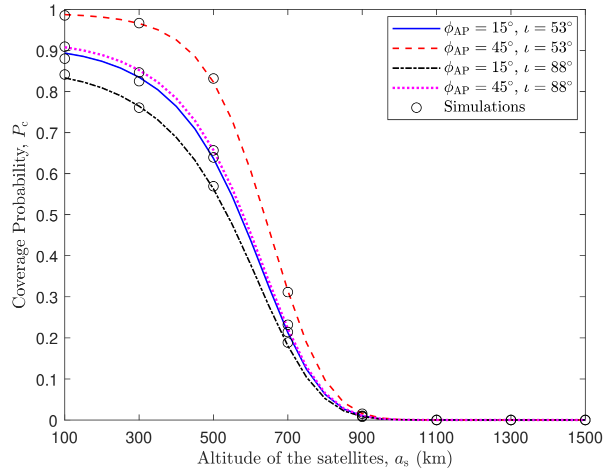


Fig. 5: Coverage probability versus the altitude of the constellation when $N = 1000$, $a_{AP} = 10$ km, and $T = 5$ dB.

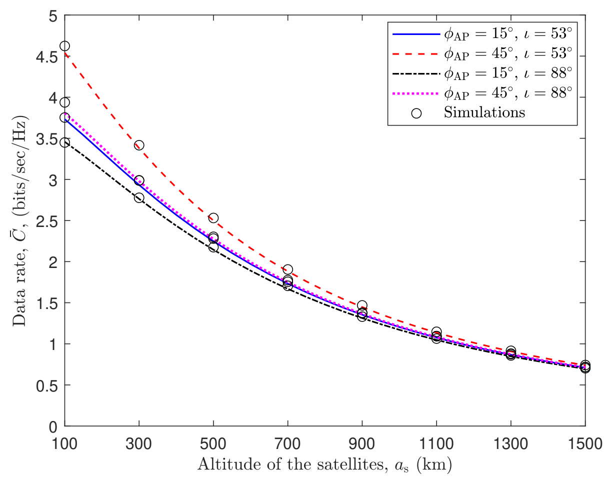


Fig. 6: Data rate versus the altitude of the constellation when $N = 1000$ and $a_{AP} = 10$ km.

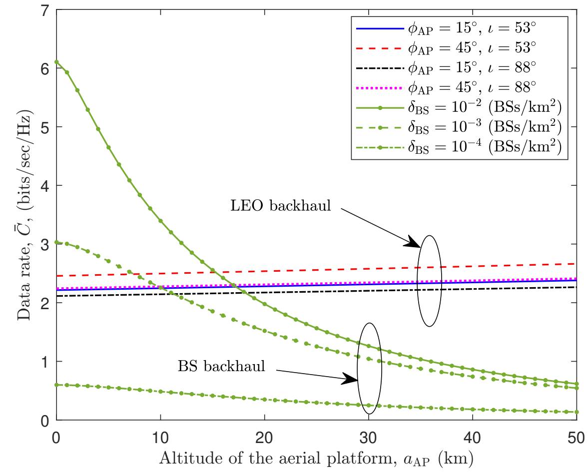


Fig. 7: Data rate versus the altitude of the aerial platform (AP) for LEO and BS backhaul networks. The LEO constellation size and altitude are set to 1000 and 500 km, respectively.

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