Throughput and Coverage Trade-Off in Integrated Terrestrial and Non-Terrestrial Networks: an Optimization Framework

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***Abstract*—In past years, non-terrestrial networks (NTNs) have emerged as a viable solution for providing ubiquitous connectivity for future wireless networks due to their ability to reach large geographical areas. However, the efficient integration and operation of an NTN with a classic terrestrial network (TN) is challenging due the large amount of parameters to tune. In this paper, we consider the downlink scenario of an integrated TN-NTN transmitting over the S band, comprised of low-earth orbit (LEO) satellites overlapping a large-scale ground cellular network. We propose a new resource management framework to optimize the user equipment (UE) performance by properly controlling the spectrum allocation, the UE association and the transmit power of ground base stations (BSs) and satellites. Our study reveals that, in rural scenarios, NTNs, combined with the proposed radio resource management framework, reduce the number of UEs that are out of coverage, highlighting the important role of NTNs in providing ubiquitous connectivity, and greatly improve the overall capacity of the network. Specifically, our solution leads to more than 200% gain in terms of mean data rate with respect to a network without satellites and a standard integrated TN-NTN when the resource allocation setting follows 3GPP recommendation.**

I. Introduction

In the midst of an era witnessing fast development of cellular communications, the demand for high-data-rate connectivity has soared. This has resulted in more stringent requirements on providing high capacity and guaranteeing ubiquitous connectivity for the network. The usage of heterogeneous networks (HetNets) has proven to be an appealing solution in a bid to answer those demands [1]. Indeed, by creating a multi-tier architecture of the network, its inherent flexibility allows an effective data offloading, which in turn leads to higher capacity and better coverage throughout the network. Recently, non-terrestrial networks (NTNs) have emerged as a viable solution to complement the terrestrial network (TN), and ensure that uncovered geographical areas can be served [2]. An NTN is a network where aerial vehicles such as drones (i.e. UAVs), high-altitude platform station (HAPS) or satellites act as a relay node or a base station (BS) to serve the user equipment (UE) in the network. The intrinsic benefit of NTNs is their ability to provide coverage for wide areas, reaching geographical locations where it would have been expensive or difficult to deploy macro BSs (MBS). Among the different deployment options, it seems that the low-earth orbit satellites will spearhead the process of achieving high-capacity connectivity from space [3], [4]. The low-earth orbit (LEO) satellite is a non-geostationary satellite that orbits at an altitude between 200 and 2000 km. Its shorter distance to Earth means that, compared to other satellite architectures, there will be a better signal strength and lower latency, less energy needed for launching and less power required for the transmission of the signal from/to the satellite. Taking all this into account, the concept of an integrated TN-NTN may be the way forward to ensure efficient services for terrestrial and aerial UEs [5]. In most practical networks, each UE is associated to the BS which provides the highest reference signal received power (RSRP) in the network. This association policy has its limits since it does not account for the fluctuating traffic demands of UEs, and can lead to poor load balancing and thus performance. A better performing UE association policy should take into account, not only the strength and/or quality of the UE signal, but also the load on each cell. Although load balancing has been well studied in the cellular literature, most of the related work does not consider NTNs. The most advanced analysis in this front [5] has recently studied an integrated TN-NTN deployed in an urban area, and has revealed that offloading part of the traffic to LEO satellites would not only improve the overall signal quality of the network, but also reduce outages. However, optimal operation points are not derived. From a load balancing perspective, the common approach is to build a framework which maximizes a selected utility function using a pricing based association strategy [6], [7]. In [8] and [9], following such approach, the authors study the uplink performance of an integrated TN-NTN where the LEO satellites are used to provide backhaul to the ground BSs. The objective in both papers is to maximize the uplink sum data rate satisfying backhaul capacity constraints, while [9] also considers minimal rate constraints. [8] optimizes the user association and power allocation through matching algorithms. In [9], the authors also consider the split of the bandwidth between the fronthaul and backhaul link as a variable.

In this paper, we extend the load balancing literature, deriving for the first time the optimal radio resource management – in terms of joint bandwidth split, UE association, and power

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control– in an integrated TN-NTN. The objective is to improve the overall capacity of a large-scale rural network, while providing coverage guarantees to all UEs, by dynamically tailoring the complementary capabilities of both network tiers. Importantly, our results show that the developed framework improves the mean data rate by more than 200 % with respect to a network without satellites and a standard integrated TN-NTN with a resource allocation setting that follows the 3GPP recommendations [10], [11].

II. System Model & Problem Formulation

In this section, we present the system model and the problem formulation.

A. System Model

We consider a downlink cellular network consisting of M macro BSs and N LEO satellites, all serving K UEs that are deployed in a rural area. We denote as W the total bandwidth of the system, which the mobile network operator shares between the terrestrial and non-terrestrial tier. In our study, we suppose that such bandwidth W is operated over the S band, i.e. around 2 GHz, and that macro and satellite BSs use orthogonal fractions of it. In the remainder of the paper, we will denote by $\mathcal{T}$ (resp. $\mathcal{S}$) the set of terrestrial (resp. non-terrestrial) BSs. Moreover, let $\mathcal{U} = \{1, \cdots, i, \cdots, K\}$ be the set of UEs and $\mathcal{B} = \mathcal{T} \cup \mathcal{S} = \{1, \cdots, j, \cdots, M+N\}$ the set of all BSs. With respect to the channel model, the large-scale channel gain between a macro BS j and a UE i is calculated as follows:

$$\beta_{ij} = G_{T_X} \cdot PL_{ij} \cdot SF_{ij}, \tag{1}$$

where G_{T_X} is the transmit antenna gain, PL_{ij} is the path loss, and SF_{ij} is the shadow fading. On the contrary, if a satellite BS j serves a UE i, then the large-scale channel gain is the following [12]:

$$\beta_{ij} = G_{T_X} \cdot PL_{ij} \cdot SF_{ij} \cdot CL \cdot PL_s \tag{2}$$

where CL is the clutter loss, i.e. an attenuation caused by buildings and vegetation in the vicinity of the UE, and PL_s is the scintillation loss (rapid variations in the amplitude and phase of the signal due to the structure of the ionosphere). Considering that a UE will only be served by a macro BS or a satellite, and that the terrestrial and non-terrestrial tiers do not interfere each other due to the orthogonal bandwidth allocation, we can compute the signal-to-interference-plus-noise ratio (SINR) for each UE i as follows:

$$\gamma_{ij} = \frac{\beta_{ij} p_j}{\sum\limits_{j' \in \mathcal{I}_j} \beta_{ij'} p_{j'} + \sigma^2}, \tag{3}$$

where p_j is the transmit power allocated per resource element (RE) at BS j, $\mathcal{I}_j$ is the set of BSs that are interfering with serving BS j, and σ^2 is the noise power. Thereafter, assuming that BS j equally shares its available bandwidth W_j among its k_j served UEs, the average data rate for the UE i connected to BS j can be computed as:

$$R_{ij} = \frac{W_j}{k_j} \log_2(1 + \gamma_{ij}). \tag{4}$$

B. Problem Formulation

Since we want to ensure a proportionally fair resource allocation, our goal is to optimize the sum of the log-throughput (SLT) across all UEs in the network. To achieve this goal, we want to find the optimal bandwidth split between the non-terrestrial and terrestrial tiers of the network. Taking this into account, we introduce ε as the share of the bandwidth allocated to the LEO satellites. Thus, the bandwidth W_j of the BS j can be computed as $W\varepsilon$ if it is a satellite or as $W(1-\varepsilon)$ if it is a macro BS. Let us also define a binary variable $x_{i,j}$ which is equal to 1 if UE i is associated to the BS j, and 0 otherwise. Our aim is then to optimize the UE-BS association, the transmit power allocation at each BS as well as the bandwidth allocation to each tier to maximize the SLT of the network. This can be written as follows:

$$\max_{\mathrm{X},\mathrm{p},\mathrm{k},\varepsilon} \quad \sum_{i\in\mathcal{U}} \sum_{j\in\mathcal{S}} x_{ij} \log(\varepsilon R_{ij}) + \sum_{j\in\mathcal{T}} x_{ij} \log((1-\varepsilon) R_{ij}) \tag{5a}$$

$$\text{s.t.} \quad x_{ij} \in \{0,1\},\ i \in \mathcal{U}, j \in \mathcal{B}, \tag{5b}$$

$$\sum_j x_{ij} = 1,\ \forall i \in \mathcal{U}, \tag{5c}$$

$$\sum_i x_{ij} = k_j,\ \forall j \in \mathcal{B}, \tag{5d}$$

$$\sum_j k_j = K, \tag{5e}$$

$$p_j \le p_j^{\mathrm{MAX}},\ \forall j \in \mathcal{B}, \tag{5f}$$

$$\sum_j x_{ij} p_j \beta_{ij} \ge p_{\min},\ \forall i \in \mathcal{U}, \tag{5g}$$

$$\varepsilon \in [0,1], \tag{5h}$$

where $\mathrm{p} = [p_1, \ldots, p_{M+N}]^T$ is the vector representing the transmit power at each BS, $\mathrm{k} = [k_1, \ldots, k_{M+N}]^T$ is the vector which shows the number of UEs associated to each BS, and $\mathrm{X} = [x_{ij}]_{i\in\mathcal{U}, j\in\mathcal{B}}$ is the binary association matrix.
The artificial inclusion of vector k will later allow us to determine whether a BS is overloaded or not. Constraint (5c) ensures that each UE is associated with a unique BS, while constraint (5e) indicates that all UEs in the network must be served. Furthermore, the maximum transmit power allocated per RE in each BS j is restricted by p_j^{MAX} in constraint (5f). Finally, constraint (5g) ensures the coverage of the entire network by imposing that the minimum RSRP for each UE is greater than a set threshold $p_{\min}$.

III. Utility Optimization Using Lagrange Multipliers

In this section, we study the solution to our optimization problem (5a). Due to the nature of X, this is a mixed discrete optimization problem, hence complex to solve. To simplify the problem, we will first optimize the UE-BS association and the bandwidth allocation considering fixed transmit power, similarly to [7]. Then, we will optimize the transmit power level considering the first two parameters fixed.

A. Utility optimization under fixed transmit power

Since the transmit power is fixed, we consider Problem (5a) without the Constraint (5f). We can solve this problem using the Lagrange multipliers, as it has been proposed in [6], [7]. We introduce $\lambda = [\lambda_1, \ldots, \lambda_K]^T$, $\mu = [\mu_1, \ldots, \mu_{M+N}]^T$, α, and ρ as the dual variables for constraints (5g),(5d),(5e) and (5h), respectively. The Lagrangian function is then:

$$\begin{aligned}
&\mathcal{L}(X, k, \varepsilon, \lambda, \mu, \alpha, \rho) = \rho(1-\varepsilon) - \alpha\left(\sum_{j\in\mathcal{B}} k_j - K\right) \\
&+ \sum_i \left(\sum_{j\in\mathcal{S}} x_{ij}\log(\varepsilon R_{ij}) + \sum_{j\in\mathcal{T}} x_{ij}\log((1-\varepsilon)R_{ij})\right) \\
&+ \sum_i \lambda_i\left(\sum_{j\in\mathcal{B}} x_{ij}p_j\beta_{ij} - p_{\min}\right) + \sum_{j\in\mathcal{B}}\mu_j\left(k_j - \sum_i x_{ij}\right).
\end{aligned} \tag{6}$$

After this, we are able to compute the derivative of the Lagrangian with respect to all the variables that we want to optimize, i.e. x_{ij}, k_j and ε, as

$$\frac{\partial\mathcal{L}}{\partial x_{ij}} = \begin{cases}\log(\varepsilon R_{ij}) + \lambda_i p_j\beta_{ij} - \mu_j, & \text{if } j\in\mathcal{S},\\ \log((1-\varepsilon)R_{ij}) + \lambda_i p_j\beta_{ij} - \mu_j, & \text{otherwise.}\end{cases} \tag{7}$$

The choice of the BS association is made by finding which one maximizes the derivative. Therefore, we can derive the following expression:

$$x^*_{ij} = \begin{cases}1, & \text{if } j = \arg\max_{j'} \frac{\partial\mathcal{L}}{\partial x_{ij'}},\\ 0, & \text{otherwise.}\end{cases} \tag{8}$$

This association criterion is actually quite intuitive. Indeed, as we will see later, the dual variable μ_j represents the cost of association to BS j. Each UE is thus associated to the BS, which maximizes the difference between the data rate and the cost of association. For the vector k, we derive its optimal value by computing the partial derivative of the Lagrangian, and finding its root:

$$k^*_j = e^{\mu_j - \alpha - 1}. \tag{9}$$

Finally, we isolate all the terms of the Lagrangian function related to ε, and then compute the partial derivative with respect to this parameter as:

$$\begin{aligned}
\frac{\partial\mathcal{L}}{\partial\varepsilon} &= \frac{\partial}{\partial\varepsilon}\left(\sum_i\left(\sum_{j\in\mathcal{S}} x_{ij}\log(\varepsilon) + \sum_{j\in\mathcal{T}} x_{ij}\log(1-\varepsilon)\right) - \varepsilon\rho\right) \\
&= \frac{1}{\varepsilon}\left(\sum_i\sum_{j\in\mathcal{S}} x_{ij}\right) - \frac{1}{1-\varepsilon}\left(\sum_i\sum_{j\in\mathcal{T}} x_{ij}\right) - \rho \\
&= \frac{1}{\varepsilon}K_{\mathcal{S}} - \frac{1}{1-\varepsilon}(K - K_{\mathcal{S}}) - \rho,
\end{aligned} \tag{10}$$

where $K_{\mathcal{S}}$ represents the number of UEs associated to a satellite in the network. Equating (10) to 0, we obtain:

$$\rho\varepsilon^2 - (K+\rho)\varepsilon + K_{\mathcal{S}} = 0, \tag{11}$$

which allows us to find the following optimal value:

$$\varepsilon^* = \frac{K + \rho - \sqrt{(K+\rho)^2 - 4\rho K_{\mathcal{S}}}}{2\rho}. \tag{12}$$

From eq. (12), we can observe that the proportion of bandwidth allocated to the Non-Terrestrial tier is directly proportional to the number of UEs associated with an LEO satellite. In fact, if we gradually increase the value of $K_{\mathcal{S}}$ from 0 to K, the value of ε^* slowly shifts from 0 to 1. We thereby introduce the Lagrangian dual function, which can be written as:

$$\mathcal{D}(\lambda, \mu, \alpha, \rho) = \max_{X,k,\varepsilon}\mathcal{L}(X, k, \varepsilon, \lambda, \mu, \alpha, \rho). \tag{13}$$

Accordingly, the Lagrangian problem (5a) can then be rewritten as:

$$\min_{\mu,\lambda,\alpha,\rho}\mathcal{D}(\lambda, \mu, \alpha, \rho). \tag{14}$$

By injecting the expressions obtained in (8), (9), and (12), we get:

$$\begin{aligned}
&\mathcal{D}(\lambda, \mu, \alpha, \rho) = \mathcal{L}(X^*, k^*, \varepsilon^*, \lambda, \mu, \alpha, \rho) \\
&= \sum_i\left(\sum_{j\in\mathcal{S}} x^*_{ij}\log(\varepsilon^* R_{ij}) + \sum_{j\in\mathcal{T}} x^*_{ij}\log((1-\varepsilon^*)R_{ij})\right) \\
&+ \sum_i\lambda_i\left(\sum_j x^*_{ij}p_j\beta_{ij} - p_{\min}\right) + \sum_j\mu_j\left(k^*_j - \sum_i x^*_{ij}\right) \\
&+ \rho(1-\varepsilon^*) - \alpha\left(\sum_j k^*_j - K\right).
\end{aligned} \tag{15}$$

In order to minimize this function, we use the subgradient method to update the Lagrange multipliers, as already suggested in [6], [7], as follows:

$$\mu_j(t+1) = \mu_j(t) - \delta_1(t)\left(k^*_j - \sum_i x^*_{ij}\right), \tag{16}$$

$$\lambda_i(t+1) = \lambda_i(t) - \delta_2(t)\left(\sum_j x^*_{ij}p_j\beta_{ij} - p_{\min}\right), \tag{17}$$

$$\alpha(t+1) = \alpha(t) - \delta_3(t)\left(K - \sum_j k^*_j\right), \tag{18}$$

$$\rho(t+1) = \rho(t) + \delta_4(t)\varepsilon^*, \tag{19}$$

where $\delta_1(t)$, $\delta_2(t)$, $\delta_3(t)$, and $\delta_4(t)$ represent the step-sizes used for each dual variable. Since the dual problem is always convex, the usage of the subgradient method with decreasing step sizes guarantees convergence to the optimal solution of this problem [13].

Eq. 16 explains how the proposed framework balances the load among the BSs. Indeed, as stated previously, μ_j is the cost of association to BS j. This price will only rise if the right component in the equation is negative, meaning that the number of UEs associated to the BS is excessively large. This way, a BS with fewer UEs has a lower cost and it is more attractive, and vice-versa.

B. Transmit power optimization under fixed association

Once the UE-BS association and bandwidth allocation problem has been solved, we fix X and ε to further optimize the transmit power at each BS and maximize the log-throughput of the network. For ease of reading, we will denote by $f(p)$ the sum log-throughput of the network (5a) to indicate that it is a function of the transmit power vector p. The transmit power optimization problem can then be expressed as:

$$\max_{p} \quad f(p) \tag{20a}$$

$$\text{s.t.} \quad \sum_j x_{ij} p_j \beta_{ij} \geq p_{\min},\ \forall i \in \mathcal{U}, \tag{20b}$$

$$p_j \leq p_j^{MAX},\ \forall j \in \mathcal{B}. \tag{20c}$$

Since the objective function is concave w.r.t. p, we can try to approximate the zero of the gradient using the Newton-Raphson iterative method to maximize the utility function, as demonstrated in [7]. As indicated in [14], it is also possible to use only diagonal entries of the Hessian matrix to reduce the computational complexity of inverting it. To this end, the first and second order derivatives are computed as follows:

$$\begin{aligned}\frac{\partial f(p)}{\partial p_j} &= \sum_i \frac{\gamma_{ij}}{r_{ij}\left(1+\gamma_{ij}\right)} \frac{x_{ij}}{p_j} \\ &\quad - \sum_i \sum_{j' \neq j} \frac{\beta_{ij}\gamma_{ij'}^2}{\beta_{ij'} r_{ij'}\left(1+\gamma_{ij'}\right)} \frac{x_{ij'}}{p_{j'}},\end{aligned} \tag{21}$$

and

$$\begin{aligned}\frac{\partial^2 f(p)}{\partial p_j^2} &= -\sum_i \left(\frac{1}{r_{ij}^2} + \frac{1}{r_{ij}}\right) \frac{\gamma_{ij}^2}{\left(1+\gamma_{ij}\right)^2} \frac{x_{ij}}{p_j^2} \\ &\quad + \sum_i \sum_{j' \neq j} \frac{\beta_{ij}^2 \gamma_{ij'}^3 \left(2r_{ij'} + \gamma_{ij'}\left(r_{ij'}-1\right)\right)}{\beta_{ij'}^2 r_{ij'}^2 \left(1+\gamma_{ij'}\right)^2} \frac{x_{ij'}}{p_{j'}^2},\end{aligned} \tag{22}$$

where

$$r_{ij} = \log\left(1+\gamma_{ij}\right). \tag{23}$$

The Newton step is then:

$$\Delta p_j = \frac{\partial f(p)}{\partial p_j} \Bigg/ \left|\frac{\partial^2 f(p)}{\partial p_j^2}\right|. \tag{24}$$

Once we update the transmit power vector using (24), it is necessary to project the value in a region where constraints (20b) and (20c) are respected. Naturally, the upper bound of our feasible region is the maximum transmit power for each BS. For the lower bound, we utilize the minimal coverage constraint, i.e. we know that for a BS j, all UEs associated to it should be receiving a signal power greater than $p_{\min}$. This can be translated as:

$$\forall i \in \mathcal{U}_j, \quad p_j \quad \geq \quad \frac{p_{\min}}{\beta_{ij}}, \tag{25}$$

with $\mathcal{U}_j$ being the set of UEs associated to the BS j. We are therefore able to establish the lower bound of the feasibility region for each BS j as:

$$\tau_j = \max_{i \in \mathcal{U}_j} \left(\frac{p_{\min}}{\beta_{ij}}\right). \tag{26}$$

Finally, the transmit power update done at the end of step t is written as such:

$$p_j^{(t+1)} = \left[p_j^{(t)} + \delta_5(t)\Delta p_j\right]_{\tau_j}^{p_j^{\text{MAX}}}, \tag{27}$$

with $\delta_5(t)$ being a step-size factor.

IV. Simulation results and analysis

In this section, we assess the effectiveness of our proposed optimization framework for UE association, bandwidth allocation, and transmit power control in an integrated TN-NTN. We analyse a rural scenario where the macro BSs are deployed in an hexagonal grid layout [15]. Without loss of generality, we consider an LEO constellation employing earth-fixed beams, such that, at a given instant, a UE can only be served by a unique satellite, and we restrict our study to an area of 2500 km^2, corresponding to the coverage provided by the beam of an LEO satellite [11].

Parameter	Value
Total Bandwidth W	40 MHz
Carrier frequency f_c	2 GHz
Subcarrier Spacing	15 kHz
UE density	2 UE/km^2
Inter-Site Distance	1732 m
Number of Macro BSs	1067
Terrestrial Max Tx Power per RE p_j^{MAX} [10]	17.7 dBm
Satellite Max Tx Power per RE p_j^{MAX} [11]	15.8 dBm
Antenna gain (Terrestrial) G_{T_X} [16]	14 dBi
Antenna gain (Satellite) G_{T_X} [11]	30 dBi
Shadowing Loss (Terrestrial) SF [17]	$4 - 8$ dB
Shadowing Loss (Satellite) SF [12]	$0 - 12$ dB
Line-of-Sight Probability (Satellite / Terrestrial)	Provided in [12] / [17]
White Noise Power Density [16]	-174 dBm/Hz
Coverage threshold $p_{\min}$	-120 dBm

Table I: Simulation parameters.

As for the UE deployment, we consider an inhomogeneous deployment. Indeed, we first randomly select 30% of the macro BSs, and for these macro BSs, we deploy the UEs in a ”hot-spot” manner, to possibly create overload in the related cells and allow our framework to demonstrate its effectiveness. Half of the UEs are deployed among those hot-spots, and the other half are uniformly spread across the entire area. The most important simulation parameters, set according to

[10]–[12], [16]–[18], are listed in Table I. We compare the performance of our framework with two different benchmarks: The `Baseline` relates to a standard terrestrial network where a bandwidth of 10 MHz is available at the macro BSs [10] and the `3GPP` NTN scenario where the bandwidth W is split accordingly to the 3GPP recommendations [11], i.e., 30 MHz allocated to the satellite and 10 MHz allocated to the macro BSs. Note that in both benchmarks the UEs associate to the BS providing the largest RSRP.

A. Framework convergence analysis

In this section, we analyse the convergence of the proposed optimization framework. Specifically, Figure 1 shows the iterative evolution of 1) the network SLT, along with 2) the optimal bandwidth split (ε) and 3) the actual fraction of UEs associated to the satellite in the network, i.e. $\frac{k_0}{\sum_j k_j}$.

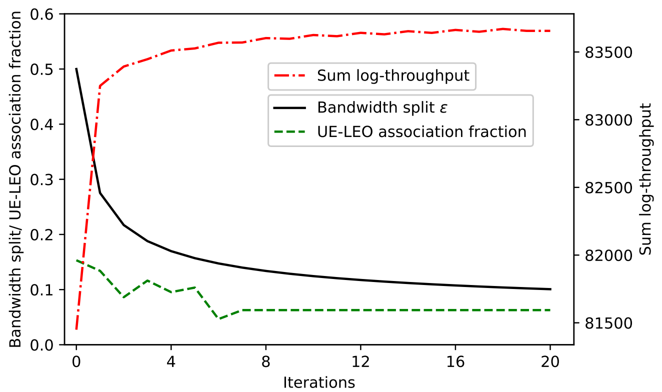

Figure 1: Evolution of the bandwidth allocation proportion and the utility function of our framework.

When initializing the algorithm presented in Sec. III, the bandwidth split, ε is set to 0.5, and the fraction of UEs associated to the LEO satellite is 0.15. The initial UE-BS association follows the max-RSRP rule. During the iterative process, we can see that the log-throughput continuously improves, while the ratio of UEs associated to the LEO satellite and the fraction of bandwidth allocated to it decrease. Eventually, the algorithm converges after 20 iterations, with an improved SLT and 11% of the bandwidth being allocated to the LEO satellite and approximately 6% of the UEs associated to it. Note that this bandwidth split is different than the one recommended in `3GPP` specifications [11]. For readability purposes, we chose not to display the evolution of the transmit power. Considering that all BSs were initially transmitting at their maximum power, we observe an 82% decrease of the average transmit power. This is explained by the fact that our framework reduces the transmit power of the BSs that have no UEs and thus no coverage constraint (5g) to uphold. In the following, we denote by ε_{opt} the optimal bandwidth split derived by the proposed framework.

B. Network coverage analysis

In this section, we study the benefits of integrating an NTN to a terrestrial network in terms of the coverage, i.e. the capability to provide wireless services. Figure 2 shows the cumulative distribution function (CDF) of the RSRP perceived at each UE from the serving BS in four different scenarios: 1) the `Baseline` setting, 2) a scenario where all the bandwidth is allocated to the terrestrial network ($\varepsilon = 0$) and the UE association and power control is done through our framework, 3) the `3GPP` setting and 4) the scenario where bandwidth split, association, and power are allocated through the proposed framework (ε_{opt}). In the first two scenarios, we observe a similar performance in terms of coverage since all the UEs are served by macro BSs, which leads to 7% of the UEs to be out of coverage since their respective RSRPs are below the threshold $p_{\min}$. In contrast, when integrating the NTN in the last two scenarios, the proportion of UEs out of coverage drastically drops down to around $0.4\ \%$. Indeed, the satellite can reach UEs located at the cell edge and provide them with a signal of much better quality than that provided by the strongest macro BSs.

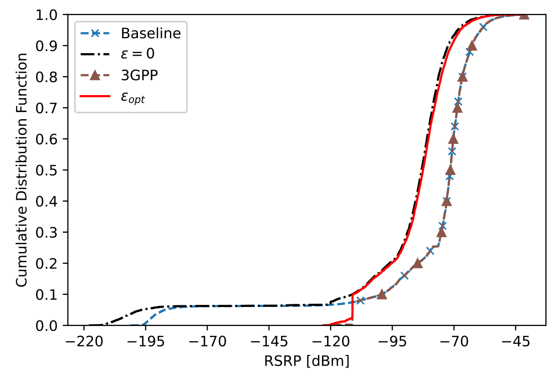

Figure 2: CDFs of the UE RSRP, with (ε_{opt}, `3GPP`) and without ($\varepsilon = 0$, `Baseline`) an active satellite.

C. UE rate analysis

In this section, we compare the data rate performance achieved by our framework with the one of the `Baseline` and `3GPP` settings. Also, we consider the case where only the user association and the power control are optimized and the bandwidth split is fixed, i.e., $\varepsilon \in \{0, 0.25, 0.5, 0.75\}$. Figure 3 shows the CDFs of the data rate achieved when considering the various deployment and resource allocation scenarios. Also, Table II presents the 5-th percentile, the mean, the median, and the 95-th percentile of the different data rate distributions resulting from the most relevant of the compared solutions.

	$\varepsilon = 0$	ε_{opt}	ε = 0.75	3GPP	Baseline
5-th %ile (kbps)	0	81	614	558	0
Mean (Mbps)	44.4	38.3	12.0	11.7	11.1
Median (Mbps)	28.3	27.1	7.7	7.3	7.1
95-th %ile (Mbps)	136.6	112.7	37	36.4	34.1

Table II: Data-rate analysis.

We first notice that higher data rates, in average, are achieved when we allocate a large split of the bandwidth to the

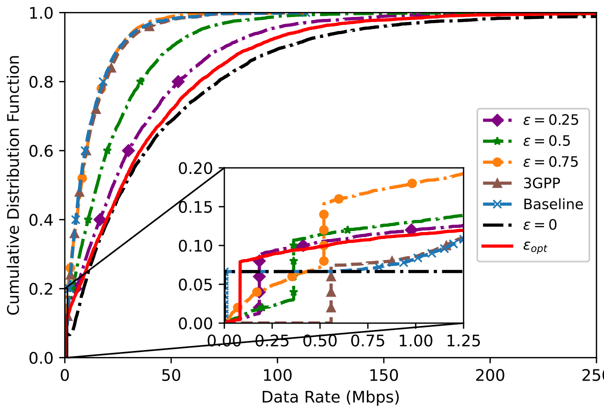

Figure 3: CDFs of UE data rates for various bandwidth allocation settings.

terrestrial network. This is because of the large spectrum reuse in the area under investigation. However, it is important to note that the tail of the rate distribution greatly suffers if we prioritize the terrestrial network when controlling the spectrum split. With the `Baseline` setting and when all the bandwidth is allocated to macro BSs ($\varepsilon = 0$), around 7% of the UEs are out of coverage, as we observed in the previous section, and their rate is null. When the NTN bandwidth is increased, the coverage holes of the network are reduced, and the rate experienced by the cell edge UEs increases. This can be observed in the zoom of Fig. 3. Overall, we can highlight the underlying trade-off between cell-edge (5-th percentile UEs) and cell-center (mean/median and 95-th percentile UEs) throughput. If the operator gives a small share of the bandwidth to the satellite, it may achieve large cell-center UE data rates at the expense of coverage holes and degraded performance at the cell edge. In contrast, if the operator decides to allocate a large share of the bandwidth to the satellite, the cell edge performance greatly improves, at the expense of the cell-center UE data rate. For example, a UE which would be out of coverage when $\varepsilon = 0$ or in the `Baseline` scenario experiences a data rate of roughly 81 kbps if, using the proposed framework, we optimally set ε to 0.11. With our proposal, the mean UE rate decreases by 14% with respect to the setting of $\varepsilon = 0$ but results in a gain of more than 200 $\%$ with respect to the `Baseline` and the `3GPP` settings. Therefore, our framework is able to find the best solution to this trade-off by improving the coverage condition of the UEs that suffer from large path losses whilst providing large data rates to cell-center UEs.

V. Conclusion

In this paper, we have studied the throughput-coverage trade-off in a hybrid network comprised of terrestrial macro BSs and an LEO satellite. We have proposed a framework to control the UE association, transmission power, and bandwidth allocation between terrestrial and satellite BSs. Our proposal is able to distribute the load, while mitigating the number of coverage holes and maximizing the SLT in the network. Specifically, we demonstrated that by incorporating an LEO satellite on top of the terrestrial network in rural areas, the proportion of UEs out-of-coverage significantly drops down. Also, by studying the scenario where both tiers share the bandwidth, we were able to underline the trade-off between minimizing the coverage holes and enhancing the maximum throughput of the network, and strike the optimal point. Finally, our results indicate that the UE-BS association resulting from our framework greatly improves the performance of the network in terms of mean and 95-th percentile of log-throughput compared to the max-RSRP rule. Our analysis highlights the critical role that NTNs will play in the following years in providing reliable service throughout the world. Our future works will include an analysis from an energy efficiency point of view, as well as a refinement of the framework presented in this paper.

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