Fair Carrier Allocation for 5G Integrated Satellite-Terrestrial Backhaul Networks

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***Abstract*—The anticipated exponential growth in network traffic is posing significant challenges for the implementation of 5G networks. In this context, a major problem is the backhaul network which acts as a bottleneck preventing the efficient flow of ultra-dense and heavy traffic between the end users and the core network. Spectrum scarcity has emerged as the primary problem encountered when trying to accommodate the traffic upsurge. In this paper, we investigate the carrier allocation problem in the context of Integrated Satellite-Terrestrial Backhaul (ISTB) networks. In particular, we consider the satellite component to be integrated with the conventional terrestrial wireless backhaul network thus providing evident benefits in terms of data-offloading. To enhance the overall spectral efficiency of the proposed network, we consider that both terrestrial and satellite segments operate in the Ka band, where the sharing between terrestrial microwave links and satellite communications is already allowed. A novel carrier allocation algorithm based on fairness is proposed, which ensures that all backhaul links are continuously active to satisfy the operator's coverage needs. The problem is NP-hard by definition. As a consequence, we present a two-step sequential carrier allocation strategy specifically tailored to tackle the interference issues emerging from the spectral co-existence. Supporting results based on numerical simulations show that the proposed carrier allocation can provide a 2x improvement in terms of spectral efficiency when compared to benchmark terrestrial-only backhaul networks.**

I. Introduction

The upcoming fifth generation of cellular systems (5G) deployment have posed numerous challenges, mainly in terms of supporting very high data rates with low end-to-end delays [1], [2]. In particular, it is foreseen a throughput improvement of 1,000 times over currently existing 4G technology with 5 times reduced end-to-end latency. Accomplishing these goals while keeping a good balance between spectral and energy efficiency has been the focus of many research works. One of the key challenges is to substantially improve the underlying backhaul infrastructure, which has been identified as the key bottleneck for the 5G deployment [2]–[5].

In order to improve the capacity of mobile wireless backhaul networks, the concept of a seamlessly Integrated Satellite-Terrestrial Backhaul Network (ISTB) capable of jointly exploiting the terrestrial and satellite links depending on the traffic demands has emerged as a promising enabler. The relevance of ISTB is confirmed by the numerous on-going research projects on this area [6]–[8]. Satellite backhaul offers a solution not only for remote and difficult-to-reach locations but also in terms of data off-loading for delay-tolerant traffic from the terrestrial network and as an alternative routing path in case of terrestrial link failure or congestion.

In this paper, we consider a spectrum sharing paradigm where the satellite and the terrestrial system intelligently collaborate not only to enhance the backhaul network capacity but also to overcome current spectrum scarcity while reducing the spectrum licensing costs. In this spectrum sharing approach, both terrestrial and satellite segments operate in the 17.7-19.7 GHz band, where European Conference of Postal and Telecommunications administrations (CEPT) allows uncoordinated satellite terminals to co-exists with terrestrial wireless backhaul links [9]. In this scenario, two types of interference should be considered: (1) interference from terrestrial backhauling transceivers to the satellite backhauling terminals; and (2) interference among the terrestrial links due to the frequency re-use. Therefore, effective interference mitigation is indispensable to leverage the full potential of such ISTB networks.

There is a vast literature on interference mitigation techniques, most of them based on the availability of expensive and complex antenna arrays at the transmitter and/or at the receiver side [10], [11]. The magnitude of the benefits in terms of spectral efficiency that arise from the use of multi-antenna technology are significant, but they come at the expense of substantial operator expenditure in new hardware equipment. In this paper, we tackle the interference problem from a simple carrier allocation point-of-view, where the spectral efficiency gain arises essentially from the effort to pack a high number of backhaul links efficiently into the minimum number of carrier frequencies. The carrier allocation requires relatively low investment on the backhaul network infrastructure and minimal operating cost, since it is based on software modules running in central controllers.

Carrier allocation has been extensively considered for terrestrial backhaul networks [5], [12] but rarely for ISTB networks. Carrier allocation has been investigated in [13], [14] for cognitive satellite communications in the presence of incumbent terrestrial links. However, in [13], [14] either one of the two system has to adapt its carrier allocation in order to minimize the impact caused to the other system in terms of interference. Carrier allocation for ISTB is considered in [15], where the goal is to optimize the network sum-rate. As we will show later in this paper, the assignment proposed in [15] favors low-interference links in detriment of others which can hardly get a good channel assignment and become deactivated.

This is unacceptable from the operator point-of-view, since backhaul networks are carefully planned to provide service to a desired coverage and, once deployed, all links should be active to be able to distribute the traffic. To comply with this requirement, here we consider the fair allocation of carrier frequencies which is formulated as a max-min assignment problem. The later is NP-hard in general [16] and, in this case, the coupling between the terrestrial carrier assignment and the satellite backhaul link rates makes the problem very difficult to solve. As a consequence, we propose a two-step suboptimal method where we first determine the carrier allocation of the satellite system and, on a second step and assuming the resulting satellite segment allocation, we design the carrier assignment for the terrestrial segment.

The remainder of this paper is organized as follows. Section II describes the system model. Section III introduces the interference model and notation. Section IV presents the novel carrier allocation method. Finally, supporting numerical results are provided in Section V, and Section VI states the conclusion.

II. System Model

We consider a multi-hop wireless backhaul network composed of several terrestrial stations. Some of them are equipped with a satellite dish antenna and, therefore, can receive backhaul traffic through the satellite network. Let us assume N terrestrial nodes indexed by $n = 1, \ldots, N$, which can send, receive and relay backhaul traffic. We consider the terrestrial nodes to be interconnected through L unidirectional terrestrial communication links, indexed by $l = 1, \ldots, L$, forming $L/2$ bidirectional links. Let $\mathcal{O}(n)$ and $\mathcal{I}(n)$ represent the set of terrestrial links that are outgoing and incoming, respectively, from node n. Regarding the satellite segment, we consider $M \leq N$ terrestrial nodes equipped with satellite dish antennas. In this paper, we focus on the space-to-Earth communication links assuming that the return link is implemented in an exclusive frequency band. Therefore, the number of satellite links is equal to the number of hybrid satellite-terrestrial nodes. Fig. 1 illustrates a sample ISTB topology.

Let us assume that we have K carrier frequencies available, $k = 1, \ldots, K$, each of bandwidth B_c, which represent a standard bandwidth supported by both terrestrial and satellite system. We assume the number of terrestrial links L to be greater than the number of available carriers K, which is the general and most challenging case. Let $\mathbf{a}_t \in \mathbb{Z}_+^L$ be the terrestrial carrier allocation vector, whose elements $a_t(i) \in [1, \ldots, K]$ contain the identification number of the carrier that has been assigned to the i-th terrestrial link. Note that the definition of $\mathbf{a}_t$ implies that only one carrier is assigned to each link, but according to $L > K$, the same carrier can be used for different links. Additionally, full-duplex scenarios in which the same carrier is used for transmission and reception at the same terrestrial station should be avoided. The latter constraint can be mathematically expressed as follows:

$$\mathbf{a}_t(j) \neq \mathbf{a}_t(i), \quad j \in \mathcal{I}(n), i \in \mathcal{O}(n), \forall n. \tag{1}$$

Similarly, let $\mathbf{a}_s \in \mathbb{Z}_+^M$ be the satellite carrier allocation vector, whose elements $a_s(j) \in [1, \ldots, K]$ contain the identification number of the carrier that has been assigned to the j-th satellite link. The space-to-Earth links work on a single carrier communication mode and, thus, they can only be assigned one carrier frequency and this should not be shared with other satellite links. Based on this discussion, the following constraint shall be considered:

$$a_s(i) \neq a_s(j) \quad \text{for} \quad i, j = 1, \ldots, M, \ i \neq j \tag{2}$$

which ensures that a single carrier is not assigned to multiple satellite links.

III. Interference Model

Regarding the interference modeling, the interference power seen by the l-th terrestrial link operating at the k-th carrier is the sum of the power received from terrestrial emitters operating in the same carrier frequency and can be expressed as follows:

$$I_t(l,k) = \sum_{\substack{i \in \mathcal{T}(l) \\ i \neq l}} P_{\text{tx}}^{\text{TER}}(i) \cdot G_{\text{tx}}^{\text{TER}}(\theta_{i,l}) \cdot h(i,k,l) \cdot G_{\text{rx}}^{\text{TER}}(\theta_{l,i}) \tag{3}$$

where $\mathcal{T}(l)$ denotes the set of terrestrial links sharing the same frequency carrier with the l-th terrestrial link, $P_{\text{tx}}^{\text{TER}}(i)$ is the transmit power of the i-th link' transmit station, $G_{\text{tx}}^{\text{TER}}(\theta)$ and $G_{\text{rx}}^{\text{TER}}(\theta)$ represent the antenna gain of the terrestrial transmitter/receiver at an offset angle θ, $\theta_{i,l}$ denotes the offset angle (from the boresight direction) of the i-th link transmit antenna in the direction of the l-th link receiver antenna, and $h(i,k,l)$ is the free-space propagation loss between the i-th and l-th terminals for a certain frequency k.

The Signal-to-Interference plus Noise Ratio (SINR) of the l-th terrestrial backhaul link operating at the k-th carrier can be expressed as,

$$\text{SINR}_{\text{t}}(l,k) = \frac{P_{\text{tx}}^{\text{TER}}(l) \cdot G_{\text{tx}}^{\text{TER}}(0) \cdot h(l,k,l) \cdot G_{\text{rx}}^{\text{TER}}(0)}{I_t(l,k) + N_t}, \tag{4}$$

where N_t is the noise power at the terrestrial receiver.

The satellite links will be also affected by the interference caused by the terrestrial backhaul links due to the spectrum sharing condition. In particular, the interference level seen at the m-th satellite link operating at the k-th carrier can be written as,

$$I_s(m,k) = \sum_{i \in \mathcal{S}(m)} P_{\text{tx}}^{\text{TER}}(i) \cdot G_{\text{tx}}^{\text{TER}}(\theta_{i,m}) \cdot h(i,k,m) \cdot G_{\text{rx}}^{\text{SAT}}(\theta_{m,i}) \tag{5}$$

where $\mathcal{S}(m)$ denotes the set of terrestrial links that share the same carrier frequency than the m-th satellite link, $G_{\text{rx}}^{\text{SAT}}(\theta)$ is the gain of the satellite dish receiving antenna at an offset angle θ, and $h(i,k,m)$ denotes the propagation loss between the transmitter of the i-th link and the receiver of the m-th satellite link when operating at the k-th carrier.

As a consequence, the SINR of the satellite backhaul links can be computed as follows,

$$\text{SINR}_\text{s}(m,k) = \frac{P_s \cdot G_s \cdot h_s(m,k) \cdot G_\text{rx}^\text{SAT}(0)}{I_s(m,k) + I_\text{co} + N_s}, \tag{6}$$

where P_s refers to the satellite transmit power, G_s denotes the satellite antenna gain, $h_s(m,k)$ denotes the space-to-Earth propagation loss of the m-th satellite link operating at the k-th carrier, I_co is the co-channel interference due to the use of multibeam satellite, and N_s is the noise power seen at the satellite dish antenna.

IV. Proposed Carrier Allocation

Our main goal is to design a fair carrier allocation such that all the links in the network achieve similar throughput. To do so, we proposed the following max-min optimization problem:

$$\begin{aligned} \max_{\mathbf{a}_t,\mathbf{a}_s} \min_{j,i} \quad & \{R_t(j), R_s(i)\} \\ \text{s.t.} \quad & a_t(j), a_s(j) \in [1,K]\,,\ j=1,\dots,L\ j=1,\dots,M \\ & a_s(i) \neq a_s(j)\ \ i,j=1,\dots,M,\ i\neq j \\ & a_t(j) \neq a_t(i),\ \ j\in\mathcal{I}(n), i\in\mathcal{O}(n), \forall n, \end{aligned} \tag{7}$$

where $R_t(j) = B_c \log_2(1+\text{SINR}_t(j,\mathbf{a}_t))$ and $R_s(j) = B_c \log_2(1+\text{SINR}_s(j,\mathbf{a}_t,\mathbf{a}_s))$. The problem in (7) is difficult to solve as the terrestrial carrier allocation is tightly coupled with the satellite backhaul link rates. Even the problem involving terrestrial links only remains intractable due to the presence of interference in the terrestrial rate [17], which depends on the carrier allocation $\mathbf{a}_t$. The only way to solve (7) is via brute-force search which has exponential complexity and thus, not efficient in practical systems for large K, M and L.

In this paper, we propose a suboptimal method where we first determine the carrier allocation of the satellite based on metrics obtained by assuming no presence of terrestrial system and, on a second step and assuming the resulting satellite segment allocation, we design the carrier assignment for the terrestrial part of the network. As discussed before, the latter is not a tractable problem and, thus, finding the optimal solution is very challenging. Therefore, we propose an algorithm to solve the terrestrial assignment iteratively.

The order in which each part of the integrated network is optimized first is driven by the degrees of freedom of the resource allocation problem, which in general is higher for the terrestrial network since it has more flexibility in terms of number of links to adapt to the existing spectral environment.

A. Carrier Assignment: Satellite Backhaul Network

In this first step, we proceed as if there were no terrestrial network (i.e. $I_s(m,k)=0$, $m=1,\dots,M$, $k=1,\dots,K$) and, thus, the satellite carrier allocation is done based on each satellite link achievable rate. However, unlike the maximization of the sum-rate [14], [15], the max-min optimization cannot be casted as a classical assignment problem. Furthermore, the min-max assignment problems are NP-hard [16]. In this paper, we develop an efficient approximation algorithm.

Algorithm 1 Max-Min assignment algorithm

Require: M, K, $\mathbf{R}_\text{s}$.

Initialize $\mathcal{M}_0 = \emptyset$. This set contains the assigned links.
Initialize $\mathcal{K}_0 = \emptyset$. This set contains the assigned carriers.
for $t = 0:1:M-1$ **do**
  Select the rows and columns of $\mathbf{R}_\text{s}$ corresponding to the remaining unassigned carriers and links according to $\mathcal{M}_t$ and $\mathcal{K}_t \Rightarrow \widehat{\mathbf{R}}_\text{s}$
  Identify the link that will be assigned in this iteration by finding the minimum element of the resulting $\widehat{\mathbf{R}}_\text{s}$,

$$m^* = \min_m \widehat{R}_\text{s}(k,m) \tag{9}$$

  Find the carrier with maximum rate for the m^*-th satellite link,

$$k^* = \max_k \widehat{R}_\text{s}(k,m^*) \tag{10}$$

  Assign carrier k^* to the m^*-th satellite link: $\mathcal{M}_{t+1} = \mathcal{M}_t \cup m^*$ and $\mathcal{K}_{t+1} = \mathcal{K}_t \cup k^*$.
  Update carrier assignment $\mathbf{a}_\text{s}(m^*) = k^*$.
end for
return The carrier assignment: $\mathbf{a}_s$.

Let us rearranged the SINR level per carrier and per user in the satellite links as follows,

$$\mathbf{SINR}_\text{s} = \begin{bmatrix} \text{SINR}_\text{s}(1,1) & \cdots & \text{SINR}_\text{s}(1,M) \\ \vdots & \ddots & \vdots \\ \text{SINR}_\text{s}(K,1) & \cdots & \text{SINR}_\text{s}(K,M) \end{bmatrix}, \tag{8}$$

where the rows indicate the carrier frequencies and the columns indicate the satellite links. The SINR matrix in (8) can be transformed into rate matrix by computing $\mathbf{R}_s = \log_2(1+\mathbf{SINR}_\text{s})$ (element-wise operation). The proposed max-min carrier assignment algorithm is described with detail in Algorithm 1. In Algorithm 1, we follow a sequential carrier assignment, where the link with the worst achievable rate is assigned to the best available carrier frequency.

B. Carrier Assignment: Terrestrial Backhaul Network

The terrestrial carrier assignment should not only consider the interference caused to terrestrial nodes but also the interference caused to the satellite receivers. As mentioned above, exhaustive or brute-force search over all permutation is a simple and straightforward method to solve the terrestrial carrier assignment but its main disadvantage is the corresponding computational burden, especially when the number of links and carriers increases, we quickly face an extremely large computational expense. Given such computational difficulties, in this paper, we propose a simple and sub-optimal ad-hoc method, whose results are encouraging as we discuss in Section V.

Given the terrestrial intra-system interference in (3), the carrier allocation will tend to be carrier hungry in the sense that, if the channel condition on an empty carrier is acceptable for a particular link, this link should be allocated to the empty carrier instead of being co-allocated in a carrier where other links have been already assigned. Regarding the terrestrial intra-system interference, let us define the SINR matrix of the terrestrial links as follows,

$$\mathbf{SINR}_t = \begin{bmatrix} \text{SINR}_\text{t}(1,1) & \cdots & \text{SINR}_\text{t}(K,1) \\ \vdots & \ddots & \vdots \\ \text{SINR}_\text{t}(1,L) & \cdots & \text{SINR}_\text{t}(K,L) \end{bmatrix}, \quad (11)$$

where the rows indicate the carrier frequencies and the columns indicate the terrestrial links. Similarly, we can obtain the corresponding rate matrix $\mathbf{R}_t$ by computing the following element-wise operation $\log_2(1+\mathbf{SINR}_\text{t})$.

On the other hand, the terrestrial interference seen at the satellite receivers should be minimized. Let us define $\mathbf{G}(l) \in \mathbb{R}^{M\times K}$ as a matrix containing the interference level $g_l(m,k)$, which is defined as the interference caused by the l-th terrestrial link operating at k-th carrier and received at the m-th satellite link. The latter can be written as,

$$g_l(m,k) = P_\text{tx}^\text{TER}(l)\cdot G_\text{tx}^\text{TER}(\theta_{l,m})\cdot h(l,k,m)\cdot G_\text{rx}^\text{SAT}(\theta_{m,l}). \quad (12)$$

The information contained in $\mathbf{G}(l)$ is used to identify the satellite link that gets the highest level of interference when the l-th terrestrial link operates in carrier k. This is, for each k-th carrier, $M_\text{w}(l,k) = \max_m [\mathbf{G}(l)]_k$, where $[\mathbf{G}(l)]_k$ denotes the k-th column of matrix $\mathbf{G}(l)$ and $M_\text{w}(l,k)$ indicates the worst satellite link in terms of interference when terrestrial link l operating in carrier k. For convenience, let us define the following matrix containing these worst satellite links as,

$$\mathbf{M}_\text{w} = \begin{bmatrix} M_\text{w}(1,1) & \cdots & M_\text{w}(K,1) \\ \vdots & \ddots & \vdots \\ M_\text{w}(1,L) & \cdots & M_\text{w}(K,L) \end{bmatrix}. \quad (13)$$

Next, the SINR level of these worst satellite links is computed considering the satellite carrier allocation in section IV-A when only the worst terrestrial link is active. These SINR values are captured in the following matrix,

$$\mathbf{SINR}_\text{s,w} = \begin{bmatrix} \text{SINR}_\text{s,w}(1,1) & \cdots & \text{SINR}_\text{s,w}(K,1) \\ \vdots & \ddots & \vdots \\ \text{SINR}_\text{s,w}(1,L) & \cdots & \text{SINR}_\text{s,w}(K,L) \end{bmatrix}, \quad (14)$$

which captures the individual interference effect of each terrestrial link operating at the different carriers. Matrix $\mathbf{SINR}_\text{s,w}$ can be transformed into rate matrix $\mathbf{R}_\text{s,w}$ by computing $\log_2(1+\mathbf{SINR}_\text{s,w})$ of each matrix element.

The proposed terrestrial assignment algorithm takes both rate matrices $\mathbf{R}_t$ and $\mathbf{R}_\text{s,w}$ as inputs, corresponding to the terrestrial and satellite segment performance, respectively, and tries to perform max-min optimization of both of them. To reduce the bi-objective optimization problem into a single-objective optimization problem we consider the weighted sum technique in which the two rate matrices are combined in a single one by performing simple weighted addition, i.e. $w_1\mathbf{R}_t + w_2\mathbf{R}_\text{s,w}$. In this paper, the weights are all set to one so that no priority is given to either terrestrial or satellite links. Different weighting as well as more elaborated techniques for bi-objective optimization will be considered in future work.

The proposed algorithm for the terrestrial carrier assignment is summarized in Algorithm 2, which is based on the sequential algorithm presented in section IV-A. The main difference is that the rate input matrix is based on the combination of $\mathbf{R}_\text{s,w}$ and $\mathbf{R}_t$, and the later is updated at every iteration according to the spectrum decisions taken in previous iterations. This procedure is repeated until the terrestrial sum-rate evolution converges to a steady state solution.

Algorithm 2 Proposed terrestrial carrier allocation

Require: L, K, $\mathbf{SINR}_\text{s,w}$.
1: Initialize $\mathcal{L}_0 = \emptyset$. This set contains the assigned links.
2: Initialize $\mathcal{K}_0 = \emptyset$. This set contains the assigned carriers.
3: **for** $t = 0:1:L-1$ **do**
4: Compute $\mathbf{R}_t$ only for the remaining unassigned links tacking into account previous assignments $\mathcal{L}_t$ and $\mathcal{K}_t$.
5: Combine matrices into one: $\mathbf{R} = \mathbf{R}_t + \mathbf{R}_\text{s,w}$.
6: Apply step 5 and 6 of **Algorithm 1** to matrix $\mathbf{R}$ to obtain the selected carrier k^* and selected terrestrial link l^*.
7: Assign carrier k^* to the l^*-th terrestrial link: $\mathcal{L}_{t+1} = \mathcal{L}_t \cup m^*$ and $\mathcal{K}_{t+1} = \mathcal{K}_t \cup k^*$.
8: Update carrier assignment $\mathbf{a}_t(l^*) = k^*$.
9: **end for**
10: **repeat**
step 1 until Step 9 taking into account previous allocation $\mathbf{a}_t$.
11: **until** a stable solution is reached.
12: **return** The carrier assignment: $\mathbf{a}_t$.

V. Simulation Results

To show the performance of the proposed max-min carrier assignment, the ISTB network topology depicted in Fig. 1 is considered. It consists of 15 terrestrial nodes, 2 of which equipped with satellite transmission capabilities, interconnected via 22 bidirectional links and 2 satellite-to-Earth links. This makes $L = 44$ terrestrial uni-directional links and $M = 2$ satellite forward links. The topology in Fig. 1 is based on a true backhaul topology that is used in Finland which has been kindly provided by the Finnish communications regulatory authority, and it has been taken as a main topology for validation within the SANSA project [6]. As a benchmark for comparison, we will consider the current carrier allocation of the topology in Fig. 1, as listed in the database provided by the Finnish regulator which considers a block of 8 carriers of 56 MHz (excluding the satellite links) spanning from 17700 to 17924 MHz and from 18708 to 18934 MHz. For convenience, we kept the same carrier bandwidth as the benchmark, i.e. $B_c = 56$ Mhz. We assume a multi-beam satellite located at orbital position 13°E. The beam pattern covering the considered area has been simulated as in [18]. A summary of the system parameters considered for the simulation set-up is given in Table I.

Fig. 2(a) illustrates the distribution of the terrestrial link rates obtained with the proposed max-min carrier allocation, which are compared with the ones obtained with the sum-rate maximization proposed in [15]. Both algorithms are run over the considered topology assuming $K = 4$. From Fig. 2, it is observed that the sum-rate optimization is penalizing the individual rate of 2 of the network links in order to achieve higher overall network throughput, while the link rate distribution obtained with the proposed max-min is fairly spread between 0.6 and 1.2 Mbps.

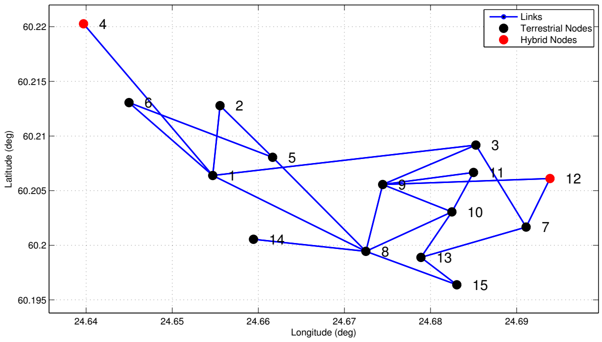
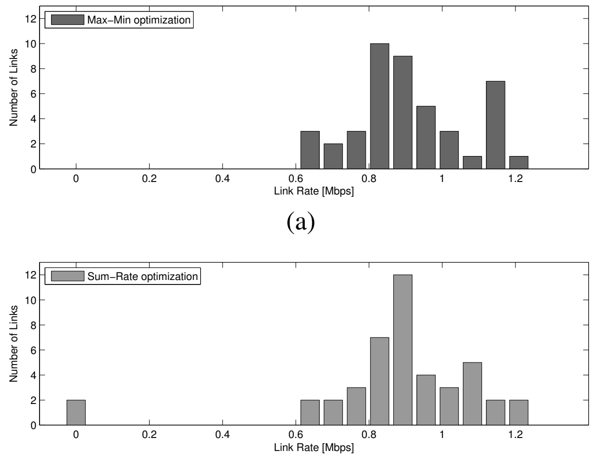


Fig. 1: ISTB network topology

TABLE I: Simulation Parameters

Parameter	Value
Terrestrial Segment	
Parameter	**Value**
Antenna pattern	ITU-R F.1245-2
Max. antenna gain ($G_{\text{tx/rx}}^{\text{TER}}(0)$)	38 dBi (55cm drum)
Transmit Power ($P_{\text{tx}}^{\text{TER}}$)	-20.65 dBW
Link distance	Between $427 - 1750$ m
Noise power (N_t)	-121.52 dBW
Antenna height	Between $10 - 48$ m
Terminal altitude above the sea level	From terrain data available online
Satellite Segment	
Parameter	**Value**
Satellite location	13°E
Satellite antenna gain (G_s)	Between $53.81 - 53.84$ dBi
Dish antenna pattern	ITU-R S.465
Max. dish antenna gain ($G_{\text{rx}}^{\text{SAT}}(0)$)	42.1 dBi (90cm dish)
Co-channel interference (I_{co})	10.54 dB
Transmit power (P_s)	9.23 dBW
Link distance	35.786 km
Noise power (N_s)	-126.94 dBW
Dish antenna height	Half of the terrestrial height
Terminal altitude above the sea level	From terrain data available online

The effect of the aggressive frequency re-use is illustrated in Fig. 3, where we show the sum-rate evolution of the overall ISTB network as the number of carrier frequencies are reduced. Fig. 3 includes the results obtained with the proposed algorithm as well as the results achieved with the sum-rate maximization proposed in [15] and the results achieved with the benchmark carrier allocation provided by the Finnish regulator. The optimal (brute-force) solution is not illustrated due to computational issues (variations of 8 carriers over 46 links translate into 8^{46} possible assignments). As expected, the ISTB network sum-rate decreases as the number of carrier frequencies reduces, as a consequence of sharing more spectral resources. Hence, the network interference increases translating into a reduced achievable rate. The most important conclusion extracted from Fig. 3 is that the proposed algorithm provides a fair carrier assignment while achieving similar overall network throughput compared to the sum-rate maximization counterpart. Furthermore, and focusing on $K = 8$, the proposed carrier allocation solution provides 13% more throughput than the benchmark allocation. This performance gain comes at minimal cost, since the carrier allocation is based on software modules which are run in a central network manager unit. Higher gain is expected for topologies with higher number of links (not examined here due to the lack of space).



(a)

(b)

Fig. 2: Terrestrial link rate distributions with $K = 4$ for: (a) Max-Min rate optimization, (b) Sum-Rate maximization.

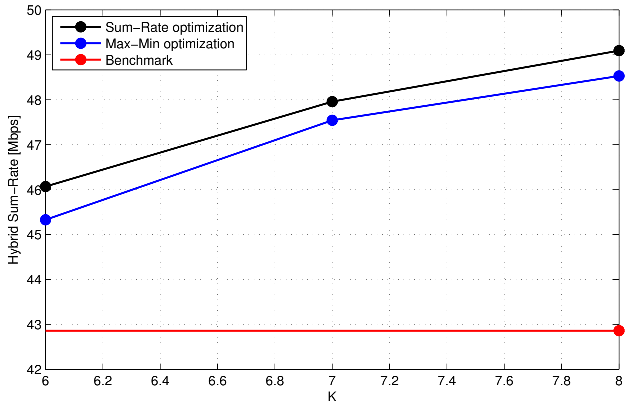


Fig. 3: Sum-Rate achieved by the ISTB network as a function of the number of carriers K

Finally, we examined the performance of the proposed algorithm for the satellite and terrestrial segment and for different number of carrier frequencies in terms of spectral efficiency computed as the sum-rate in bits per second (bps) divided by the overall bandwidth in hertz. For the ISTB network, the SE can be formulated as,

$$\text{SE} = \frac{\sum_{i=1}^{L} R_t(i) + \sum_{j=1}^{M} R_s(j)}{KB_c}. \qquad (15)$$

The obtained results are summarized in Table II, where we detail the SE obtained with the satellite and the terrestrial segment separately and the overall SE obtained with the ISTB network. Moreover, for the satellite case, we provide two results: (i) assuming no-terrestrial interference (noted in Table II as "w/o Terrestrial") and (ii) assuming the effect of the terrestrial interference (noted in Table II as "w/ Terrestrial"). It can be observed that the proposed allocation ensure no performance degradation to the satellite segment due to the

TABLE II: Spectral efficiency results [bps/Hz]

K	SE Satellite w/o Terrestrial	SE Satellite w/ Terrestrial	SE Terrestrial	SE ISTB
8	0.89	0.89	107.44	108.33
7	1.02	1.02	120.26	121.28
6	1.19	1.19	133.72	134.91
5	1.42	1.42	156.52	157.95
4	1.78	1.78	178.97	180.75
3	2.37	2.21	198.07	200.28

spectral co-existence with the terrestrial system unless the number of carriers is really small. In the latter case, the generated interference cannot be controlled with the carrier allocation only. On the other hand, the terrestrial SE increases as K increases, confirming the efficiency of the proposed algorithm even when the amount of spectral resources is low. It is worth to highlight the SE of the ISTB network at $K = 3$, i.e. with high frequency re-use, which goes up to 200.28 bps/Hz, which compared with the 95.67 bps/Hz of the benchmark, translates into 2.09x increase.

VI. Conclusion

In this paper, we investigated the carrier allocation problem in integrated terrestrial-satellite wireless backhauling networks, where aggressive frequency re-use between terrestrial backhaul links, and also between the terrestrial and satellite segments is considered. Unlike previous works on this subject, we focused on fairness optimization via the max-min throughput optimization. A two-step algorithm based on sequential carrier allocation has been proposed which takes into account the interference constraints resulting from the spectrum sharing scenario. Finally, we validated and compared the proposed carrier allocation algorithm through numerical simulation experiments, showing that spectral efficiency is significantly improved compared to the benchmark and that the available spectrum resources are successfully allocated so that there are no big discrepancies between different links' throughput.

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