RETURN LINK OPTIMIZED RESOURCE ALLOCATION FOR SATELLITE COMMUNICATIONS IN THE KU/KA-BAND

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Abstract

Broadband satellite networks play an important role in today's worldwide telecommunication infrastructure, providing services to an increasing number of users. Therefore, an efficient management of the spectrum resources is required in order to meet the fast-growing service demand. To this purpose, this paper addresses the optimization of the return carrier frequency plan for a broadband network benefiting from adaptive return channel selection (ARCS). The optimization problem is formulated as a multi-objective instance aiming at minimizing the total bandwidth and the unused throughput by using integer linear programming techniques. So as to capture events in which multiple terminals experience fade simultaneously, the spatial correlation of the attenuation fields has been incorporated in the optimization process. Moreover, physical layer characteristics and a minimum guaranteed throughput per user have been included as optimization constraints. Hence, the final outcome of this paper is a general technique providing an optimized carrier allocation plan, i.e., the number of carriers required to cover a certain area and guarantee a given throughput to each user.

1 Introduction

During the design phase of satellite broadband networks, an adequate sizing of the space segment resources is of key importance given its direct link to the business operational expenditure (OPEX). The minimization of the total bandwidth required to support the return link of the network becomes more complex if an adaptive return carrier selection (ARCS) scheme is used, given the need to consider the spatial and temporal correlations of the attenuation fields.

ARCS consists in the selection, out of a predefined and fixed set of return carriers, of the most adequate carrier that ensures that a link can be established [1]. In other words, it requires the system planner to define a frequency plan spanning multiple combinations of symbol rate, modulation, and coding rate able to match the characteristics of the channel in clear sky, moderate fade, and deep fade conditions [2]–[4]. Hence, it is important to capture the probability of having several user terminals experiencing a given amount of fade simultaneously, in order to have enough carriers of each type to satisfy the traffic requests.

Carrier allocation is a classic problem in satellite communications, usually tackled by means of multi-objective optimization techniques. In [5] and [6] the authors focus on the traffic characteristics (TCP and UDP), while in [7] and [8] the packet loss, the delay, and the required power are considered as metrics for the optimization. Unlike these works, in this paper we focus on the spatial and temporal correlation of the fading events in order to characterize the channel. In the traditional approach to system planning, the designer would employ long-term statistical distributions of the total attenuation, resulting from the use of models such as those of the ITU-R [9], in order to determine the worst location in the covered area. By resorting to these statistics, the designer would choose the return carrier characteristics providing the required service under fade conditions for a predefined percentage of a typical year. However, the traditional approach does not take the spatial correlation of the atmospheric fade into account. As a consequence, the network may end up either overdimensioned (by using more return link bandwidth than needed to support all quality-of-service (QoS) requirements) or congested (e.g., during heavy rain events, if not enough carriers are provisioned to support the services). In other words, congestion would

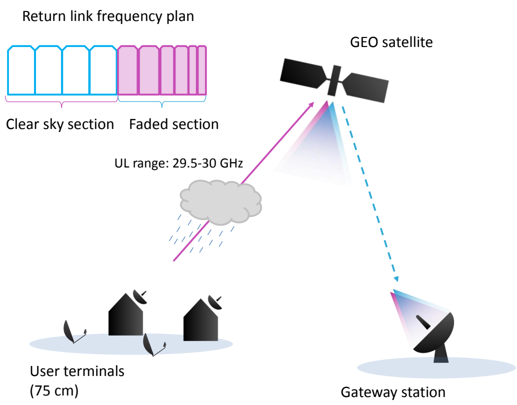


Figure 1: Return link of a satellite communication system affected by rain attenuation.

entail a reduction of the effective per-user throughput, while the overdimensioning would cause a sub-utilization of the return link capacity.

The objective of this work is therefore to investigate the optimization of the return link carrier plan for a broadband platform supporting ARCS, with a view towards minimizing the total bandwidth required. The spatial correlation of fade is captured by means of a rain field simulator able to reproduce the statistical properties of rain field clusters by generating a set of maps [10]. The main goal is to obtain a carrier plan that minimizes the total bandwidth required, and at the same time meets the QoS targets. To this purpose, the following QoS constraints are taken into account in the optimization process:

- a maximum acceptable outage probability, per user, referred to a typical year;
- a minimum guaranteed throughput per user.

Additionally, the problem is further constrained by using a limited and defined set of possible return link carriers, reflecting the capabilities of the physical layer and the characteristics of the ARCS scheme. The relevance for the industry of such a formulation stems from the actual deployed broadband platforms, which may not fully implement all the features described by the standard [1].

The remainder of the paper is organized as follows: in Section 2, the considered scenario is sketched, as well as the map generation and the carriers' characteristics. The optimization methodology is detailed in Section 3, and the numerical results are provided in Section 4. Eventually the conclusions are drawn.

2 System Model

The reference system used for the development of the planning methodology is composed of a geostationary network operating in the Ka-band (uplink at 29.5 - 30 GHz, downlink at 19 GHz, circularly polarized) with user terminal effective isotropic radiated power (EIRP) capability of up to 48 dBW. To simplify the exercise, it is assumed that the location of the hub or gateway station ensures a complete decorrelation of the fade, allowing the analysis to focus on the attenuation fields at the uplink frequency of the return link segment, as sketched in Fig. 1. In the following, the characteristics of the considered carriers and the map generation are discussed.

2.1 Spatially-Correlated Attenuation Fields

As discussed in the Introduction, a key aspect to consider in the planning of broadband networks deploying ARCS is the number of users experiencing a given amount of fade simultaneously. In order to include the spatial correlation of the fading in the optimization problem, spatially-correlated attenuation profiles have been generated by resorting to the rain field simulator MultiEXCELL [10]. Indeed, rain attenuation is the main contributor to the total attenuation at 29 GHz. Each profile takes the form of a map associating a value of the available power C/N_0 at the user terminal situated in a location to the pixel corresponding to that geographical location. Each map represents an attenuation field over an area of 230×238 km^2, where each pixel covers an area of 1×1 km^2. For the sake of simplicity, only one user per pixel is considered. Thousands of maps have to be generated in order to create a map set representative of the long-term behavior of the attenuation over the considered geographical area, where each map is an independent realization of the attenuation field over the same area. Then, an estimate of the probability density function (PDF) of the available power can be obtained for each pixel by considering the values of C/N_0 associated to that specific pixel across all the maps. The corresponding cumulative distribution function (CDF) of C/N_0, obtained as the cumulative sum of the PDF, is required to include the constraint on the outage probability per user in the optimization procedure. By selecting, for each pixel, the value of C/N_0 that guarantees the desired outage probability according to the corresponding CDF, a single map (referred to in the following as Fade Map) can be obtained. Further details on the generation of maps and their processing can be found in [10] and [11].

2.2 Carrier Set Definition

As ARCS works under the principle of selecting the most suitable carrier based on the traffic and the channel capability, it is important to specify the relevant characteristics of the carriers. In the following, each carrier type (or simply carrier, for brevity) is uniquely characterized by its symbol rate, modulation format, coding rate, and activation threshold $(C/N_0)_{th}$. We define a carrier set as the set containing all supported combinations of these features. The size and members of this set will be dictated by the technology used to provide the service.

In the following, we consider six possible couples of modulation and coding (MODCODs, denoted by MC 0 - 5 for brevity) and fourteen different values of symbol rate (ranging from 128 kHz to 4096 kHz). Each pixel (or, equivalently, user), can be assigned to one carrier only, while each carrier may serve multiple users in a frequency-and-time division multiple access (FTDMA) regime [12]. In order to be assigned to a certain carrier, a user must have an available power (derived from the Fade Map) greater than the activation threshold of that carrier.

3 Optimization Problem

It is important to recall that an ARCS approach implies a fixed return link frequency plan over the life of the service. Once the link planning process has been executed for the clear sky condition, it is possible to determine the amount of carriers required to support the entire traffic. Therefore, the return link frequency plan can be divided in two sections: a clear sky section, supporting all terminals not experiencing fade, and a fade section, supporting terminals under fade. For the purposes of our optimization problem, we will focus on minimizing the total bandwidth required to implement the fade section of the return plan, and will therefore restrict our analysis to pixels experiencing fade. The optimization procedure proposed in this paper consists of three steps:

- a preliminary allocation aiming at satisfying the constraint on the outage probability;
- a successive reallocation to minimize the number of carriers required, considering that a carrier can support multiple pixels (in a FTDMA scheme);
- a final numerical optimization (exploiting integer linear programming techniques) targeting a further reduction of the total occupied bandwidth and the unused per-carrier throughput.

3.1 Preliminary Allocation

The objective of the preliminary allocation phase is to establish a one-to-one correspondence between a pixel under fade and the most efficient carrier it supports, given its available C/N_0. In the steps that follow, we will assume that there is a single user per pixel in each map.

Pixels subject to rain fade are identified by comparing the values of C/N_0 in the Clear Sky Map with the corresponding values in the Fade Map and by assuming a given tolerance θ. The pixel (i, j) belonging to the Fade Map is considered to be in clear sky conditions if

$$\left(\frac{C}{N_0}\right)^{(i,j)}_{\text{clear sky}} - \left(\frac{C}{N_0}\right)^{(i,j)}_{\text{fade}} < \theta \,.$$

Tolerance θ is an extra degree of freedom that can be exploited during the design process. Its motivation is twofold: from a numerical point of view, it helps dealing with the granularity of the estimated PDF of the available power of each user. On the other hand, from the deploying point of view, it helps in reducing the number of switches over time between the clear-sky state and the fading state of each user, by introducing a hysteresis.

For the preliminary allocation, pixels and potential carriers are matched by comparing each pixel's available C/N_0 against the set of $(C/N_0)_{th}$ corresponding to the carrier activation thresholds. When a pixel supports multiple carriers, the carrier providing the highest efficiency (in bit/s/Hz) is selected. At this stage it is also possible to determine the number of non-served users: it corresponds to the number of pixels such that

$$\left(\frac{C}{N_0}\right)^{(i,j)}_{\mathrm{fade}} < \min\left(\frac{C}{N_0}\right)_{th}.$$

It is important to note that, in a FTDMA scheme, a user can be assigned to only one carrier at a given time.

3.2 Reallocation

Since we aim at minimizing the total bandwidth and the unused rate of the system, we exploit the possibility to assign multiple users to a single carrier, provided that the latter has a throughput high enough to serve more than one user. In this way, it is possible to have an efficient exploitation of the system resources. In the following, we assume that all the users need the same (and fixed) amount of throughput $t_{\min}$. The number of carriers of type i needed when considering multiple users per carrier is

$$n_i^{(1)} = \left\lceil \frac{n_i^{(0)}}{\lfloor t_i/t_{\min} \rfloor} \right\rceil \tag{1}$$

where $n_i^{(0)}$ is the number of carriers of type i from the preliminary allocation step (when one user per carrier was considered), and t_i is the throughput conveyed by carrier type i. Finally, the unused rate per carrier type can be calculated as

$$r_i^{(1)} = n_i^{(1)} t_i - n_i^{(0)} t_{\min} \tag{2}$$

and the total unused rate over all the carriers is

$$R^{(1)} = \sum_{i=1}^{N} r_i^{(1)} \tag{3}$$

where N is the number of carrier types. In the same way, the total occupied bandwidth is

$$B^{(1)} = \sum_{i=1}^{N} B_i n_i^{(1)} \tag{4}$$

where B_i is the bandwidth of carrier type i.

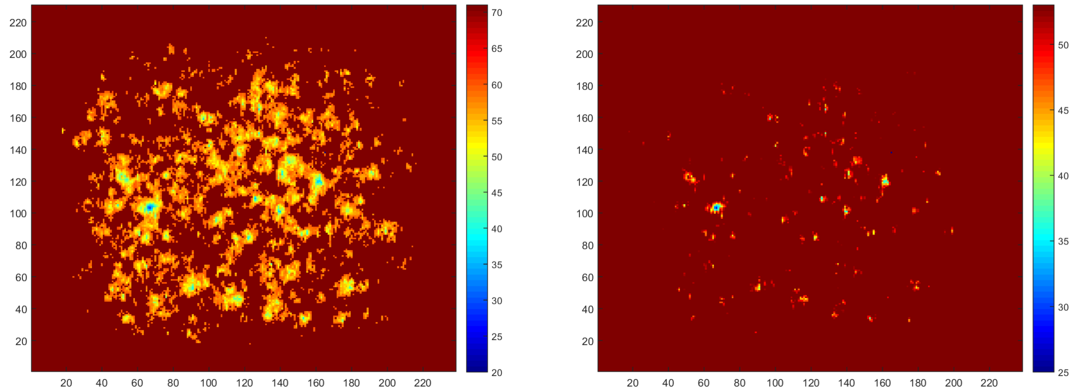
3.3 Numerical Optimization

The resource reallocation is used as input for the numerical optimization, which results to be an integer linear programming (ILP) instance [13]. The notations used in the problem formulation is the following:

- $n_i^{(2)}$ represents the number of carriers of type i after the last step of the optimization;
- $r_i^{(2)}$ is the unused rate of carrier i, computed by replacing $n_i^{(1)}$ with $n_i^{(2)}$ in (2);
- λ is a real nonnegative weighting factor;
- $R^{(2)}$ is the total unused rate, computed by replacing $r_i^{(1)}$ with $r_i^{(2)}$ in (3);
- $B^{(2)}$ is the total bandwidth, computed by replacing $n_i^{(1)}$ with $n_i^{(2)}$ in (4).

The carrier allocation that minimizes the total bandwidth and the unused rate can be found by solving the following ILP problem

$$\min_{\{n_i^{(2)}\}} \; \lambda R^{(2)} + (1-\lambda) B^{(2)} \tag{5}$$



(a) Map of the users under rain fading (Fade Map).

(b) Non-served users in the Fade Map.

Figure 2: Maps under rain fading.

subject to:

$$\sum_{i=1}^{k} n_i^{(2)} \geq \sum_{i=1}^{k} n_i^{(1)} \quad \text{for} \quad k = 1, \dots, N-1 \tag{6}$$

$$\sum_{i=1}^{N} n_i^{(2)} = \sum_{i=1}^{N} n_i^{(1)} \tag{7}$$

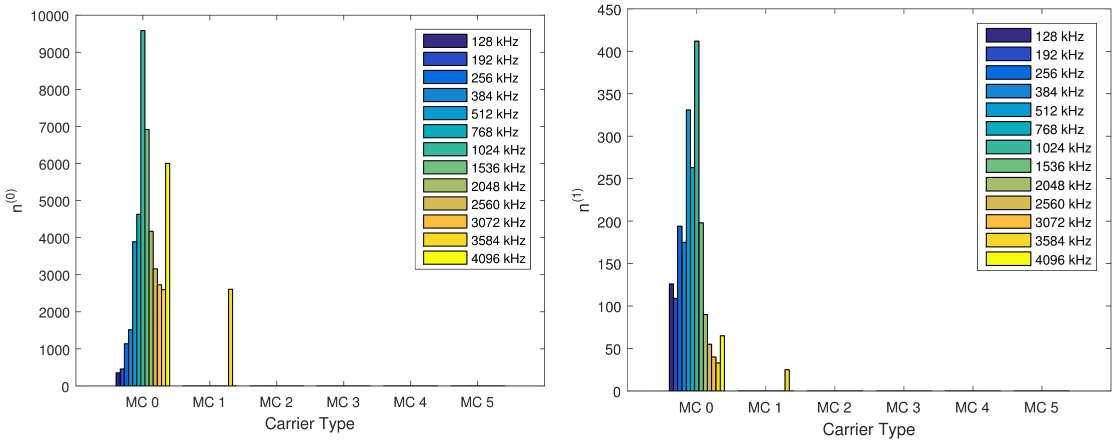
where $n_i^{(2)} \in \mathbb{N}$ for $i = 1, \dots, N$. The ordering of the carrier follows the activation thresholds, i.e. $(C/N_0)_{th}^{(i)} > (C/N_0)_{th}^{(j)}$ if $i > j$, with $i, j \in [1, N]$. The weighting factor λ is necessary to balance the two objectives of the minimization in (5), i.e., the total bandwidth and the unused rate. Indeed, these two quantities may differ for orders of magnitude, and the weighting factor is needed to rescale them and make them comparable. The constraints (6) and (7) prevent the solving algorithm to assign a user to a carrier with an activation threshold higher than its value of C/N_0. In other words, a carrier can be allocated to a user only if it belongs to the user's allowed carrier set, which is formed by all the carriers having activation threshold lower than the user's value of C/N_0.

4 Numerical Results

In the following, a system availability equal to the 99% of the time will be considered. Such value will be adopted in the construction of the Fade Map (obtained by generating 8610 maps with MultiEXCELL), assuming a tolerance θ with respect to the clear sky condition equal to 0.01 dB. The resulting Fade Map is shown in Fig. 2a: the red area represents users in clear sky conditions, while the rest of the map (yellow, green, and blue areas) are users under rain fade. Furthermore, the number of non-served users (NSUs) (i.e., those users for which the attenuation is so strong that no MODCOD can be activated) has been evaluated: a yearly outage probability equal to 1% causes the 1.5% of the pixels to be under severe rain condition, which means that the 1.5% of the users in the map cannot be served. The locations of the NSUs in the Fade Map is shown in Fig. 2b.

The histogram in Fig. 3a shows the result of the preliminary allocation, while Table 1 reports the details of the carrier allocation plan after the reallocation represented with histograms in Fig. 3b. The reallocation represents an intermediate step in the optimization process, but still the improvements are evident: by comparing Fig. 3a and Fig. 3b, the number of used carriers is reduced of orders of magnitude.

Finally, the optimized allocation plan, obtained by solving the problem in (5) by using Matlab mixed-integer linear programming (MILP) solver, is reported in Table 2, showing that only the two carrier types with the lowest activation thresholds are actually used. Moreover, the number of the first carrier type (i.e., carrier with bandwidth equal to 128 kHz and using the MODCOD 0) has not been diminished. Indeed, users allocated to such carrier cannot be reallocated to higher carries due to lack of power, whereas users previously allocated to higher carriers can be moved to the lower ones in order to minimize the objective function in (5). In other words, the reallocation can be done only in one direction: from the carriers with higher activation thresholds to the ones with lower activation thresholds.



(a) Preliminary carrier allocation.

(b) Carrier allocation after the reallocation.

Figure 3: Carrier allocation in steps 1 and 2.

Table 1: Allocation plan after the reallocation.

B_i (kHz)	MC ID	$n_i^{(1)}$	$r_i^{(1)}$ (kbps)	$n_i^{(1)} t_{\min}$ (kbps)
128	0	126	2586.9	8850
192	0	109	631.8	11450
256	0	194	4256.2	28450
384	0	175	3057.1	37900
512	0	331	6248.6	97250
768	0	263	4159.6	115750
1024	0	412	2833.7	239625
1536	0	198	149.5	172950
2048	0	90	1238.0	104250
2560	0	55	96.52	78950
3072	0	40	590.2	68200
3584	0	33	721.9	64925
4096	0	65	642.1	150050
3584	1	25	387.8	65175

Table 2: Allocation plan after the optimization.

B_i (kHz)	MC ID	$n_i^{(2)}$	$r_i^{(2)}$ (kbps)	$n_i^{(2)} t_{\min}$ (kbps)
128	0	126	2586.9	8850
192	0	1990	11534.1	49750

Table 3: Improvements after the optimization.

	Overall Bandwidth B (GHz)	Overall Unused Rate R (Mbps)
Reallocation	2.2	6330.5
Optimization	0.4	14.1
Improvement	1.8	6316.4

Concluding, Table 3 reports the improvements provided step by step by the proposed optimization in terms of total bandwidth and unused rate.

5 Conclusions

In this paper, a general procedure to optimize the carrier allocation plan for the return link of a satellite communication system using ARCS has been proposed. This procedure aims at minimizing at the same time the total occupied bandwidth and the unused rate of the system while satisfying QoS constraints (such as a guaranteed throughput and an outage probability) for all the users. To this purpose, the optimization process has been split into three steps, the last one falling in the framework of multi-objective ILP problems solvable in polynomial time. The proposed optimization methodology is an automated tool that can reduce the waste of scarce resources such as the bandwidth and the data throughput during the system planning phase, preventing the detrimental effects of under- and overdimensioning of the network.

Acknowledgements

We thank Prof. Lorenzo Luini of Politecnico di Milano, Italy, for having supplied the attenuation maps used in this study.

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