Flexible Beam-User Mapping for Multibeam Satellites

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***Abstract*—A non-rigid mapping between satellite beams and users is explored, so that users are not necessarily served by their dominant beams. As baseline cases we consider traditional satellite payloads and flexible bandwidth allocation across beams, along with the development of a simplified optimization algorithm. The explored solutions are tested in a satellite scenario that consists of a chain of beams in a two-color scheme under a common polarization, addressing multiple traffic demand distributions. The flexibility that the beam-free approach brings along provides a better geographic match when facing strongly non-uniform traffic demands. This is translated into a reduction of the unmet capacity, up to 29% on average for the selected asymmetric traffic demand scenarios.**

***Index Terms*—Flexible payload, Multibeam satellite, Non-uniform traffic.**

I. Introduction

In conventional satellite systems, radio resources are typically distributed uniformly across the coverage, resulting in a far from optimal solution to non-uniform traffic demand, as that commonly found in a satellite coverage. More recent satellites are technologically prepared, to some extent, for a flexible and smart allocation of the radio resources to match the offered throughput to the specific traffic demand in the coverage.

The resource allocation for advanced satellite payloads has been studied under different criteria and resource management strategies. The separate flexible allocation of bandwidth and power to match the traffic demand has been addressed in [1]–[3], whereas the joint flexible distribution of power and bandwidth has been also addressed in [3], [4]. Alternatively, beam hopping solutions employ the time domain as degree of freedom for resource assignment [5], [6]. However, the common assumption is that users are only served by their dominant beam, resulting in a fixed beam-user mapping. By disregarding the conventional cell boundaries, additional flexibility is extracted for the assignment of resources. The idea of a beam-free approach for satellite systems has been previously studied for precoding solutions in [7], [8], and for Power Domain NOMA (PD-NOMA) applications in [9]. This changes the paradigm of the user scheduling with a joint collaboration of the beams for serving the users in the system. Furthermore, a more flexible mapping between users and beams has shown some potential for improvement with respect to the canonical assignment, especially for scenarios with strong asymmetries [10], [11]. This potential improvement is achieved through the pulling of unused resources. Thus, a donor beam provides idle resources to a recipient beam, mitigating the traffic congestion of the latter. This additional flexibility can complement that already provided by flexible payloads, extending their range of operation.

In this paper, the free mapping between user and beams is addressed as an additional degree of flexibility in the resource assignment. The available bandwidth is split into different carriers that can be freely assigned to the beams within basic co-channel interference constraints. A resource allocation design is presented for the joint allocation of bandwidth and mapping between beams and users. For benchmarking purposes, the same beam free approach is also considered for a traditional satellite payload with fixed bandwidth per beam. In both fixed and flexible bandwidth allocation cases, the potential benefits provided by the elasticity in the size of the cells served by the different beams is studied.

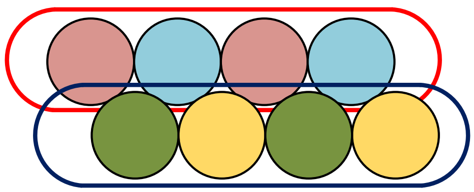
We focus on a satellite scenario that consists of a chain of beams served by the same polarization, as that found along the Pacific Coast in the United States, or also in the four-color mapping case based on two orthogonal polarizations, when beams in a given row are served by alternating frequency bands under the same polarization [4]. In this scenario, multiple traffic demand distributions are considered for the evaluation of the techniques.

The paper is organized as follows. First, the system description and resource allocation problem are presented in Section II. Next, the baseline techniques are presented in Section III, with the numerical results provided in Section IV. Finally, conclusions are given in Section V.

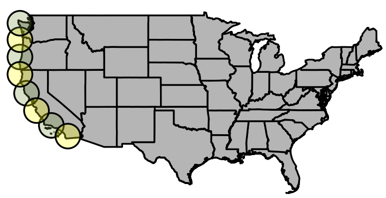
Notation: Lower boldface letters denote vectors. The carriers power and bandwidth are denoted by $P^{\sim}$ and $W^{\sim}$, respectively.

II. System Model

A satellite system that illuminates K beams alongside one dimension is considered, as presented in Fig. 1, where the number of users to be served at a given time instant is N. This particular scenario can be found in conventional four color reuse schemes operating with those beams making use of the same polarization, and also in two color reuse schemes. To serve the users, the available bandwidth W^{total} is split into $2M$ carriers with a fixed carrier bandwidth $W^{\sim} = W^{total}/2M$. An advanced satellite payload with flexible bandwidth capability is considered by allowing a flexible number of carriers M_b at beam b. Co-channel interference is neglected by preventing the same carrier from being used in two adjacent beams, with $M_a + M_b \leq 2M \ \forall \ (a,b)$ adjacent beams. As to the carrier power, the total power budget for communication P^{total} is uniformly distributed among the carriers as $P^{\sim} = P^{total}/KM$, derived from the use of amplifiers shared by several beams which do not have overlapping portions of bandwidth [3]. To describe the relation between beams and users, let $\mathsf{B}(n)$ denote the index of dominant beam for the user n.



(a)



(b)

Fig. 1. Examples of the one-dimensional satellite coverage. (a) Four color reuse scheme. Each row of beams operate with the same polarization (red or blue) (b) Two-color scheme over a coast area. Partial Viasat-1 beam footprint [4].

User terminals are assumed to be single-carrier receivers. The system has to perform the carrier selection for the users taking into account the flexible allocation of the carriers in the beams. This joint allocation process can be a complex task if the carriers are shared among different users. For an initial evaluation of the free beam-user mapping, a one-to-one mapping between carriers and users is assumed to simplify the problem. If no pre-arranged attachment between users and beams is set, the offered user rate $R^{off}(n), n = 1, \dots, N$, can be written as

$$R^{off}(n) = \sum_{b=1}^{K} s_{n,b} W^{\sim} \log_2 \left(1 + \frac{P^{\sim} |h_b(n)|^2}{N_o W^{\sim}} \right) \quad (1)$$

where $s_{n,b}$ is a binary variable that denotes the beam-user mapping of the user n to the beam b, and $h_b(n)$ the corresponding channel magnitude, including antenna responses. With this notation, the number of carriers per beam, M_b, reads as

$$M_b = \sum_{n=1}^{N} s_{n,b}, \ b = 1, \dots, K. \quad (2)$$

The purpose of the system is to match the user demanded rates with the corresponding offered rates, $R^{off}(n)$. This approach is commonly found in the literature under different constraints and variants, see, e.g., [2], [3], [12]. In the case under study, the resource allocation will be driven by the unmet capacity, or amount of non-served traffic demand, expressed as

$$U = \sum_{n=1}^{N} (R^{req}(n) - R^{off}(n))^{+} \ , (x)^{+} = \max(x, 0) \quad (3)$$

where $R^{req}(n)$ is the demanded rate by the user n. The optimization of the unmet capacity presents challenges for practical optimization purposes if the minimization of the expression in (3) is directly pursued. Alternatively, the problem can be reformulated as a convex optimization problem with the maximization of the sum-rate subject to different rate constraints that limit the offered rates to the users:

$$\begin{aligned} \max \quad & \sum_{n=1}^{N} R^{off}(n) \\ \text{subject to} \quad & R^{off}(n) \leq R^{req}(n), \forall \, n. \end{aligned} \quad (4)$$

In this work, a basic traffic model is assumed to facilitate the analytical resolution of the resource allocation. If we assume that all active users expect the rate provided by a full carrier from its dominant beam $\mathsf{B}(n)$ as

$$R^{req}(n) = W^{\sim} \log_2 \left(1 + \frac{P^{\sim} |h_{\mathsf{B}(n)}|^2}{N_o W^{\sim}} \right) \ , \ n = 1, \dots, N, \quad (5)$$

then the offered user traffic $R^{off}(n)$ cannot surpass the defined requested traffic $R^{req}(n)$. Thus, the constraints on the user rates can be dropped and the optimization of unmet capacity is achieved with the maximization of the sum-rate.

If we define a vector $\boldsymbol{s} = [s_{1,1} \dots s_{N,K}] \in \mathbb{R}^{NK}$ to collect the beam-user mapping, the resource allocation problem to perform the joint carrier-beam allocation and beam-user mapping is expressed as

$$\begin{aligned} \max \quad & g(\boldsymbol{s}) = \sum_{n=1}^{N} \sum_{b=1}^{K} s_{n,b} W^{\sim} \log_2 \left(1 + \frac{P^{\sim} |h_b(n)|^2}{N_o W^{\sim}} \right) \\ \text{subject to} \quad & \sum_{b=1}^{K} s_{n,b} \leq 1, \forall \, n \\ & \sum_{n=1}^{N} s_{n,a} + \sum_{n=1}^{N} s_{n,b} \leq 2M \ \forall \ \text{adjacent}(a,b) \\ & s_{n,b} \in \{0, \ 1\}, \forall \, n, b. \end{aligned} \quad (6)$$

This problem is a binary linear program (LP) that can be easily solved. In principle, the resolution of the beam-user mapping involves NK variables for the assignment of the N users to the K beams. Nevertheless, the search space can be reduced to only $2N$ variables, due to the significant differences in the illumination from the different beams at a given Earth location. The directivity of the satellite antennas is such that those users far from a given beam footprint have a very low gain, in such a way that the search for viable beams for a given user is restricted to its dominant beam and the second dominant beam.

III. Baseline Schemes

In order to understand the potential of freedom when mapping beams and users, different baseline solutions are built by considering traditional satellite payloads and/or constrained beam-user mapping.

A. *Traditional satellite payload*

The assumption of traditional satellite payloads results in a fixed resource allocation with uniform allocation of the carriers, $M_b = M\ \forall\ b$. Under this assumption, the LP problem in (6) is modified accordingly, with the beam-user mapping as the only degree of freedom:

$$\begin{aligned} \max \quad & g(\boldsymbol{s}) = \sum_{n=1}^{N}\sum_{b=1}^{K} s_{n,b} W^{\sim} \log_2\left(1 + \frac{P^{\sim}|h_b(n)|^2}{N_o W^{\sim}}\right) \\ \text{subject to} \quad & \sum_{b=1}^{K} s_{n,b} \leq 1, \forall\, n \\ & \sum_{n=1}^{N} s_{n,b} \leq M\ \forall\ b \\ & s_{n,b} \in \{0,\ 1\}, \forall\, n, b. \end{aligned} \tag{7}$$

This linear assignment problem can be solved with the application of a generalized version of the Hungarian algorithm [13].

B. *Constrained beam-user mapping*

The most common strategy in satellite systems in the resource allocation is to consider that users are only served by their dominant beams. To explore this conventional beam-user mapping, the constraints $s_{n,b} = 0\ \forall\ b \neq \mathsf{B}(n)$ need to be imposed in (6) and (7), for flexible and fixed bandwidth allocation, respectively.

IV. Numerical Results

A chain of 12 beams is considered following the system definition in Section II and parameters in Table I. Diverse traffic profiles are considered in the simulations as the number of users per beam is a random variable following an independent uniform distribution between 0 and $2M$, $\mathcal{U}\{0, 2M\}$; for simplicity, the user locations are uniformly distributed within each beam. 100,000 Monte-Carlo simulations are performed to simulate the different techniques that are collected in Table II. In anticipation of the use of practical modulation and coding schemes, a minimum signal to interference and noise ratio (SINR) is enforced when allocating resources from a neighbour beam. For the parameters in Table I, the SNR at the center of the beam is approximately 15 dB, which goes down to 8.7 dB if users in the inner areas of the neighbor beams in Fig. 2 are served. As a remark, the carrier to interference (C/I) at the extended beam boundary in the figure is 24 dB, with no significant impact on the SINR. Note that the blue (red) beam can serve users in either its footprint or in the inward yellow (purple) areas in the neighbor beam. For the considered simulation settings, each of these inward areas amount to roughly 12% of the total beam area.

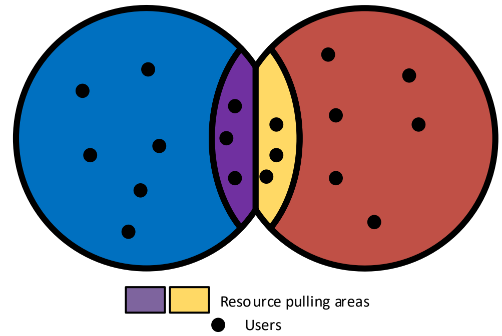


Fig. 2. User selection areas for two adjacent beams. Users within the blue (red) area are uniquely served by the blue (red) beam. Users within purple or yellow areas can be served by either beam.

TABLE I
System parameters for the forward link

Diagram pattern	Bessel modeling
Beam roll-off	3 dB
Radius at 3 dB	50 km
Number of beams	12
Maximum antenna gain	52 dBi
Average free space losses	210 dB
Average atmospheric losses	0.4 dB
Total available transmission power	400 W
Total available bandwidth	500 MHz
Polarization	Single
Frequency reuse scheme	2-color
Number of carriers M per color	30
Effective SNR	13.44 dB
Frequency band [GHz]	20
Receiver Parameters	
Receiver cloud noise temperature	280°K
Receiver terminal noise temperature	310°K
Receiver ground noise temperature	45°K
LNB Noise Figure	2 dB
Receiver antenna efficiency	0.65
Receiver antenna diameter	0.6 m
Losses due to terminal depointing	0.5 dB

TABLE II
Explored techniques in the simulations

Technique	Satellite Payload
Fixed BW - Fixed Mapping	Traditional
Flexible BW - Fixed Mapping	Advanced
Fixed BW - Free Mapping	Traditional
Flexible BW - Free Mapping	Advanced

The techniques will be compared in terms of the normalized unmet capacity, measured as

$$\mathrm{NU} = \frac{\sum_{n=1}^{N} R^{req}(n) - R^{off}(n)}{\bar{N} W^{\sim} \log_2(1 + \mathrm{SNR}_{eff})} \tag{8}$$

where $\bar{N}$ is the average number of users in the simulations, and SNR_{eff} an effective SNR corresponding to a super-user that embodies the user channels across all locations, such that[1]

$$\log_2(1+\mathrm{SNR}_{eff}) = \mathbb{E}\left[\log_2\left(1+\frac{P^{\sim}|h|^2}{N_o W^{\sim}}\right)\right] \quad (9)$$

where h is a random channel value, and the expectation is taken across all locations within the beam. Thus, the unmet capacity is normalized by the average traffic demand in the system to facilitate the comparison of different techniques. Under this normalization, values close to 0 correspond to a high traffic provision, whereas values close to 1 mean that a lot of traffic remains unserved.

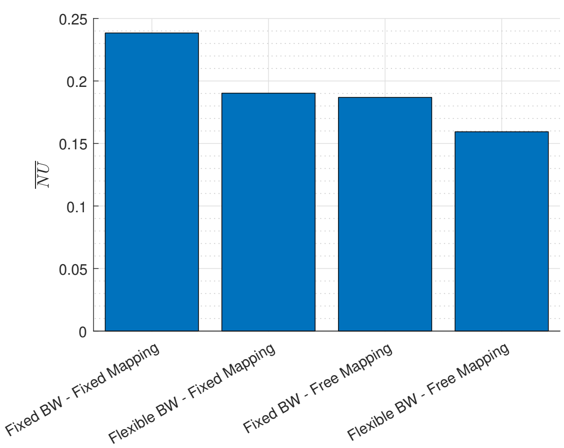


Fig. 3. Average normalized unmet capacity for the different techniques for diverse traffic profiles

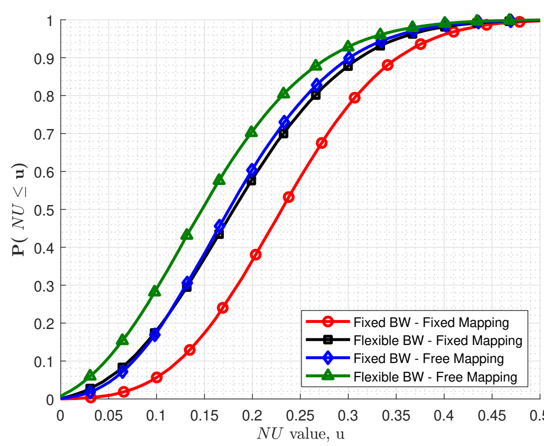


Fig. 4. Cumulative distribution function of the percentage of normalized unmet capacity for the different techniques.

The average results for the different schemes in Table II are presented in Fig. 3, whereas the cumulative distribution function (cdf) of the normalized unmet values are presented in Fig. 4. It can be readily seen in both figures that the joint allocation of bandwidth and the beam-user mapping provides the best performance overall. Interestingly, the flexibility in the mapping of users and beams is competitive against the flexibility of bandwidth allocation, when both are applied on their own.

The numerical results from Fig. 3 and 4 were obtained for different beam traffic profiles that are uniform on average. However, the contribution of resource pulling can excel under strongly skewed traffic distributions. For illustration purposes, let us consider the asymmetric scenario displayed in Fig. 5, where we have hot-spots in the form of pairs of congested beams surrounded by empty beams. The number of users in the highly congested beams follows a uniform random distribution between M and $2M$. The corresponding numerical results are presented in Fig. 6 for $10,000$ different realizations: on average, the beam-user mapping freedom can reduce the unmet capacity around 29% with respect to the fixed case. As opposed, the flexible bandwidth allocation is not able to improve the response to the requested traffic. This particular scenario showcases the limitations of the bandwidth allocation. When two adjacent beams have a high concentration of traffic, the system is unable to provide more carriers to them without inflicting co-channel interference. The beam-user mapping goes around this limitation by just pulling resources from a neighbour beam. By looking at the cdf of the unmet demand in Fig. 7, we notice a significant improvement with respect to the fixed mapping case, which, depending on the relative location of the users inside the beam, can provide an offered traffic improvement between 0% and 32%. As the number of users increases while keeping the same ratio between users and carriers, the corresponding curves become more vertical, around the abscissa 0.22 for the free mapping solutions and 0.31 for the fixed mapping solutions.

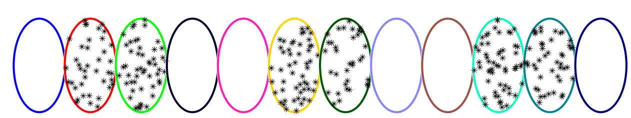


Fig. 5. Traffic demand concentrated in hot-spots.

Finally, it is important to remark that the displayed gains are accomplished without additional complexity at the gateway, payload or the receiver terminals, the latter being conventional. The gateway needs to update its mapping software to account for the inward terminals in neighboring cells served by non-dominant beams. The terminals do not need to report phase information, only channel magnitude (or SNR) with respect to two adjacent beams.

V. CONCLUSIONS

In this paper, we have considered a beam free approach with flexible allocation between users and beams. It has been evaluated for both traditional and more advanced satellite payloads, focusing on the service to chains of beams under a two color reuse scheme. This contribution complements existing

[1]The antenna radiation diagram, based on Bessel modeling, is assumed to be the same for all beams.

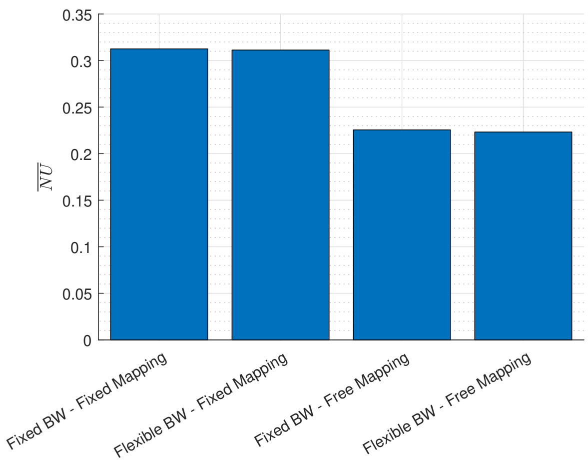


Fig. 6. Average normalized unmet capacity for the different techniques in the asymmetric scenario.

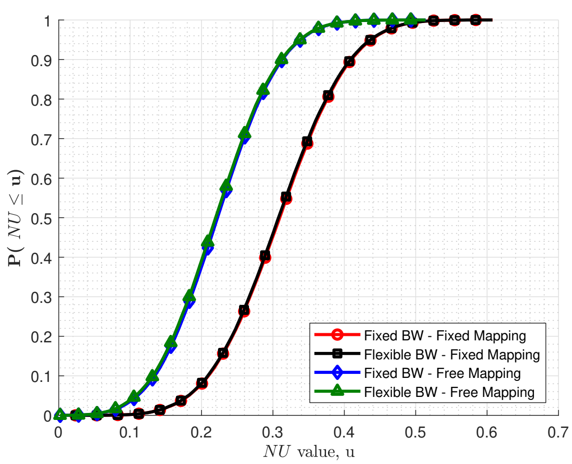


Fig. 7. Cumulative distribution function of the normalized unmet capacity for the asymmetric scenario.

results for flexible power, bandwidth and time allocation to the different beams, accounting for the corresponding traffic demand, usually under rigid attachments between users and beams. Numerical results show that a not so rigid mapping can provide a significant reduction of the unmet capacity. In particular, encouraging results are obtained for strongly asymmetric traffic demand scenarios. It is important to remark that this is achieved without additional complexity at the gateway, payload or the receive terminals; the latter need to report to the gateway only the magnitude of the two strongest received carriers.

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