Precoded Cluster Hopping for Multibeam GEO Satellite Communication Systems

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ABSTRACT

Beam-Hopping (BH) and precoding are two trending technologies for high throughput satellite (HTS) systems. While BH enables the flexible adaptation of the offered capacity to the heterogeneous demand, precoding aims at boosting the spectral efficiency. In this paper, we consider a HTS system that employs BH in conjunction with precoding in an attempt to bring the benefits of both in one. In particular, we propose the concept of Cluster-Hopping (CH), where a set of adjacent beams are simultaneously illuminated with the same frequency resource. On this line, we propose an efficient time-space illumination pattern design, where we determine the set of clusters that shall be illuminated simultaneously at each hopping event along with the dwelling time. The CH time-space illumination pattern design formulation is shown to be theoretically intractable due to the combinatorial nature of the problem and the impact of the actual illumination design on the resulting interference. For this, we make some design decisions on the beam-cluster design that open the door to a less complex, still well-performing solution. Supporting results based on numerical simulations are provided which validate the effectiveness of the proposed CH concept and time-space illumination pattern design with respect to benchmark schemes.

Keywords: Satellite Communications, Multibeam Satellite, Beam Hopping, Precoding, Demand-Matching

1 INTRODUCTION

The first generation of broadband multibeam satellites was launched in the 2000s, with the main objective to deliver internet services to people who had no access to faster forms of internet connectivity (ViaSat Inc., 2018). Driven by the success of the first generation of broadband satellites, new advanced satellite systems were set up during the 2010s with spot beams. Viasat–1 is a clear example of such next generation of satellites, which is able to serve 72 spot beams and reaching a total capacity of 140 Gbps. Clearly, these accomplishments established the birth of the so–called generation of High Throughput Satellites (HTS) systems (Cola et al., Apr. 2015). While wireline and wireless terrestrial broadband service lack the ability to leap across continents, oceans, and difficult–to–access areas, the inherent large coverage footprint of satellite communication networks make them the most suitable solution to expand networks over the world. Therefore, satellite can complement the terrestrial networks and offer important socio–economic benefits, while increasing the satellite competitiveness.

From frequency/bandwidth to power allocation and coverage, the forthcoming generation of commercial satellite communication payloads offer enhanced flexibility to dynamically satisfy the customers' demands (Kisseleff et al., 2020; NetWorld 2020, 2019). Such reconfigurable satellite systems are clamored by operators and manufacturers to be one of the most ground-breaking evolutions of satellite communications with an impact on lowering mission costs and enabling satellite systems to become more agile and responsive to market needs (AIRBUS, 2021; SES, 2020). These future satellite architectures are expected to offer Terabit per second in–orbit capacity when and where needed. Such throughput enhancements can only be achieved by pushing forwards the multibeam architecture with reduced beam–size, taking advantage of frequency reuse and reconfiguring the satellite capacity according to the heterogeneous traffic demands.

In response to the combination of ever-growing data demand with the inherent satellite spectrum scarcity (Kodheli et al., 2020), an intelligent allocation of satellite resources considering the new degrees of flexibility shall be conceived, particularly considering both the actual users' position as well as their traffic demand. This paper focuses on two of the most promising disruptive techniques to tackle these specific challenges: linear precoding and time-flexible beam hopping.

1.1 Linear Precoded for Satellite Systems

While conventional satellite systems are designed to operate using an interference avoidance approach through a proper reuse of the available spectrum amongst beams, more recent paradigms have been proposed and studied which go in the opposite direction through the management and the exploitation of the interference amongst beams. The objective is clearly to maximize the use of the user link available spectrum (in terms of spectral efficiency), which represents a limited resource of the system. In this context, the work in (Vazquez et al., 2016) summarizes the Multi–User Multiple Input Single Output (MU–MISO) digital signal processing techniques, such as linear precoding, that can be applied in the user link of a multibeam satellite system operating in full frequency reuse. While the concept of MU–MISO in satellite networks have been mostly theoretical, an actual live-based demonstration supported by the European Space Agency (ESA) has been carried out in (ESA project LiveSatPreDem, 2020), validating the feasibility of such technique considering the recently amended DVB-S2X specifications to support it. It is worth to remark that precoding is embedded at the gateway, thus keeping the complexity of payload and User Terminal (UT) infrastructure low.

In general, one of the main challenges faced by HTS systems (particularly for precoded systems) is the feeder link congestion, i.e. the congestion on the bidirectional communication link between the gateway and the satellite. The increase in the capacity of the user link requires a corresponding increase in the capacity of the feeder link, which is currently limited by few GHz of available bandwidth (Kyrgiazos et al., 2014). In principle, the exploitation of higher frequency bands (e.g. Q/V) by this wireless link could address this issue. However, often this approach is not feasible in practice due to weather impairments at high frequencies (Zhang et al., 2017). A common alternative is the deployment of multiple gateways, where each gateway conveys the signals to be transmitted to a cluster of spot beams. This concept of beam-clustering would be relevant to this paper and will be addressed in the next section.

1.2 Time-Flexible Beam Hopping

Beam Hopping (BH) was originally proposed to deal with large multibeam coverage areas, by focusing the satellite resources to certain subset of beams, which is active for some portion of time, dwelling just long enough to satisfy the requested demands (Freedman et al., 2015). In doing so, BH is able to increase useable capacity and reduce unmet traffic demands, particularly in the presence of heterogeneous traffic demand.

The conventional BH illumination pattern is illustrated in Figure 1(a), where the active spot beams are designed to have a border area formed by inactive beams such that a degree of isolation exists between each active beam. Note that the set of illuminated beams changes in each time–slot based on a time–space transmission pattern that is periodically repeated. The time axis is divided in windows of duration T_H, which repeat following a regular pattern. Each BH window is segmented in N_s time slots and in each time slot a different set of beams is illuminated. By modulating the period and duration that each of the beams is illuminated, different offered capacity values can be achieved in different beams.

The BH procedure on one hand allows higher frequency reuse schemes by placing inactive beams as barriers for the co–channel interference, and on the other hand allows the use of a reduced number of on–board power amplifiers, with a consequent reduction of payload mass. BH benefits have been well demonstrated, e.g. (ESA project BEAMHOP, 2016), and the satellite standard DVB-S2X has recently included guidelines to enable beam hopping operation.

On the downside, we noticed that, in certain scenarios where more than one adjacent beam is requesting high demand, the performance of BH is affected by the limitation of not being able to simultaneously activate neighboring beams with the same spectrum resource. The latter motivates the contribution of this paper.

In summary, BH provides the means to flexibly adapt the offered capacity to the time and geographic variations of the traffic demands, while precoding exploits the multiplexing feature enabled by the use of multiple antenna feeds at the transmitter side to boost the spectral efficiency. These two effective strategies can create unique opportunities if they are properly combined.

1.3 Contribution: Precoded Cluster Hopping

The contributions of this paper are summarized as follows:

1. **Cluster Hopping Concept:** We propose the novel Cluster Hopping (CH) concept as a natural combination of BH with precoding. In CH, multiple set of adjacent beams are illuminated at the same time with the same frequency resource. We define a cluster as the set of adjacent active beams that are served by a single gateway so that the whole coverage area can be served through multiple clusters/gateways. An example of the proposed CH is shown in Figure 1(b) and (c), which requires the use of precoding to deal with the resulting interference as no separation line of inactive beams is considered within a beam cluster. CH was first introduced by the authors in (Kibria et al., 2019). Herein, we expand (Kibria et al., 2019) with more technical details and expanding the numerical results.
2. **Illumination Pattern Design:** The illumination pattern design for conventional BH systems has been studied in (Alegre-Godoy et al., 2012; Anzalchi et al., 2010; Angeletti et al., 2012; Cocco et al., 2018; Lei et al., 2020). While (Alegre-Godoy et al., 2012; Anzalchi et al., 2010) focused on heuristic iterative sub-optimal algorithms, (Angeletti et al., 2012; Cocco et al., 2018) considered genetic and simulated annealing algorithms respectively targeting global optimal solutions at the expenses of increased computational complexity. Finally, (Lei et al., 2020) proposed to integrate deep learning into the optimization procedure in order to accelerate the optimization procedure. Herein, we propose an illumination pattern design for CH (and therefore considering precoding the corresponding clusters), under a fair beam-demand satisfaction objective. In particular, we formulate the illumination pattern design as a max-min of the offered versus demanded capacity subject to a set of practical constraints. The presence of binary assignment variable as well as non-linearity caused by the interference as a function of such binary assignment variable makes the problem non-convex and difficult to solve. To tackle this, we propose to limit the clustering to a specific forms that allow us to simplify (1) simplify

the relationship between a specific beam illumination instance and the resulting interference, and (2) Reduce the search space of the feasible solutions and therefore obtain a low-complex solution. Although optimality cannot be guaranteed, this solution is shown to reach satisfactory results with affordable complexity.

3. **Numerical Evaluation:** Finally, we present supporting results based on numerical simulations using the software tool (SnT University of Luxembourg, 2020). We evaluate the beam demand satisfaction under different beam-clustering designs and different number of simultaneously-activated beams, for different demand instances. We also compare the proposed CH with respect to the conventional BH technique and with respect to (Ginesi et al., 2017). The latter represents a preliminary study carried out by ESA, where precoding was first combined with BH and a pragmatic, iterative and heuristic approach was proposed for the illumination pattern design.

The rest of this paper is organized as follows. Section 2 introduces the system model and relevant nomenclatures. Section 3 presents the proposed cluster hopping concept considered in this paper and addresses the illumination pattern design. Supporting simulation results are presented in Section 4, and finally, concluding remarks as well as future research directions are provided in Section 6.

2 SYSTEM MODEL

Let us consider a high throughput multi-beam satellite system with a total of N_b beams, from which only a subset of Q beams, $Q < N_b$, can be simultaneously activated at a particular time instance. We define the illumination ratio as Q/N_b, e.g, a $1/4$ illumination ratio means that 25% of the total number of beams is illuminated. We assume that the beams that are illuminated employ full-frequency reuse, meaning that all of them operate over the same spectrum B_{w}. For the sake of clarity, the feeder links (connection between gateways and satellite) is considered ideal, i.e. noiseless and without channel impairments.

In this paper, we use the following terminologies:

- **Cluster**: A group of adjacent beams simultaneously illuminated with the same spectrum B_{w}. To cope with the resulting interference, clusters are precoded.
- **Snapshot**: A particular arrangement of illuminated and non-illuminated clusters. For illustration purposes, Figure 1(b) and (c) show 3 and 3 snapshots, respectively. There can be as many as 2^{N_C} possible snapshots, being N_c the number of considered clusters. Of course, not all snapshots are valid in the sense that only a given number of non-adjacent clusters can be illuminated simultaneously because of payload limitations, i.e. the illumination ratio.
- **Time-Slot**: A time-slot or time-instance defines the time granularity of the hopping operation, i.e., the minimum illumination period for a selected snapshot. The hopping window, T_H is equally divided into N_s time-slots. Therefore, $T_H = N_s \times T_s$, where T_s denotes the duration of the time-slot.
- **Hopping Window**: As anticipated, the hopping window consists of N_s time-slots and has a total duration of T_H. It also represents the maximal time period allowed to provide service to all the users in the coverage area.

Let us focus on a particular snapshot and on a particular cluster within that snapshot. The signal vector received by the N_c active beams within the i-th cluster is denoted as $\mathbf{y}_i \in \mathbb{C}^{N_c \times 1}$ and further expressed as,

$$\mathbf{y}_i = \mathbf{H}_i \mathbf{x} + \mathbf{n}_i \quad (1)$$

where $\mathbf{x} \in \mathbb{C}^{Q\times 1}$ denote the transmitted symbols with $\mathbb{E}\left[\mathbf{x}\mathbf{x}^H\right] = \mathbf{I}_Q$; $\mathbf{H}_i \in \mathbb{C}^{N_c\times Q}$ refers to the channel matrix of cluster i, which includes the components of all active beams and is assumed to be perfectly known at the transmitter, and $\mathbf{n}_i \in \mathbb{C}^{N_c\times 1}$ denotes the additive Gaussian zero-mean unit-variance noise, i.e. $\mathbb{E}\left[\mathbf{n}_i\mathbf{n}_i^H\right] = \mathbf{I}_{N_c}$.

For the sake of clarity, we drop the cluster sub-index i throughout the following, which applies to any cluster. The entry at the k-th row and q-th column of the downlink channel matrix $\mathbf{H}$ in (1) between the multibeam satellite and the N_c beams of the cluster is modeled as,

$$[\mathbf{H}]_{k,q} = \frac{\sqrt{G_{Rx}G_{k,q}}}{4\pi\frac{d_k}{\lambda}\sqrt{\kappa T_{Rx}B_{\mathrm{w}}}} \tag{2}$$

where

- G_{Rx} is the receiver antenna gain (assumed to be the same for all UT for simplicity),
- $G_{k,q}$ is the gain from the q-th beam seen at the k-th beam,
- d_k is the distance between the satellite and k-th beam,
- λ denotes the wavelength,
- κ denotes the Boltzmann constant,
- T_{Rx} is the clear sky noise temperature of the receiver.

Consequently, the received signal of the k-th beam can be written as,

$$y_k = \underbrace{\mathbf{h}_k^T x_k}_{\text{desired}} + \underbrace{\sum_{\substack{j\in\mathcal{C}\\ j\neq k}} \mathbf{h}_k^T x_i}_{\text{intra-cluster interf.}} + \underbrace{\sum_{u\notin\mathcal{C}} \mathbf{h}_k^T x_u}_{\text{inter-cluster interf.}} + n_k, \tag{3}$$

where $\mathbf{h}_k^T$ denotes the k-th row of matrix $\mathbf{H}$, and we distinguish two types of interference: (i) intra-cluster interference, with $\mathcal{C}$ denoting the set of beams belonging to the same cluster as beam k, and (ii) inter-cluster interference, which considers all the transmission signals not intended to cluster $\mathcal{C}$.

3 CLUSTER HOPPING DESIGN

Both interference components in (3) can be mitigated by considering precoding over all Q active beams. Although this is the best approach in terms of achievable capacity, its implementation is limited by the feeder link congestion. For such number of active beams, multiple and coordinated gateway stations are required, which is considered unlikely in practice due to the synchronization accuracy needed for coordinated precoding (Arapoglou et al., 2016).

Therefore, our first design decision is to mitigate the intra-cluster interference only by precoding clusters independently. Regarding the inter-cluster interference, its effect will be minimized by considering avoiding adjacent clusters to be simultaneously activated. These two assumptions, shall allow us to (i) upload the signals using multiple non-cooperative gateways, (ii) pursue a design under the assumption of negligible inter-cluster interference, and (iii) reduce the number of possible snapshots and thus, the search space of the cluster hopping design.

Taking into account the aforementioned assumptions, the offered capacity to beam k belonging to cluster $\mathcal{C}$ can be expressed as,

$$c_k = B_{\text{w}} \text{f}_{DVB} \left(\frac{P_{\text{beam}} \left| \mathbf{h}_k^H \mathbf{w}_k \right|^2}{\sum_{\substack{j\in\mathcal{C} \\ j\neq k}} P_{\text{beam}} \left| \mathbf{h}_k^H \mathbf{w}_j \right|^2 + 1} \right) \text{ [bits/sec]} \tag{4}$$

where f_{DVB} denotes the Sinal-to-Interference and Noise Ratio (SINR) versus Spectral Efficiency (SE) mapping function according to the Adaptive Coding and Modulation (ACM) scheme considered by the Digital Video Broadcasting (DVB) standard (DVB-S2X, 2014). The transmit power per beam is assumed to be fixed and equally distributed across beams, and it is denoted as P_{beam}. It is out of the scope of this paper to optimize the transmit power.

As a consequence, the cluster capacity can be obtain by adding all the capacity of the beams belonging to that cluster: $C_i = \sum_{k\in\mathcal{C}_i} c_k$, where we have again re-introduced the cluster sub-index i.

3.1 Objective

The objective is to obtain the optimal illumination pattern, i.e., set of snapshots and their dwelling time, such that the demands of the beams/clusters are fairly satisfied. In other words, the optimal illumination pattern would be such that achieves $c_i \approx d_i$, $i = 1, \ldots, N_b$ and $C_i \approx D_i$, $i = 1, \ldots, N_c$, where d_i and D_i denote the demand of i-th beam and i-th cluster, respectively. Note that this work focuses on the demand-matching at beam level. The task to distribute the beam capacity to the different end-users of that beam is known as user scheduling (Guidotti and Vanelli-Coralli, 2020; Honnaiah et al., 2021).

3.2 Proposed Illumination Design

Let us define our design variable with a set of binary vectors $\mathbf{x}_t$ of dimension $N_c \times 1$, with components $x_t[i]$ being equal to 1 when cluster i is active at the time-slot t.

Since the optimization of the illumination design is performed at the hopping window level, we scale down the cluster demand at hopping-window level as $\hat{D}_i = T_H D_i$ [bits/hopping window], and the offered cluster capacity at time-slot level as $\hat{C}_i = T_s C_i$ [bits/time-slot]. With these definitions, we can state that the actual offered capacity at hopping window level can be computed as $\hat{R}_i = \sum_{t=1}^{N_s} x_t[i]\hat{C}_i$ [bits/hopping window], where the cluster offered capacity $\hat{C}_i$ can be easily pre-computed and stored.

As discussed, without making any assumption on the snapshot design, the number of possible binary arrangements in $\mathbf{x}_t$ is 2^{N_c}, which might become untractable for realistic multibeam patterns. However, not all are valid snapshots for our problem, as we have a couple of constraints, namely maximum number of active beams per time-slot (i.e. $\sum_{i=1}^{N_c} x_t[i] = Q'$), Q' denoting the number of active clusters, and activation of adjacent clusters shall be avoided. The latter constraint can be expressed as,

$$\mathbf{x}_t^T \mathbf{A} \mathbf{x}_t = 0, \tag{5}$$

where matrix $\mathbf{A} \in \{0,1\}^{N_c\times N_c}$, represents the binary adjacency matrix of the clusters. It is a square symmetric matrix, i.e., $\mathbf{A}_{i,j} = \mathbf{A}_{j,i}$ and $\mathbf{A}_{i,j} = 1$ when cluster i is adjacent to cluster j.

With all these in mind, the proposed cluster illumination pattern design is formulated in (6).

$$
\begin{aligned}
\max \quad & \min_{\{\mathbf{x}_t, t=1,\ldots,N_s\}} \left(\frac{\hat{R}_1}{\hat{D}_1}, \ldots, \frac{\hat{R}_{N_c}}{\hat{D}_{N_c}} \right) \\
\text{s.t.} \quad & \sum_{i=1}^{N_c} x_t[i] = Q', \\
& \mathbf{x}_t^T \mathbf{A} \mathbf{x}_t = 0, \ \text{t} = 1, \ldots, N_s \\
& x_t[i] \ \text{binary}, \ \text{t} = 1, \ldots, N_s \ \text{i} = 1, \ldots, N_c
\end{aligned}
\tag{6}
$$

We can simplify the $\max - \min$ optimization problem in (6) by turning it into a maximization problem with the help of an additional slack variable γ along with a new constraint $\frac{\hat{R}_1}{\hat{D}_1} \geq \gamma \triangleq \hat{R}_1 \geq \hat{D}_1 \gamma$:

$$
\begin{aligned}
\max_{\{\mathbf{x}_t, t=1,\ldots,N_s\}} \quad & \gamma \\
\text{s.t.} \quad & \sum_{i=1}^{N_c} x_t[i] = Q', \\
& \mathbf{x}_t^T \mathbf{A} \mathbf{x}_t = 0, \ \text{m} = 1, \ldots, N_s \\
& x_t[i] \ \text{binary}, \ \text{t} = 1, \ldots, N_s \ \text{i} = 1, \ldots, N_c \\
& \hat{R}_i \geq \hat{D}_i \gamma, \ \text{i} = 1, \ldots, N_c
\end{aligned}
\tag{7}
$$

One can observe that problem (7) is a Linear Programming (LP) problem involving a binary assignment variable. Although the inherent combinatorial problem remains, with the proposed constraints and a careful beam-clustering design, one can reduce significantly the search space. The beam-clustering aspects are discussed in the following section, while some numbers about the search space of problem (7) are provided in Section 4.

For solving (7), in this paper we rely on the optimization software Gurobi (GUROBI, 2021), which is convenient to solve mixed integer linear programming (MILP) problems such as the one in (7).

3.3 Clustering Definition

The offered capacity per-cluster, i.e. $\hat{R}_i$, strongly depends on the cluster shape and size. Deriving optimal clustering optimization would require an exhaustive search over all possible combinations of clustering options, including irregular cluster size and overlapping clusters, rendering a huge search space. Moreover, the cluster definition also impacts on the complexity of the system, as the number of possible snapshots is a function of the number of clusters. For example, cluster with small size will yield to a bigger search space for the problem in (7), while clusters with big size will reduce the search space but provide less flexibility in the CH operation. To keep the complexity of (7) within tractable limits, we opt to have compact shaped, non-overlapping and equal size cluster due to the following reasons:

- In the case of overlapping clusters, there will be a very large number of possible clusters making a huge search space for the proposed problem.
- Compact shaped clusters are preferred versus linear or quasi-linear shaped clusters, in order to exploit the precoding benefits.

- The size of the clusters, as discussed before, brings a complexity-performance trade-off. Different cluster sizes will be evaluated in Section 4.

4 SIMULATION RESULTS

The simulation set-up for evaluating the performance of the proposed precoded CH in a HTS system is as follows. The 67-beam GEO satellite beam pattern shown in Fig. 2 is considered. The pattern has been generously provided by ESA in the context of the project FlexPreDem (ESA Project FlexPreDem, 2020). The transmit power per-beam P_{beam} is a function of the illumination ratio, as it is calculated as $P_{\text{beam}} = P_{\text{total}}/Q$. In other words, the total power P_{total} is equally distributed across the active beams. The rest of the simulation parameters are provided in Table 1.

Table 1. Simulation Parameters

Satellite longitude	13°E (GEO)
Satellite height	35,786 km
Number of beams, N_b	67
Beam radiation pattern	Provided by ESA
Max. Beam radiation pattern gain	52 dBi
Downlink carrier frequency	19.5 GHz
Satellite total power, P_{total}	6000 Watt
User Link Bandwidth	500 MHz
Roll-off Factor	20 %
Effective User Link Bandwidth, B_{w}	417 MHz
Roll-off factor	20%
Illumination ratio, (Q/N_b)	1/4, 1/6 and 1/8
Duration of a time-slot, T_s	1.3 ms
Hopping Window, T_H	256 T_s
User terminal antenna gain, G_{Rx}	39.55 dBi
Noise Power, $(\kappa T_{Rx} B_{\text{w}})$	-118.42 dBW

First of all, provide some numbers in terms of the complexity scalability with the clustering definition. As shown in the Table 2, assuming a cluster size equal to 6 beams for all clusters will result in a total of 21211 clusters if no further assumptions are made. On the other hand, assuming a cluster size equal to 4 beams for all clusters will result in a total of 1675 clusters. However, if we make the assumptions proposed in Section 3.3, these numbers can be reduced to 17 and 11, respectively, resulting in a more manageable number. As a consequence, we evaluate the performance of the CH concept under these later clustering options, both shown in Fig. 3. The actual complexity of problem (7) is dictated by the number of snapshots resulting from the combination of the clustering definition and the illumination ratio. In other words, the binary combinations within $\mathbf{x}_t$ are constrained by the number of clusters that can be simultaneously activated (Q') and the adjacent cluster avoidance. Considering these constraint, the number of snapshots N_p for different illumination ratios is given in Table 2. As expected, higher illumination ratios allow to activate higher number of clusters per snapshot, therefore resulting in higher number of possible snapshots. Still, the numbers shown in Table 2 are tractable allowing to final a solution to problem (7) in a matter of seconds with conventional personal computers.

The proposed precoded CH scheme is evaluated in terms of unmet capacity and unused capacity. Both are figures of merits widely used for resource allocation in satellite communications. The first corresponds to the amount of demanded capacity that cannot be satisfied with the actual offered capacity and is defined as $C_{\text{unmet}} = \sum_{i=1}^{N_b} (d_i - c_i)^+$, where $(x)^+ = \max(0, x)$. The second corresponds to the amount of offered

Table 2. Clustering Impact on the Combinatorial Problem Complexity

Size of Cluster	**Number of clusters (compact, non-compact, over-lapping, non-overlapping)**	**Number of clusters (compact, over-lapping, non-overlapping)**	**Number of clusters (compact, non-overlapping)**
4 Beams	21211	483	17
6 Beams	1675	132	11
Assuming compact and non-overlapping clusters			
Size of Cluster	**Number of snapshots (Illum. Ratio 1/4)**	**Number of snapshots (Illum. Ratio 1/6)**	**Number of snapshots (Illum. Ratio 1/8)**
4 Beams	304	263	101
6 Beams	36	35	11

capacity which exceeds the demanded capacity, and it is given by $C_{\text{unused}} = \sum_{i=1}^{N_b}(c_i - d_i)^+$. Ideally, both unmet and unused capacity should be zero.

Next, we present the performance evaluation of the proposed precoded CH system, which is compared with a conventional BH scheme and the work in (Ginesi et al., 2017). The results presented herein have been obtained with the MATLAB-based software tool in (SnT University of Luxembourg, 2020). For the conventional BH scheme, we use solve the same problem as in (7) but assuming single-beam clusters and, as a consequence, without precoding. All our results include the inter-cluster interference.

Fig. 4 left-side shows a particular demand distribution composed of 3 types of beams represented with different colors depending on their demand: high demand, medium demand, and low demand. Fig. 4 right-side shows the per-beam demand versus the offered per-beam capacity for the three techniques under evaluation. The clustering option of 4 beams/cluster has been considered for the CH solution in this case. We can observe that (Ginesi et al., 2017) satisfies well the low-beam demands while it struggles in meeting the demand of high-demand beams. Similarly, the conventional BH also shows difficulties in matching the demand of high-demand beams, while it shows some mismatch as well for the rest of the beams. Finally, the proposed CH is shown to properly follow the demand of any type of beam. Table 3 summarizes the system unmet and unused capacity results, i.e. C_{unmet} and C_{unused}, for the demand in Fig. 4. Table 3 also shows the total offered capacity and the satisfaction percentage, which represents the amount of beams that are satisfied. Note that the benchmark (Ginesi et al., 2017) does not apply a specific illumination ratio, as the number of active beams per time-slot change over time. The first observation is that the proposed CH technique with illumination ratio 1/6 is providing the best unmet - unused capacity trade-off, with both close to zero. Furthermore, CH is showing better demand satisfaction percentage too. The best results are achieved with illumination ratio 1/6 because this provides an overall system offered capacity of 25.46 Gbps, which closely matches the overall requested demand of 26.46 Gbps. From the results in Table 3, we conclude that CH combined with a proper illumination ratio outperforms the benchmark schemes.

To complement the previous results, we now evaluate the fairness of the proposed solution in Fig. 5, where the ratio of the per-beam demand versus the achieved per-beam offered capacity is shown, as well as the resulting Jain's fairness index proposed in (Jain et al., 1984). In this paper, we use the Jain's fairness metric as a measure of how the offered capacity matches the demand at a beam level. For this, we define ζ_i as the ratio between the offered capacity C_i and the demanded/ideal capacity D_i, i.e., $\zeta_i = \frac{C_i}{D_i}$,

Table 3. Unmet and Unused System Capacity Results for Demand in Fig. 4. Total demand is 26.46 Gbps.

Technique	Illum. Ratio	Offered Capacity	Unmet Capacity	Unused Capacity	Satisfaction %
[Ginesi et. al 2017]	Not applicable	17.75 Gbps	9.03 Gbps	0.32 Gbps	85.40 %
Conventional BH	1/4	27.17 Gbps	8.99 Gbps	9.71 Gbps	79.89 %
	1/6	21.98 Gbps	8.26 Gbps	3.78 Gbps	79.99 %
	1/8	16.64 Gbps	9.83 Gbps	0 Gbps	64.61 %
Proposed CH	1/4	30.95 Gbps	2.58 Gbps	7.07 Gbps	93.66 %
	1/6	25.46 Gbps	1.50 Gbps	0.50 Gbps	94.00 %
	1/8	18.89 Gbps	7.57 Gbps	0 Gbps	72.79 %

$i = 1, \ldots, N_b$. In this context, the Jain's fairness index is defined as,

$$J_{\text{FI}} = \frac{\left(\sum_{i=1}^{N_b} \zeta_i\right)^2}{N_b \sum_{i=1}^{N_b} \zeta_i^2} \in [\frac{1}{N_b}, 1]. \tag{8}$$

From Fig. 5, it can be observed that the proposed CH outperforms the benchmark schemes in terms of fair per-beam demand satisfaction, as the values of ζ_i are closer to the idea value of 1 for all beams. The fairness of the proposed approach is confirmed by the Jain's index shown in the legend of Fig. 5, where the proposed CH reaches a Jain's index of 0.99 (superior to that of the benchmarks).

Let us test now another demand instance with bigger demand areas, like the one shown in Fig. 6 left-side. For such big areas of demand, we expect the clustering of 6 beams/cluster to be a better fit. Table 4 shows the results achieved with the proposed CH for different clustering options and different illumination ratios. The best match is given by the 6 beam/cluster option with 1/6 illumination ratio, where the unmet and unused capacity are equal to 0.86 Gbps and 1.59 Gbps, respectively, with a satisfaction percentage of 97 %. The results shown in Table 4 evidence the fact that not only is important to select an accurate illumination ratio but also a clustering definition adapted to the expected demands. Finally, to confirm the superiority of the 6 beam/cluster for such type of demand distributions, Fig. 6 right-side provides the per-beam details of demand versus offered capacity. It can be observe that the 4 beam/clustering option not only has problems in satisfying high-demands but also presents some mismatches for the low-demand beams.

Table 4. Unmet and Unused System Capacity Results for Demand in Fig. 6. Total demand is 26.85 Gbps.

Technique	Illum. Ratio	Offered Capacity	Unmet Capacity	Unused Capacity	Satisfaction %
Proposed CH 6 beams/cluster	1/4	36.82 Gbps	0.10 Gbps	10.07 Gbps	99.69 %
	1/6	27.58 Gbps	0.86 Gbps	1.59 Gbps	97.08 %
	1/8	15.05 Gbps	11.80 Gbps	0 Gbps	58.03 %
Proposed CH 4 beams/cluster	1/4	30.25 Gbps	2.27 Gbps	5.67 Gbps	94.06 %
	1/6	25.90 Gbps	5.38 Gbps	4.44 Gbps	82.58 %
	1/8	18.73 Gbps	11.07 Gbps	2.95 Gbps	65.50 %

5 PRACTICAL CONSIDERATIONS

5.1 CSI acquisition

Besides the synchronization aspects natural from beam-hopped transmission (Freedman et al., 2015), the main challenge of the proposed cluster hopping concept is the need of Channel State Information (CSI) at the gateway side. The most challenging problem in beam–hopped and precoded satellite systems is how often a ground terminal can measure its CSI vector (meaning the channel coefficient w.r.t. the satellite antennas). While the CSI estimation procedure can be based on already existing methods, the cluster hopping scheme requires some ad–hoc adaptations due to time–variant nature of the cluster hopping procedure. In fact, since the set of illuminated beams changes over time, each user terminal is able to estimate a subset of coefficients of the complete CSI vector, which depends on the particular cluster than is being illuminated at that particular time instant. The latter can potentially lead to situations in which the gateway does not have available all the needed coefficients to compute the precoding matrix. When the channel is relatively stable, the use of previous CSI estimates may solve the problem, otherwise joint processing of previous and new CSI coefficients would be required as well as prediction methods.

Furthermore, the general problem in beam–hopped satellite systems is how often a ground terminal can measure its CSI vector (meaning the channel coefficient w.r.t. the satellite antennas). Clearly, a ground terminal can only perform measurements when it is being illuminated, and the number of measured CSI components depends on the particular cluster than it is being illuminated at that particular time instant. We should distinguished 2 cases:

- Illumination pattern composed of non–overlapping clusters: This is the case assumed in this paper. In this case, each ground terminal only needs the knowledge of the CSI components related to the satellite antennas that are active in the cluster that it belongs to. Therefore, we propose to rely on the CSI gathered in the previous time instant that this particular cluster was illuminated (which of course will imply some additional delay depending on the illumination period).
- Illumination pattern composed of overlapping clusters: This would be the case when dealing with high traffic demand areas that need to be illuminated most of the time. For the sake of clarity, let us assume an example composed of 3 beams and 2 non–orthogonal clusters, the first cluster composed of beam 1 and beam 2; and the second cluster composed of beam 2 and beam 3. Let us focus on the terminals belonging to beam 2 coverage area. Note that beam 2 is always active but once together with beam 1 and once together with beam 3. Therefore, this configuration implies that high–demand beams that are more often illuminated (i.e. beam 2) will have more accurate CSI that lower–demand beams (i.e. beam 1 and beam 3), which are less often activated.

Generally speaking, we do not foresee the outdated CSI to have a strong impact. This is because a single DVB-S2(X) super-frame is enough to obtain a good channel estimation and, therefore, the outdated CSI will only be needed for the initial (single) super-frame.

5.2 Future payload antenna systems

The results presented in this paper have been obtained assuming a Direct Radiating Array (DRA) based footprint pattern which have been generated with internal software by ESA in 20 GHz, with 750 elements spaced 5 lambda, able to provide 67 beams within the desired coverage area. The trends in the satellite communications industry are evolving towards more advanced antenna architectures, e.g. (defocused) phased array fed reflector (PAFR), whose phase response may differ from the conventional Single-Feed-per-Beam architecture or the DRA considered in this paper.The PAFR may offer some benefits such as lower cost, high beam resolution, and smaller array size

6 CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

In this paper, we have proposed the combination of precoding and time-flexible payloads with BH capabilities. Focusing on the convergence of both techniques, we have proposed the so-called *Cluster Hopping* (CH) concept, which seamlessly combines these two paradigms and utilizes the strong points of each one. Supporting results based on numerical simulations are provided which validate the effectiveness of the proposed system in comparison with conventional BH and other works available in the literature.

Particularly, CH shows great promise when dealing with high demands that cover large portionals of Earth, thus spanning multiple satellite beams. The results of this study have highlighted the importance of an appropriate clustering design together with an appropriate illumination ratio, both based on the expected demand distribution. The latter opens opportunities for future research in this subject, namely the optimal clustering definition based on demand distribution input and the appropiate portion of beams that needs to be activated at a time. Furthermore, this study has considered the transmit power out of the scope for the sake of clarity but the transmit power represents another degree of freedom that can be considered within the optimization problem.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

E. Lagunas led this manuscript in both technical contribution, production of results and writing. M. Kibria contributed to the technical ideas and help in producing the numerical results. H. Al-Hraishawi and N. Maturo contributed to the developed techniques. S. Chatzinotas contributed in conceiving the main idea and supervised the findings of this work. All authors contributed to the manuscript and approved the submitted version.

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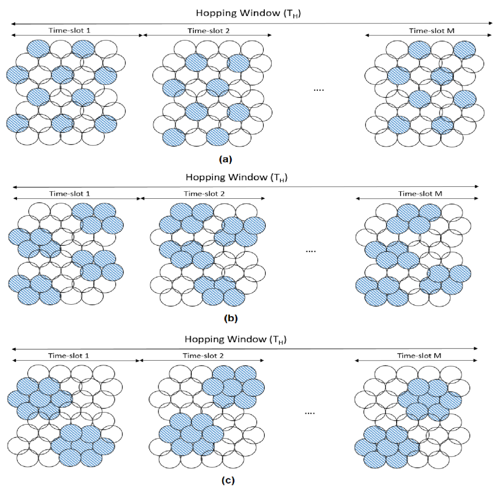

Figure 1. Beam Hopping illumination pattern: (a) Conventional Beam Hopping; (b) Proposed Cluster Hopping with 4-beam clusters; and (c) Proposed Cluster Hopping with 7-beam clusters.

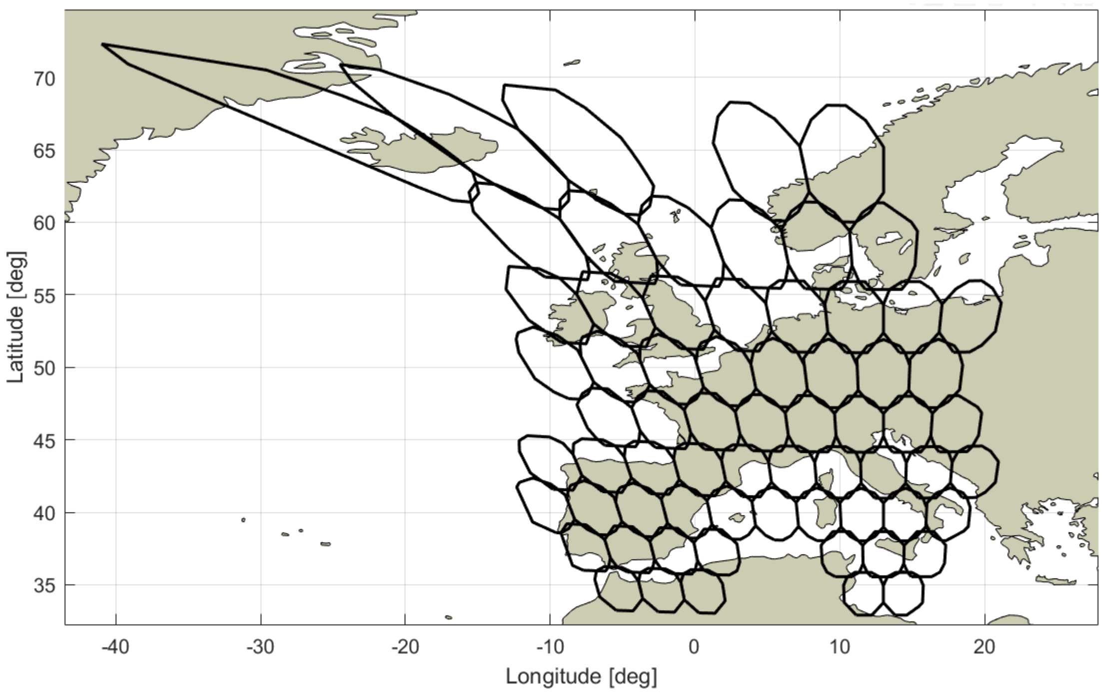

Figure 2. Considered beam pattern with $N_b = 67$ beams.

FIGURE CAPTIONS

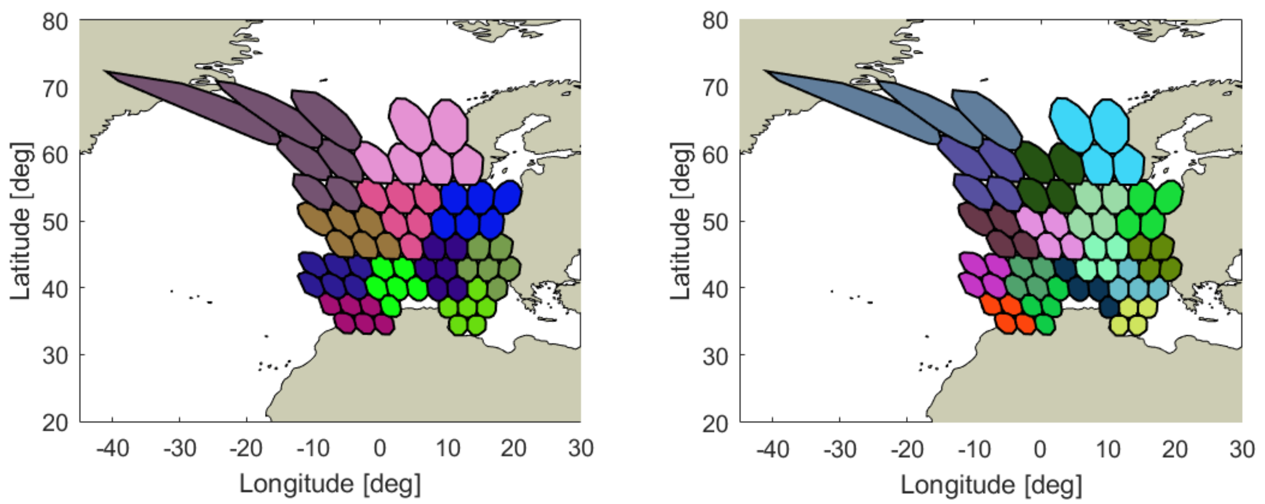

Figure 3. Considered beam-clustering options: (left) 11 clusters of 6 beams/cluster; (right) 17 clusters with 4 beams/cluster.

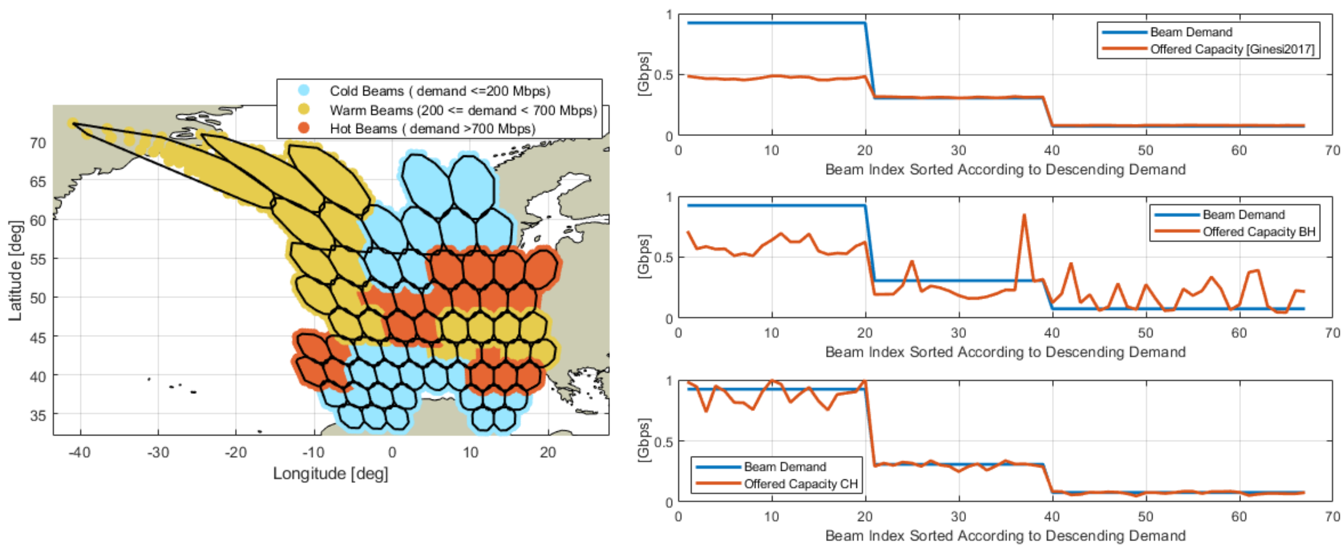

Figure 4. Demand Instance 1: (left) Considered beam demand distribution; (right) Offered per-beam capacity versus per-beam demand.

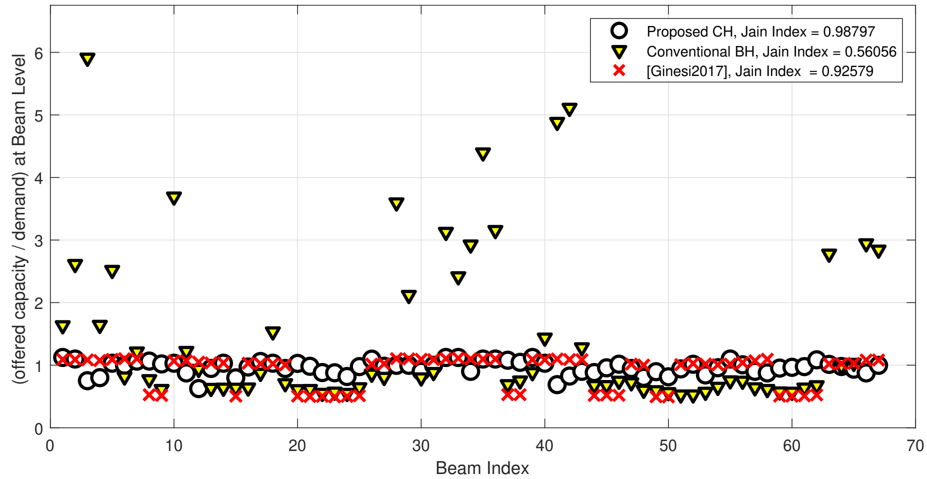

Figure 5. Fairness Results: Per-beam offered capacity divided by per-beam demand and Jain's Fairness Index for demand instance shown in Fig. 4.

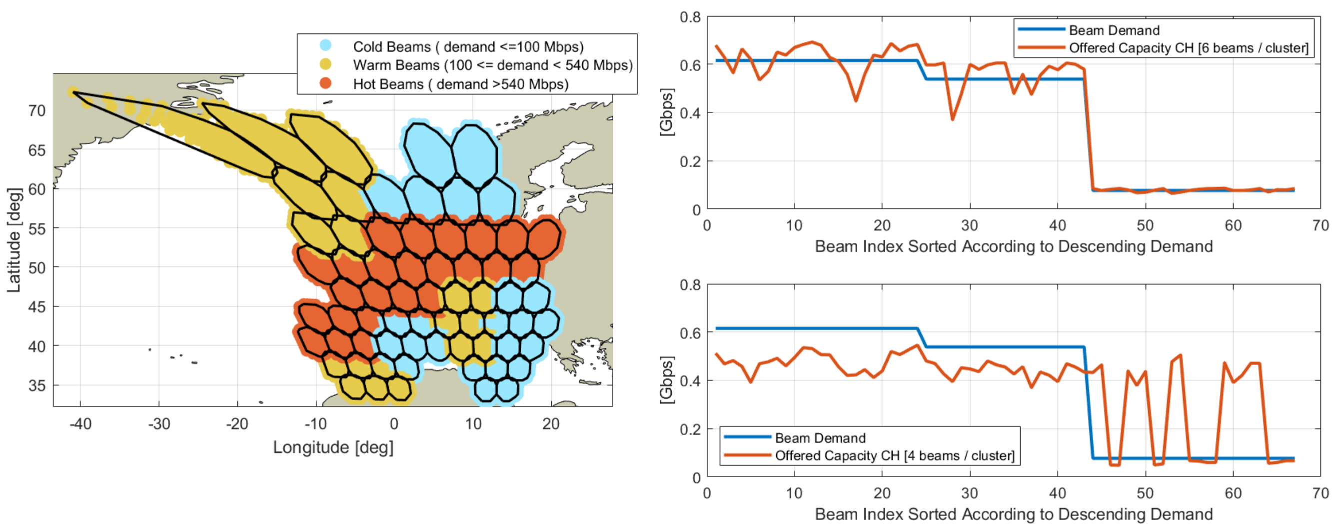

Figure 6. Demand Instance 2: (left) Considered beam demand distribution; (right) Offered per-beam capacity versus per-beam demand.