Adaptive Resource Allocation for Satellite Illumination Pattern Design

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***Abstract*—To ensure quality of service to the users within the coverage area, time-flexible satellite system needs to design a beam illumination strategy, i.e. a time–space transmission pattern that is periodically repeated. The beam activation dwells just long enough to satisfy the traffic demand. The beam illumination pattern design is typically a combinatorial problem with a non-convex structure due to the presence of inter-beam interference. The computational complexity of existing solutions addressing this problem are unbearable for practical systems. In this paper, we propose a low-complexity beam illumination design which splits the task into two sequential sub-problems: (i) Estimation of number of time-slots to be allocated to each geographical area in order to satisfy its demand; (ii) Assignment of illumination slots over the time domain. Note that the outcome of step (ii) determines the resulting interference environment and, as a consequence, the resulting offered capacity. The latter is, at the same time, an input needed for step (i). For this reason, we propose an adaptive system where the two steps are iteratively executed until convergence. Furthermore, we show that a random assignment for step (ii) significantly reduces the complexity without a major impact on the performance. The proposed design is validated and compared with existing schemes using numerical results.**

***Index Terms*—Flexible payloads, adaptive, beam hopping, selective precoding**

I. Introduction

Satellite communication systems represent a fundamental element to deliver Information and Communication Technologies (ICT) services to all regions of the world at an affordable cost [1]. Such resilient and ubiquitous connectivity at an affordable price appears to be the most promising solution to bridge the digital divide particularly for least developed countries [2].

Very High Throughput Satellite (VHTS), the next generation satellite communication system, is featured with multiple high directional spot beams, which not only provides a great increase in system's throughput but also the flexibility that allows system to allocate resources according to the geographical distribution of users' demands [3]. Usually the flexibility of VHTS considers two main degrees of freedom: time and/or frequency domain [4]. This paper focuses on time-domain Beam Hopping (BH).

Conventional BH relies on an illumination pattern design that identifies a sub-set of beams to be activated for a given duration of time. The dwelling time of active beams is carefully designed to achieve a matching between supplied beam capacity and actual beam demand [5]. An inherent characteristic of conventional BH is that the illumination pattern is typically enforced to avoid activation of geographically adjacent beams. This is to avoid harmful leakage between overlapping beam footprints that may lead to unacceptable interference levels. The latter has been the design constraint of most of the works in the literature [3], [5]–[9].

Preventing the activation of geographically adjacent beams may limit the flexibility of the BH system to adapt to large clusters of traffic demand. An alternative to such constrained design would be to allow the activation of adjacent beams and apply interference mitigation techniques to managed the resulting inter-beam interference. The latter concept was initially introduced in [10], [11] with the name of Cluster Hopping (CH), which considered the integration of BH and linear precoding to the illumination pattern design. With the goal of a fair beam demand satisfaction, the authors proposed a CH design assuming fixed clusters of predefined size and shape.

Recently, the strict cluster definition of [10], [11] was found to be inefficient in adapting to different demand distributions on ground [12]. In particular, the authors in [12] proposed a BH scheme with potential cluster formation whenever needed depending on the input demand of the system. The work in [12] has mainly two drawbacks: (1) To get an estimate of the number of time-slots per-beam needed to satisfy the demand, an accurate estimate of the per-beam supplied capacity is assumed; and (2) The resulting optimization-based design renders a significant complex procedure with large computational time.

In this paper, we address the two aforementioned drawbacks, which generally appear in beam pattern illumination design, e.g. [3], [8], [13]. For the first challenge, i.e. the estimation of the number of time-slots per-beam needed to satisfy the demand, we propose an adaptive scheme to sequentially learn the actual supplied capacity. For the second challenge, i.e. the computational complexity involved in calculating the optimal beam illumination pattern, we will show that a semi-random allocation scheme is able to provide a significant good performance with negligible complexity.

The remainder of this paper is organized as follows. In Section II we present the system model. Section III focuses on the proposed dynamic beam illumination design. In Section IV we describe the proposed relaxation and solution. In Section V we provide supporting results based on numerical simulations. Finally, Section VI concludes the paper.

II. System Model

We consider the forward link of a time-flexible geostationary (GEO) satellite communication. While the coverage area is virtually covered with a grid of N spot beams, the satellite can only simultaneously activate a limited set of K beams according to the limited on-board amplifiers. The satellite payload is assumed to be transparent, with lossless processing on-board and ideal feeder link.

The average traffic demands in [bps] at beam level is assumed to be known and it is denoted as g_l, $l = 1, \ldots, N$, and $\mathbf{g} = [g_1, \ldots, g_N]^T$ represents the demand vector of all beams.

We assume that the satellite is required to satisfy the demands within a limit time window T_H. The time window is equally divided into M time slots of duration T_s, where T_s denotes the minimum dwelling time of the time-hopping system. To make full use of frequency, we consider all active beams share the same frequency band B.

A. Channel Model

Let $\mathbf{H} \in \mathbb{C}^{N \times N}$ represents the channel matrix which contains all the channel state information of the forward-link downlink. Specifically, the channel from the l antenna of the satellite payload to the user k on the ground can be written as [14],

$$H_{k,l} = \frac{\sqrt{G_R^{(k)} G_l\left(x_k, y_k\right) e^{j\phi_{k,l}}}}{4\pi \frac{d_k}{\lambda}} \tag{1}$$

where $G_R^{(k)}$ is the receiver antenna gain at user k; $G_l\left(x_k, y_k\right)$ stands for the beam pattern gain of satellite antenna l received by user k which is estimated according to the user's longitude x_k and latitude y_k; $\phi_{k,l}$ represents the phase component associated with the antenna beam pattern; d_k represents the distance from the satellite to that user; λ denotes the wavelength of the carrier frequency band.

B. Selective Precoding Strategy

Our final goal is to obtain the beam illumination time-plan within a hopping window T_H. To be able to adapt the beam illumination time-plan to any input demand, we do not impose any restriction in terms of activation of adjacent beams. Therefore, whenever any two or more geographically adjacent active beams would generate strong inter-beam interference, linear precoding is assumed to be implemented to mitigate such co-channel interference [15].

However, the precoding operation entails significant complexity at the gateway side, which exponentially scales with the number of beams to be precoded [16]. Hence, the beam illumination pattern design proposed in this work would target the cluster formation avoidance (see Section III).

Taking into account that the spot beams on satellite are high directional, the interference between the beams which are geographical far away would be quite small. We grouping active beams into different clusters, which are subsequently independently precoded. Let $L[t]$ be the number of clusters at time slot t, among which all the passive beams are assumed to form one single cluster for convenience. Denote $\mathbf{W}_i \in \mathbb{C}^{c_i \times c_i}$ the precoding matrix for cluster i, where c_i denotes its cardinality.

At a particular time instance t, we can encounter 3 type of clusters: (i) The cluster composed of all inactive beams, the matrix is given by $\mathbf{W} = \mathbf{0}$ as they do not transmit information; (ii) For each geographically isolated active beam, no precoding is needed and the matrix is given by $\mathbf{W} = \sqrt{P_b}$, where P_b denotes the fix transmit power per beam; (iii) For the rest of clusters composed with more than one beam, the MMSE precoding [17], [18] is assumed,

$$\hat{\mathbf{W}} = \eta\sqrt{P_{\mathrm{b}}}\mathbf{H}^H\left(\mathbf{H}\mathbf{H}^H + \alpha\mathbf{I}\right)^{-1} \tag{2}$$

where $\mathbf{H}$ represents the channel matrix of all the users in the cluster and α stands for a predefined regularization factor. The variable η is a normalization factor typically considered to comply with the total satellite power constraints [17].

C. Received Signal Model

Let $z_k[t]$ be the received signal at user k in time slot t, and $\mathbf{z}_i[t] = [z_k[t] | k \in \mathcal{C}_i]^T$ be the vector of received signals corresponding to cluster i. The vector $\mathbf{z}[t] = [\mathbf{z}_1^T[t], ..., \mathbf{z}_L^T[t]]^T$ including all users' received signal can be expressed as

$$\mathbf{z}[t] = \mathbf{H}\mathbf{W}[t]\mathbf{s}[t] + \mathbf{n} = \tilde{\mathbf{H}}\begin{bmatrix}\mathbf{W}_1 & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \ddots & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{W}_L\end{bmatrix}\tilde{\mathbf{s}}[t] + \mathbf{n} \tag{3}$$

where $\mathbf{W}[t] \in \mathbb{C}^{N \times N}$ gathers the precoding matrix for all beams, $\mathbf{s}[t] \in \mathbb{C}^{N \times 1}$ denotes the transmitted symbol vector; and $\mathbf{n}$ stands for the noise vector. In this paper, the zero-mean additive Gaussian noise is assumed at all the users where $\mathbb{E}\left[\mathbf{n}\mathbf{n}^H\right] = \sigma_T^2\mathbf{I}$ and $\sigma_T = \sqrt{\tau T_{Rx} B}$; τ denotes the Boltzmann constant and T_{Rx} is the clear sky noise temperature of the receiver [14].

III. Beam Illumination Problem

Let us denote $x_{n,t} \in [0, 1]$ as the binary assignment variable indicating the illumination of beam n in time-slot t,

$$x_{n,t} = \begin{cases} 1, & \text{if beam } n \text{ is illuminated in time slot } t,\\ 0, & \text{otherwise.}\end{cases} \tag{4}$$

Note that based on practical mass limitations of the payload, the number of illuminated beams in time slot t is constrained as $\sum_{n=1}^{N} x_{n,t} \leq K$, $\forall t$.

The achievable rate of user k in time slot t can be expressed as

$$r_n[t] = B\log_2\left(1 + \frac{x_{n,t}|\mathbf{h}_n\mathbf{w}_n^t|^2}{\sum_{k \neq n} x_{k,t}|\mathbf{h}_n\mathbf{w}_k^t|^2 + \sigma_T^2}\right) \tag{5}$$

where $\mathbf{w}_n^t$ denote the precoding vector designed for user n in time slot t, e.g., column of $\mathbf{W}[t]$ which corresponds to user n. Then the average of the provided rate of beam n during the time window is given by $c_n = \frac{1}{M}\sum_{t=1}^{M} r_n[t]$.

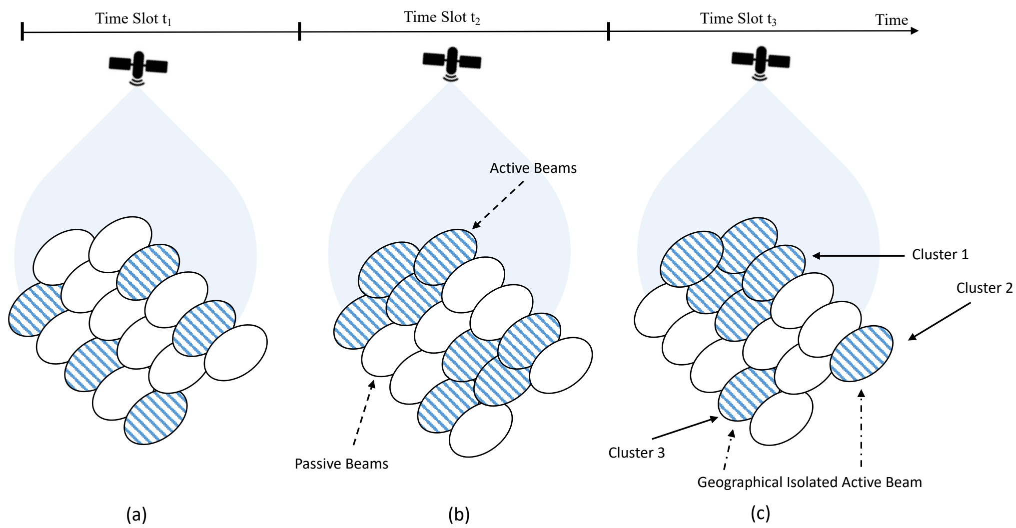


Fig. 1: Proposed flexible cluster hopping scheme

Similar to [12], we focus on minimizing the use of precoding while satisfying the average beam demand. In other words, the main problem is formulated as,

$$\begin{aligned} P_0 : \min_{\mathbf{x}_1,\ldots,\mathbf{x}_M} \quad & \sum_{t=1}^{M} \mathbf{x}_t^T \boldsymbol{\Omega} \mathbf{x}_t \\ \texttt{s.t.} \quad C_1 : & \sum_{n=1}^{N} x_{n,t} \leq K, \forall t \\ C_2 : & \sum_{t=1}^{M} \mathbf{e}_n^T \mathbf{x}_t = d_n, \forall n \\ C_3 : & \mathbf{x}_t \in \{0,1\}^N, \forall t \end{aligned} \tag{6}$$

where $\boldsymbol{\Omega}$ denotes the adjacency matrix of the beam pattern, with element (n, m) equal to 1 if and only if beam n and beam m are geographically adjacent to each other. Note that the demand satisfaction constraint $c_n \geq g_n, \forall n$ is converted into C_2 which satisfies beams' demands in number of time slots. The procedure converting the demand in [bps] into number of time slots is one of the challenges of the general beam illumination design and is typically approximated as,

$$d_n[\text{Number of } T_s] = \lceil M \cdot \frac{g_n}{\zeta_n} \rceil \tag{7}$$

where $\boldsymbol{\zeta}$ denotes the average supplied capacity. How to accurately estimate $\boldsymbol{\zeta}$ and how to efficiently solve problem (6) is addressed in the following section.

IV. Proposed Adaptive Solution

Problem (6) is a combinatorial optimization problem, whose complexity is extremely high (exponentially increasing complexity with N), making it hard to use in practical systems. As illustrative example, only considering a single time-slot, the number of combinations assuming $N = 100$ and $K = 10$ is the binomial coefficient $\binom{N}{K} = \frac{N!}{K!(N-K)!}$, which results in $1.7e + 13$ potential combinations. It is obvious that obtaining an optimal solution is rather challenging.

On the other hand, the estimation of the supplied capacity $\boldsymbol{\zeta}$ is difficult to predict. This is because $\boldsymbol{\zeta}$ strongly depends on the solution of (6). Note that the illumination pattern would determine the perceived interference and the resulting perceived throughput at each user of the system. Such coupling between the supplied capacity $\boldsymbol{\zeta}$ and the optimization variables $(\mathbf{x}_1, \ldots, \mathbf{x}_M)$ claim for an adaptive design strategy.

To solve the capacity prediction issue, we propose an adaptive scheme to approximate the average rates of each beam according to the instantaneous supplied capacity. On the other hand, to avoid the computational cost of complex solutions for problem (6), we propose a pseudo-randomization procedure to generate the beam illumination time-plan. In summary, the proposed scheme mainly composes 3 main parts: traffic demand conversion from [bps] to number of time-slots following (7), randomized illumination pattern design, and the loop to adaptively modify the estimated offered capacity based on the instantaneous capacity. A simplified scheme is shown in Fig. 2.

A. *Pseudo-Random Illumination Pattern Design*

Given the demand in number of time slot, the illumination pattern is designed by the proposed pseudo-randomization algorithm which allocate the required number of time slot among the time window T_H to beams. We proposed a sequential pseudo-random assignment as described in **Algorithm 1**, where we sequentially assign the active time-slots beam after beam while making sure that the maximum number of active beams per time-slot is not violated. Essentially, the algorithm excludes certain time-slots from the available choice if the accumulated active beams is already equal to K.

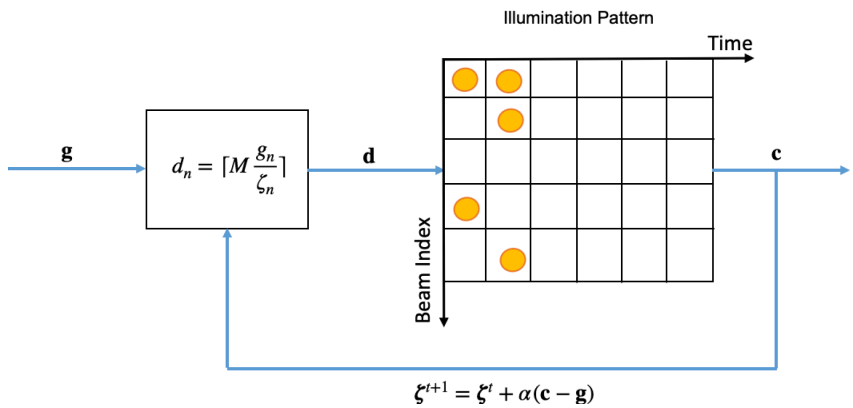


Fig. 2: Proposed adaptive scheme for the beam illumination pattern design

Algorithm 1 Pseudo Randomization Pattern Design

Initialization: $\mathbf{d}, \mathbf{l} = \mathbf{0}_M, n = 0, A = \{1, \cdots, M\}$
repeat
  $n = n + 1$
  Update the unavailable set $B = \{i | l_i = K, i = 1, \cdots, M\}$
  Calculate the available index set $E = A \backslash B$
  Random a vector p, then map its to binary with the first largest d_n to be 1 from the available set E and the rest to be 0
  Update the status of each time slot by $\mathbf{l} = \mathbf{l} + \mathbf{p}$
until Completion

Algorithm 2 Adaptive Resource Allocation

Initialization: $\mathbf{g}, \boldsymbol{\zeta}, \alpha$
repeat
  Demand conversion $d_n = \lceil M \frac{g_n}{\zeta_n} \rceil$
  Pseudo randomization pattern design
  Calculate the provided rate $\mathbf{c}$
  Update average rate $\boldsymbol{\zeta}^{t+1} = \boldsymbol{\zeta}^t + \alpha (\mathbf{c} - \mathbf{g})$
until

B. Adaptive Control Loop

It is clear that given an illumination pattern $\{\mathbf{x}_1, \cdots, \mathbf{x}_M\}$, one can calculate the supplied capacity $\mathbf{c}$ for all beams with the assumed strategy to do clustering and precoding. The instantaneous capacity observations can be fed-back to the demand conversion block to improve the estimated supplied capacity $\boldsymbol{\zeta}$.

The feedback of the proposed scheme is to update the average rates and is given by,

$$\boldsymbol{\zeta}^{t+1} = \boldsymbol{\zeta}^t + \alpha (\mathbf{c} - \mathbf{g}) \tag{8}$$

where α denotes the learning rate.

The detail of the proposed adaptive control loop algorithm is given in **Algorithm 2** .

V. Numerical Evaluation

We consider a GEO satellite system with $N = 67$ spot-beams. The summary of parameters of the assumed satellite system are given in Table I. The beam pattern used in simulations has been kindly provided by the European Space Agency (ESA) in the context of ESA FlexPreDem project [19], and it corresponds to a Direct Radiating Array (DRA) generated with software with 750 elements spaced 5 λ.

The beam demand g_n is generated uniformly at random between $400r$ and $1500r$ [bps], i.e., $400r \leq g_n \leq 1500r$. Herein, r represents the demand density factor which is given by $0.1, 0.3, 0.5$. For each selected r, there will be 100 instances generated for testing. To simplify the simulations, a single user located at the beam center is assumed, which aggregates the overall beam demand.

TABLE I: Simulation Parameters

Satellite Orbit	13°E (GEO)
Satellite Per Beam Power	80 W
OBO	3 dB
Addition Payload Loss	2 dB
Number of Virtual Beams, N	67
Beam Radiation Pattern ($G_{k,l}e^{j\phi_{k,l}}$)	Provided by ESA
Downlink Carrier Frequency	19.5GHz
User Link Bandwidth, B	500MHz
Roll-off Factor	20%
Number of time slots (M)	2000

For a given demand input, there is a specific value for K that ensures feasibility of problem (6). Herein, we present a method to calculate the value of K according to the expected traffic demands. According to Eq. (7), to satisfy the demands for all beams, the minimal number of active beams is given by $K_{avg} = \lceil \frac{\sum_{n=1}^{N} g_n}{M} \rceil$.

A. Convergence of the adaptive scheme

Fig. 3 shows the convergence of the proposed adaptive scheme with pseudo-randomization for one instance with demand density $r = 0.5$ and $M = 2000$. The red line indicates the variation of average difference between the provided capacity and the corresponding required demand along the process of iteration; While the green line indicates the increase

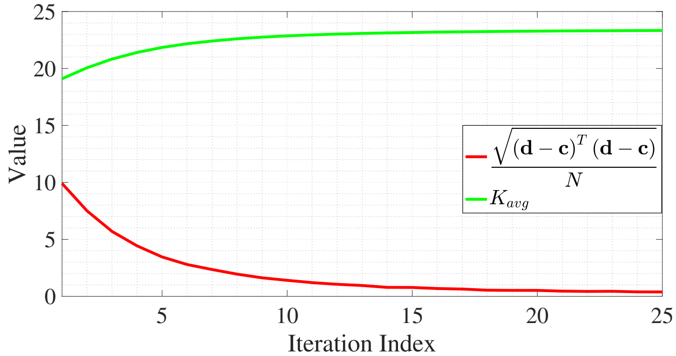


Fig. 3: The convergence of the adaptive scheme

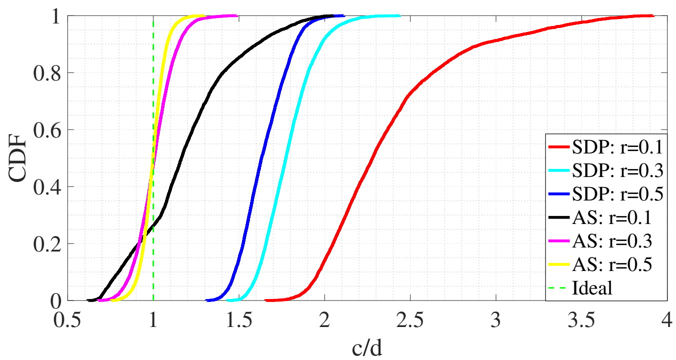


Fig. 4: The comparison of adaptive scheme with SDP at different demands.

of average number of active beams. From Fig. 3, we can conclude that both of the two parameters are converging. Moreover, it would cost only 15 to 20 iteration times to reach the convergence, which is friendly for application and could be further adjusted based on the learning rate.

B. Comparison with optimization methods

Fig. 4 compares the proposed adaptive scheme (AS) with SDP method proposed in [12] in terms of demand-matching performance for different demand densities with $M = 20$. Similarly, to measure the demand matching, we make use of the CDF of the ratio of the per-beam provided capacity to its corresponding demand. Then the ideal solution is the one whose provided capacity is equal to the required demand, which is shown by the green dash line. It is easy to identify that the lines calculated by the proposed method would be closer to the ideal line at each level of demand density. The bad performance of the SDP method comes from inappropriate estimation of the average rates of beams, allocating too much time slot to beams.

Fig. 5 compares the complexity between AS and SDP methods with $M = 10, 20, 30$ for an instance whose $r = 0.3$, where we make use of the MATLAB function "timeit" which measures the time required to run the function. As you can find, the time required by SDP would increase rapidly with the increase of M, however, the proposed method increase a little bit.

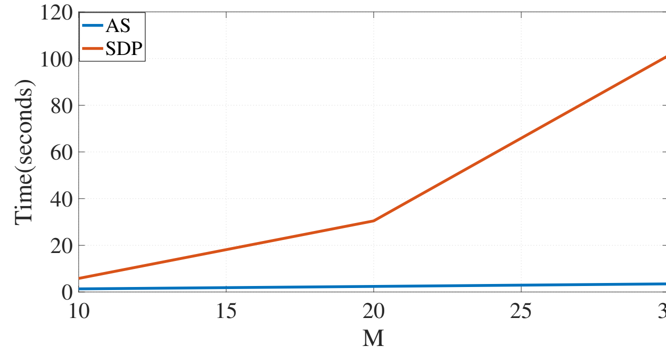


Fig. 5: The comparison of complexity.

C. Sensitivity of K

Fig. 6 shows the impact of the maximum number of active beams K into the demand-matching performance for different demand densities and assuming $M = 20$. In particular, Fig. 6 shows the cumulative density function (CDF) of the per-beam ration of supplied capacity divided by beam demand (which ideally should be equal to 1). For each case, the maximal number of active beams K at each time slots is selected with 3 values, i.e. $K_{avg}, K_{avg} + 5, , K_{avg} + 10$. As we can find, it almost makes no difference to the demand matching performance as long as K is equal or greater than K_{avg}. As a consequence, K will selected with K_{avg} for the remaining simulations.

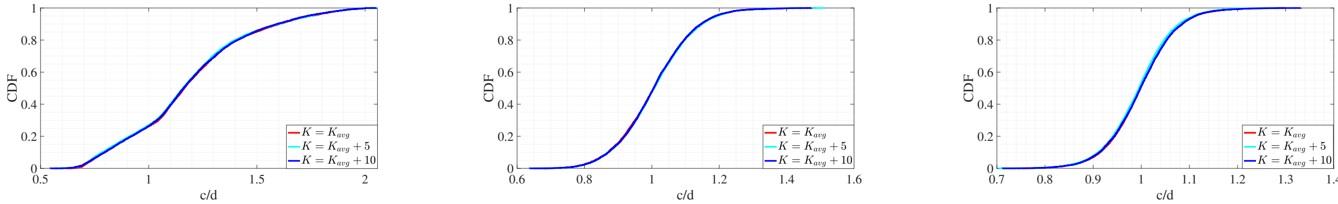
D. Impact of time window length

To explore the influence of the length of time window T_H into final demand-matching performance, numerical simulations are conducted. We run experiments for three different demand densities, i.e. $r = 0.1, 0.3, 0.5$, each of which is with 5 different length of time window, i.e. $20T_s, 50T_s, 100T_s, 200T_s$ and $2000T_s$.

It can be observed from Fig. 7 that, as the length of time window increases, the provided capacity of the beams are more likely to be close to the required demands for all different demand density. That is because the larger the time window is, the richer the available choices will have when designing the illumination pattern. In other words, the adaptive scheme could give a much more accurate average rates for higher demand density.

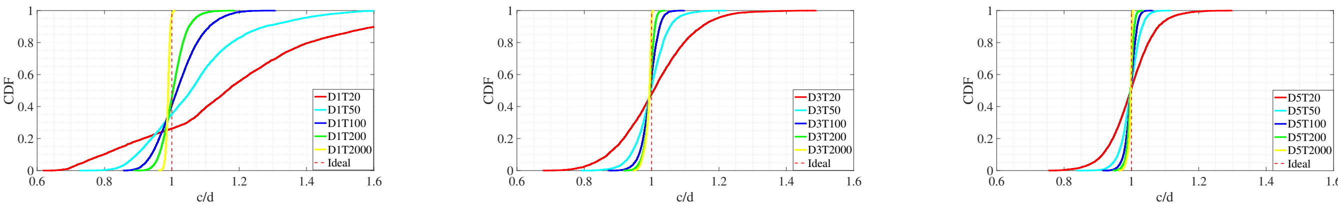
VI. Conclusion

In this paper, we propose a low-complexity strategy that adaptively allocate time slots to beams according to their demands for the satellite communication system which is equipped with beam hopping capabilities. Numerical simulations have shown that the proposed strategy presents a low-complexity alternative to benchmark schemes and the adaptive loop is shown promising in tracking the supplied capacity and, therefore, accurately estimating the number of time-slots to be allocated to each beam.



(a) $r = 0.1$ (b) $r = 0.3$ (c) $r = 0.5$

Fig. 6: Evaluation of the impact of parameter K in demand-matching performance



(a) $r = 0.1$ (b) $r = 0.3$ (c) $r = 0.5$

Fig. 7: Comparison of length of time window in demand matching at different density of demands.

ACKNOWLEDGMENT

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