DEPLOYING JOINT BEAM HOPPING AND PRECODING IN MULTIBEAM SATELLITE NETWORKS

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ABSTRACT

This paper studies the application of Beam Hopping (BH) as a key enabler to provide high level of flexibility to manage scarce on-board resources, particularly power, based on the irregular and time variant traffic requests/demands distributed within the coverage of a satellite multibeam system. However, while high throughput full frequency reuse pattern is employed among beams, the performance of BH is significantly degraded due to the generated inter-beam interference, and applying precoding is essential. In this context, we propose Joint Precoding and BH (J-PBH) in a multibeam system. The proposed J-PBH has the following functionality: serving beams follows an illumination pattern where at consecutive time instants high-demand beams are served more often than low-demand beams. Then, a Zero Forcing precoding is employed aiming at equalizing inter-beam interference. Consequently, the proposed J-PBH flexibly manage on-board power resources between high- and low-demand beams. Numerical simulations are presented which validate the proposed J-PBH benefits.

1. INTRODUCTION

Glossaries

(1) *Demand Capacity (DC)*: the capacity requested by users.
(2) *Offered Capacity (OC)*: represents the maximum delivered capacity of the system.
(3) *Unused system Capacity (Unused-C)*: the difference between the offered capacity and the usable system capacity.
(4) *Unmet capacity Demand (Unmet-D)*: the difference between the capacity demand and the offered capacity.

1.1. Motivation

Built on the MIMO framework, the use of multiple spot beams, i.e. multibeam, in modern broadband satellites have been recently considered by employing fractional frequency reuse among the beams, leading to provide higher spectral efficiency [1]. However, one of the major challenges is that adjacent beams create high levels of interference due to the side lobes of their radiation pattern on the Earth surface. To cope with this interference, denoting N_c as the number of employed disjoint frequency bands among beams, a promising solution is to use full frequency reuse pattern ($N_c = 1$) by resorting to precoding in the forward link and multiuser detection in the return link [2]-[4]. Note that the performance of interference mitigation technique is sensitive to the quality of available Channel State Information (CSI) at the gateway. In addition, the precoding/detecting is realized at the gateway to guarantee low complex user terminals and payload infrastructure. Apart from interference limitation, another major challenge is that previous and current systems have shown that in broadband multibeam satellites the demand in high-demanded beams is left unmet, i.e. Unmet-D, while capacity is left unused, i.e. Unused-C, in the low-demanded beams, leading to have an unbalance distribution of scarce on-board resources over the service coverage. Beam Hopping (BH) has been proposed as a promising technological enabler to provide a very high level of flexibility to manage irregular and time variant traffic requests in the satellite coverage area [5]-[6]. Indeed, applying BH leads to optimize the Unused-C and Unmet-D at the beams and allocate on-board resources to each beam upon its demand. However, considering full frequency reuse pattern, the performance of BH is significantly degraded by inter-beam interference and applying precoding/multiuser detection is essential.

1.2. Contribution

This work attempts to propose a Joint Precoding and BH (J-PBH) technique in the forward link of a multibeam system. In this context, we consider a BH managing time scheme aiming at flexibly managing on-board resources (particularly power)at the multibeam service coverage. In addition, a linear Zero Forcing (ZF) precoding scheme is designed in order to manage inter-beam interference. Moreover, we complement the design by formulating ZF precoding problem based on individual on-board per feed power constraint. This is done in order to further efficiently and more realistic use of payload power resources. This is obtained by considering the ZF and its relation to the theory of generalized inverse in the linear algebra. For the sake of relaxing computational complexity of analyzing proposed J-PBH, throughout this paper a perfect CSI is considered at the transmitting segment.

The rest of the paper is organized as follows. Section II presents the signal model. The concept of generalized inverse is presented in Section III. Section IV presents precoding design. Section V provides numerical results. Finally, we derive our conclusion in Section VI.

Notation: Boldface uppercase letters denote matrices and boldface lowercase letters refer to column vectors. $(.)^H$, $(.)^T$ denote Hermitian transpose, transpose matrices, respectively. $\mathbf{I}_N$ builds the $N \times N$ identity matrix. $(\mathbf{A})_{i,j}$ represents the (i-th, j-th) element of matrix The notation $diag$ represents a diagonal matrix. Finally, E$\{.\}$ and $||.||$ refer to the expected value operator and the Frobenius norm operators, respectively.

2. SYSTEM DESCRIPTION AND BH SCHEME

We consider the forward link of a multibeam satellite system, where a single Geosynchronous (GEO) satellite is equipped with an array fed reflector antenna with N feeds and served through a single gateway. The total number of generated beams is denoted by K with ($N = K$). By employing a Time Division Multiplexing (TDM) scheme, at each time instant, a total of M single antenna users is served at the multibeam coverage area with $N \geq M$.

To flexibly allocate on-board resources we consider a BH scheme with the following functionality: a beam illumination pattern which contains a set of T service times is used. At each time instant t, with $t \in T$, a set of K_a high-demanded beams operates in active mode, i.e. illuminated-beams, and K_p low-demanded beams in passive mode, i.e. non-illuminated-beams, depending on the traffic requested at each beam with $K_a < K$, $K_p < K$ and $K_a + K_p = K$ so that M users serve within K_a active beams and all the N on-board feed resources are used to serve $K_{a]}$ active beams. Note that the passive beams have no service. In the same time instant t, based on demand weight and the requested traffic at K_a active beams, single or Multiple user terminal can be served at each active beam with one individual traffic stream per user terminal, leading to optimizing Unmet-D and Unused-C respectively active and passive beams. To establish the possibility of serving multiple user per active beam with individual traffic stream per user, it is conceived that each user serves through an individual feed and a sufficient condition of $N \geq M$ feeds is available at the payload. Obviously, the active beams with multiple traffic streams serve through multiple feeds with overlapped coverage. In addition, the on-board power resources can be flexibly assigned to the feeds based on its available traffic. For instance, Figure 1 shows the distribution of active and passive beams covered France in $T = 4$ consecutive time slots. Figure 2 depicts a multibeam system with BH scheme.

Considering full frequency reuse pattern ($N_c = 1$), the interference among active beams in the user link, i.e. the link between satellite and users, is the bottleneck of the whole system and precoding is applied. Indeed, this interference has two main parts: (i) *intra-active-beam interference* the generated interference among the multiple feed served users at each active beam; and (ii) *inter-active-beam interference* the generated interference among different set of multiple feeds that serve adjacent active beams (see Figure 1). Note that, the feeder link, i.e. the bidirectional link between gateway and satellite, is considered to be ideal.

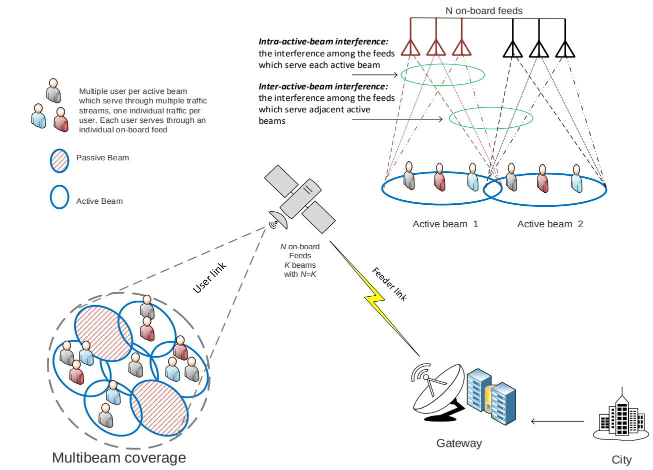
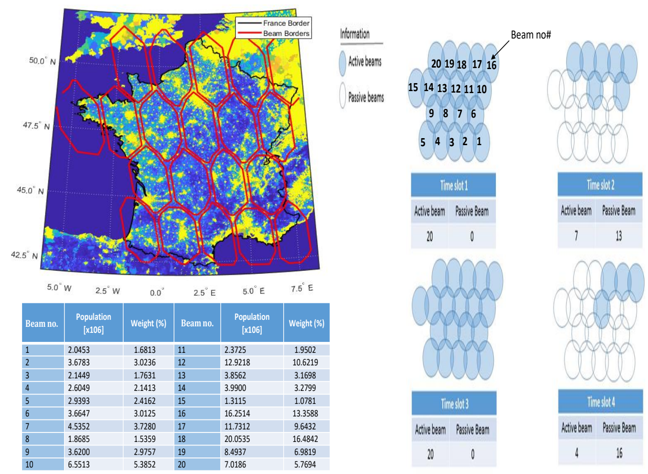


Fig. 1. A multibeam satellite system with active and passive beams.



Beam no.	Population [x106]	Weight (%)	Beam no.	Population [x106]	Weight (%)
1	2.0453	1.6813	11	2.3725	1.9502
2	3.6783	3.0236	12	12.9218	10.6219
3	2.1449	1.7631	13	3.8562	3.1698
4	2.6049	2.1413	14	3.9900	3.2799
5	2.9393	2.4162	15	1.3115	1.0781
6	3.6647	3.0125	16	16.2514	13.3588
7	4.5352	3.7280	17	11.7312	9.6432
8	1.8685	1.5359	18	20.0535	16.4842
9	3.6200	2.9757	19	8.4937	6.9819
10	6.5513	5.3852	20	7.0186	5.7694

Time slot 1	
Active beam	Passive Beam
20	0

Time slot 2	
Active beam	Passive Beam
7	13

Time slot 3	
Active beam	Passive Beam
20	0

Time slot 4	
Active beam	Passive Beam
4	16

Fig. 2. Population data over France in a single time slot [7]. Yellow color shows the distributions of the population at different beams (Top-Left). The population weight table of the beams (Bottom-Left). Distribution of active and passive beams in 4 time slots (Right). The beams with bigger population weight operates more in active mode. For instance, beam 16 works in active more in all $T = 4$ time slots due to having high population weight.

2.1. Signal model

In the considered multibeam architecture, the received signal at any arbitrary time instant t can be modeled as

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

where $\mathbf{y}(t) = [y_1(t), ..., y_M(t)]^T$ is a $M \times 1$ vector containing the stacked received M signals at K_a active beams. The $M \times 1$ vector $\mathbf{x}(t)$ is the stacked transmitted signals at all on-board N feeds with $M = N$. The $M \times 1$ vector $\mathbf{n}(t) = [n_1(t), ..., n_M(t)]^T$ accounts for the zero mean unit variance Additive White Gaussian Noise, i.e. E$\{\mathbf{n}(t)\mathbf{n}(t)^H\} = \mathbf{I}_M$. In the sequel, matrix $\mathbf{H}(t)$ is the overall $M \times N$ user link channel matrix whose element $\left[\mathbf{H}(t)\right]_{i,k}$ presents the aggregated gain of the link between the i-th user, $i = 1, ..., M$, and the k-th satellite feed, $k = 1, ..., N$,. The channel matrix can be further decomposed as

$$\mathbf{H}(t) = \mathbf{D}(t)\mathbf{G}(t), \tag{2}$$

with $\mathbf{D}(t)$ is assumed to be a $M \times M$ diagonal matrix which accounts for the propagation losses in the user link with $\mathbf{D}(t) = \text{diag}\big(d_1(t), ..., d_i(t), ..., d_M(t)\big)$, where $d_i(t)$ is the propagation effect at i-th user. The matrix $\mathbf{G}(t)$ of size $M \times N$ models the satellite antenna gain with $\mathbf{G}(t) = \big(\mathbf{g}_1^T(t), ..., \mathbf{g}_i^T(t), ..., \mathbf{g}_M^T(t)\big)^T$ in which $\mathbf{g}_i(t)$ is a M dimensional row vector of $\mathbf{G}(t)$ denoting the gain for the i-th user. Then, Considering $\mathbf{g}_i(t) = \big(g_{i,1}(t), ..., g_{i,k}(t), ..., g_{i,N}(t)\big)$, the notation $g_{i,k}(t)$ refers to the feed transmit gain (in power) from the k-th feed ($k = 1, ..., N$) at the satellite payload to the i-th user ($i = 1, ..., M$).

2.2. Gateway processing

Let us consider that the gateway employs a precoding scheme to mitigate the inter- and intra-active beam interference. For any time instant t, the incorporation of the precoder in (1) results in

$$\mathbf{x}(t) = \mathbf{W}(t)\mathbf{u}(t), \tag{3}$$

where $\mathbf{u}(t) = (\mathrm{u}_1(t), ..., \mathrm{u}_i(t), ..., \mathrm{u}_M(t))^T$ is the transmit symbol vector of size $M \times 1$ such that the i-th entry of $\mathbf{u}(t)$, i.e. $\mathrm{u}_i(t)$, is the symbol destined to the i-th user with $\mathrm{E}\{\mathbf{u}(t)\mathbf{u}^H(t)\} = \mathbf{I}_M$. The matrix $\mathbf{W}(t) \triangleq (\mathbf{w}_1(t), ...\mathbf{w}_k(t), ..., \mathbf{w}_M(t))$ of size $N \times M$ is the weight of ZF precoding and $\mathbf{w}_k(t)$ of size $N \times 1$ is the k-th column of the matrix $\mathbf{W}(t)$. Besides, the precoding matrix $\mathbf{W}(t)$ must comply with the following power constraint

$$diag[\mathbf{W}(t)\mathbf{W}(t)^H] \leq \Psi(t), \tag{4}$$

where $\Psi(t) = diag(\sqrt{\psi_1(t)}, ..., \sqrt{\psi_k(t)}, ..., \sqrt{\psi_N(t)})$, with $\psi_k(t)$ denotes the allocated power to the k-th feed and can be defined as $\psi_k(t) \triangleq p_k + \Delta p_k(t)$. The term $p_k = \frac{P}{N}$ is the per-beam transmitted power. P is the total power at N feeds. $\Delta p_k(t)$ is the additional power allocated to k-th feed depending on the traffic which serves. Distributing Δp_k within N ($k = 1, ..., N$) feeds can be possible by means of Flexible Travelling Wave Tube Amplifier (FlexTWTA) technology [10], where the saturated power of a FlexTWTA is adjusted according to the capacity demand of feeds. For instance, let us consider a FlexTWTA which serves two feeds with different capacity demand. The FlexTWTA flexibly transfers required power adapted with the traffic weight at each feed through changing the operational point of the amplifiers employed in FlexTWTA.

3. CONCEPT OF GENERALIZED INVERSE

The concept of generalized inverse in linear algebra has a close meaning of design a ZF precoder in multiuser system framework [8]. Typically, $N \times M$ matrix $\mathbf{H}^{-}(t)$ denotes the generalized inverse of matrix $\mathbf{H}(t)$ such that $\mathbf{H}^{-}(t) \approx \mathbf{H}^{-1}(t)$. In this context, $\mathbf{H}^{-}(t)$ is defined as follows

$$\mathbf{H}^{-} \triangleq \mathbf{H}^{\dagger}(t) + \mathbf{R}^{\perp}(t)\mathbf{Q}(t) \tag{5}$$

where $\mathbf{H}^{\dagger}(t) \triangleq \mathbf{H}^H(t)(\mathbf{H}(t)\mathbf{H}^H(t))^{-1}$. Moreover, $\mathbf{R}^{\perp}(t) \triangleq \mathbf{I}_N - \mathbf{H}^{\dagger}(t)\mathbf{H}(t)$ is the orthogonal projection onto the null space of $\mathbf{H}(t)$ and matrix $\mathbf{Q}(t)$ represents an arbitrary matrix of size $N \times M$. This changes the precoder design problem to an optimization via the elements of $\mathbf{R}^{\perp}(t)$ and generalized inverse via $\mathbf{Q}(t)$.

4. CALCULATION PRECODING MATRIX

The Signal to Noise plus Interference Ratio (SINR) in (1) for i-th user is rewritten as

$$\text{SINR}_i = \frac{|[\mathbf{H}(t)\mathbf{W}(t)]_{i,i}|^2}{\sum_{j \neq i} |[\mathbf{H}(t)\mathbf{W}(t)]_{i,j}|^2 + 1} \quad i = 1, ..., M. \tag{6}$$

Subscripts j denotes the user generates either inter- or intra-active-interference on i-th user. The ZF design of $\mathbf{W}(t)$ in (6) for i-th user in matrix notation implies $\sum_{j \neq i} |[\mathbf{H}(t)\mathbf{W}(t)]_{i,j}|^2 = 0$ and is equivalent to

$$\mathbf{H}(t)\mathbf{W}(t) = \text{diag}(\sqrt{\textbf{SINR}(t)}) \qquad i = 1, ..., M, \tag{7}$$

where $\sqrt{\textbf{SINR}} = [\sqrt{\text{SINR}_1(t)}, ..., \sqrt{\text{SINR}_i(t)} ..., \sqrt{\text{SINR}_M(t)}]$ is a vector with non-negative elements that denotes the SINRs of M users.

Let $f(.)$ be an arbitrary function of SINR in arbitrary time instant t, i.e. $f(\textbf{SINR}(t)$. Then, the objective problem can be formulated as

$$\begin{aligned} \max_{\textbf{SINR}(t) \geq \mathbf{0}, \mathbf{W}(t)} \quad & f(\textbf{SINR}(t)) \\ s.t. \quad & \mathbf{H}(t)\mathbf{W}(t) = \text{diag}\sqrt{\textbf{SINR}(t)} \\ & [\mathbf{W}(t)\mathbf{W}^H(t)]_{k,k} \leq \frac{P}{N} + \Delta p_k(t) \quad k = 1, ..., N \end{aligned} \tag{8}$$

The authors in [9] have proposed a heuristic solution to calculate $\Delta p_k(t)$ in (8) which is as follows

$$\Delta p_k(t) = \frac{\big[2^{(\frac{R_{umet,k}T}{\tau_k B})}(\text{SINR}_k(t) + 1)\big] - 1}{\text{SINR}_k(t)}, \tag{9}$$

with $\tau_k \triangleq \frac{\frac{R_{req,k}}{\nu_k}}{\sum_{n=0}^{N_{\text{TWTA}}-1}(\frac{R_{req,n}}{\nu_n})}T$, such that $R_{umet,k}$ is the Unmet-D at the active beam and user which serve through k-th feed. B is the band served by each TWTA amplifier embedded in applied FlexTWTA power distributing chain and T is the total number of time slots that active beams serve (see Figure 2 with $T = 4$). The SINR_k denotes the average SINR of the user serves through k-th feed considering uniform power. τ_k represents the number of time slots that the beam served by k-th feed operates in active mode (for instance in Figure 2 the beam 8 operates in 2 time slots in active mode). $R_{req,k}$ is the DC at the active beam that serves through k-th feed. ν_k denotes the average spectral efficiency, i.e. OC, provided by k-th feed at the active beam which serves. N_{TWTA} is the total number of TWTAs employed in FlexTWTA.

Given (5), the optimization problem in (8) yields

$$\begin{aligned} \max_{\textbf{SINR}(t) \geq \mathbf{0}, \mathbf{W}(t)} \quad & f(\textbf{SINR}(t)) \\ s.t. \quad & \mathbf{W}(t) = \mathbf{H}^{\dagger}(t) + \mathbf{R}^{\perp}(t)\mathbf{Q}(t))\text{diag}\sqrt{\textbf{SINR}(t)} \\ & [\mathbf{W}(t)\mathbf{W}^H(t)]_{k,k} \leq \frac{P}{N} + \Delta p_k(t) \qquad k = 1, ..., N. \end{aligned} \tag{10}$$

The problem (10) is a non-convex problem and a NP-hard problem. To cope with this complexity, the authors in [11] have propsed using fairness criterion to relax the problem in (10) as follows $\mathbf{SINR}(t) = s_f(t)\mathbf{1}$, where s_f is a feasible value of SINR in M users. The notation $\mathbf{1}$ is a vector of ones. Therefore, the expression of $\mathbf{W}(t)$ in the constraint of (10) taking into account the aforementioned feasible point is written as

$$\mathbf{W}(t) = \sqrt{s_f(t)}\big(\mathbf{H}^{\dagger}(t) + \mathbf{R}^{\perp}(t)\mathbf{Q}(t)\big) \tag{11}$$

Employing (11), the problem in (10) can be rewritten as

$$\begin{aligned} \max_{s_f(t)\geq \mathbf{0}, \mathbf{W}(t)} \quad & f(s_f(t)\mathbf{1}) && (12)\\ s.t. \quad & \mathbf{W}(t) = (\mathbf{H}^{\dagger}(t) + \mathbf{R}^{\perp}(t)\mathbf{Q}(t))\sqrt{s_f(t)} \\ & [\mathbf{W}(t)\mathbf{W}^H(t)]_{k,k} \leq \tfrac{P}{N} + \Delta p_k(t) \qquad k = 1, ..., N \end{aligned}$$

For some $\mathbf{Q}(t)$, the problem (12) then is reduced to

$$\max_{s_f(t)\geq 0} \quad \mathrm{s}_f(t) \tag{13}$$

$$s.t. \quad \mathrm{s}_f(t)\|\big(\mathbf{H}^{\dagger}(t) + \mathbf{R}^{\perp}(t)\mathbf{Q}(t)\big)^H\mathbf{a}_n\|^2 \leq \tfrac{P}{N} + \Delta p_k(t)$$

where $\mathbf{a}_n$ denotes zeros vector with single one in the n-th element, $n = 1, ..., N$. Now, it is clear that

$$\mathrm{s}_f(t) = \frac{P + N\Delta p_k(t)}{N\ \max_n \|\big(\mathbf{H}^{\dagger}(t) + \mathbf{R}^{\perp}(t)\mathbf{Q}(t)\big)^H\mathbf{a}_n\|^2} \tag{14}$$

Indeed, the $\mathbf{Q}(t)$ can be a solution to

$$\min_{\mathbf{Q}(t), \mathrm{r}(t)} \quad \mathrm{r}(t) \tag{15}$$

$$s.t. \quad \|\big(\mathbf{H}^{\dagger}(t) + \mathbf{R}^{\perp}(t)\mathbf{Q}(t)\big)^H\mathbf{a}_n\| \leq \mathrm{r}(t) \qquad n = 1, ..., N$$

Problem (15) is a convex second order cone program and it can be solved by a standard optimization package [12].

5. NUMERICAL RESULTS

In order to further compare the performance of the proposed J-PBH in in Sections 2 and 4, Monte Carlo simulations are presented in this section. The simulation setup is based on an array fed reflector antenna provided by European Space Agency (ESA) in the context of SatNexIII project with $N = 22$ feeds and $K = 20$ beams, at each time instant, which serve a single user per feed, i.e. $M = 20$ spread over the France [13]. The contour of the beams is depicted in Figure 2. Results have been averaged for a total of 500 channel realizations. The detail of simulation parameters are collected in Table 1. Note that the channel statistics corresponds to the city of France. As a performance metric, we compute the SINR for each user, after interference mitigation and then its throughput (bit/s) is inferred according to DVB-S2x standard for a PER of 10^{-6} [14]. Note that this relationship has been obtained from [14] considering the PER curves.

For a best practice and in order to clarify the performance of proposed J-BPH, we consider 4 frequency reuse pattern ($N_c = 4$) as a reference scenario [4]. To show the benefits of proposed J-PBH, we analysed the performance of ZF precoding proposed in (11) within a set of 4 time slots presented in Figure 2. Note that the obtained results are averaged over the considered 4 time slots.

The obtained results are summarized in Figure 3. Clearly, reference scenario (i.e. 4 frequency reuse pattern) provides low average offered performance compared to the proposed J-PBH (i.e. precoding in (11) and BH in Section 2). Moreover, it is seen that the proposed J-PBH is able to adapt the resources to the demand, thus providing low values of average Unused-C and Unmet-D with respect to the reference scenario. Note that the results in Figure 3 just a preliminary experimental results and more precise evaluation and discussion on employing J-PBH is left to our future works.

6. CONCLUSION

This paper investigated the capability to flexibly allocate scarce on-board resources, particularly power, through applying BH scheme in the forward link of a multibeam satellite system while time variant traffic demands distributed within the coverage. However, in case of using full frequency reuse pattern, the performance of BH is decreased due to inter-beam interference. We proposed a J-PBH scheme where at consecutive time instants high-demand beams are served more often than low-demand beams through an illumination pattern. Then, an ZF precoding technique is employed to equalize interference among beams.

Table 1. Simulation parameters

Link	Title	Description
Forward link parameters	Satellite height	35786 km (GEO)
	Earth radius	6378.137 Km
	Numer Of Satellites	1
	Feed radiation pattern	ESA [13]
	Number of feeds N	22
	Number of beams K	20
	Total bandwidth	500 MHz
	Roll-off factor	0.25
	Coverage area	France
	clear sky gain	17.68 G/T
	Satellite antenna gain	57 dBi
User link	Frequency	20×10^9Hz
	user antenna gain	41.7 dBi

Nº of Configuration	Number of total active and passive beams								Average offered capacity considering DVB-S2x [Gb/s]	Average unused system capacity [Gb/s]	Average unmet capacity demand [Gb/s]
	Time slot 1		Time slot 2		Time slot 3		Time slot 4				
	Act.	Pas.	Act.	Pas.	Act.	Pas.	Act.	Pas.			
4 frequency reuse	20	0	20	0	20	0	20	0	14.46	3.29	8.09
J-PBH	20	0	7	13	20	0	4	16	23.86	2.71	2.66

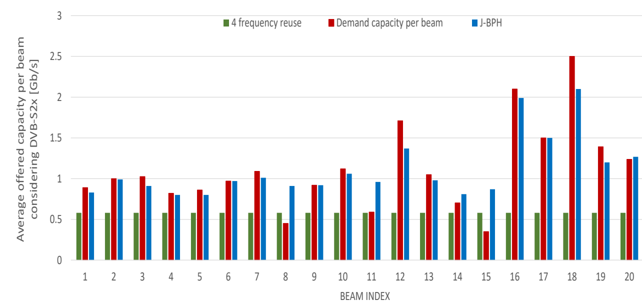


Fig. 3. Average throughput (Gb/s) evaluation based on DVB-S2x. $\mathrm{DC}_k = RS_k$ is the DC at k-th active beam with S_k refers to the population weight at corresponding active beam. R is a tentative benchmark reference value provided by satellite service providers. The Average DC can be also calculated by $\sum_{k=1}^{N} \frac{RS_k}{N}$. We consider in average $R = 2.6$ [Gb/s].

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