Interference Management versus Interference Cancellation: SATCOM Case

Lei Jiang and Maria-Angeles Vázquez-Castro

Dpt. Telecom. and Systems Engineering, Universitat Autónoma de Barcelona, Spain
{jiang.lei,angeles.vazquez}@uab.es
http://wirelessatcom.uab.es/index.htm

Abstract. Interference management and interference cancellation are addressed in the satellite communication (SATCOM) system. We first introduce the two options for a multibeam payload: flexible (FLEX) where allocation is fully flexible in the frequency domain, and conventional on which beamforming (BF) is applied. Further, two optimization problems are proposed, P1: spectral mask vector design and power allocation in the FLEX SATCOM system by interference management, and P2: BF weighting vector design and power allocation in the BF SATCOM system by interference cancellation. Specifically, we provide a resource allocation algorithm for each system. The performance of the resource allocation algorithm is evaluated with asymmetrical traffic distribution models. The numerical results show that, by using interference cancellation, BF system with full frequency reuse provides the best performance. For the FLEX system, the bandwidth can be utilized more efficiently with larger frequency reuse factor and smaller bandwidth granularity.

Keywords: Multibeam satellite, resource allocation, interference management, and interference cancellation.

1 Introduction, Previous Work and Contribution

Current satellite communication (SATCOM) systems make use of frequency reuse by means of multiple beams grouped in clusters throughout the coverage. Power and bandwidth allocation should be optimized to adapt the asymmetric traffic distribution and channel conditions (e.g. at Ka band, where rain attenuation can be of dozens of dBs). In this paper, the co-channel interference of satellite system is formulated mathematically in both frequency and time-space domains. Two techniques will be analyzed: one is the interference management based on flexible (FLEX) system where the bandwidth allocation is fully flexible in the frequency domain, the other is the interference cancellation based on conventional system on which beamforming (BF) is applied. The payloads of flexible and conventional SATCOM systems refer to [1, 2].

Given the Channel State Information (CSI), the transmitter can manage the interference in frequency domain by splitting the total available bandwidth into numerous carriers and managing the carrier and power allocation for each

G. Giambene and C. Sacchi (Eds.): PSATS 2011, LNICST 71, pp. 260–273, 2011.

beam. The interference management has been discussed in [4, 5, 3, 6]. In [3], an axiomatic-based interference model for Signal to Interference plus Noise Ratio (SINR) balancing problem is proposed with individual target SINR per user, but it is focused on the terrestrial wireless communications. In [4], a power allocation policy is suggested to stabilize the system based on the amount of unfinished work in the queue and the channel state. In [5], the authors make an effort to design a tradeoff strategy between different objectives and system optimization. However, the co-channel interference is not taken into account. The authors in [6, 7] discuss power and carrier allocation problem in SATCOM system, but [6] only focuses on the return uplink and [7] discusses the beamforming vector design in terms of sum-rate.

The interference cancellation can be realized by precoding techniques, i.e. Dirty Paper Coding (DPC) and BF. It is well known from the literature [8, 9] on mobile terrestrial channel that for a given composite channel matrix, the sum-rate capacity is achieved by "Gaussian codes" and DPC. In fact, DPC is the optimal (capacity achieving) strategy in MIMO broadcast (BC) channels. However, DPC is difficult to implement in practical systems due to the high computational burden of successive encodings and decodings. BF is a suboptimal strategy that can serve multiple users simultaneously, but with reduced complexity relative to DPC. In BF, each user stream is precoded by a beamforming weight vector for reducing/eliminating the mutual interference among different streams. However, the precoding techniques increase the transmitted signal power (precoding loss). As discussed in [10], the precoding loss is negligible with larger constellations and is always bounded, i.e. for the QPSK constellation, the precoding loss is never greater than 1.5dB. Besides, it quickly falls towards 0dB for larger constellations.

Most of the interference management and interference cancellation techniques discussed in the above literatures are focused on the terrestrial communication systems. However, SATCOM systems have a different geometrical topology and the satellite payload poses a number of constraints not present in terrestrial systems [11]. Specifically, the contributions of this paper can be summarized as

- An unified system model formulation, which is valid both in frequency and space-time domains. As the system is interference-limited, this model allows us for the derivation of SINR for different interference countermeasure mechanisms in an unified way.
- Optimization of a SATCOM system by interference management with full flexibility in the frequency domain. In particular, we solve the problem P1: optimization of the spectral mask vector and power allocation under the individual SINR constraints (we will call this system "FLEX").
- Optimization of a SATCOM system by interference cancellation with beamforming in the conventional system [2], where the frequency bandwidth is reused by a subset of beams. In particular, we solve the problem P2: beamforming weight vector design and power allocation under the individual SINR constraints (we will call this system "BF").

The rest of the paper is organized as follows: in Section 2, the unified system model is formulated. In Section 3, the SINR expression in frequency domain is formulated, a spectral mask vector design and SINR balancing problem is proposed and solved. Section 4 formulates the SINR in time-space domain, and resource allocation optimization problem is proposed and solved in this section. Section 5 provides selected numerical results. Finally, the summarizing conclusions are presented in Section 6.

We adopt the following notations: bold uppercase letters denote matrices and bold lowercase letters denote vectors, $(\cdot)^T$ and $(\cdot)^H$ denote transpose and conjugate transpose, respectively, $(\cdot)^\dagger$ denotes pseudo-inverse, $\varepsilon(\cdot)$ stands for the expectation, $\lambda_{\max}(\cdot)$ denotes the maximum eigenvalue, $\upsilon_{\max}(\cdot)$ indicates the eigenvector related to the maximum eigenvalue, $\operatorname{diag}\{(\cdot)\}$ denotes a diagonal matrix with the elements $(\cdot)$ along its diagonal, and $\mathbf{I}_N$ denote the identity matrix of size $N \times N$.

2 System Model

In this section, an unified SATCOM system model for both multibeam FLEX system (in frequency domain) and BF system (in time-space domain) is formulated. In a multibeam satellite systems, the beamforming antenna generates K beams over the coverage area. Let us assume a MIMO BC model equipped with K transmit antennas and the ith user terminal with N_i receive antennas. For simplicity, we assume that all the users are homogeneous and experience independent fading. The signal received by a user i can be expressed as

$$\mathbf{y}_i = \mathbf{H}_i\mathbf{x} + \mathbf{n}_i, \quad i = 1, \ldots, K, \tag{1}$$

where $\mathbf{x} \in \mathbb{C}^{K\times 1}$ is the transmitted symbol from the satellite antennas, $\mathbf{H}_i \in \mathbb{C}^{N_i\times K}$ is the channel gain matrix to the ith user, $\mathbf{n}_i \in \mathbb{C}^{N_i\times 1}$ is zero-mean complex circular Gaussian noise with variance σ^2 at user i, and $\mathbf{y}_i$ is the received signal vector by user i. The transmitter has a power constraint $\varepsilon\{\mathbf{x}\mathbf{x}^H\} \leq P_{\text{tot}}$. We assume that each user is equipped with a single antenna, i.e. $N_i = 1$, for $\forall i$, this is a common assumption in the satellite scenario, e.g. in [12,1,2]. Depending on different system assumptions, e.g FLEX or BF, $\mathbf{x}$, $\mathbf{H}_i$, $\mathbf{n}_i$ and $\mathbf{y}_i$ have different dimension, size and meaning. We will discuss in detail the system model for both FLEX and BF systems in the following sections.

2.1 FLEX System in Frequency Domain

In this section we analysis the FLEX system model. The total available bandwidth, B_{tot}, is divided in N_c carriers providing carrier granularity of $B_c = B_{\text{tot}}/N_c$. Note that we assume Time-Division Multiplex (TDM). For a single carrier slot, the signal model can be expressed as equation (1). We are interested in the multiple carriers TDM mode, hence, for a specific beam i, the transmitted symbols over N_c carriers are defined as $\mathbf{s}_i = [s_{i1}, s_{i2}, \cdots, s_{iN_c}]^T$. Let the spectral mask matrix $\mathbf{W} \in \mathbb{R}^{N_c\times K}$ be defined as $\mathbf{W} = [\mathbf{w}_1, \mathbf{w}_2, \cdots, \mathbf{w}_K]$, and the ith column vector $\mathbf{w}_i \in \mathbb{R}^{N_c \times 1}$ be defined as $\mathbf{w}_i = [w_{i1}, w_{i2}, \cdots, w_{iN_c}]^T$, which is the spectral mask vector for beam i and indicates which TDM carriers are allocated to beam i.

Let $\mathbf{A} = diag\{\alpha_1, \ldots, \alpha_K\}$ be the channel attenuation amplitude matrix over the user and $\mathbf{G}$ is the antenna gain matrix, which is defined as

$$\mathbf{G} = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1K} \\ g_{21} & g_{22} & \cdots & g_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ g_{K1} & g_{K2} & \cdots & g_{KK} \end{bmatrix}, \tag{2}$$

where g_{ij} is the square root of the gain of the j-beam on-board antenna towards the ith user. Let $\mathbf{H} = \mathbf{AG}$ be the overall channel matrix, and $\mathbf{W}_i = \text{diag}\{\mathbf{w}_i\}$. Then, from the unified system model in equation (1), the received signal by all the N_c carriers for beam i, $\mathbf{y}_i \in \mathbb{C}^{N_c \times 1}$, can be expressed as

$$\mathbf{y}_i = h_{ii}\mathbf{x}_i + \sum_{k=1(k \neq i)}^{K} h_{ik}\mathbf{x}_k + \mathbf{n}_i, \tag{3}$$

where $\mathbf{x}_i$ is the spectral masked symbol vector for beam i, defined as $\mathbf{x}_i = \mathbf{W}_i\mathbf{s}_i$. The first term corresponds to the desired signals coming from the ith on-board antenna. The second term is the sum of interference signals from the other on-board antennas. $\mathbf{n}_i \in \mathbb{C}^{N_c \times 1}$ is a column vector of zero-mean complex circular Gaussian noise with variance σ^2 at beam i.

2.2 BF System in Time-Space Domain

For the BF SATCOM system, we are interested in the full frequency reuse pattern, therefore, the user streams are separated by different time-space beamforming directions, as opposed to frequency slot separation in the FLEX system.

The overall channel matrix $\mathbf{H}$ is the same as shown in Section 2.1, $\mathbf{F} \in \mathbb{C}^{K \times K}$ denotes the beamforming weight matrix be defined as $\mathbf{F} = [\mathbf{f}_1, \mathbf{f}_2, \cdots, \mathbf{f}_K]$, and $\mathbf{s} = [s_1, s_2, \cdots, s_K]^T$ is the symbol vector. s_i and $\mathbf{f}_i$ are the data symbol and the beamforming weight vector for beam i, respectively. We can reformulate equation (1) for the BF system with the desired signal and interference as (e.g. user i)

$$y_i = \mathbf{h}_i\mathbf{f}_i s_i + \sum_{k=1(k \neq i)}^{K} \mathbf{h}_i\mathbf{f}_k s_k + n_i, \tag{4}$$

where $\mathbf{h}_i$ and $\mathbf{f}_i$ are the ith row vector and ith column vector of $\mathbf{H}$ and $\mathbf{F}$, respectively.

3 Interference Management in Frequency Domain

In modern satellite networks, multibeam antenna technology is used because it can increase the total system capacity significantly [13]. However, each beam will compete with others for resources, e.g. power and bandwidth, to achieve satisfactory communications. This is due to the fact that the traffic demand among the beams of the coverage is potentially highly asymmetrical. The FLEX SATCOM system can minimize the co-channel interference by balancing the power and carrier allocation in frequency domain. In this section, we will address the problem (P1) of spectral mask vector design and power allocation for the FLEX SATCOM system.

3.1 SINR Formulation

For the FLEX SATCOM system in frequency domain, in order to derive the expression of SINR per beam from the system model, we can reformulated the spectral mask matrix as $\mathbf{W} = [\tilde{\mathbf{w}}_1^T, \tilde{\mathbf{w}}_2^T, \cdots, \tilde{\mathbf{w}}_{N_c}^T]^T$, where $\tilde{\mathbf{w}}_j = [w_{1j}, w_{2j}, \cdots, w_{Kj}]$, indicates which beams are allocated carrier j. Let the ith row of $\mathbf{H}$ be defined as $\mathbf{h}_i = [h_{i1}, h_{i2}, \cdots, h_{iK}]$ and $\tilde{\mathbf{h}}_i = \mathbf{h}_i|_{(h_{ii}=0)}$ is the channel of interference contribution. We assume that the amplitude of the transmitted symbols is normalized (i.e. $|x_{ij}|^2 = 1, \forall i, j$).

Then, the transmitted signal power of all the carriers for beam i can be given by the diagonal elements of the matrix $\mathbf{U}_i \in \mathbb{R}^{N_c \times N_c}$ as

$$\mathbf{U}_i = |h_{ii}|^2 \mathbf{W}_i \mathbf{W}_i^H. \tag{5}$$

And the co-channel interference power of all the carriers for beam i can also be given by the diagonal elements of the matrix $\mathbf{R}_i^{\text{int}} \in \mathbb{R}^{N_c \times N_c}$ as

$$\mathbf{R}_i^{\text{int}} = \text{diag}\left\{ \left[\tilde{\mathbf{h}}_i \tilde{\mathbf{w}}_j^H \tilde{\mathbf{w}}_j \tilde{\mathbf{h}}_i^H \right]_{j=1,2,\cdots,N_c} \right\}. \tag{6}$$

Thus, the interference power plus the noise matrix, $\mathbf{R}_i$, will be given as

$$\mathbf{R}_i = \mathbf{R}_i^{\text{int}} + \sigma^2 \mathbf{I}_{N_c}. \tag{7}$$

Consequently, the SINR for beam i, defined as $\mathbf{\Gamma}_i \in \mathbb{R}^{N_c \times N_c}$, can be expressed as

$$\mathbf{\Gamma}_i = \mathbf{U}_i (\mathbf{R}_i)^{-1}. \tag{8}$$

Note that in Section 3.2, the Rayleigh quotient optimization problem will be addressed based on the SINR formulation $\mathbf{\Gamma}_i$ in equation (8). Obviously, $\mathbf{\Gamma}_i$ is a diagonal matrix, because both $\mathbf{U}_i$ and $\mathbf{R}_i$ are diagonal matrixes. Thus, the SINR for the jth carrier used by beam i will be the jth diagonal element of the matrix $\mathbf{\Gamma}_i$. This means that for each carrier j of beam i, the SINR can be formulated as

$$\gamma_{ij} = \frac{|h_{ii} w_{ij}|^2}{\sum_{k=1 (k \neq i)}^{K} |h_{ik} w_{kj}|^2 + \sigma^2}. \tag{9}$$

Consequently, the beam-level sum-rate can be expressed as

$$R_i = \sum_{j=1}^{N_c} \frac{B_{\text{tot}}}{N_c} \eta_{ij} = \sum_{j=1}^{N_c} B_c \eta_{ij}, \tag{10}$$

where $\eta_{ij} = f(\gamma_{ij})$ is the spectral efficiency, and $f(\gamma_{ij})$ equals to $\log_2(1+\gamma_{ij})$ for Shannon limit with Gaussian coding, or can be a quasi-linear function in DVB-S2 [15] with respect to the SINR.

Note that the optimization problem with a SINR constraint is equivalent to the rate constraint. E.g., for the Gaussian coding case, if we consider that the rate required by the ith user is $\hat{R}_i$, the SINR requirement can be derived from $R_i = \log_2(1+\gamma_i)$ as $\hat{\gamma}_i = 2^{\hat{R}_i} - 1$. Therefore, in the following sections, we focus on the optimization problem with a SINR constraint per user.

3.2 Resource Allocation Optimization with Interference Management

In order to best match offered and requested traffic per beam, we develop a methodology to jointly optimize power and carrier allocation. Existing results on the references [4, 5] on similar problems assume power limitation and the optimization is exclusively over the power allocation. However, we assume an additional degree of freedom: carrier allocation (spectral mask vector design). We propose to use Binary Power Allocation (BPA) ($|w_{i,j}|^2 = \{0, P_{\text{sat}}\}$) and quantized bandwidth allocation in order to decrease the complexity, where P_{sat} is the saturation power per carrier.

Optimization Problem Formulation. The problem we need to solve is both a problem of SINR balancing (as in [3, 14]) and a problem of allocating the carriers (optimize the spectral mask matrix). We do not only balance the power allocation, but also optimize the strategy of carrier allocation (i.e. the structure of matrix $\mathbf{W}$). Therefore, the theory of SINR balancing is not applicable straightforwardly here. The problem can be formulated as

$$\begin{aligned} &\max_{\mathbf{W}} \sum_{i=1}^{K} \frac{\gamma_i(\mathbf{W})}{\hat{\gamma}_i}, \\ &\text{subject to } \; \gamma_i \le \hat{\gamma}_i, \\ &\sum_{i=1}^{K} \mathbf{w}_i^H \mathbf{w}_i \le P_{\text{tot}}; \text{and } |w_{ij}|^2 = \{0, P_{\text{sat}}\}, \forall i, j. \end{aligned} \tag{11}$$

where P_{tot} and P_{sat} are the total available satellite power and the saturation power per carrier, respectively, which are the constraints of satellite payload.

Algorithmic Solution. The general analytical solution of (11) is a complex problem due not only to the clear non-convexity but also to the need of preserving the geometry of the optimization model (i.e. $\mathbf{W}$). Therefore, we propose an iterative solution where each iteration is based on a two-step process as shown

Table 1. Algorithm solution for the flexible carrier allocation SATCOM system

1: Initialize: $R_i \Leftarrow 0, i = 1, 2, \cdots, K$.
2: Generating beam set $\mathcal{A}_s$: $\mathcal{A}_s = \left\{ i_1, i_2, \cdots, i_N \| 0 \leq \frac{R_{i_n}}{\hat{R}_{i_n}} \leq \frac{R_{i_n-1}}{\hat{R}_{i_n-1}} < 1 \right\}$. where $i_n \in \{1, 2, \cdots, K\}, n = 1, 2, \cdots, N$.
3: Repeat: $k = i_1$
4: Solve the Rayleigh quotient problem: $\max \frac{\mathbf{e}_j^H \mathbf{\Gamma}_k \mathbf{e}_j}{\mathbf{e}_j^H \mathbf{e}_j}$ subject to $\|\|\mathbf{e}_j\|\|^2 = 1, \forall j$.
5: $w_{k,j} \Leftarrow \mathbf{e}_j^H \mathbf{e}_j (P_{\text{sat}})^{1/2}$.
6: Update $\mathbf{U}_k$, $\mathbf{R}_k$, $\mathbf{\Gamma}_k$, $\mathbf{W}$, and R_k.
7: go to step 3, until $k = i_N$.
8: go to step 2, until $\mathcal{A}_s$ is empty or $\sum_{i=1}^{K} \mathbf{w}_i^H \mathbf{w}_i \leq P_{\text{tot}}$.

in Table 1. First, we obtain an analytical solution of the carrier allocation on a per-beam basis. Second, we obtain the power allocated to the selected carriers from the power constraint.

Note that, in Step 4, $\mathbf{e}_j \in \mathbb{R}^{N_c \times 1}$ is a unity column vector with only the jth element non-zero. Herein $\mathbf{e}_j$ is introduced to indicate which carrier is allocated. The solution of Rayleigh quotient problem shown in Step 4 is given as $\mathbf{e}_j = \upsilon_{\max}(\mathbf{\Gamma}_k)$. Hence, $w_{k,j}$ for jth carrier of beam k can be obtained with the solution of $\mathbf{e}_j$ as $w_{k,j} = \mathbf{e}_j^H \mathbf{e}_j (P_{\text{sat}})^{1/2}$.

In Step 6, the resource allocation matrix, SINR and data rate for the selected beam are updated. After the iterative algorithm convergence (the detailed study of convergence shown in [12, 2, 1]), we can obtain the resource allocation matrix (spectral mask matrix): $\mathbf{W}$.

4 Interference Cancellation in Time-Space Domain

As we indicated in Section 1, the interference cancellation can be realized by BF in the conventional system [2], where a subset of beams can be illuminated simultaneously by reusing the frequency bandwidth. In BF, each illuminated beam is multiplied by a beamforming weight vector ($\mathbf{f}_i$) for reducing/eliminating the mutual interference. This interference cancellation takes advantage of the spatial relative location between users in order to support multiple users simultaneously. As pointed out in [16, 17], the sum-rate capacity optimization problem of MIMO BC using DPC and BF is discussed. However, in this paper, the problem is not maximize the sum-rate, but the beamforming weight vector design and power allocation for each user with individual SINR constraints (Problem P2). We will discuss this problem in this section.

4.1 SINR Formulation

Based on the unified system model presented in equation (1), we can define the pre-coded transmitted symbols, $\mathbf{x} \in \mathbb{C}^{K\times 1}$, as $\mathbf{x} = \mathbf{F}\mathbf{s}$, where $\|\mathbf{x}\|^2 \leq P_{\text{tot}}$, $\mathbf{F} \in \mathbb{C}^{K\times K}$ is the beamforming weight vectors (defined in Section 2.2) and $\mathbf{s} \in \mathbb{C}^{K\times 1}$ is the normalized symbol vector. Note that we need to normalize the symbol power after introducing the beamforming weight vector, we have that $p_i = \frac{\|s_i\|^2}{\varsigma_i}$ with $\varsigma_i = \|\mathbf{f}_i\|^2$.

Following the ith user received signal (in equation (4)), we can define the SINR as

$$\gamma_i = \frac{p_i\|\mathbf{h}_i\mathbf{f}_i\|^2}{\sum_{k=1(k\neq i)}^{K} p_k\|\mathbf{h}_i\mathbf{f}_k\|^2 + \sigma_i^2} = \frac{\frac{\tilde{p}_i}{\varsigma_i}\|\mathbf{h}_i\mathbf{f}_i\|^2}{\sum_{k=1(k\neq i)}^{K} \frac{\tilde{p}_k}{\varsigma_k}\|\mathbf{h}_i\mathbf{f}_k\|^2 + \sigma_i^2}. \tag{12}$$

where $\tilde{p}_i = \|s_i\|^2$ is the actually transmitted power towards the ith user. It can be observed that the downlink SINR is not a convex cost-function because of the coupling among the beamforming vectors in the denominator. This makes the optimization of the beamforming complex and computationally demanding.

4.2 Resource Allocation Optimization with Interference Cancellation

In the Zero-Forcing beamforming (ZFBF), weights are selected so as the co-channel interference is cancelled. Let $\mathcal{S} \subset \{1,\ldots,K\}$ denote the user subset from all the users in the co-channel beams that are selected for transmission. One easy choice of $\mathbf{F}(\mathcal{S})$ that gives zero-interference is the pseudo-inverse of $\mathbf{H}(\mathcal{S})$ (if channel matrix $\mathbf{H}$ is not full rank). Then, the ZFBF transmit beamformer matrix will be given by

$$\mathbf{F} = \mathbf{H}^\dagger = \mathbf{H}^H(\mathbf{H}\mathbf{H}^H)^{-1}, \tag{13}$$

thus $\|\mathbf{h}_i\mathbf{f}_i\|^2 = 1$, and $\|\mathbf{h}_i\mathbf{f}_k\|^2 = 0$ (if $k \neq i$).

Hence, assuming Gaussian codes the upper bound of the maximum throughput can be achieved by water-filling algorithm, and the water level is directly extracted from the overall payload power constraint. However, what we are interested is not the maximum throughput, but the resource allocation with individual QoS constraints (individual traffic requirement). This problem has been essentially solved on the terrestrial system in [14], and here we follow their approaches but with an instantaneous analysis instead of statistical.

With fixed beamforming matrix $\widetilde{\mathbf{F}}$, the downlink power allocation is a well-known SINR balancing problem (in [3, 14]). The problem can be formulated as

$$\mathcal{C}(\widetilde{\mathbf{F}}, P_{\text{tot}}) = \max_{\mathbf{p}} \left(\min_{1\leq i\leq K} \frac{\gamma_i(\widetilde{\mathbf{F}}, \mathbf{p})}{\hat{\gamma}_i} \right),$$

$$\text{subject to} \sum_{i=1}^{K} p_i\varsigma_i \leq P_{\text{tot}}. \tag{14}$$

where $\hat{\gamma}_i$ is the requested SINR, γ_i is the SINR with the optimized beamforming matrix $\widetilde{\mathbf{F}}$ and allocated power $\mathbf{p}$. $\mathbf{p} = [p_1, \cdots, p_K]$ is the power allocation vector for all the K users. The increased transmitted power compared to transmission without beamforming, quantified by precoding loss, which for square QAM constellations calculates to $\varrho_p^2 = \frac{M}{M-1}$. Even for moderate sizes M this loss is negligible and vanishes as M increases [10]. Therefore, we will not focus on this point in this paper.

The optimum of (14) can be achieved by an eigenvalue optimization problem (presented in [3]) as

$$\mathcal{C}(\widetilde{\mathbf{F}}, P_{\text{tot}}) = \frac{1}{\lambda_{\max}\left(\mathbf{\Psi}_E(\widetilde{\mathbf{F}}, P_{\text{tot}})\right)}. \tag{15}$$

where $\mathbf{\Psi}_E$ is the extended coupling matrix (defined in (12) of [3]). The optimal power vector $\mathbf{p}$ is obtained as the first K components of the dominant eigenvector of $\mathbf{\Psi}_E(\widetilde{\mathbf{F}}, P_{\text{tot}})$.

In [3], the authors also discussed how to jointly optimize the beamforming vector and power allocation. The problem can be written as

$$\begin{aligned} &\mathcal{C}(P_{\text{tot}}) = \max_{\mathbf{F},\mathbf{p}} \left(\min_{1\le i\le K} \frac{\gamma_i(\mathbf{F},\mathbf{p})}{\hat{\gamma}_i} \right), \\ &\text{subject to} \sum_{i=1}^{K} p_i \varsigma_i \le P_{\text{tot}}, \\ &\|\mathbf{f}_i\|^2 = \varsigma_i, 1 \le i \le K. \end{aligned} \tag{16}$$

where ς_i is the weighting factor in order to normalize the symbol power. The global optimum can be achieved by an eigenvalue optimization problem as

$$\mathcal{C}(P_{\text{tot}}) = \frac{1}{\min_{\mathbf{F}} \lambda_{\max}\left(\mathbf{\Psi}_E(\mathbf{F}, P_{\text{tot}})\right)}. \tag{17}$$

Therefore, the optimum beamforming weight matrix $\mathbf{F}$ is associated with the minimum of the maximal extended coupling matrix eigenvalue. And the optimal power vector $\mathbf{p}$ is obtained as the first K components of the dominant eigenvector of $\mathbf{\Psi}_E(\mathbf{F}, P_{\text{tot}})$.

5 Numerical Results

The simulations are carried out with the following assumptions

– Beams layout: the satellite system coverage is assumed to be regional (e.g. EU25 countries as presented in [2]), with 70 user beams for the whole coverage.

Table 2. Satellite payload parameters

Parameters	Value
Downlink frequency	19950Mhz
Available bandwith (B_{tot})	500Mhz
Output Back-Off (OBO)	4.5dB
Repeater loss (L_{repeater})	2.55dB
Antenna feed loss (L_{antenna})	1.17dB
Satellite Tx. antenna gain (G_{tx})	47.14dB
TWTA saturation power (P_{sat})	120Watts (if not otherwise stated)
Slope of the traffic distribution (β)	8×10^6bps (if not otherwise stated)
Propagation loss ($L_{\text{propagation}}$)	211.10dB
Ground terminal G/T $(G/T)_{gt}$	18.70 dB/K
Boltzmann constant (k_B)	$1.38 \times 10^{-23}\text{m}^2\text{kgs}^{-2}\text{K}^{-1}$

- Traffic distribution model: the distribution of traffic through the coverage area is highly unbalanced. As an example, we suppose a linear traffic requested distribution is defined as $\hat{R}_i = i\beta; i = 1, 2, \cdots, K$, β is the slope of the linear function.
- Antenna model: a tapered aperture antenna pattern is implemented in the simulation. And the extensive number of satellite payload parameters are list in Table 2.
- Performance metrics:
  - average spectral efficiency (η) is defined as the total useful allocated traffic with respect to the allocated bandwidth, i.e., $\eta = \frac{\sum_{k=1}^{K} \min\{R_k, \hat{R}_k\}}{\sum_{k}^{K} B_k}$, where B_k is the bandwidth allocated to beam k.
  - traffic Matching Ratio (MR) (ρ) is defined as the total useful allocated traffic with respect to the total requested traffic, i.e., $\rho = \frac{\sum_{k=1}^{K} \min\{R_k, \hat{R}_k\}}{\sum_{k=1}^{K} \hat{R}_k}$.

5.1 Simulation Results

The useful throughput (presented in Table 3) is defined as the traffic allocated to all the users with individual SINR constraint per user. We can see that the BF SATCOM system can achieve the best performance. About 15% $\sim$ 56% improvement can be achieved by BF SATCOM system comparing with flexible one

Table 3. Useful throughput comparison

System scenario	FLEX (B_c =62.5MHz)				BF
f_R	1	3	4	7	1
Useful throughput (Gbps)	14.67	17.10	17.31	12.77	19.88

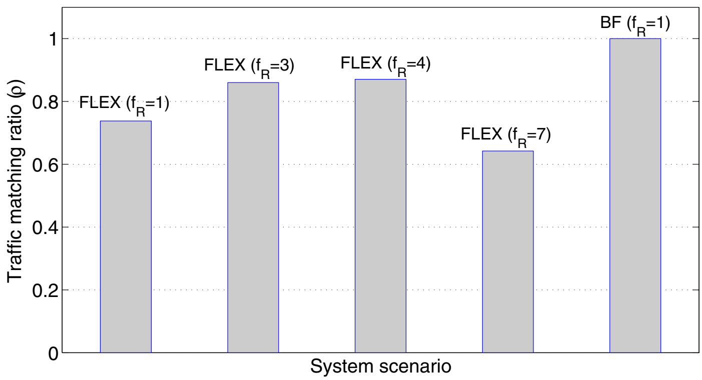

Fig. 1. Traffic matching ratio (ρ) of FLEX system and BF system (B_c = 62.5MHz)

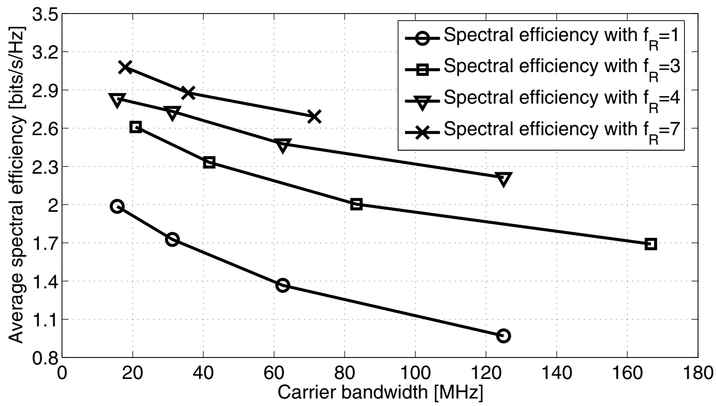

Fig. 2. Average spectral efficiency vs. B_c (for the FLEX system)

with different f_R. The reason is that the BF system reuse the whole bandwidth without co-channel interference. However, for the FLEX system, although more bandwidth is available by low frequency reuse factor, the co-channel interference will deteriorate the performance of the useful throughput.

In Fig. 1, the results show the same trend as the useful throughput in Table 3. We can see that the BF system with $\rho = 1$ can satisfy all the users' traffic requirement. The results of FLEX system show that the performance of ρ (also the useful throughput in Table 3) first increases and then decreases as the f_R increases. The reason is that, as we increase the f_R, the co-channel interference for the FLEX system will decrease, because the beams reusing the same frequency band are separated much farther from each other. However, the aggregated bandwidth will decrease as the f_R increases, since the total available bandwidth is fixed for each cluster (e.g. $B_{\text{tot}} = 500$MHz in our simulation).

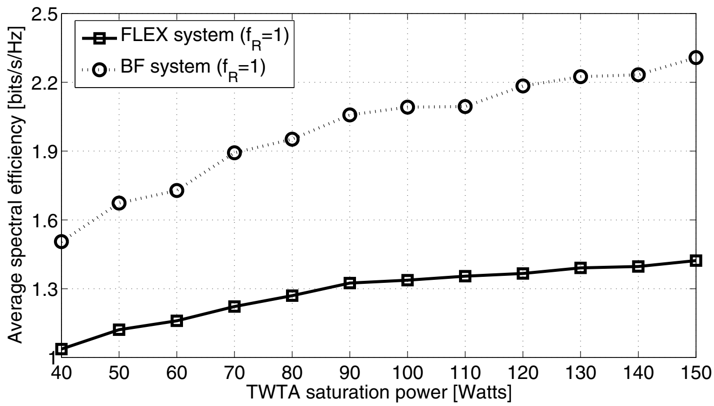

Fig. 3. Average spectral efficiency vs. saturation power P_{sat} ($B_c = 62.5$MHz, f_R=1)

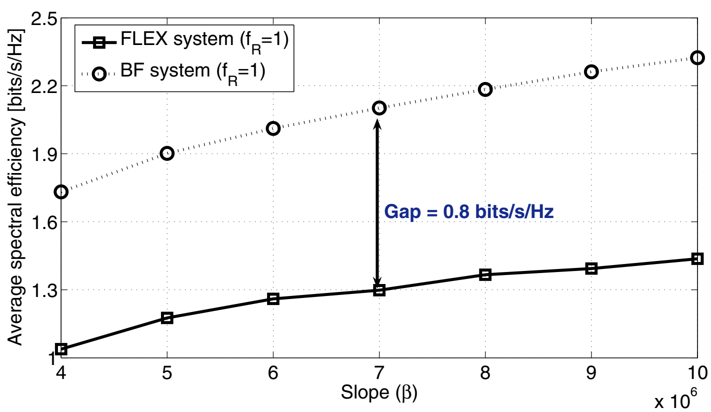

Fig. 4. Average spectral efficiency vs. slope (β) ($B_c = 62.5$MHz, f_R=1)

The performance of the average spectral efficiency as a function of the bandwidth granularity (B_c) of the FLEX system is shown in Fig. 2. The results show that the average spectral efficiency decreases as the B_c increases. The reason is that the greater the carrier bandwidth, the more the unused but offered traffic is, which implies greater difference between the total offered traffic and the total useful offered traffic. The results also indicate that, under a given bandwidth granularity, the lower the frequency reuse factor, the smaller the average spectral efficiency. Because we define the average spectral efficiency as the ratio of total useful allocated traffic to the aggregated bandwidth. Thus, although more aggregated bandwidth is available for the lower frequency reuse factor, the increased bandwidth is not efficiently used since the co-channel interference power is increased as we have indicated in Fig. 1. Conversely, for the case of higher frequency reuse factor, e.g., $f_R = 7$, it achieves the best average spectral efficiency because the bandwidth is used more efficient than the other cases.

We compare the average spectral efficiency of FLEX and BF systems in Fig. 3 by using the set of coding and modulation combinations in DVB-S2. This result is the expected one from the high average spectral efficiency that is obtained with the case of BF and high saturation power, along with higher available bandwidth, which allows perfect matching to heavily loaded beams.

Fig. 4 gives the simulation results for the average spectral efficiency with different linear traffic distribution slope. The results show that, for both FLEX and BF systems, the more unbalanced the distribution is, the larger average spectral efficiency can be achieved, because these two type of systems can take advantage of the nonuniformity of distribution by allocating resources more efficiently. This figure also shows that the spectral efficiency performance gap between FLEX and BF SATCOM system is about 0.8bits/s/Hz under the assumptions, i.e. B_c = 62.5MHz, f_R=1 and P_{sat} = 120Watt.

6 Conclusions

In this paper we have derived an analytical solution of the resource allocation for an interference-limited SATCOM system. We introduce two options for a multibeam payload: FLEX with resource allocation flexibility in the frequency domain, and BF conventional system. Two optimization problems are addressed with given individual constraints per-beam, P1: optimization of the spectral mask vector design and power allocation for FLEX system, and P2: beamforming weight vectors design and power allocation for BF system. The performance is evaluated based on the practical implementation, e.g. DVB-S2. The numerical results show that BF system with full frequency reuse ($f_R = 1$) provides the best performance, e.g. approx. 15% $\sim$ 56% improvement can be achieved by BF SATCOM system comparing with FLXE one with different f_R. The disadvantage of BF system is that the energy of the transmitted signal is increased, i.e. the precoding loss. But we have shown that this loss is negligible, especially for larger constellations modulation. For the FLEX system, the bandwidth can be utilized more efficiently with larger frequency reuse factor and smaller bandwidth granularity. We also evaluate the performance of FLEX and BF systems for the asymmetrical traffic distribution. For both systems, they can adapt well to the nonuniform traffic distribution, and BF system outperforms FLEX system about 0.8bits/s/Hz in terms of average spectral efficiency under the assumptions of B_c = 62.5MHz, f_R=1 and P_{sat} = 120Watt.

Acknowledgment. The authors gratefully acknowledge valuable discussions on the topic with the DLR and MDA. This work has been partly funded by the European Space Agency (ESA) under the project of "Study of Beam Hopping Techniques in Multi-Beam Satellite Systems".

References

1. Lei, J., Vázquez-Castro, M.A.: Frequency and Time-Space Duality Study for Multibeam Satellite Communications. In: Proc. IEEE Int. Conf. on Commun., Cape Town, South Africa, pp. 1–5 (May 2010)

2. Alberti, X., Cebrian, J.M., Del Bianco, A., Katona, Z., Lei, J., Vázquez-Castro, M.A., Zanus, A., Gilbert, L., Alagha, N.: System Capacity Optimization in Time and Frequency for Multibeam Multi-media Satellite Systems. In: 5th Advanced Satellite Multimedia Systems Conf., Cagliari, Italy (September 2010)
3. Schubert, M., Boche, H.: Solution of the Multiuser Downlink Beamforming Problem with Individual SINR Constraints. IEEE Trans. Veh. Technol. 53(1), 18–28 (2004)
4. Neely, M.J., Modiano, E., Rohrs, C.E.: Power Allocation and Routing in Multibeam Satellites with Time-Varying Channels. IEEE/ACM Trans. Netw. 11(1), 138–152 (2003)
5. Choi, J.P., Chan, V.W.S.: Optimum Power and Beam Allocation Based on Traffic Demands and Channel Conditions over Satellite Downlinks. IEEE Trans. on Wireless Commun. 4(6), 2983–2993 (2005)
6. Barcelo, J.E., Vázquez-Castro, M.A., Lei, J., Hjøungnes, A.: Distributed Power and Carrier Allocation in Multibeam Satellite Uplink with Individual SINR Constraints. In: IEEE Globecom, Honolulu, USA, pp. 1–6 (November–December 2009)
7. Zorba, N., Realp, M., Pérez-Neira, A.I.: An Improved Partial CSIT Random Beamforming for Multibeam Satellite Systems. In: 10th Int. Workshop on Signal Process. for Space Commun., Rhodes Island, Greece (October 6–8, 2008)
8. Yu, W., Cioffi, J.: Sum Capacity of Gaussian Vector Broadcast Channels. IEEE Trans. Inform. 52(2), 754–759 (2006)
9. Jindal, N., Jafar, S., Vishwanath, S., Goldsmith, A.: Sum Power Iterative Water-Filling for Multi-Antenna Gaussian Broadcast Channels. IEEE Trans. Inform. 51(4), 1570–1580 (2005)
10. Windpassinger, C., Fischer, R.F.H., Vencel, T., Huber, J.B.: Precoding in Multiantenna and Multiuser Communications. IEEE Trans. on Wireless Commun. 3(4), 1305–1316 (2004)
11. Vázquez-Castro, M.A., Seco, G.: Cross-Layer Packet Scheduler Design of a Multibeam Broadband Satellite System with Adaptive Coding and Modulation. IEEE Wireless Trans. 6(1), 248–258 (2007)
12. Lei, J., Vázquez-Castro, M.A.: Joint Power and Carrier Allocation for the Multibeam Satellite Downlink with Individual SINR Constraints. In: IEEE Int. Conf. on Commun., Cape Town, South Africa, pp. 1–5 (May 2010)
13. Letzepis, N., Grant, A.J.: Capacity of the Multiple Spot Beam Satellite Channel with Rician Fading. IEEE Trans. Inform. 54(11), 5210–5222 (2008)
14. Weidong, Y., Guanghan, X.: Optimal Downlink Power Assignment for Smart Antenna Systems. In: IEEE Int. Conf. on Acoustics, Speech and Signal Process., Seattle, USA, vol. 6, pp. 3337–3340 (May 1998)
15. ETSI EN 302 307 v1.1.1, Digital Video Broadcasting (DVB): Second generation framing structure, channel coding and modulation system for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications
16. Shariff, M., Hassibi, B.: A Comparison of Time-Sharing, DPC, and Beamforming for MIMO Broadcast Channels with Many Users. IEEE Trans. on Commun. 55(1), 11–15 (2007)
17. Taesang, Y., Goldsmith, A.: On the Optimality of Multiantenna Broadcast Scheduling Using Zero-Forcing Beamforming. IEEE Selected Areas in Comm. 24(3), 528–541 (2006)