Joint Precoding with Flexible Power Constraints in Multibeam Satellite Systems

Symeon Chatzinotas∗, Gan Zheng∗, Björn Ottersten†
∗SnT - securityandtrust.lu, University of Luxembourg,
Email: {Symeon.Chatzinotas, Gan.Zheng, Bjorn.Ottersten}@uni.lu
†Royal Institute of Technology (KTH), Sweden, Email: bjorn.ottersten@ee.kth.se

Abstract—In conventional multibeam satellite systems, frequency and polarization orthogonalization have been traditionally employed for mitigating interbeam interference. However, the paradigm of multibeam joint precoding allows for full frequency reuse while assisting beam-edge users. In this paper, the performance of linear beamforming is investigated in terms of meeting traffic demands. More importantly, generic linear constraints are considered over the transmit covariance matrix in order to model the power pooling effect which can be implemented through flexible traveling wave tube amplifiers (TWTA) or multiport amplifiers. The performance of this scheme is compared against conventional spotbeam systems based on the rate-balancing objective. In this context, it is shown that significantly higher spectral efficiency can be achieved through beamforming, while flexible power constraint offers better rate-balancing.

I. INTRODUCTION

Spotbeam satellite systems have been inspired by the success of the cellular paradigm, which allows carefully planned spatial frequency reuse while keeping intercell interference within acceptable limits. In addition, the demand for interactive data services (e.g. internet, video on demand etc) on top of broadcasting has supported the implementation of spotbeam systems, which allow for finer partitioning of the coverage area and independent stream transmission within each beam.

In this direction, a number of beams instead of a single global beam can be employed in order to cover the same coverage area. Currently, tens or hundreds of beams are possible with a frequency reuse factor of three or four. However, due to the nature of radio signals, the beam patterns partially overlap on the earth surface creating interbeam interference. The beam patterns and the corresponding allocated power have to be carefully planned to ensure that interbeam interference stays within acceptable limits, which are determined by the Carrier to Interference ratio (C/I) of the beam-edge users.

A similar effect has been limiting the performance of terrestrial cellular networks for decades, but has been alleviated based on the paradigm of multicell joint processing. According to this paradigm, user signals in the downlink channel are jointly precoded before being transmitted by neighboring BS antennas in order to mitigate inter-cell interference. One of the practical obstacles in its implementation is the existence of a backhaul network which enables this form of cooperation amongst neighboring BSs.

In this context, a similar approach (multibeam joint processing) could be applied in spotbeam satellite systems (Fig. 1). The main advantage is that the signals for all beams are transmitted from the Gateway Station (GS) through the satellite to the users (Forward Link-FL) and backwards (Return Link-RL). As a result, joint processing can take place at the GS and there is no need for expensive backhauling (assuming single GS).

In the remainder of this paper, an overview of related work is presented in section II. In section III, the considered system model is presented and the employed channel model is described. In section IV, the rate balancing objective for beamforming over the MISO broadcast channel with flexible power constrains is studied. In section V, the downlink performance of beamforming is compared to conventional spotbeam systems through numerical simulations and section VI concludes the paper.

A. Notation

Throughout the formulations of this paper, $E[\cdot]$ denotes the expectation, $(\cdot)^\dagger$ denotes the conjugate transpose matrix, $(\cdot)^T$ denotes the transpose matrix and $\odot$ denotes the Hadamard product.

II. PRELIMINARIES & RELATED WORK

This section provides some preliminaries on the available joint precoding techniques, as well as an overview of related work in the satellite literature.
A. Precoding Techniques

In the MISO Broadcast Channel (BC) literature, a number of linear and non-linear techniques have been proposed, such as Dirty Paper Coding (DPC), Tomlinson-Harasima Precoding (THP), Zero Forcing (ZF), Regularized ZF (R-ZF) and Opportunistic Beamforming (OB). DPC is a non-linear technique based on known interference precancellation which has been shown to achieve the MIMO BC capacity [1]. THP is a more practical implementation of DPC based on modulo operations over the constellation symbols [2]. ZF is one of the linear techniques based on prefiltering the transmit signal vector with the channel pseudoinverse [3]. R-ZF extends ZF by taking into account the noise variance in order to improve performance in the low Signal to Noise (SNR) regime [4]. OB is another linear technique, where each user selects amongst predefined random beamformers (codebook) based on his channel state [5].

B. Satellite Communications

In the SatCom literature, the majority of work focuses on the conventional scenario where polarization or frequency orthogonalization is employed to mitigate inter-beam interference. For example, authors in [6] optimize the power and beam allocation in order to meet traffic demands and adapt to channel conditions. Lately, multibeam joint processing scenarios have been studied in various settings [7]–[17]. More specifically, forward link cases have been investigated in [8], [13], [15]–[17], while reverse link cases in [9]–[11]. In all forward link studies, fixed satellite services were considered since reliable channel state feedback can only be acquired for slow-fading channels due to the long propagation delays. In this context, various characteristics of the multibeam satellite channel were taken into account such as beam gain [7], [15], [16], rain fading [17], correlated shadowing areas [15] and interference matrix [16]. In terms of precoding techniques, Tomlinson-Harasima Precoding (THP) was studied in [7] and [16], while linear precoding such as ZF and R-ZF were evaluated in [7], [17]. Finally, authors in [15] have considered an opportunistic beamforming technique based on a codebook of orthonormal precoders and low-rate feedback.

In this paper, the objective is to evaluate the performance gain of multiecell joint precoding in meeting traffic demands. In this direction, the performance of linear beamforming is compared with a conventional spotbeam system with fractional frequency reuse. In addition, generic linear constraints are considered over the transmit covariance matrix in order to model the power pooling effect which can be implemented through flexible TWTA and multiport amplifiers.

III. System Model

Let us now consider a satellite service for transmitting independent multimedia (e.g., video on demand, VOD) or data (e.g., internet) streams to fixed Satellite Terminals (STs) over Europe. The service area is covered by a single GEO bent-pipe transparent satellite equipped with tens of spotbeams following a fixed pattern. The focus is on a single GS which manages a cluster of $K = 7$ adjacent beams. It should be noted that the uplink of the feeder link is assumed ideal and out-of-cluster interference is not considered. By employing a TDMA scheduling scheme, a single user per beam is served for each slot. Since the design of conventional satellite systems is based on beam-edge users, we consider a worst case scenario in Fig. 2, where most users are positioned in the intersection of three adjacent beams. Detailed parameter values of the satellite scenario are defined in table I.

A. Satellite Channel Model

The considered satellite channel is affected by free space loss, beam gain pattern and shadowing, as described in the following paragraphs. In addition, the channel is assumed to be narrowband. For wideband channels, multicarrier techniques such as OFDM can be employed to create flat faded channels.

1) Free Space Loss (FSL): Due to the earth curvature and the wide satellite coverage, the free space loss in each spotbeam will not be identical. In order to model this effect,
the FSL coefficient of the $j$th spotbeam can be written as [18]:

$$b_{\text{max}}(j) = \left( \frac{\lambda}{4\pi} \right)^2 \frac{1}{d_0^2 + d(j)^2},$$  

(1)

where $d(j)$ denotes the distance (in thousands of km) of the $j$th beam center from center of the central beam and $d_0 \approx 35,786$.

2) **Beam gain:** The link gain matrix defines the average SNR of the each user and it mainly depends on two factors: the satellite antenna beam pattern and the user position. Let us now define the user position based on the angle $\theta$ between the beam center and the receiver location with respect to the satellite. In this context, the beam gain is determined by [7]:

$$b(\theta, j) = b_{\text{max}}(j) \left( \frac{J_1(u)}{2u} + 36 \frac{J_3(u)}{u^3} \right)^2$$  

(2)

where $u = 2.07123 \sin \theta / \sin \theta_{\text{MB}}$ and $J_1$ is the first-kind Bessel function of order $1$. The coefficient $b_{\text{max}}(j)$ represents the gain at the $j$th beam centre when FSL is taken into account as given by (1).

3) **Rain Fading:** The main impairment in broadband fixed satellite communication is rain fading, where the received power in dBS can be modelled as a lognormal variable [19]:

$$\log(\xi_{\text{DB}}) \sim \mathcal{N}(\mu, \sigma),$$  

(3)

while the complex channel can be written as:

$$h = \xi^{\frac{1}{2}} e^{-j\phi},$$  

(4)

where $\xi$ is the signal power in linear scale and $\phi$ denotes a uniformly distributed phase. Correlated Areas (CAs) [20] are defined as areas on the earth surface where users undergo correlated fading due to rain clouds. The characteristics of a CA largely depend on the size of the rain front and the user distribution. In terms of channel modelling, the user terminals belonging to a single CA will appear highly correlated, while user terminals from different CAs completely uncorrelated. In the context of this investigation, each spotbeam is assumed to be part of a different CA and therefore rain fading across beams appears uncorrelated.

4) **Multiuser Channel Model:** By combining the aforementioned impairments, the received signal at the $k$th user can be expressed as:

$$y_k = \left( b_{\text{MB}}^k \otimes \hat{h}_k \right) x + z_k,$$  

(5)

where $z_k$ denotes Additive White Gaussian Noise (AWGN) with unit normalized variance and $x$ denotes the $K \times 1$ transmitted symbol vector. The $1 \times K$ vector $b_k$ represents the combined effect of FSL and beam gain. The vector $\hat{h}_k$ represents the effect of slow fading due to rain, while the overall channel at the $k$th user is defined as $h_k = \xi_k^{\frac{1}{2}} \otimes \hat{h}_k$. Each user is assumed to experience identical rain fading $\xi_k$ with respect to all beams but with different phase.

5) **Flexible Power Constraints:** Advanced satellite power amplifier concepts such as flexible TWTAs, Multi Port Amplifiers (MPAs) and Phase Combined TWTs can be employed at the satellite to alleviate the individual power constraints imposed by the independent RF chains of the beams. With this in mind, generic linear power constrains are considered in the next section in order to encompass different levels of flexibility.

IV. RATE BALANCING WITH FLEXIBLE POWER CONSTRAINTS

Suppose the data intended for user $k$ is $s_k$ with $\mathbb{E}[|s_k|^2] = 1$. Before transmission, it is weighted by the $K \times 1$ beamforming vector $t_k$ and therefore the combined transmit signal for all users is

$$x = \sum_{k=1}^{K} t_k s_k.$$  

(6)

In the following subsections, we first consider the generic power constraints, then we formulate and solve the rate balancing problem.

A. **Generic Power Constraints**

We assume that the $l-$th general power constraint can be expressed as:

$$\sum_{k=1}^{K} t_k^\dagger Q_l t_k \leq q_l, \forall l$$  

(7)

which include many known considerations as special cases. Examples include but are not limited to (we omit the constraint index $l$ for simplicity):

- sum power constraint over all beams: $Q = I$;
- per-beam (e.g., beam $n$) power constraint: $Q_n$ is a zero matrix except its $n$-th diagonal element being 1;
- $N$ beams in the set $Q = \{k_1, \ldots, k_N\}$ have power sharing constraint: $Q$ is a zero matrix except its diagonal elements with indices in $Q$ being 1.

B. **Rate Balancing**

The received Signal to Interference and Noise Ratio (SINR) for the $k$th user is:

$$\Gamma_k = \frac{|t_k^\dagger h_k|^2}{\sum_{j \neq k} |t_j^\dagger h_k|^2 + W N_0}$$  

(8)

where $N_0$ is the noise power density and the achievable rate is:

$$C_k = W \log(1 + \Gamma_k).$$  

(9)

Suppose the required traffic demand is $F = [F_1 \ldots F_k]$ and we aim to maximize the ratio of the minimum achieved
to ensure the traffic demand is not exceeded so as to save on-board power. Problem (10) is in general difficult to solve. Notice that at the optimum $\frac{C_k}{F_k} \leq 1$ could be the same for all $k$, then we reformulate it into

$$\max_{t_1, \ldots, t_K, \gamma} \gamma$$

s.t. $C_k \geq \gamma F_k$, $\forall k$,

$$\gamma \leq 1,$$

$$\sum_{k=1}^K t_k^* Q_k t_k \leq q_l, \forall l,$$

and expand it further as follows

$$\max_{t_1, \ldots, t_K, \gamma} \gamma$$

s.t. $\frac{|t_k^* h_k|^2}{\sum_{j \neq k} |t_j^* h_k|^2 + W N_0} \geq 2^{\gamma F_k}$, $\forall k$,

$$\gamma \leq 1,$$

$$\sum_{k=1}^K t_k^* Q_k t_k \leq q_l, \forall l.$$

The first constraint can be made convex by adding $\text{Im}(t_k^* h_k) = 0$ without loss of optimality and (12) becomes

$$\max_{t_1, \ldots, t_K, \gamma} \gamma$$

s.t. $t_k^* h_k \geq 2^{\gamma F_k} \left( \sum_{j \neq k} |t_j^* h_k|^2 + W N_0 \right)$, $\forall k$,

$$\gamma \leq 1,$$

$$\sum_{k=1}^K t_k^* Q_k t_k \leq q_l, \forall l.$$

Now (13) is convex except for the variable $\gamma$. To solve it, we use the bi-section search approach to find the optimum solution. To be specific, at each search iteration for a given $\gamma^t \leq 1$, we need to solve the feasibility check problem below

$$\min_{t_1, \ldots, t_K} \sum_{k=1}^K ||t_k||^2$$

s.t. $t_k^* h_k \geq 2^{\gamma F_k} \left( \sum_{j \neq k} |t_j^* h_k|^2 + W N_0 \right)$, $\forall k$,

$$\sum_{k=1}^K t_k^* Q_k t_k \leq q_l, \forall l.$$
constraints can achieve more than four times as much as that of the conventional scheme. In addition, to allow flexible total transmit power constraint, both individual beam rates and total throughput are further improved. Similar results are shown for random traffic demand in Fig. 4 and even more substantial performance gain in terms of both per beam rates and total throughput is observed for the proposed algorithm.

VI. Conclusions

In this paper, the rate-balancing performance of linear beamforming has been studied in the context of spotbeam satellite systems. The considered channel model combines the effects of beam pattern, free space loss and rain fading, while flexible power constraints are considered. The proposed technique is shown to achieve much higher spectral efficiency compared to conventional fractional frequency reuse schemes, while the effect of flexible power constraint becomes apparent when the traffic demand cannot be satisfied.

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