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 (TWTAS) 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).

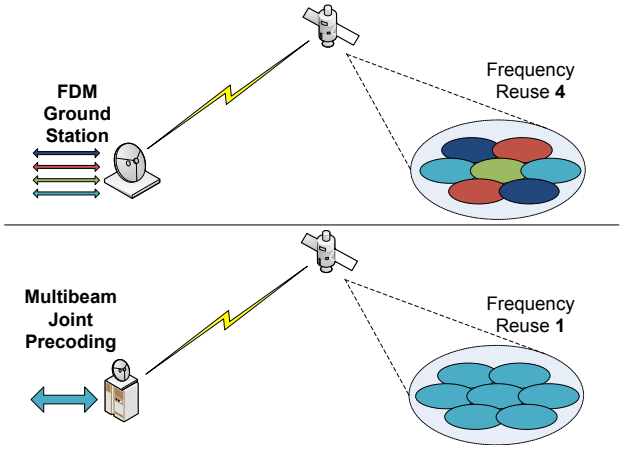


Fig. 1. A spotbeam satellite system with a Ground Station serving a 7-beam cluster. Top: Conventional 4-colour frequency reuse scheme. Bottom: Multibeam Joint Precoding paradigm.

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, $\mathbb{E}[\cdot]$ 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 multicell 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 TWTAS 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 beams. Detailed parameter values of the satellite scenario are defined in table I.

TABLE I
Satellite Scenario Parameters

Parameter	Value
Orbit	GEO
Downlink band	Ka-band
Wavelength	$\lambda = 1.5cm$
Number of Beams	$K = 7$
Beam Diameter	$D = 250Km$
3dB Angle	$\theta_{3\text{dB}} = 0.4^o$
Rain Fading Mean	$\mu = -2.6$
Rain Fading Variance	$\sigma = 1.63$
Polarization	Single
Satellite Noise Temperature	575^oK
Max Antenna Rx Gain	55.5dBi
Max Antenna Tx Gain	52dBi
TWTA RF Power @ Saturation	80W
Downlink Free Space Loss	210dB
User Link Bandwidth	500MHz
Clear sky receiver temperature	207^oK
Traffic Demand, fixed or uniform with mean	[1.2 1.2 1.2 3 3 3 6] Gbps
Frequency Reuse Factor for Conventional Scheme	4

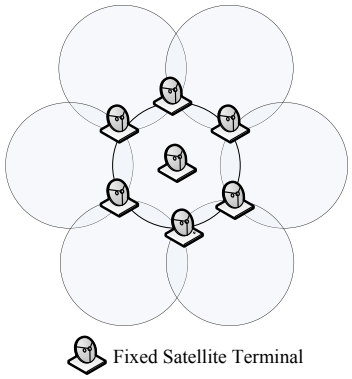


Fig. 2. Spotbeam satellite system scenario with 7 beams and 7 users. One user is positioned in the centre of the coverage area, while the remaining six are positioned in worst-case positions, namely the intersection of three adjacent beams.

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 jth spotbeam can be written as [18]:

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

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

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 θ between the beam center and the receiver location with respect to the satellite. In this context, the beam gain is determined by [7]:

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

where $u = 2.07123 \sin\theta / \sin\theta_{3\text{dB}}$ and J_i is the first-kind Bessel function of order i. The coefficient $b_{\max}(j)$ represents the gain at the jth 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]:

$$\log(\xi_{\text{dB}}) \sim \mathcal{N}(\mu, \sigma), \quad (3)$$

while the complex channel can be written as:

$$h = \xi^{\frac{1}{2}} e^{-\text{j}\phi}, \quad (4)$$

where ξ is the signal power in linear scale and ϕ 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 kth user can be expressed as:

$$y_k = \left(\mathbf{b}_k^{\frac{1}{2}} \odot \tilde{\mathbf{h}}_k\right) \mathbf{x} + z_k, \quad (5)$$

where z_k denotes Additive White Gaussian Noise (AWGN) with unit normalized variance and $\mathbf{x}$ denotes the $K \times 1$ transmitted symbol vector. The $1 \times K$ vector $\mathbf{b}_k$ represents the combined effect of FSL and beam gain. The vector $\tilde{\mathbf{h}}_k$ represents the effect of slow fading due to rain, while the overall channel at the kth user is defined as $\mathbf{h}_k \triangleq \mathbf{b}_k^{\frac{1}{2}} \odot \tilde{\mathbf{h}}_k$. Each user is assumed to experience identical rain fading ξ_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 $\mathbf{t}_k$ and therefore the combined transmit signal for all users is

$$\mathbf{x} = \sum_{k=1}^{K} \mathbf{t}_k s_k. \quad (6)$$

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:

$$\sum_{k=1}^{K} \mathbf{t}_k^\dagger \mathbf{Q}_l \mathbf{t}_k \leq q_l, \forall l \quad (7)$$

which include many known considerations as special cases[1]. Examples include but are not limited to (we omit the constraint index l for simplicity):

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

B. Rate Balancing

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

$$\Gamma_k = \frac{|\mathbf{t}_k^\dagger \mathbf{h}_k|^2}{\sum_{j \neq k} |\mathbf{t}_j^\dagger \mathbf{h}_k|^2 + W N_0} \quad (8)$$

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

$$C_k = W \log(1 + \Gamma_k). \quad (9)$$

Suppose the required traffic demand is $\mathbf{F} = [F_1 \dots F_k]$ and we aim to maximize the ratio of the minimum achieved

[1]Most of known special cases yield a diagonal $\mathbf{Q}$ matrix, but herein no such assumption is made, since it does not affect the derivations.

rate over requested rate among beams by joint multi-beam processing[2], i.e.,

$$\begin{aligned} \max_{\mathbf{t}_1,\cdots,\mathbf{t}_K} \quad & \min_{k=1,\cdots,K} \frac{C_k}{F_k} \\ \text{s.t.} \quad & C_k \le F_k, \\ & \sum_{k=1}^{K} \mathbf{t}_k^\dagger \mathbf{Q}_l \mathbf{t}_k \le q_l, \forall l. \end{aligned} \tag{10}$$

The first constraint is to ensure that 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 $\frac{C_k}{F_k} \le 1$ could be the same for all k, then we reformulate it into

$$\begin{aligned} \max_{\mathbf{t}_1,\cdots,\mathbf{t}_K,\gamma} \quad & \gamma \\ \text{s.t.} \quad & C_k \ge \gamma F_k, \ \forall k, \\ & \gamma \le 1, \\ & \sum_{k=1}^{K} \mathbf{t}_k^\dagger \mathbf{Q}_l \mathbf{t}_k \le q_l, \forall l, \end{aligned} \tag{11}$$

and expand it further as follows

$$\begin{aligned} \max_{\mathbf{t}_1,\cdots,\mathbf{t}_K,\gamma} \quad & \gamma \\ \text{s.t.} \quad & \frac{|\mathbf{t}_k^\dagger \mathbf{h}_k|^2}{\sum_{j\neq k} |\mathbf{t}_j^\dagger \mathbf{h}_k|^2 + WN_0} \ge 2^{\gamma F_k}, \ \forall k, \\ & \gamma \le 1, \\ & \sum_{k=1}^{K} \mathbf{t}_k^\dagger \mathbf{Q}_l \mathbf{t}_k \le q_l, \forall l. \end{aligned} \tag{12}$$

The first constraint can be made convex by adding $\mathrm{Im}(\mathbf{t}_k^\dagger \mathbf{h}_k) = \mathbf{0}$ without loss of optimality and (12) becomes

$$\begin{aligned} \max_{\mathbf{t}_1,\cdots,\mathbf{t}_K,\gamma} \quad & \gamma \\ \text{s.t.} \quad & \mathbf{t}_k^\dagger \mathbf{h}_k \ge \sqrt{2^{\gamma F_k}\left(\sum_{j\neq k} |\mathbf{t}_j^\dagger \mathbf{h}_k|^2 + WN_0\right)}, \ \forall k, \\ & \gamma \le 1, \\ & \sum_{k=1}^{K} \mathbf{t}_k^\dagger \mathbf{Q}_l \mathbf{t}_k \le q_l, \forall l. \end{aligned} \tag{13}$$

Now (13) is convex except for the variable γ. 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 $\gamma^t \le 1$, we need to solve the feasibility check problem[3] below

$$\begin{aligned} \min_{\mathbf{t}_1,\cdots,\mathbf{t}_K} \quad & \sum_{k=1}^{K} \|\mathbf{t}_k\|^2 \\ \text{s.t.} \quad & \mathbf{t}_k^\dagger \mathbf{h}_k \ge \sqrt{2^{\gamma^t F_k}\left(\sum_{j\neq k} |\mathbf{t}_j^\dagger \mathbf{h}_k|^2 + WN_0\right)}, \ \forall k, \\ & \sum_{k=1}^{K} \mathbf{t}_k^\dagger \mathbf{Q}_l \mathbf{t}_k \le q_l, \forall l. \end{aligned} \tag{14}$$

to see whether γ^t is a feasible value.

Although it is not necessary to minimize the total transmit power while checking the feasibility in (14), it saves power when the rate constraints are easily satisfied.

V. Numerical Results

In this section, the rate-balancing performance of multibeam joint precoding is compared with a conventional spotbeam system. For multibeam joint precoding, let us consider a satellite system as described in section III with detailed parameters listed in Table I. The conventional spotbeam system has the same bandwidth W and noise density while it employs a frequency re-use scheme with factor 4 in order to mitigate inter-beam interference. In the simulation, it is labeled as "Conventional Scheme". In the proposed beamforming system, user k could achieve the rate below,

$$C_k = W \log\left(1 + \frac{|\mathbf{t}_k^\dagger \mathbf{h}_k|^2}{\sum_{j\neq k} |\mathbf{t}_j^\dagger \mathbf{h}_k|^2 + WN_0}\right) \tag{15}$$

while for the conventional system, supposing that the power actually used for beam k is p_k, the achievable rate for user k is

$$C_k^b = \frac{W}{4} \log\left(1 + \frac{4p_k |h_{k,k}|^2}{WN_0}\right). \tag{16}$$

As listed in Table I, we assume each satellite RF saturation power is 80 dBW, which is the individual power constraints. We also consider the total power constraints of $7 \times 80 = 560$ dBW. We choose the average achievable rates $\mathbb{E}[C_k]$ and $\mathbb{E}[C_k^b]$ as the performance metric. We consider two kinds of traffic demands. The first one is fixed to be $\mathbf{F} = [1.2\ 1.2\ 1.2\ 3\ 3\ 3\ 6]$ Gbps while the other is uniformly distributed with the above vector being the mean, i.e. $\mathbb{E}[\mathbf{F}] = [1.2\ 1.2\ 1.2\ 3\ 3\ 3\ 6]$.

In Fig. 3, the optimized rate results for each beam are shown when the traffic demand is fixed[4]. First note that all rates are balanced for each scheme and proportional fairness among beams is guaranteed, as expected. As can be seen, substantial rate gain is achieved for each beam by joint beam processing compared with single beam processing. As to total throughput, the proposed multibeam processing with individual power

[2]In the considered optimization problem, the objective is to meet the capacity requirements without exceeding them even if there are available resources. This is why the constraint $C_k \le F_k$ is introduced.

[3]Although this adds to the complexity of the beamformer design, this is not a major issue since the computation takes place on the ground.

[4]In both figures, the x axis enumerates the system users using as index the index of the beam which they are located in, with index one referring to the centre beam in Fig. 2.

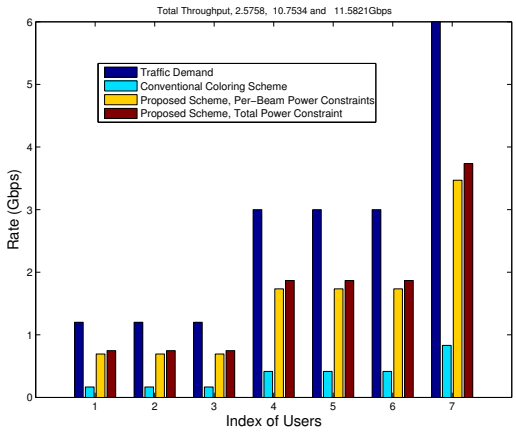


Fig. 3. Spectral efficiency for $K = 7$ beams and fixed traffic demand.

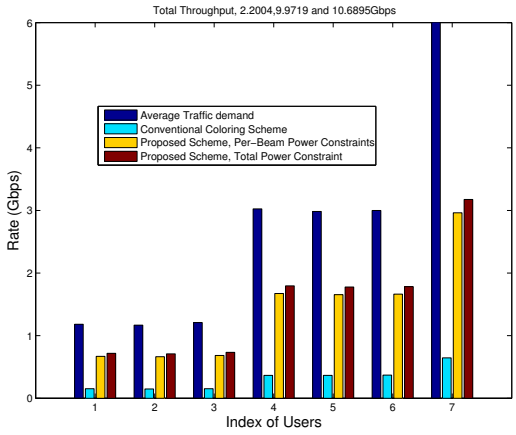


Fig. 4. Spectral efficiency for $K = 7$ beams and random traffic demand.

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.

Acknowledgment

This work was partially supported by the National Research Fund, Luxembourg under the CORE project "CO^{2}SAT: Cooperative and Cognitive Architectures for Satellite Networks".

References

[1] H. Weingarten, Y. Steinberg, and S. Shamai, "The capacity region of the Gaussian multiple-input multiple-output broadcast channel," *IEEE Trans. Inf. Theory*, vol. 52, no. 9, pp. 3936–3964, 2006.

[2] M. Tomlinson, "New automatic equalizer employing modulo arithmetic," *Electron. Lett.*, vol. 7, pp. 138–139, Mar 1971.

[3] T. Yoo and A. Goldsmith, "Optimality of zero-forcing beamforming with multiuser diversity," in *IEEE International Conference on Communications (ICC 2005)*, vol. 1, May 2005, pp. 542–546.

[4] V. Nguyen and J. Evans, "Multiuser transmit beamforming via regularized channel inversion: A large system analysis," in *IEEE Global Telecommunications Conference (GLOBECOM 2008)*, Dec. 2008, pp. 1–4.

[5] I.-M. Kim, Z. Yi, D. Kim, and W. Chung, "Improved opportunistic beamforming in Ricean channels," *IEEE Trans. Commun.*, vol. 54, no. 12, pp. 2199 –2211, 2006.

[6] J. Choi and V. Chan, "Optimum power and beam allocation based on traffic demands and channel conditions over satellite downlinks," *IEEE Trans. Wireless Commun.*, vol. 4, no. 6, pp. 2983 – 2993, 2005.

[7] M. Diaz, N. Courville, C. Mosquera, G. Liva, and G. Corazza, "Nonlinear interference mitigation for broadband multimedia satellite systems," in *International Workshop on Satellite and Space Communications (IWSSC 2007)*, 2007, pp. 61 –65.

[8] G. Gallinaro, G. Caire, M. Debbah, L. Cottatellucci, R. Mueller, and R. Rinaldo, "Perspectives Of Adopting Inteference Mitigation Techniques In The Context Of Broadband Multimedia Satellite Systems."

[9] N. Letzepis and A. Grant, "Capacity of the multiple spot beam satellite channel with Rician fading," *IEEE Trans. Inf. Theory*, vol. 54, no. 11, pp. 5210 –5222, 2008.

[10] M. Moher, "Multiuser decoding for multibeam systems," *IEEE Trans. Veh. Technol.*, vol. 49, no. 4, pp. 1226 –1234, Jul. 2000.

[11] R. M. M. Debbah, G. Gallinaro, R. Rinaldo, and A. Vernucci, "Interference mitigation for the reverse-link of interactive satellite networks," in *9th International Workshop on Signal Processing for Space Communications (SPSC 2006)*, Noordwijk, The Netherlands, 2006.

[12] J. Millerioux, M. Boucheret, C. Bazile, and A. Ducasse, "Iterative interference cancellation and channel estimation in multibeam satellite systems," *International Journal of Satellite Communications and Networking*, vol. 25, no. 3, pp. 263–283, 2007.

[13] D. Zheng and P. Karabinis, "Adaptive beam-forming with interference suppression and multi-user detection in satellite systems with terrestrial reuse of frequencies," in *IEEE 62nd Vehicular Technology Conference (VTC-Fall 2005)*, vol. 4, 2005, pp. 2637 – 2641.

[14] A. Dreher, N. Niklasch, F. Klefenz, and A. Schroth, "Antenna and receiver system with digital beamforming for satellite navigation and communications," *IEEE Trans. Microwave Theory Tech.*, vol. 51, no. 7, pp. 1815 – 1821, 2003.

[15] N. Zorba, M. Realp, and A. Perez-Neira, "An improved partial CSIT random beamforming for multibeam satellite systems," in *10th International Workshop on Signal Processing for Space Communications (SPSC 2008)*, 2008, pp. 1 –8.

[16] M. Poggioni, M. Berioli, and P. Banelli, "BER performance of multibeam satellite systems with Tomlinson-Harashima precoding," in *IEEE International Conference on Communications (ICC 2009)*, 2009, pp. 1 –6.

[17] L. Cottatellucci, M. Debbah, E. Casini, R. Rinaldo, R. Mueller, M. Neri, and G. Gallinaro, "Interference mitigation techniques for broadband satellite system," in *24th AIAA International Communications Satellite Systems Conference (ICSSC 2006)*, San Diego, USA, 2006.

[18] G. Maral and M. Bousquet, *Satellite Communications Systems*, 4th ed. Wiley, 2002.

[19] M. Filip and E. Vilar, "Optimum utilization of the channel capacity of a satellite link in the presence of amplitude scintillations and rain attenuation," *IEEE Trans. Commun.*, vol. 38, no. 11, pp. 1958 –1965, Nov. 1990.

[20] M. Vasquez-Castro and G. Granados, "Cross-layer packet scheduler design of a multibeam broadband satellite system with adaptive coding and modulation," *IEEE Trans. Wireless Commun.*, vol. 6, no. 1, pp. 248–258, 2007.