ROBUST MULTIBEAM SATELLITE SYSTEMS FOR UNDERLAY LICENSED SHARED ACCESS

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ABSTRACT

This paper deals with the problem of multibeam satellite precoding design under spectrum sharing constraints. These regulation restrictions allow the coexistence with other wireless services such as terrestrial mm-wave wireless local loop systems. This work focuses on the case where the satellite operator can use a certain frequency band whenever the signal power strength is limited over the coverage area. The precoding design is optimized considering this restriction by means of formulating a robust optimization. Numerical results show the trade-off between the achievable rates of the satellite segment and the regulation violation outage.

***Index Terms*—** Multibeam satellite systems, precoding, spectrum sharing.

1. INTRODUCTION

Towards obtaining the expected 1000-fold capacity increase in next generation 5G networks, the use of the spectrum shall be reconsidered [1]. In other words, although certain techniques can severely increase the spectral efficiency, whenever very high throughput services are targeted, a more aggressive frequency reuse is mandatory. Under this context, spectrum regulation plays a central role.

As a matter of fact, satellite communications are essential in the development of future 5G systems [2]. Indeed, there are certain services which can only be provided by satellite systems. This is the case of high definition multimedia content delivery and aeronautic wireless connection. Apart from the aforementioned use cases, fixed satellite services are gaining a lot of attention due to their frequency assignment (i.e. Ka band) which might be also employed for cellular backhauling.

Although satellite operators are reticent to share the spectrum with terrestrial ones, it is evident that whenever a peaceful shared used of the spectrum between these two agents is performed, overall system capacity will exponentially increase [3, 4]. This shared use of the spectrum is promoted by public institutions and; precisely, the European Commission is promoting new spectrum licenses coined as licensed shared access (LSA) [5]. These licenses offer a more flexible spectrum regulation by means of allowing more than one incumbent to use a given frequency band under certain conditions to be agreed by all agents.

This paper considers that a satellite operator and a terrestrial mobile network operator agree on sharing certain portion of the Ka band. With this, the spectrum licensing cost can be shared among these two players. This agreement becomes worthy whenever the conceived regulation rules allow an efficient use of spectrum between both users. For this preliminary work, only satellite transmission is considered and the terrestrial transmission will be addressed in the future. Indeed, we consider an underlay network where terrestrial radio links can coexist under the presence a satellite interference. Remarkably, the satellite user terminals shall also limit the interference to the terrestrial ones. However, this is out of the scope of this paper.

Assuming that the satellite employs full frequency reuse among beams towards increasing the system capacity, precoding is mandatory in order to not only mitigate the multiuser interference but also to restrict the overall signal power strength over the coverage area. As a result, the interference from the satellite to the terrestrial terminals is constrained and it can be controlled whenever a change in the regulation is made. This is done by revisiting the precoding design in [6] and providing a robust solution to the problem.

The main contributions of the paper are:

- To propose a suboptimal but robust precoding design which controls the signal power strength in the satellite coverage area and optimizes the achievable rates.
- To analyse the trade-off between system capacity and regulation violations by means of extensive numerical simulations.

The rest of the paper is organized as follows. Section II describes the multibeam satellite transmission model. Section III presents the precoding design under receive power constraints by means of investigating the robust optimization. Section IV shows the simulation results in terms of throughput and spectrum regulation outage. Section V concludes the

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paper and provides future research directions.

2. SYSTEM MODEL

Let us consider a multibeam satellite system where the satellite is equipped with an array fed reflector antenna with a total number of feeds equal to N. These feed signals are combined and they generate a beam radiation pattern forming a total number of K beams. Depending on the overall payload and feeder link (i.e. the link between the satellite and ground station) requirements, the system designer elects a single feed per beam configuration ($K = N$) or multiple feed per beam ($K < N$).

The multibeam radiation pattern supports data multiplexing among beams leading to an efficient communication since rate allocation can be performed separately for each beam. Unfortunately, adjacent beams create multiuser interference which becomes the major bottleneck of the communication. In order to solve this problem, the system designer can allocate different frequency bands to each beam leading to a large reduction of the interference at expenses of reducing the available bandwidth. In case the system designer targets larger achievable throughputs, frequency reuse among beams is compulsory so as interference mitigation techniques either at the user terminals (multiuser detection) or at the transmit side (precoding). This paper focuses on the latter option.

The receive signal can be modelled as

$$\mathbf{y} = \mathbf{H}^H \mathbf{x} + \mathbf{n}, \tag{1}$$

being $\mathbf{y} \in \mathbb{C}^{K\times 1}$ the vector containing the received signals at each user terminal. Vector $\mathbf{n} \in \mathbb{C}^{K\times 1}$ contains the noise terms of each user terminal. The entries of this vector are assumed to be Gaussian distributed with zero mean, variance equal to σ^2 and uncorrelated with both the desired signal and the rest of noise entries (i.e. $E\left[\mathbf{n}\mathbf{n}^H\right] = \sigma^2 \mathbf{I}_K$). The channel matrix can be described as follows:

$$\mathbf{H} = \mathbf{A}\mathbf{G}, \tag{2}$$

where $\mathbf{A} \in \mathbb{R}^{K\times K}$ is diagonal matrix whose diagonal entries are the atmospheric fading terms. Matrix $\mathbf{G} \in \mathbb{R}^{K\times K}$ takes into account the rest of gain and loss factors. Its (k, n)-th entry can be described as follows

$$(G)_{k,n} = \frac{G_R a_{kn}}{4\pi \frac{d_k}{\lambda} \sqrt{K_B T_R B_W}} \tag{3}$$

with d_k the distance between the k-th user terminal and the satellite. λ is the carrier wavelength, K_B is the Boltzmann constant, B_W is the carrier bandwidth, G_R^2 the user terminal receive antenna gain, and T_R the receiver noise temperature. The term a_{kn} refers to the gain from the n-th feed to the k-th user. It is important to mention that the $\mathbf{G}$ matrix has been normalized to the receiver noise term.

In order to minimize the multiuser interference generated by the full frequency reuse and the on-board beamforming generation, precoding is considered. Under this context, the transmitted symbol vector will be (4), where $\mathbf{s} \in \mathbb{C}^{K\times 1}$ is a vector that contains the transmitted symbols which we assume uncorrelated and unit norm $\left(E\left[\mathbf{s}\mathbf{s}^H\right] = \mathbf{I}_K\right)$, matrix $\mathbf{W} \in \mathbb{C}^{K\times K}$ is the linear precoding matrix to be designed.

$$\mathbf{x} = \mathbf{W}\mathbf{s}. \tag{4}$$

So far, several techniques have been proliferating towards obtaining an efficient $\mathbf{W}$ [7]. In contrast to those works, this paper considers the optimization of $\mathbf{W}$ jointly with the restriction of the radiated power in the overall coverage area. This is presented in the next section considering that the maximum allowable power is ρ. Note that, this maximum interference power level to the terrestrial systems becomes crucial in low elevation satellite systems where the direction of arrival for the satellite and terrestrial signal can be close enough preclude reliable communications [4]. This is specially true in satellite user terminals located at high altitude.

3. MULTIBEAM SATELLITE PRECODING WITH SPECTRUM SHARING CONSTRAINTS

This sections tackles the main contribution of the paper. First, the previous works are identified and; posteriorly, the proposed technique is presented.

3.1. Preliminaries

In a preliminary work [6], the authors formulated the overall radiation power restriction as received power restriction. This is a low complexity approach since restricting the radiated power in the coverage area is an unaffordable optimization problem. Under this context, assuming that the users among the beams are uniformly distributed, the radiated power can be restricted on average by only considering the receive power constraints of the served users. The optimization problem is formulated as follows

$$\begin{aligned} &\underset{\mathbf{W}}{\text{maximize}} \quad \sum_{k=1}^{K} R_k \\ &\text{subject to} \\ &\sum_{j=1}^{K} |\mathbf{h}_k^H \mathbf{w}_j|^2 \leq \rho \quad k = 1, \ldots, K \end{aligned} \tag{5}$$

where R_k denotes the achievable rate of user k, vector $\mathbf{h}_k$ is the channel experienced by user k ($\mathbf{h}_k$ is the column k of the global channel matrix $\mathbf{H}$), vector $\mathbf{w}_j$ is the beamformer for user j (it is the column j of the precoder matrix $\mathbf{W}$). Remarkably, the receive power is not only composed by desired signal power but by interference.

The achievable rate is limited by the interference from the rest of beamformers included in the precoder.

$$R_k = \log_2\left(1 + \frac{|\mathbf{h}_k^H \mathbf{w}_k|^2}{\sum_{j\neq k}^{K} |\mathbf{h}_k^H \mathbf{w}_j|^2 + \sigma^2}\right), \tag{6}$$

where σ^2 denotes the noise power value at the receiver assumed to be the same for all of them.

This first approach does not consider the tentative impact of restricting the transmit power at satellite. With this, the optimal precoding design becomes the zero forcing precoder (ZF)

$$\mathbf{W}_{\text{ZF}} = \beta_{\text{ZF}} \mathbf{H} \left(\mathbf{H}^H \mathbf{H}\right)^{-1}, \tag{7}$$

where β_{ZF} becomes

$$\beta_{\text{ZF}} = \sqrt{\rho}. \tag{8}$$

Evidently, as long as the satellite has sufficient transmit power, the receive power constraints limit the communication link performance and it is mandatory that all power is devoted to the desired signal power strength rather than the interference. Under these assumptions, the maximum achievable rate for any user is

$$R_k = \log_2\left(1 + \frac{\rho}{\sigma^2}\right). \tag{9}$$

In the following, two improvements are provided to this preliminary work. First, considering a zero forcing precoding strategy, a power allocation scheme is presented in order to optimize the sum-rate. Second, the regulatory restrictions are incorporated as a robust optimization, assuming that the receivers locations are unknown.

3.2. Power Allocation under Spectrum Sharing Constraints

Incorporating a per beam power transmit constraint in (5) makes the problem non-convex and impossible to be solved efficiently. This paper takes the suboptimal approach identified in [8] and assumes that ZF precoding is employed. Under this context, the transmit power can be optimized as follows

$$\begin{aligned} &\underset{\mathbf{p}}{\text{maximize}} \quad \sum_{k=1}^{K} R_k \\ &\text{subject to} \\ &0 \leq \left[\mathbf{W}_{ZF}\mathbf{W}_{ZF}^H \text{diag}(\mathbf{p})\right]_{k,k} \leq P \quad k = 1, \ldots, K \\ &p_k \leq \rho \quad k = 1, \ldots, K. \end{aligned} \tag{10}$$

Where $\mathbf{p}$ denotes the per beam transmit power and P the maximum available transmit power per beam. The receive power restrictions are transformed into the last inequality due to the ZF precoding (with $\beta_{ZF} = 1$). The user rates become

$$R_{k,ZF} = \log_2\left(1 + \frac{p_k}{\sigma^2}\right), \tag{11}$$

leading to a convex optimization problem in terms of $\mathbf{p}$. Thus, (10) result in a simple yet efficient precoding design whenever only receive power constraints are considered. Simulations results of this method will be provided in the simulation section.

However, even though the receive power constraint of the served users is considered, there might be cases where at some regions of the multibeam coverage area, the signal power strength becomes larger than ρ leading to a violation of spectrum regulation. Note that, in case the overall coverage power restrictions are imposed, the problem will become infeasible since the number of satellite user terminals is extremely large.

In order to take into account all possible user locations, an uncertainty is incorporated to the channel matrix model. With this, the channel matrix can be decomposed by

$$\mathbf{H}_u = \bar{\mathbf{H}} + \Delta, \tag{12}$$

where $\bar{\mathbf{H}}$ is the nominal channel value and Δ is a matrix which incorporates the uncertainty. As a result, considering that the precoder is obtained given a set of users, problem (10) can be robustly optimized by the worst case solution as follows

$$\begin{aligned} &\underset{\mathbf{p}}{\text{maximize}} \quad \underset{\Delta}{\text{minimize}} \quad \sum_{k=1}^{K} R_k \\ &\text{subject to} \\ &0 \leq \left[\mathbf{W}_{ZF}\mathbf{W}_{ZF}^H \text{diag}(\mathbf{p})\right]_{k,k} \leq P \quad k = 1, \ldots, K \\ &\sum_{l=1}^{K} \left[\mathbf{W}_{ZF}\mathbf{H}_u\mathbf{H}_u^H\mathbf{W}_{ZF}^H \text{diag}(\mathbf{p})\right]_{l,k} \leq \rho \quad k = 1, \ldots, K \\ &\Delta \in \mathcal{U}, \end{aligned} \tag{13}$$

where $\mathcal{U}$ defines the uncertainty set which can be presented in several ways [9]. For this case, the following uncertainty case is considered

$$\mathcal{U} : \Delta \in \mathbb{R}^{K \times K} \quad \text{so that} \quad |\lambda_{max}(\Delta)| \leq \alpha. \tag{14}$$

Note that whenever α is increased, larger uncertainty channel values are considered. For the considered scenario, α is a parameter to be set by the system designer and it strongly depends on the scenario. In the simulation section the variation of this parameter is analysed.

The optimization problem in (13) is non-convex problem so that, in order to solve it, a relaxed upper bound optimization is provided in the next theorem.

Theorem 1. Problem (10) is upper bounded by the following optimization problem.

$$
\begin{aligned}
&\underset{\mathbf{p}}{\text{maximize}} \quad \sum_{k=1}^{K} R_k \\
&\text{subject to} \\
&0 \leq \left[\mathbf{W}_{ZF}\mathbf{W}_{ZF}^{H}\text{diag}(\mathbf{p})\right]_{k,k} \leq P \quad k = 1,\ldots,K \\
&\sum_{l=1}^{K} \left[\mathbf{W}_{ZF}\mathbf{A}\mathbf{W}_{ZF}^{H}\text{diag}(\mathbf{p})\right]_{l,k} \leq \rho \quad k = 1,\ldots,K
\end{aligned}
\tag{15}
$$

where

$$\mathbf{A} = \bar{\mathbf{H}}\bar{\mathbf{H}}^{H} + \left(\alpha^2 + 2\lambda_{max}\left(\bar{\mathbf{H}}\right)\alpha\right)\mathbf{I} \tag{16}$$

Proof. The proof consists in relaxing the regulatory constraints considering the uncertainty set. Prior to that, the following relations are essential. Given, two square Hermitian matrices, $\mathbf{U}, \mathbf{V}$, the following relations hold

$$\mathbf{U}\mathbf{U}^{H} \preceq \lambda_{max}\left(\mathbf{U}\mathbf{U}^{H}\right)\mathbf{I}. \tag{17}$$

$$\mathbf{U}\mathbf{V}^{H} + \mathbf{V}\mathbf{U}^{H} \preceq 2\lambda_{max}\left(\mathbf{U}\right)\lambda_{max}\left(\mathbf{V}\right)\mathbf{I}. \tag{18}$$

with this,

$$\mathbf{W}_{ZF}\mathbf{H}_{u}\mathbf{H}_{u}^{H}\mathbf{W}_{ZF}^{H} \preceq \mathbf{W}_{ZF}\mathbf{A}\mathbf{W}_{ZF}^{H}. \tag{19}$$

As a result, the inequalities become less restrictive and; therefore, problem (15) becomes a relaxed version of (13). □

Problem (15) can be solved with iterative methods. Note that α is a parameter to be set by the system designer and it influences the optimal solution of (15). The next section depicts the impact of this value in several numerical simulations.

4. SIMULATION RESULTS

The simulation set up will be based on recent studies carried out by the European Space Agency (ESA) which provide a beam generation process and a certain channel model which embraces the broadband fixed satellite forward transmission. Only 24 out of the 245 beams are considered for the sake simplicity. They correspond to the North-West part of the coverage area.

Two different types of results are presented. First, the achievable rates considering the signal-to-interference-plus-noise ratio (SINR) and the newest satellite communication standard for fixed services DVB-S2X. With this, given a SINR it is possible to obtain a tentative throughput considering [10]. In addition, the spectrum regulation violation is analysed by means of considering additional users positions in the coverage. Precisely, once the precoding design is obtained, 1000 additional user locations are evaluated in terms of the received power level.

Results are obtained with 100 runs. In addition, to solve problem (15) CVX was used, a package for specifying and solving convex programs [11, 12].The overall multibeam system parameters are described in table I.

In figure 1 throughput values are presented whereas figure 2 presents the regulation violation outage (i.e. the percentage of times the transmission violates the regulation). In both cases different regulation values are considered (ρ =3,9,12 dBs with respect to the noise power level) and the maximum available power per beam, P is set to 12 dBWs.

Evidently, the larger ρ, the larger throughput is obtained since larger power can be devoted to the desired signal. However, this value increases the interference generated at the terrestrial terminals so that the agreed ρ value shall be agreed by the two incumbents of the LSA.

In both figures it is observed that α offers a trade-off between throughput and regulation violation probability. Whereas the lower value of α, the larger throughput can be obtained, the regulation violation probability severely increases, leading to unacceptable values. In light of these simulations, regulation shall be relaxed and, in order to reach acceptable satellite throughput levels, regulatory bodies might let a certain interference over the coverage area.

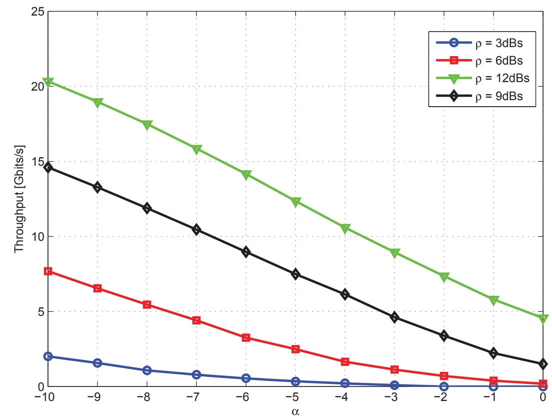

Figure 1. Throughput versus α for different regulation constraints.

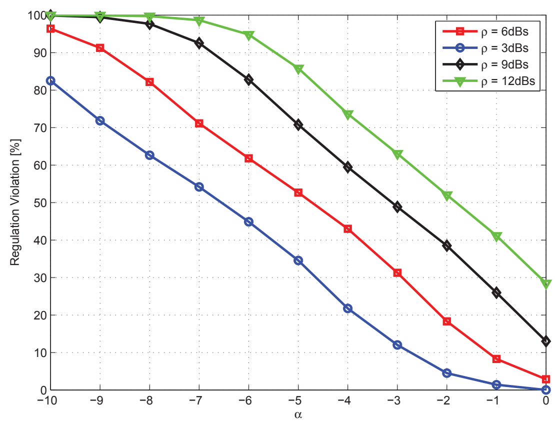

Figure 2. Regulation outage versus α for different regulation constraints.

Finally, it is important to remark that ρ also impacts the

Table 1. USER LINK SIMULATION PARAMETERS

Parameter	Value
Satellite height	35786 km (geostationary)
Satellite longitude, latitude	$10° East, 0°$
Earth radius	6378.137 Km
Feed radiation pattern	Provided byESA
Number of feeds N	245
Beamforming matrix **B**	Provided by ESA
Number of beams	245
User location distribution	Uniformly distributed
Carrier frequency	20 GHz (Ka band)
Total bandwidth	500 MHz
Roll-off factor	0.25
User antenna gain	41.7 dBi
G/T in clear sky	17.68 dB/K

regulation violation outage. Since larger power is allowed, the probability of violating the regulation increases.

5. CONCLUSIONS

This paper proposes a precoding technique that is able not only to mitigate the multiuser interference in multibeam satellite systems, but also to preserve the signal power strength in the coverage area under a certain value. This precoding technique is based on a ZF structure, which results novel not only for multibeam satellite systems, but also for general wireless communications. The design is constructed via worst case robust optimization which offers a precoding technique able to restrict the radiated power yet obtaining efficient achievable rates. Numerical simulations in a multibeam satellite scenario support the conceived design.

REFERENCES

[1] A. Osseiran, F. Boccardi, V. Braun, K. Kusume, P. Marsch, M. Maternia, O. Queseth, M. Schellmann, H. Schotten, H. Taoka, H. Tullberg, M.A. Uusitalo, B. Timus, and M. Fallgren, "Scenarios for 5G mobile and wireless communications: the vision of the METIS project," *Communications Magazine, IEEE*, vol. 52, no. 5, pp. 26–35, May 2014.

[2] B.G. Evans, "The role of satellites in 5G," in *Advanced Satellite Multimedia Systems Conference and the 13th Signal Processing for Space Communications Workshop (ASMS/SPSC), 2014 7th*, Sept 2014, pp. 197–202.

[3] K. Liolis, G. Schlueter, J. Krause, F. Zimmer, L. Combelles, J. Grotz, S. Chatzinotas, B. Evans, A. Guidotti, D. Tarchi, and A. Vanelli-Coralli, "Cognitive radio scenarios for satellite communications: The CoRaSat approach," in *Future Network and Mobile Summit (FutureNetworkSummit), 2013*, July 2013, pp. 1–10.

[4] S.K. Sharma, S. Chatzinotas, and B. Ottersten, "Satellite cognitive communications: Interference modeling and techniques selection," in *Advanced Satellite Multimedia Systems Conference (ASMS) and 12th Signal Processing for Space Communications Workshop (SPSC), 2012 6th*, Sept 2012, pp. 111–118.

[5] P. Ahokangas, M. Matinmikko, S. Yrjola, M. Mustonen, H. Posti, E. Luttinen, and A. Kivimaki, "Business models for mobile network operators in Licensed Shared Access (LSA)," in *Dynamic Spectrum Access Networks (DYSPAN), 2014 IEEE International Symposium on*, April 2014, pp. 263–270.

[6] M. Angel Vazquez, A. Perez-Neira, and M. Angel Lagunas, "Linear Precoding in Multibeam Satellite under Licensed Shared Access," in *Advanced Satellite Multimedia Systems Conference and the 13th Signal Processing for Space Communications Workshop (ASMS/SPSC), 2014 7th*, Sept 2014, pp. 312–317.

[7] Gan Zheng, S. Chatzinotas, and B. Ottersten, "Generic optimization of linear precoding in multibeam satellite systems," *Wireless Communications, IEEE Transactions on*, vol. 11, no. 6, pp. 2308–2320, June 2012.

[8] A. Wiesel, Y.C. Eldar, and S. Shamai, "Zero-Forcing Precoding and Generalized Inverses," *Signal Processing, IEEE Transactions on*, vol. 56, no. 9, pp. 4409–4418, Sept 2008.

[9] Jiaheng Wang, M. Bengtsson, B. Ottersten, and D.P. Palomar, "Robust MIMO Precoding for Several Classes of Channel Uncertainty," *Signal Processing, IEEE Transactions on*, vol. 61, no. 12, pp. 3056–3070, June 2013.

[10] "Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications; Part 2: DVB-S2 Extensions (DVB-S2X)," *ETSI EN 302 307-2*, 2014.

[11] Michael Grant and Stephen Boyd, "CVX: Matlab software for disciplined convex programming, version 2.1," `http://cvxr.com/cvx`, Mar. 2014.

[12] Michael Grant and Stephen Boyd, "Graph implementations for nonsmooth convex programs," in *Recent Advances in Learning and Control*, V. Blondel, S. Boyd, and H. Kimura, Eds., Lecture Notes in Control and Information Sciences, pp. 95–110. Springer-Verlag Limited, 2008, `http://stanford.edu/~boyd/graph_dcp.html`.