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Performance Analysis of Joint Precoding and MUD Techniques in Multibeam Satellite Systems

Miguel Ángel Vázquez*, Màrius Caus*, Ana Pérez-Neira†

Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)

† Dept. of Signal Theory and Communications Universitat Politècnica de Catalunya

Email:{mavazquez, marius.caus, aperez}@cttc.cat

Abstract—This paper considers interference mitigation techniques in the forward link of multibeam satellite systems. In contrast to previous works, either devoted to receiver interference mitigation (e.g. multiuser detection) or transmitter interference mitigation (precoding), this work evaluates the achievable rates of the joint combination of both techniques. On the one hand, precoding cannot properly mitigate all the inter-beam interference while maintaining a sufficiently high signal-to-noise ratio. On the other hand, the receiver cost and complexity exponentially increases with the number of signals to be simultaneously detected. This highlights that the receiver cannot deal with all the interferences so that in general only 2 signals are jointly detected. As a result, the use of precoding within a coverage area jointly with multiuser detection can both benefit from each other and extremely increase the achievable rates of the system. This is numerically evaluated in a close-to-real coverage area considering simultaneous non-unique decoding strategies. The results show the benefits of this joint scheme that eventually can increase the current precoding performance a 100 %.

I. INTRODUCTION

Broadband ubiquitous connectivity is one of the key requirements of the fifth generation (5G) communications [1]. Indeed, providing a large data rate (50 Mbit/s - 1 Gbit/s) everywhere and anytime is a very challenging feature. Under this context and considering the elevated capital expenditures for deploying backhaul networks in low populated areas, the use of the satellite component is becoming attractive as an essential backhaul element for 5G communications [2].

Consequently, both academia and industry are investigating novel approaches to conceive satellite systems able to attend near a Terabit per second forward link capacity in order to serve a huge number of simultaneous users. As a matter of fact, this can only be done if the different beams that provide connectivity to the user terminals share all the available bandwidth. This aggressive frequency reuse leads to a large increase of the inter-beam interference making interference mitigation (IM) techniques mandatory.

Inter-beam interference in the forward link can be mitigated either at the receiver or at the transmitter side. While receiver based (multiuser detection [10]) IM increases the complexity and cost of the user terminal, transmitter based (precoding [3]) IM assumes that the receiver performs single user detection leading to substantial reduction of the receiver complexity.

However, precoding needs to waste communication resources for feeding back the channel state information to the gateway. In addition, even though the transmitter has an accurate version of the channel matrix, the achievable rates are reduced due to multicast transmission of general satellite standards [3] and other impairments [4].

As a general statement, electing either to perform IM at the receiver or at the transmitter requires a deep cost-performance analysis considering the peculiarities of a certain coverage area. However, for the multiuser detection (MUD) case it is evident that the receiver cannot detect more than 2 signals simultaneously due to the exponential increase of the complexity. If more simultaneous two sources are to be detected, additional diversity such as spatial or code ones should be incorporated; thus, allowing an interference cancellation stage previous to the MUD. Consequently, the receiver based IM approach can only get rid of the largest interference signal, leading to not-so-large signal-to-noise-plus-interference ratio (SINR). This limits the frequency reuse among beams and in general it is only considered a frequency reuse factor of 2 [5], [6]; thus, offering a limited achievable system throughput.

Furthermore, precoding suffers from additional limitations. Indeed, one of the main challenges is the feeder link excessive traffic requirements since it has to transmit all the precoded data from the gateway to the satellite payload. Even though this link is placed at the Q/V band where a large bandwidth is available, the use of multiple gateways is required [7]. Since the data is precoded in isolated geographic areas, the precoding technique shall be reconsidered [8]. Based on the results of [8], even though the gateways exchange all the channel state information, the precoding gains are limited compared to the single gateway case.

In light of the above discussion, this paper investigates how to improve the current precoding limitations [3] by means of considering that the receivers are able to perform MUD. In contrast to the case where single user detection is considered, the user terminal can increase its achievable rate by decoding the signals from its neighbouring beams. In this work, a preliminary evaluation in terms of capacity is presented. To simplify the analysis, a unicast satellite transmission (one user served per frame) is considered as well as perfect channel state information and single gateway architecture.

To the best of authors' knowledge, this is the first time this analysis is done. In the terrestrial cellular context, [9] shows how the different decoding strategies can increase the overall throughput. In the satellite context, one of the pioneering

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works that studies the use of receiver-based IM techniques is presented in [10]. Furthermore, the recently coined non-orthogonal multiple access (NOMA) [11] proposes the use of multiuser superposition transmission by resorting to successive interference cancellation (SIC) techniques. Similarly to [9], the aim of this paper is to provide the information theoretical limits that practical schemes such as MUD and SIC can achieve in multibeam satellite systems that leverage on precoding techniques.

In contrast to the aforementioned works, this paper conducts a capacity analysis when different decoding strategies and precoding techniques are applied. The numerical results are performed with a real multibeam radiation pattern, making out validations close to the real performance. As it is expected, the use of IM at the receiver side jointly with current precoding techniques yield to a large increase of the overall throughput. The contributions of the paper are twofold. First, we evaluate different receiver strategies without the use of precoding and; posteriorly, we show how precoding increases the system achievable rate. Moreover, a novel precoding technique is first evaluated for multibeam satellite systems and it is observed that larger throughputs can be obtained compared to the current state of the art.

The rest of the paper is organized as follows. Section II introduces the channel model of multibeam satellite systems. Section III presents a set precoding techniques that offer a good performance complexity trade-off. Section IV shows the different achievable rates when the receiver uses different decoding strategies. Section V presents the numerical results. Section VI concludes.

Notation: We adopt the notation of using lower case boldface for vectors, \mathbf{v} , and upper case boldface for matrices, \mathbf{A} . The transpose operator and the conjugate transpose operator are denoted by the symbols $(\cdot)^T$, $(\cdot)^H$ respectively. \mathbf{I} denotes the identity matrix. \mathbb{C} denotes the complex numbers. $\|\cdot\|$ denotes the Euclidean norm. $|\cdot|$ denotes the absolute value. \circ denotes the Hadamard product.

II. 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.

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 (MUD) or at the transmit side (precoding). This paper focuses on the combination of both.

Considering that all beams radiate in the same frequency band, the receive signal can be modelled as

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

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 1 and uncorrelated with both the desired signal and the rest of noise entries (i.e. $E[\mathbf{n}\mathbf{n}^H] = \mathbf{I}_K$). The channel matrix can be described as follows:

$$\mathbf{H} = \mathbf{A}\mathbf{G}, \quad (2)$$

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

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

for $k = 1, \dots, K$, $n = 1, \dots, N$ 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.

For notation convenience, channel matrix \mathbf{H} can be represented by

$$\mathbf{H} = (\mathbf{h}_1^T, \dots, \mathbf{h}_K^T)^T, \quad (4)$$

where \mathbf{h}_i refers to the channel vector of the i -th user.

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 (5), where $\mathbf{s} \in \mathbb{C}^{K \times 1}$ is a vector that contains the transmitted symbols which we assume uncorrelated and unit norm ($E[\mathbf{s}\mathbf{s}^H] = \mathbf{I}_K$), matrix $\mathbf{W} \in \mathbb{C}^{K \times K}$ is the linear precoding matrix to be designed.

$$\mathbf{x} = \mathbf{W}\mathbf{s}. \quad (5)$$

For notational convenience, matrix \mathbf{W} can be decomposed as follows

$$\mathbf{W} = (\mathbf{w}_1, \dots, \mathbf{w}_K), \quad (6)$$

where \mathbf{w}_i is the precoding vector for the i -th user.

III. PRECODING DESIGNS

Precoding aims at mitigating the inter-beam interference while maintaining the desired signal signal-to-noise ratio (SNR) high. Attending to the performance computational complexity trade-off the adequate precoding schemes are zero-forcing (ZF) and minimum mean square error (MMSE) under a simple scaling factor power allocation [13]. ZF design can be written as

$$\mathbf{W}_{\text{ZF}} = \gamma_{\text{ZF}} (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H, \quad (7)$$

where γ_{ZF} controls the transmit power. In other words, if the payload is equipped with flexible multiport amplifiers where the total power is shared among them, γ_{ZF} is set so that

$$\gamma_{ZF, SPC} = \frac{P_{\max}}{\text{Tr}(\mathbf{H}^H \mathbf{H})}, \quad (8)$$

where the sub-index SPC refers to sum-power constraints and P_{\max} is the maximum transmit power. Alternatively, if the aforementioned power sharing among feeds does not exist and each feed has its unique power budget, the scaling factor becomes

$$\gamma_{ZF, PFC} = \frac{P_{\max}}{N \max(\text{diag}(\mathbf{H}^H \mathbf{H}))}, \quad (9)$$

where the sub-index PFC stands for per-feed power constraints and it has been assumed that all feeds have the same transmit power constraint

While ZF technique nulls the inter-beam interference, MMSE design leaves certain interference with the aim of increasing the SNR of the desired signal. Mathematically, the precoding design takes the form of a regularized ZF scheme

$$\mathbf{W}_{\text{MMSE}} = \gamma_{\text{MMSE}} \left(\mathbf{H}^H \mathbf{H} + \frac{1}{P_{\max}} \mathbf{I} \right)^{-1} \mathbf{H}^H, \quad (10)$$

where γ_{MMSE} shall be obtained as for the ZF case.

In this paper we will evaluate an additional precoding design based on the signal-to-leakage-interference optimization. This scheme was first conceived for the MIMO broadcast channel in [14]. This scheme sequentially obtains the optimal precoding vector the following objective function

$$\frac{P_{\max} |\mathbf{h}_i^H \mathbf{w}_i|^2}{P_{\max} \sum_{l \neq i} |\mathbf{h}_l^H \mathbf{w}_i|^2 + 1}, \quad (11)$$

whose efficient solution can be obtained in closed form such as

$$\mathbf{w}_{i, \text{SLNR}} = \left(\sum_{l \neq i} \mathbf{h}_l \mathbf{h}_l^H + \frac{1}{P_{\max}} \mathbf{I} \right)^{-1} \mathbf{h}_i. \quad (12)$$

The complete channel matrix is obtained computing (12) for $i = 1, \dots, K$ so that

$$\mathbf{W}_{\text{SLNR}} = \gamma_{\text{SLNR}} (\mathbf{w}_{1, \text{SLNR}}, \dots, \mathbf{w}_{K, \text{SLNR}}), \quad (13)$$

where γ_{SLNR} is computed considering either SPC or PFC similarly to the ZF technique.

As mentioned earlier, apart from the ZF technique, the both MMSE and SLNR do not completely null the interference power levels in order to increase the desired user SNR. The next section describes how these remaining interfering signals can be used for increasing the achievable rates by means of different receiver operation modes.

IV. CAPACITY ANALYSIS

This section aims at conducting the capacity analysis in the multibeam satellite context. When the transmitted data is linearly precoded, the signal received by the i th user can be expressed as

$$y_i = \gamma \mathbf{h}_i^H \mathbf{w}_i s_i + \sum_{l \neq i} \gamma \mathbf{h}_i^H \mathbf{w}_l s_l + n_i, \quad 1 \leq i \leq K. \quad (14)$$

Let γ denote the precoding dependent normalization factor that controls the transmitted power. It is worth emphasizing that the co-channel interference term that comes from the j th beam depends on the subspace spanned by $\mathbf{h}_i^H \in \mathbb{C}^{1 \times N}$ and $\mathbf{w}_j \in \mathbb{C}^{N \times 1}$. Building upon (14), the rest of the section is devoted to provide the rate bounds for different decoding strategies. For the ease of exposition, from here onwards we will use $\beta_{il} = |\gamma \mathbf{h}_i^H \mathbf{w}_l|^2$ to characterize the channel quality metrics.

A. Interference as noise

Resorting to this receiver structure, the interfering signals that come from adjacent beams are treated as noise. Under the Gaussian signaling assumption, the maximum achievable rate becomes

$$R_{\text{IAN}, i} = \log_2 \left(1 + \frac{\beta_{ii}}{\sum_{l \neq i} \beta_{il} + 1} \right), \quad (15)$$

for $1 \leq i \leq K$.

B. Simultaneous Non-unique Decoding

The beauty of single user detector schemes stems from the fact that the implementation of the receiver is very simple. That is because the streams can be independently decoded and, thus, the complexity does not grow with the number of beams. However, if the magnitude of the unwanted and the desired signals are similar, the system is limited by the interference and, consequently, the capacity is significantly degraded. To overcome this issue, it is necessary to take into account the structure of the interference instead of treating it as noise. Taking into account that the complexity of the receiver grows exponentially with the number of signals to the detected, it follows that only a restricted set of interfering signals can be jointly decoded together with the signal of interest. In practice, it is sufficient to consider that the interference is dominated by 1 or 2 signals. Bearing this in mind, we propose to leverage on the interference by grouping the beams in pairs, so that the number of disjoint sets is equal to $\frac{K}{2}$. In this case, the system of equations that characterize a given pair of beams is given by

$$\begin{aligned} y_i &= \gamma \mathbf{h}_i^H \mathbf{w}_i s_i + \gamma \mathbf{h}_i^H \mathbf{w}_k s_k + \sum_{l \neq i, k} \gamma \mathbf{h}_i^H \mathbf{w}_l s_l + n_i \\ y_k &= \gamma \mathbf{h}_k^H \mathbf{w}_k s_k + \gamma \mathbf{h}_k^H \mathbf{w}_i s_i + \sum_{l \neq i, k} \gamma \mathbf{h}_k^H \mathbf{w}_l s_l + n_k, \end{aligned} \quad (16)$$

where $i, k \in \{1, \dots, K\}$ and $i \neq k$. By observing (16), it can be deduced that we should select the closest beams with the highest mutual interference. Then, the residual interference is minimized and it is possible to draw an analogy with the interference channel. In this scenario the simultaneous non-unique decoding (SND) is the optimal strategy [9]. The idea is that each receiver should try to jointly decode s_i and s_k , but the

user located in the i th (k th) beam does not care about the errors when decoding s_k (s_i). A practical scheme to approach the theoretical capacity relies on the implementation of iterative receivers that jointly decode the desired and the interference signals [12], [15]. In the last iteration, the information associated with the signal of interest is extracted and the rest is discarded. Concerning the capacity analysis, when the rate assigned to the k th beam is fixed, i.e. $R_{\text{SND}, k}$, the maximum achievable rate of the i th beam for the Gaussian distribution reads

$$R_{\text{SND}, i} = \begin{cases} I_{ik} & R_{\text{SND}, k} \leq \log_2 \left(1 + \frac{\beta_{ik}}{\sum_{l \neq k, i} \beta_{il} + 1} \right) \\ R_{\text{IAN}, i} & R_{\text{SND}, k} > \log_2 \left(1 + \frac{\beta_{ik}}{\sum_{l \neq k, i} \beta_{il} + 1} \right) \end{cases}, \quad (17)$$

where

$$I_{ik} = \min \left\{ \log_2 \left(1 + \frac{\beta_{ii}}{\sum_{l \neq k, i} \beta_{il} + 1} \right), R_{\text{MAC}, ik} - R_{\text{SND}, k} \right\} \quad (18)$$

$$R_{\text{MAC}, ik} = \log_2 \left(1 + \frac{\beta_{ii} + \beta_{ik}}{\sum_{l \neq k, i} \beta_{il} + 1} \right). \quad (19)$$

It is important to remark that if the message conveyed by s_k can be reliably decoded, then joint detection is performed. Otherwise, the interference is treated as noise. Analogously to (17), given the rate of the i th beam, $R_{\text{SND}, i}$ is expressed as follows:

$$R_{\text{SND}, k} = \begin{cases} I_{ki} & R_{\text{SND}, i} \leq \log_2 \left(1 + \frac{\beta_{ki}}{\sum_{l \neq k, i} \beta_{kl} + 1} \right) \\ R_{\text{IAN}, k} & R_{\text{SND}, i} > \log_2 \left(1 + \frac{\beta_{ki}}{\sum_{l \neq k, i} \beta_{kl} + 1} \right) \end{cases}, \quad (20)$$

For the sake of brevity we refrain from writing the expressions that correspond to I_{ki} and $R_{\text{MAC}, ki}$, which can be easily deduced from (18) and (19).

It is particularly noteworthy that the rate region that is jointly achievable in the i th and k th beams is the intersection of (17) and (20). The computation of the jointly achievable rates allows us to select the best rate tuple $(R_{\text{SND}, i}, R_{\text{SND}, k})$. In this regard, Figure (1) shows how the rate region may look like for a given precoder and channel realization [9]. In this case, the highest sum-rate is determined by one of the corner points.

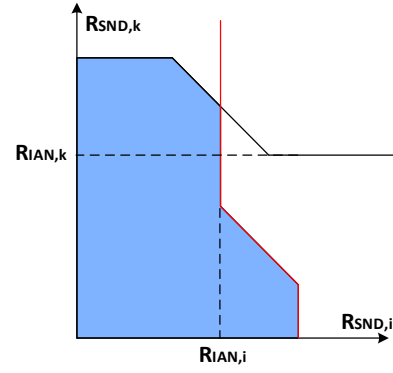


Fig. 1. Joint achievable rates for the i th and the k th beam.

V. NUMERICAL RESULTS

This section presents the numerical results considering the presented precoding techniques and the different receiver strategies. For evaluating the aforementioned techniques, a real coverage area provided by a geostationary satellite is considered. This data has been obtained in a study performed by the European space agency (ESA). We assume that at each time instant all bandwidth is shared by all beams and a single user per beam and frame is served. The simulation parameters are summarized in Table I.

TABLE I. USER LINK SIMULATION PARAMETERS

Parameter	Value
Satellite height	35786 km (geostationary)
Satellite longitude, latitude	$10^\circ East, 0^\circ$
Earth radius	6378.137 Km
Feed radiation pattern	Provided by ESA
Number of feeds N	244
Beamforming matrix \mathbf{B}	Provided by the European space agency.
Number of beams	244
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

Figure 2 presents the empirical cumulative distributed function (CDF) of the data rate whenever the receivers implement SND or IAN with different precoding techniques. For this case the maximum transmit power per beam is set to 55 Watts (PFC). According to Figure 2, SLNR offers larger rates than ZF and MMSE. Moreover, for all precoding techniques apart from ZF, SND strategy receiver mode substantially increases the achievable rate. This increase is even higher for the SLNR case. For the ZF this no-gain behaviour is expected as it completely nulls the inter-beam interference and the user terminal cannot perform any MUD operation.

In order to investigate the behaviour of the conceived techniques versus the transmit power, we include Figure 3. In this figure, it can be observed that both SND does not scale with the transmit power and it is in a saturation regime with a low sum-rate. On the contrary, the precoding based schemes (both with SND and IAN) they present an appreciable positive slope with respect to the transmit power. Again, the SLNR combined with SND is the option that offers the largest rates and; concretely, it increases the SLNR scheme at 100% over all range of transmit power.

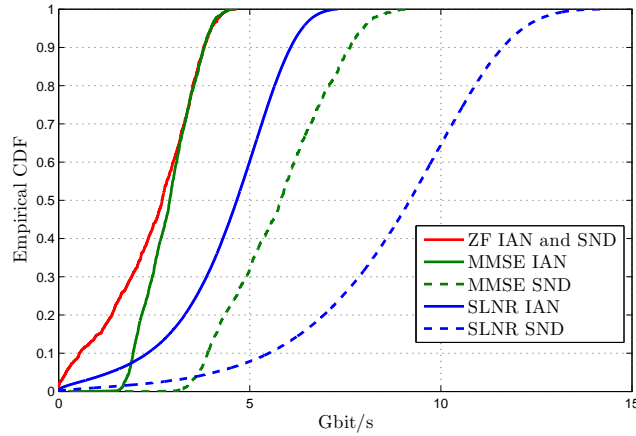


Fig. 2. Empirical CDF of users beam data rate over the coverage area. IAN and SND receiver strategies are considered only with precoding.

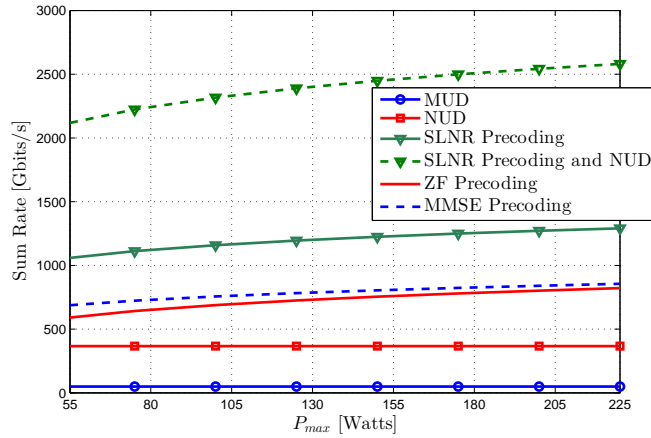


Fig. 3. Sum-rate versus per-feed transmit power.

VI. CONCLUSIONS AND FUTURE WORK

This paper investigates how high performance receivers can increase the data rate of precoding techniques in multibeam satellite systems. SND is able to significantly increase the achievable rates of a simple precoding operation with IAN. In contrast to other studies, we point out that SLNR precoding offers a higher data rates compared to ZF and MMSE both under IAN and SND. Concretely, under a single user receiver operation, SLNR increases a factor of 2 the sum-rate with respect the ZF and MMSE designs. Moreover, an additional 2 factor is obtained if the user terminals perform SND.

Considering the results of this work, it is expected that current precoding limitations are evaluated when considering high performance receivers. Indeed, the precoding designs shall be reconsidered for this operation and; furthermore, the presence of channel state information errors and multicast transmission shall be also taken into account.

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