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 23 %.**

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 scheme 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 [3]) IM increases the complexity and cost of the user terminal, trasmitter based (precoding [4]) 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 [4] and other impairments [5].

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 [6], [7] ; 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 [8]. Since the data is precoded in isolated geographic areas, the precoding technique shall be reconsidered [9]. Based on the results of [9], 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 [4] 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 conducted. In the terrestrial cellular context, [10] shows how the different decoding strategies can increase the overall throughput. In the satellite context, one of the

---

This work has received funding from the Spanish Ministry of Economy and Competitiveness (Ministerio de Economia y Competitividad) under project TEC2014-59255-C3-1-R (ELISA); and from the Catalan Government (2014SGR1567).

pioneering works that studies the use of receiver-based IM techniques is presented in [3]. 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 [10], 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 the paper and draws the conclusion.

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. $\mathbf{I}_N$ denotes the N-dimensional 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. In this work we have focused on the case where $K \geq N$.

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 (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

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

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 1 and uncorrelated with both the desired signal and the rest of noise entries (i.e. $E\left[\mathbf{n}\mathbf{n}^H\right] = \mathbf{I}_K$). 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 $\mathbf{G} \in \mathbb{R}^{K\times N}$ takes into account the rest of gain and loss factors. Its (k,n)-th entry can be described as follows

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

for $k = 1,\ldots,K$, $n = 1,\ldots,N$ 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 $\mathbf{H} \in \mathbb{C}^{K\times N}$ can be represented by

$$\mathbf{H} = \left(\mathbf{h}_1^T, \ldots, \mathbf{h}_K^T\right)^T, \tag{4}$$

where $\mathbf{h}_i \in \mathbb{C}^{1\times N}$ 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 $\left(E\left[\mathbf{s}\mathbf{s}^H\right] = \mathbf{I}_K\right)$, matrix $\mathbf{W} \in \mathbb{C}^{N\times K}$ is the linear precoding matrix to be designed. Then, it follows that the precoder vector is given by

$$\mathbf{x} = \mathbf{W}\mathbf{s}. \tag{5}$$

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

$$\mathbf{W} = \left(\mathbf{w}_1, \ldots, \mathbf{w}_K\right), \tag{6}$$

where $\mathbf{w}_i \in \mathbb{C}^{N\times 1}$ 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 signa-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 [12]. ZF design can be written as

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

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

$$\gamma^2_{\text{ZF, SPC}} = \frac{P_{\text{max}}}{\text{Tr}\left(\mathbf{W}^H_{\text{ZF}}\mathbf{W}_{\text{ZF}}\right)}, \tag{8}$$

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

$$\gamma_{\text{ZF, PFC}} = \frac{P_{\text{max}}}{N\max\left(\text{diag}\left(\mathbf{W}^H_{\text{ZF}}\mathbf{W}_{\text{ZF}}\right)\right)}, \tag{9}$$

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 which is P_{max}/N.

While ZF technique nulls the inter-beam interference if $N \geq K$, 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

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

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 multiple-input-multiple-output (MIMO) broadcast channel in [13]. This scheme sequentially obtains the optimal precoding vector the following objective function

$$\frac{P_{\text{max}}|\mathbf{h}_i\mathbf{w}_i|^2}{P_{\text{max}}\sum_{l\neq i}^{K}|\mathbf{h}_l\mathbf{w}_i|^2 + 1}, \tag{11}$$

whose efficient solution can be obtained in closed form such as

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

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

$$\mathbf{W}_{\text{SLNR}} = \gamma_{\text{SLNR}}\left(\mathbf{w}_{\text{1, SLNR}},\ldots,\mathbf{w}_{\text{K, SLNR}}\right), \tag{13}$$

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

As mentioned earlier, apart from the ZF technique, 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 decoding strategies.

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

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

Let γ denote the precoding dependent normalization factor that controls the transmitted power. It worth emphasizing that the co-channel interference term that comes from the *j*th beam depends on the subspace spanned by $\mathbf{h}_i \in \mathbb{C}^{1\times N}$ 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 $\beta_{il} = |\gamma\mathbf{h}_i\mathbf{w}_l|^2$ 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

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

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

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

where $i, k \in \{1, \cdots, K\}$ 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 [10]. 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 [14], [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

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

where

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

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

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, $R_{\text{SND, k}}$ is expressed as follows:

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

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 [10]. In this case, the highest sum-rate is determined by one of the corner points, which are achievable by a SIC receiver.

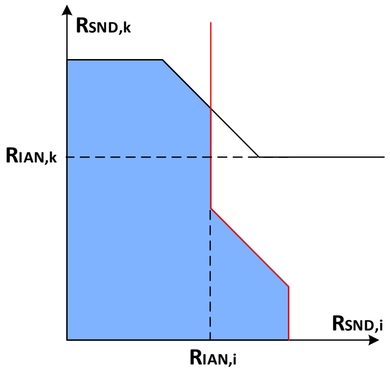

Fig. 1. Joint achievable rates for the *i*th and the *k*th beam.

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 per 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 byESA
Number of feeds N	244
Number of users K	488
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, considering per-feed power constraints. As Figure 2 shows, the SND strategy is able to provide the highest rates with the highest probability, clearly outperforming the IAN approach. It is worth highlighting that IAN and SND curves intersect, regardless of the precoding design. Hence, some rate values with low magnitude are more likely to be obtained by resorting to IAN rather than SND. That is because the rate tuples correspond to one of the corner points of Figure 1, when SND is considered. As a consequence, the rates are unbalanced, so that priority is given to one of the users. This problem can be overcome if time sharing between decoding orders is allowed when users are grouped in pairs and use SIC receivers. Then, the rate values are less spread out and the fairness is increased. Since the aim of this paper is to investigate the sum-rate maximization, the fairness issues are left for future work. It is important to remark that ZF and MMSE precoding deliver the same user data rates.

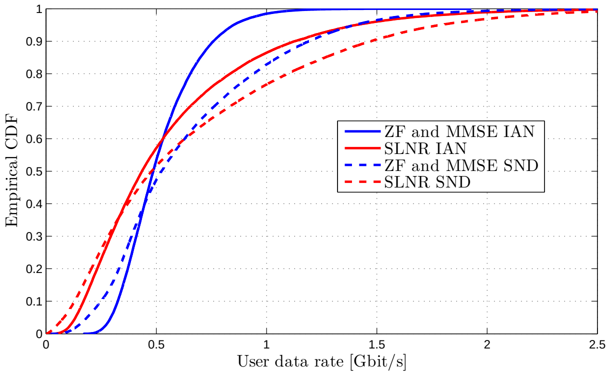

Fig. 2. Empirical CDF of users beam data rate over the coverage area.

In order to investigate the behaviour of the conceived techniques versus the transmit power, we include Figure 3. In this figure we can observe that SND receiver technique increases the sum-rate in all precoding schemes. Precisely, it increases the system capacity a factor of 23% in the MMSE and ZF case where as for the SLNR it increases the sum-rate 18%.

From Figure 3, it can be inferred that the SLNR-based precoding exhibits the highest performance. Interestingly, in the considered scenario, the performance is limited by the interference. For $P_{\max} \geq 45$ Watts, the sum-rate saturates.

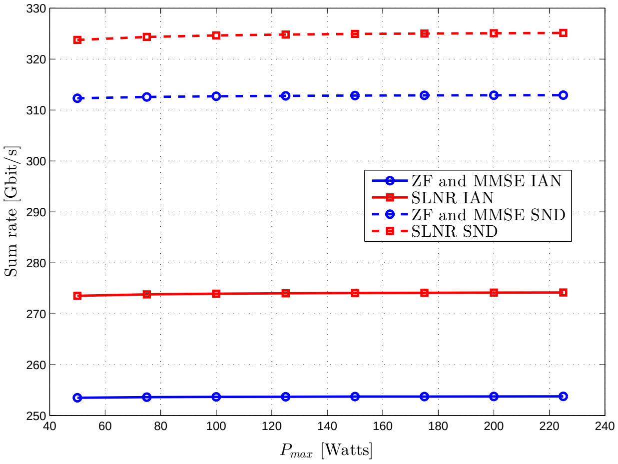

Fig. 3. Sum-rate versus per-feed transmit power.

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 higher data rates compared to ZF and MMSE both under IAN and 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.

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,” *IEEE Communications Magazine*, 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] M. L. Moher, “Multiuser decoding for multibeam systems,” *IEEE Transactions on Vehicular Technology*, vol. 49, no. 4, pp. 1226–1234, Jul 2000.

[4] M. Á. Vázquez, A. I. Pérez-Neira, D. Christopoulos, S. Chatzinotas, B. E. Ottersten, P. M. Arapoglou, A. Ginesi, and G. Taricco, “Precoding in Multibeam Satellite Communications: Present and Future Challenges,” *CoRR*, vol. abs/1506.08018, 2015. [Online]. Available: http://arxiv.org/abs/1506.08018

[5] P.-D. Arapoglou, A. Ginesi, S. Cioni, S. Erl, F. Clazzer, S. Andrenacci, and A. Vanelli-Coralli, “DVB-S2X-enabled precoding for high throughput satellite systems,” *International Journal of Satellite Communications and Networking*, vol. 34, no. 3, pp. 439–455, 2016, sAT-15-0019.R1. [Online]. Available: http://dx.doi.org/10.1002/sat.1122

[6] M. Angelone, A. Ginesi, M. Caus, A. I. Pérez-Neira, and J. Ebert, “System Performance of an Advanced Multi-User Detection Technique for High Throughput Satellite Systems,” in *21st Ka and Broadband Communications Conference*, Oct. 2015.

[7] M. Caus, A. I. Perez-Neira, M. Angelone, and A. Ginesi, “An innovative interference mitigation approach for high throughput satellite systems,” in *Signal Processing Advances in Wireless Communications (SPAWC), 2015 IEEE 16th International Workshop on*, June 2015, pp. 515–519.

[8] A. Gharanjik, B. S. M. R. Rao, P. D. Arapoglou, and B. Ottersten, “Gateway Switching in Q/V Band Satellite Feeder Links,” *IEEE Communications Letters*, vol. 17, no. 7, pp. 1384–1387, July 2013.

[9] V. Joroughi, M. A. Vázquez, and A. I. Pérez-Neira, “Precoding in Multigateway Multibeam Satellite Systems,” *IEEE Transactions on Wireless Communications*, vol. 15, no. 7, pp. 4944–4956, July 2016.

[10] W. Nam, D. Bai, J. Lee, and I. Kang, “Advanced interference management for 5G cellular networks,” *IEEE Communications Magazine*, vol. 52, no. 5, pp. 52–60, May 2014.

[11] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, “Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access,” in *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*, June 2013, pp. 1–5.

[12] B. Devillers, A. Perez-Neira, and C. Mosquera, “Joint Linear Precoding and Beamforming for the Forward Link of Multi-Beam Broadband Satellite Systems,” in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, Dec 2011, pp. 1–6.

[13] M. Sadek, A. Tarighat, and A. H. Sayed, “A Leakage-Based Precoding Scheme for Downlink Multi-User MIMO Channels,” *IEEE Transactions on Wireless Communications*, vol. 6, no. 5, pp. 1711–1721, May 2007.

[14] S. ten Brink, J. Speidel, and R.-H. Yan, “Iterative demapping and decoding for multilevel modulation,” in *IEEE Global Telecommunications Conference*, 1998.

[15] X. Wang and H. V. Poor, “Iterative (turbo) soft interference cancellation and decoding for coded CDMA,” *IEEE Transactions on Communications*, vol. 47, no. 7, pp. 1046–1061, Jul 1999.