Non-Linear Precoding based Hybrid Space-Ground Beamforming for Multi-Beam Satellite Systems

Nuan Song[◇], Tao Yang[◇], and Martin Haardt[§]

◇ Nokia Bell Labs China, Shanghai
§ Communications Research Laboratory, Ilmenau University of Technology, Ilmenau, Germany

***Abstract*—Multi-beam mobile satellite systems have a great potential in providing broadband mobile services over a large area to achieve a high system throughput. On ground beamforming techniques are quite promising but require a large feeder link bandwidth to deliver all the feeds' signals. There are two potential solutions to solve this problem. 1) Hybrid space-ground beamforming is able to reduce the feeder link bandwidth and save spectral resources, which exhibits a good trade-off between the performance and the space/ground complexity. 2) The ground-based beamforming using multiple distributed gateways divides the whole spectrum of the feeder link into several sub-sets, relaxing the bandwidth and processing requirements at each gateway. In this paper, we propose a distributed non-linear precoding based hybrid space-ground beamforming technique, where on-board beamforming aims at suppressing interference among gateways and on-ground beamforming is implemented distributively at each gateway. The proposed technique takes advantages of both the hybrid scheme and the distributed multiple gateway architecture, and does not require any cooperation or any exchange of channel state information among gateways. We show the benefits of the proposed technique over the fully on-ground beamforming schemes as well as its linear counterparts.**

***Index Terms*—non-linear precoding, multi-beam mobile satellite systems, multiple gateways, on-ground beamforming, hybrid space-ground beamforming, MIMO**

I. Introduction

Multi-beam mobile satellite systems, which rely on implementing a phased array antenna on the satellite, have a high potential in providing broadband and high-speed services via multiple spot beams to cover a large area as well as to achieve a high system throughput. In order to form multiple beams on ground, beamforming should be carried out either on board or on ground to electronically steer the beams [1], [2], [3], i.e., On-Board Beamforming (OBB) [4], [5] and On-Ground Beamforming (OGB) [6], [7], [8], [9], [10], [11]. The OBB that is fixed or programmable has limitations to mitigate interference and its adaptive version would impose significant efforts on the satellite. In contrast, the OGB has a higher flexibility and a much lower on-board complexity, which can also be designed dynamically or even adaptively. However, the OGB architecture should deliver all the feeds' signals via the feeder link, which requires a large frequency spectrum for the feeder link and a robust calibration scheme to compensate the amplitude and phase variations for all the feeds' signals.

There are two potential solutions to reduce the feeder link bandwidth. The one is to use hybrid space-ground beamforming, which does not only provide a good trade-off between the on-board and on-ground complexity, but also alleviates the efforts on the calibration of feeder link channels. Some existing references have discussed hybrid space-ground beamforming, where various OBB techniques such as fixed [12], [13], Discrete Fourier Transformation (DFT) based [14], [15], non-adaptive Channel State Information based [16], or feed selection based schemes [17] have been proposed. However, those schemes still require a large feeder link bandwidth if a large number of users are supported. The other one considers multiple gateways to receive feeds' signals in a distributed fashion. It splits the feeder link channel into several bands, each of which is allocated to one gateway. In this case, the whole system is able to accommodate a lot of users and beamforming carried out distributively at each gateway alleviates the burden on backhaul links that are required in the centralized case to connect all the gateways. References [10] and [11] consider a multiple gateway scenario to reduce the feeder link bandwidth and each gateway serves a group of beams, i.e., a cluster. It proposes zero-forcing type precoding carried out exclusively on ground (i.e., purely OGB) to mitigate both intra-cluster and inter-cluster interference. Such techniques, however, still require full or limited Channel State Information (CSI) exchange among cooperating gateways, and have a dimensionality constraint on the relationship of the number of users and the number of feed elements needed due to the zero-forcing type methods.

Furthermore, in current multi-beam satellite systems, it is always assumed that only one user is active per spot beam. If more than one user per beam is supported, user channels within one beam will have a high correlation, which leads to a significant performance degradation for linear precoding and limits the system throughput. Therefore, non-linear precoding such as the efficient Tomlinson-Harashima Precoding (THP) will be preferred. The authors in [18] show a large performance gain of THP for the multi-beam satellite system as compared to that of linear precoding, but they only consider the pure OGB, which requires significant efforts on processing at the gateway such as computational complexity, channel acquisition, and an excess utilization of bandwidth.

Therefore, our concept is to combine the hybrid space-ground beamforming with distributed multiple gateway processing. We propose a hybrid space-ground beamforming technique based on distributed on-ground non-linear precoding for

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a decentralized multiple gateway architecture. In our proposal, we assume a large number of single-antenna users, where more than one user per spot beam is enabled. The OBB is applied to perform decoupling based on the whole array so that clusters (or, groups of users) can be well separated with sufficient degrees of freedom. We apply the Signal to Leakage-and-Noise Ratio (SLNR) algorithm instead of the widely discussed zero-forcing type scheme to relax the dimensionality constraint of the latter. The distributed OGB at each gateway utilizes THP precoding to mitigate interference of potentially highly correlated users within its cluster (or group). It not only reduces the feeder link bandwidth but also avoids any CSI exchange among gateways. Additionally, processing efforts at each gateway are greatly alleviated. We analyze the performance of the proposed technique in the S-band scenario and compare it with several baseline schemes.

Notation: The operations $|\boldsymbol{X}|$, $\|\boldsymbol{X}\|_2$, $\|\boldsymbol{X}\|_F$ denote the determinant, 2-norm, and Frobenius norm of a matrix $\boldsymbol{X}$. The operator $\mathrm{abs}(\cdot)$ takes the absolute value of a scalar. $\boldsymbol{X}(:, a : b)$ is a MATLAB notation, meaning that the columns of the matrix $\boldsymbol{X}$ indexed from a to b are chosen. The Hadamard product is denoted by $\odot$. We express the block diagonal matrix $\boldsymbol{X}$ as $\boldsymbol{X} = \mathrm{blkdiag}\{\boldsymbol{X}_1, \ldots, \boldsymbol{X}_N\}$, consisting N matrices on the diagonal of $\boldsymbol{X}$.

II. System Model

Multi-beam satellite system provides two-way communications: the forward link and the reverse link. The forward link is the signal path from a gateway via the feeder uplink to the satellite and then via the service downlink to the user terminals on-ground. Vice versa, the reverse or return link is the signal path from user terminals via the service uplink to the satellite and via the feeder downlink to the gateway. In this paper, we consider the beamforming for the forward link, i.e., precoding.

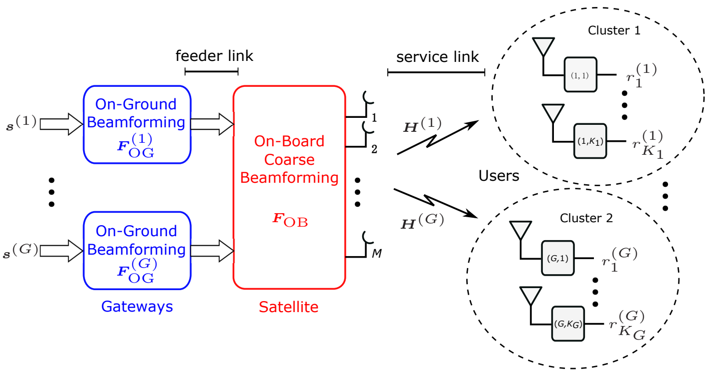

Fig. 1. Block diagram of the proposed hybrid space-ground beamforming technique with decentralized multiple gateways for a multi-beam satellite system.

The block diagram of the proposed hybrid space-ground beamforming technique with decentralized multiple gateways for the multi-beam satellite system is shown in Figure 1. The total number of spot beams is L and the number of feed elements is M. We assume that K_b users are active in one spot beam at each given time slot and $K_b \geq 1$. Thus the total number of users is $K = K_b L$. The users are divided into G clusters (or groups), where there are $K_g, g = 1 \ldots, G$ users per cluster and the g-th cluster is controlled by the g-th gateway, where $K = \sum_{g=1}^{G} K_g$ also holds. The transmitted data from all the gateways is denoted as $\boldsymbol{s} = [\boldsymbol{s}^{(1)T}, \ldots, \boldsymbol{s}^{(G)T}]^T$ and the data provided by the g-th gateway is $\boldsymbol{s}^{(g)} = [s_1^{(g)T}, \ldots, s_{K_g}^{(g)T}]^T$. Without loss of generality it is assumed that the complex data are independent and identically distributed (i.i.d.) random variables with a uniform distribution and have a unit variance. The corresponding received signal $\boldsymbol{r} = [\boldsymbol{r}_1^{(g)T}, \ldots, \boldsymbol{r}_{K_g}^{(g)T}]^T$ at all user terminals during a certain time slot is given by

$$\boldsymbol{r} = \bar{\boldsymbol{H}}\boldsymbol{A}\boldsymbol{F}_{\mathrm{OB}}\boldsymbol{F}_{\mathrm{OG}}\boldsymbol{s} + \boldsymbol{n} \triangleq \boldsymbol{H}\boldsymbol{F}_{\mathrm{OB}}\boldsymbol{F}_{\mathrm{OG}}\boldsymbol{s} + \boldsymbol{n}. \quad (1)$$

The full matrix $\boldsymbol{A} = \begin{bmatrix} \boldsymbol{a}_1^T, & \ldots, & \boldsymbol{a}_K^T \end{bmatrix}^T \in \mathbb{C}^{K \times M}$ consists of K array responses $\boldsymbol{a}_k \in \mathbb{C}^{M \times 1}$ for users $k = 1, \ldots, K$, corresponding to the complex gain of all the M feed elements at azimuth and elevation angles $\boldsymbol{\vartheta}_k, \boldsymbol{\varphi}_k$ for user k. The channel matrix for the user service link (downlink) is represented by a diagonal matrix $\bar{\boldsymbol{H}} \in \mathbb{C}^{K \times K}$. The Additive White Gaussian Noise (AWGN) with zero mean and a power spectral density N_0 is given by $\boldsymbol{n}$. We define the total channel $\boldsymbol{H} \in \mathbb{C}^{K \times M}$ that is composed of the array responses and the channel of the service link as $\boldsymbol{H} \triangleq \bar{\boldsymbol{H}}\boldsymbol{A} = \begin{bmatrix} \boldsymbol{H}^{(1)T}, & \ldots, & \boldsymbol{H}^{(G)T} \end{bmatrix}^T$.

We consider the OBB is carried out based on the whole array to ensure sufficient degrees of freedom and denote the OBB matrix by $\boldsymbol{F}_{\mathrm{OB}} = \begin{bmatrix} \boldsymbol{F}_{\mathrm{OB}}^{(1)}, & \ldots, & \boldsymbol{F}_{\mathrm{OB}}^{(G)} \end{bmatrix} \in \mathbb{C}^{M \times K}$, where $\boldsymbol{F}_{\mathrm{OB}}^{(g)} \in \mathbb{C}^{M \times K_g}$ corresponds to the OBB for the g-th cluster. The OGB is carried out in a distributed fashion at each gateway and denoted by $\boldsymbol{F}_{\mathrm{OG}}^{(g)} \in \mathbb{C}^{K_g \times K_g}$. The total OGB can thus be represented by a block diagonal matrix $\boldsymbol{F}_{\mathrm{OG}} = \mathrm{blkdiag}\left\{\boldsymbol{F}_{\mathrm{OG}}^{(1)}, \ldots, \boldsymbol{F}_{\mathrm{OG}}^{(G)}\right\} \in \mathbb{C}^{K \times K}$.

III. Hybrid Space-Ground Precoding Technique

A. Technical Problems

In our considered system, we split the design of hybrid space-ground beamforming into two stages, i.e., to design the coarse OBB and then the OGB separately. The OGB is carried out by different gateways in a distributed fashion in order to reduce the feeder link bandwidth as well as to alleviate processing efforts on ground. To ensure a well separated OGB, an efficient decoupling technique should be utilized for the OBB. In [19], a Joint Spatial Division and Multiplexing (JSDM) using Block Diagonalization (BD) method is proposed to perform the decoupling, so that per-group processing can be carried out to reduce the implementation complexity. However, such a zero-forcing method has a dimensionality constraint on the number of transmit and receive antennas and does not take into account the influence of noise when designing beamforming vectors. Furthermore, the OGB usually applies linear precoding techniques due to a lower complexity. However, linear precoding may suffer from a significant performance degradation for highly correlated channels, e.g., in the scenario

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where a lot of users are present. The reference [18] evaluates non-linear precoding methods for the multi-beam satellite system in the single-gateway scenario and shows remarkable benefits in terms of system performance. Processing efforts of non-linear precoding at a single gateway are tremendous, which can be largely reduced by distributed OGB performed at multiple gateways.

Therefore, we aim at finding hybrid space-ground beamforming solutions in our considered multiple gateway scenario, where the OBB performs the low-rank transformation and decoupling to efficiently reduce the inter-cluster interference, and the non-linear precoding based OGB is carried out distributively at each gateway to mitigate the intra-cluster interference within its cluster of users.

B. Hybrid Space-Ground Beamforming based Distributed Precoding Design

1) Design the OBB: The purpose of OBB is to mitigate the inter-cluster interference. Let us consider the channel after the OBB, which can be written as

$$\check{\boldsymbol{H}} = \boldsymbol{H}\boldsymbol{F}_{\mathrm{OB}} = \begin{bmatrix} \boldsymbol{H}^{(1)}\boldsymbol{F}_{\mathrm{OB}}^{(1)} & \boldsymbol{H}^{(1)}\boldsymbol{F}_{\mathrm{OB}}^{(2)} & \cdots & \boldsymbol{H}^{(1)}\boldsymbol{F}_{\mathrm{OB}}^{(G)} \\ \boldsymbol{H}^{(2)}\boldsymbol{F}_{\mathrm{OB}}^{(1)} & \boldsymbol{H}^{(2)}\boldsymbol{F}_{\mathrm{OB}}^{(2)} & & \boldsymbol{H}^{(2)}\boldsymbol{F}_{\mathrm{OB}}^{(G)} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{H}^{(G)}\boldsymbol{F}_{\mathrm{OB}}^{(1)} & \boldsymbol{H}^{(G)}\boldsymbol{F}_{\mathrm{OB}}^{(2)} & \cdots & \boldsymbol{H}^{(G)}\boldsymbol{F}_{\mathrm{OB}}^{(G)} \end{bmatrix}, \tag{2}$$

where the off-diagonal parts correspond to the inter-cluster interference. A straightforward way is to find the per-cluster OBB matrix $\boldsymbol{F}_{\mathrm{OB}}^{(g)}$ so that

$$\boldsymbol{H}^{(i)}\boldsymbol{F}_{\mathrm{OB}}^{(g)} = \boldsymbol{0}, \ \text{for } i \neq g. \tag{3}$$

The existing decoupling solution for massive MIMO belongs to the zero-forcing type [19]. An alternative scheme is proposed based on the Signal-to-Leakage-plus-Noise Ratio (SLNR) to relax the constraint on the number of transmit and receive antennas as well as to avoid noise enhancement, which is quite suitable for decentralized processing in [20]. Thus, in our hybrid space-ground beamforming scheme, we propose to apply the SLNR algorithm to decouple different clusters based on the whole array. The SLNR maximization problem for the g-th cluster can be formulated by

$$\begin{aligned} \max_{\boldsymbol{F}_{\mathrm{OB}}^{(g)}} \mathrm{SLNR}^{(g)} &= \frac{P_T^{(g)} \left\| \boldsymbol{H}^{(g)}\boldsymbol{F}_{\mathrm{OB}}^{(g)} \right\|_F^2}{\sum_{i=1, i\neq g}^{G} P_T^{(g)} \left\| \boldsymbol{H}^{(i)}\boldsymbol{F}_{\mathrm{OB}}^{(g)} \right\|_F^2 + \sigma_n^2 K_g} \\ &= \frac{\mathrm{tr}\left\{ \boldsymbol{F}_{\mathrm{OB}}^{(g)H} \boldsymbol{R}_g \boldsymbol{F}_{\mathrm{OB}}^{(g)} \right\}}{\mathrm{tr}\left\{ \boldsymbol{F}_{\mathrm{OB}}^{(g)H} \tilde{\boldsymbol{R}}_g \boldsymbol{F}_{\mathrm{OB}}^{(g)} \right\}}, \end{aligned} \tag{4}$$

where $P_T^{(g)}$ is the total transmit power for the cluster g, the covariance matrices of the desired channel and the leakage channel are $\boldsymbol{R}_g = \boldsymbol{H}^{(g)H}\boldsymbol{H}^{(g)}$ and $\tilde{\boldsymbol{R}}_g = \tilde{\boldsymbol{H}}^{(g)H}\tilde{\boldsymbol{H}}^{(g)} + \sigma_n^2 K_g / P_T^{(g)} \boldsymbol{I}_M$, respectively. $\tilde{\boldsymbol{H}}^{(g)} = [\ \boldsymbol{H}^{(1)T}, \ldots, \boldsymbol{H}^{(g-1)T}, \boldsymbol{H}^{(g+1)T}, \ldots, \boldsymbol{H}^{(G)T}\ ]^T$ is the channel excluding the desired panel. The SLNR maximization problem can be reduced to maximizing a lower bound [20], which maximizes the smallest generalized Rayleigh quotient as

$$\max_{\boldsymbol{F}_{\mathrm{OB}}^{(g)H}\boldsymbol{F}_{\mathrm{OB}}^{(g)} = \boldsymbol{I}_{K_g}} \ \min_{i=1,\ldots,K_g} \frac{\boldsymbol{f}_{\mathrm{OB}}^{(g,i)H} \boldsymbol{R}_g \boldsymbol{f}_{\mathrm{OB}}^{(g,i)}}{\boldsymbol{f}_{\mathrm{OB}}^{(g,i)H} \tilde{\boldsymbol{R}}_g \boldsymbol{f}_{\mathrm{OB}}^{(g,i)}} \tag{5}$$

with $\boldsymbol{f}_{\mathrm{OB}}^{(g,i)}$ being the i-th column of the matrix $\boldsymbol{F}_{\mathrm{OB}}^{(g)}$. The decoupling matrix can then be obtained by the dominant K_g eigenvectors corresponding to the K_g largest eigenvalues of $\tilde{\boldsymbol{R}}_g^{-1}\boldsymbol{R}_g$.

Please note that the above SLNR based OBB only relies on the transmit covariance matrices from all clusters, which can be obtained via long-term CSI. Accordingly, the OBB will not be as adaptive as the OGB.

2) Design the Distributed OGB: After the OBB with decoupling, the effective channel for the g-th cluster can be written as $\check{\boldsymbol{H}}_g = \boldsymbol{H}^{(g)}\boldsymbol{F}_{\mathrm{OB}}^{(g)}$, which is used to design the OGB at the g-th gateway. The non-linear THP technique is a simplified and efficient version of Dirty Paper Coding (DPC), which is less computationally demanding and thus more attractive for practical implementation. It can provide a significantly enhanced system performance as compared to linear precoding, especially for highly correlated channels. Therefore, to effectively mitigate the intra-cluster interference, we apply the HP technique to users within each cluster. The block diagram of the THP implementation is depicted in Figure 2, which is carried out after the decoupling on-board.

By calculating an LQ decomposition on the channel $\check{\boldsymbol{H}}_g$, we have

$$\check{\boldsymbol{H}}_g = \boldsymbol{L}_g\boldsymbol{Q}_g, \tag{6}$$

where $\boldsymbol{L}_g$ is a lower triangular matrix and $\boldsymbol{Q}_g$ is a unitary matrix. The feedforward and feedback filters for the THP algorithm can be obtained as

$$\boldsymbol{P}_g = \boldsymbol{Q}_g^H \tag{7}$$

and

$$\boldsymbol{B}_g = \boldsymbol{D}_g\boldsymbol{L}_g \tag{8}$$

$$\boldsymbol{D}_g = \mathrm{diag}\left\{ \boldsymbol{L}_g^{-1}(1,1), \ldots, \boldsymbol{L}_g^{-1}(K_g, K_g) \right\}, \tag{9}$$

respectively, where $\boldsymbol{L}_g^{-1}(i,i)$ is the i-th diagonal element of the matrix $\boldsymbol{L}_g$. The overall feedforward filter matrix is block diagonal, denoted by $\boldsymbol{P} = \mathrm{blkdiag}\{\boldsymbol{P}_1, \ldots, \boldsymbol{P}_G\} \in \mathbb{C}^{K\times K}$. In Figure 2, the transmitted symbols $\boldsymbol{x}^{(g)}$ are successively generated by the feedback loop, which increases the transmit power since its amplitude will exceed the modulation boundary. Thereby, a modulo operation $\mathrm{M}(\cdot)$ should be applied and the corresponding operation is defined as

$$\mathrm{M}(x_i) = x_i - \left\lfloor \frac{\mathrm{Re}(x_i)}{\tau} + \frac{1}{2} \right\rfloor \tau - \sqrt{-1} \cdot \left\lfloor \frac{\mathrm{Im}(x_i)}{\tau} + \frac{1}{2} \right\rfloor \tau, \tag{10}$$

where $\lfloor\cdot\rfloor$ denotes the floor operation and τ is a constant depending on the modulation alphabet [21]. At the user side, the matrix $\boldsymbol{D}_g$ is used as the scaling matrix for weighting data streams and a modulo operation is applied for

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demodulation. The overall weighting matrix can be written as $\boldsymbol{D} = \text{blkdiag}\{\boldsymbol{D}_1, \ldots, \boldsymbol{D}_G\} \in \mathbb{C}^{K \times K}$, which is also diagonal.

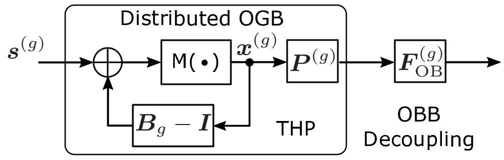


Fig. 2. Block diagram of the THP implementation for the g-th cluster.

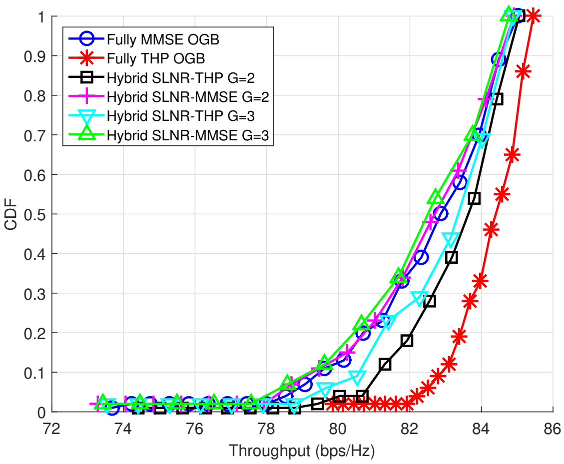
IV. Simulations

For simulations, we consider the forward link in the S-band scenario with a signal spectrum of 15 MHz. The satellite antenna is a 12-meter reflector illuminated by an array of 44 feed elements. In the forward link, 11 linguistic beams achieve a coverage over Europe, where we assume that at least one user is active in one beam and the users are generated at random locations within their own spot beams. Full frequency reuse and a single polarization of the satellite antenna are assumed. According to the channel model in [3], the channel of the user service link is modeled by Rician fading with a Rician factor of 7 dB. For the baseline, we consider the full THP and full Minimum Mean Square Error (MMSE) schemes, namely, "Fully THP OGB" and "Fully MMSE OGB", which correspond to the case where we apply THP or MMSE based OGB with the highest flexibility. We will evaluate our proposed scheme in terms of "Hybrid SLNR-THP" and "Hybrid SLNR-MMSE", depending on whether the intra-cluster precoding is carried out by THP or MMSE, respectively. The performance depicted by the achievable sum rate of the system, is calculated by $R = \sum_{k=1}^{K} \log_2(1 + \text{SINR}_k)$, where SINR_k indicates the signal-to-interference-plus-noise ratio at the user k.

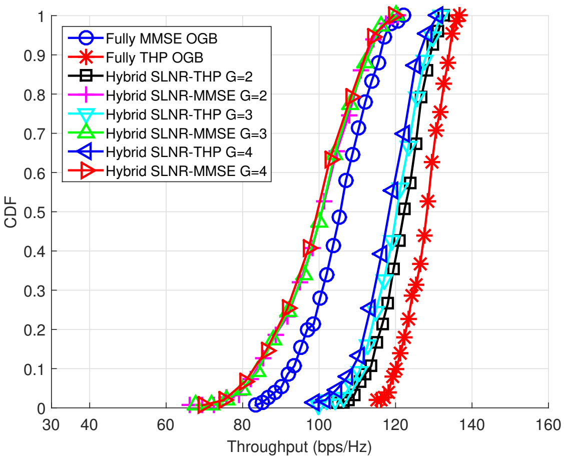
Figure 3 shows the Cumulative Distribution Functions (CDFs) of the sum rate performance for various schemes[1]. It can be observed that when we have only one user per spot beam, i.e., $K_b = 1$, there is a small gain obtained by the non-linear THP scheme, since the users are well separated and not so highly correlated. However, in the case of $K_b = 2, 3$, when more users are supported in one spot beam, linear precoding exhibits a large performance degradation as compared to the non-linear counterpart due to increased channel correlations among users. It is especially obvious that the performance of all linear schemes with $K_b = 2$ is worse than that of the case with $K_b = 3$. Furthermore, from the point view of the number of clusters G, we can see that for the linear case "Hybrid-SLNR-MMSE", almost no performance difference can be seen for different G. But the performance of "Hybrid-SLNR-THP" decreases with G being larger, since the precoding gain that can be exploited within a smaller number of users also reduces.

We also summarize the gain of the non-linear precoding scheme "Hybrid-SLNR-THP" with $G = 2, 3$ over the case

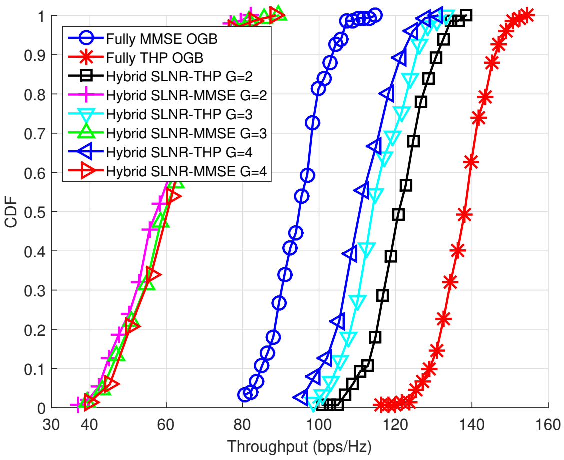
[1]Please note that the range of the x-axis in Figure 3(a) is not scaled to the same values as in the other two cases ($K_b = 2, 3$) for a better visibility.



(a) $K_b = 1, K = 11$



(b) $K_b = 2, K = 22$



(c) $K_b = 3, K = 33$

Fig. 3. The CDF of the sum rate performance of various hybrid space-ground precoding schemes at SNR = 20 dB.

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TABLE I
PERFORMANCE GAIN OF THE "HYBRID SLNR-THP" OVER THE FULLY MMSE OGB AT SNR = 20 DB

Per Beam Users	Availability 5%	Availability 50%	Availability 95%
$G = 2, K_b = 1$	2.9%	0.94%	0%
$G = 2, K_b = 2$	22.3%	15.8%	11.4%
$G = 2, K_b = 3$	30.8%	27.5%	25.4%
$G = 3, K_b = 1$	0.89%	0.4%	0.2%
$G = 3, K_b = 2$	19.6%	13.9%	10.7%
$G = 3, K_b = 3$	23.4%	20.2%	20.1%

"Fully MMSE OGB" for $K_b = 1, 2, 3$ in Table I. It can be clearly seen that our proposed distributed THP based hybrid space-ground beamforming technique is able to support a large number of users with high correlations in the multi-beam satellite system and has a remarkable gain than the widely discussed "Fully MMSE OGB".

V. CONCLUSIONS

This paper proposes a distributed THP based hybrid space-ground precoding technique for multi-beam satellite systems with multiple gateways to significantly reduce the feeder link bandwidth and the processing efforts in the fully OGB case. It combines hybrid space-ground beamforming with the distributed OGB concept. The OBB not only mitigates the inter-cluster interference via SLNR based decoupling, but also acts as a rank-reduction so that the OGB can be carried out in a reduced dimension. The THP based OGB is implemented at each gateway in a distributed fashion and thus no cooperation or CSI exchange among gateways is needed. The non-linear THP technique ensures an effective suppression of intra-cluster interference especially in scenarios with a lot of users where users have high channel correlations. Simulation results show that the proposed distributed hybrid precoding technique significantly outperforms its linear counterpart. Compared to the fully linear OGB technique, a performance gain of 20% - 30% with $K_b = 3$ per-beam active users can be obtained.

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REFERENCES

[1] P. Angeletti and N. Alagha, "Space/ground beamforming techniques for emerging hybrid satellite terrestrial networks," in *27th International Communications Satellite Systems Conference (ICSSC 2009)*, Edinburgh, Scotland, 1 – 4, June 2009.

[2] P. Angeletti, N. Alagha, and S. D'Addio, "Space/ground beamforming techniques for satellite communications," in *IEEE Antennas and Propagation Society International Symposium (APSURSI)*, 2010, pp. 1–4.

[3] J. Tronc, P. Angeletti, N. Song, M. Haardt, J. Arendt, and G. Gallinaro, "Overview and comparison of on-ground and on-board beamforming techniques in mobile satellite service applications," *International Journal of Satellite Communications and Networking*, vol. 32, no. 4, pp. 291–308, 2014.

[4] W. Li, X. Huang, and H. Leung, "Performance evaluation of digital beamforming strategies for satellite communications," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 40, no. 1, pp. 12–26, 2005.

[5] A. H. Khan, M. A. Imran, and B. G. Evans, "Ground based and onboard based beamforming for hybrid terrestrial-satellite mobile system," in *28th AIAA International Communications Satellite Systems Conference (ICSSC-2010)*, Anaheim,California, 30 August - 2 September 2010.

[6] P. Angeletti, G. Gallinaro, M. Lisi, and A. Vernucci, "On-ground digital beamforming techniques for satellite smart antennas," in *32nd ESA Antenna Workshop on Antennas for Space Applications*, Noordwijk, The Netherlands, 5 - 8 October 2010.

[7] D. Zheng and P. D. Karabinis, "Adaptive Beam-Forming with Interference Suppression in MSS with ATC," in *Proceedings of the 23rd International Communications Satellite Systems Conference (ICSSC-2005)*, Rome, Italy, 2005.

[8] L. Cottatellucci, M. Debbah, G. Gallinaro, R. Mueller, M. Neri, and R. Rinaldo, "Interference Mitigation Techniques for Broadband Satellite Systems," in *24th AIAA International Communications Satellite Systems Conference (ICSSC-2006)*, San Diego, California, 11 - 14, June 2006.

[9] G. Gallinaro, G. Caire, M. Debbah, L. Cottatellucci, R. Muller, and R. Rinaldo, "Perspectives Of Adopting Inteference Mitigation Techniques In The Context Of Broadband Multimedia Satellite Systems," in *23rd AIAA International Communications Satellite Systems Conference (ICSSC-2005)*, Sept. 2005.

[10] B. Devillers and A. Pérez-Neira, "Advanced interference mitigation techniques for the forward link of multi-beam broadband satellite systems," in *2011 Conference Record of the Forty Fifth Asilomar Conference on Signals, Systems and Computers (ASILOMAR)*, 2011, pp. 1810–1814.

[11] V. Joroughi, M. Vazquez, and A. Pérez-Neira, "Precoding in Multi-gateway Multibeam Satellite Systems," *IEEE Transactions on Wireless Communications*, vol. 15, no. 7, pp. 4944–4956, July 2016.

[12] J. Arnau-Yanez, M. Bergmann, E. A. Candreva, G. E. Corazza, R. De Gaudenzi, B. Devillers, W. Gappmair, F. Lombardo, C. Mosquera, A. Pérez-Neira, et al., "Hybrid space-ground processing for high-capacity multi-beam satellite systems," in *IEEE Global Telecommunications Conference (GLOBECOM 2011)*, 2011, pp. 1–6.

[13] B. Devillers, A. Pérez-Neira, and C. Mosquera, "Joint linear precoding and beamforming for the forward link of multi-beam broadband satellite systems," in *IEEE Global Telecommunications Conference (GLOBECOM 2011)*, 2011, pp. 1–6.

[14] P. Angeletti, G. Gallinaro, M. Lisi, and A. Vernucci, "Hybrid Space/Ground Beamforming Techniques for Satellite Telecommunications," in *19th International Communications Satellite Systems Conference (ICSSC 2001)*, Tolouse, France, 2001.

[15] I. Thibault, F. Lombardo, E. A. Candreva, A. Vanelli-Coralli, and G. E. Corazza, "Coarse beamforming techniques for multi-beam satellite networks," in *2012 IEEE International Conference on Communications (ICC)*, 2012, pp. 3270–3274.

[16] V. Joroughi, B. Devillers, M. Vázquez, and A. Pérez-Neira, "Design of an on-board beam generation process for the forward link of a multi-beam broadband satellite system," in *2013 IEEE Global Communications Conference (GLOBECOM)*, 2013, pp. 2921–2926.

[17] N. Song, T. Yang, and M. Haardt, "Efficient hybrid space-ground precoding techniques for multi-beam satellite systems," in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 2017, pp. 6284–6288.

[18] M. Álvarez-Díaz, *Design of Nonlinear Precoding and Estimation Schemes for Advanced Communication Systems*, Ph.D. thesis, University of Vigo, April 2010.

[19] A. Adhikary, J. Nam, J.-Y. Ahn, and G. Caire, "Joint spatial division and multiplexing – the large-scale array regime," *IEEE Transactions on Information Theory*, vol. 59, no. 10, pp. 6441–6463, 2013.

[20] W. W. L. Ho, T. QS Quek, S. Sun, and R. W. Heath, "Decentralized precoding for multicell MIMO downlink," *IEEE Transactions on Wireless Communications*, vol. 10, no. 6, pp. 1798–1809, 2011.

[21] W. Yu, D. P. Varodayan, and J. M. Cioffi, "Trellis and convolutional precoding for transmitter-based interference presubtraction," *IEEE Transactions on Communications*, vol. 53, no. 7, pp. 1220–1230, 2005.

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