

# EFFICIENT HYBRID SPACE-GROUND PRECODING TECHNIQUES FOR MULTI-BEAM SATELLITE SYSTEMS

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## ABSTRACT

Multi-beam mobile satellite systems aim at providing broadband and high speed mobile services over a large area to achieve a high system throughput, where hybrid space-ground beamforming is one of the most promising candidates for ground-based beamforming techniques. It not only reduces the feeder link bandwidth to save spectral resources, but also takes advantages of both the on-ground and on-board processing, exhibiting a good trade-off of the performance and the space/ground complexity. In this paper, we propose an efficient hybrid space-ground precoding technique for multi-beam mobile satellite systems. It consists of coarse on-board beamforming and reduced-rank on-ground beamforming based on the feed selection of the phased array antenna. The advantages of the proposed hybrid precoding are shown as compared to the fully on-ground beamforming as well as the existing solutions.

**Index Terms**— multi-beam mobile satellite systems, on-ground beamforming, on-board beamforming, hybrid space-ground beamforming, feed selection, MIMO

## 1. INTRODUCTION

Modern Mobile Satellite Systems (MSSs) aim at providing broadband and high speed services covering a large area. To accommodate numerous users, to improve the spectrum efficiency as well as to provide enhanced quality of service such as higher data rates or an increased link robustness, it is desired to adopt multi-spot beams, each of which serves one distinct cell within the whole service area. The so-called multi-beam MSSs rely on implementing a phased array antenna (e.g., an array-fed reflector) on the satellite, and accordingly multiple beams are generated to achieve the Spatial Division Multiplexing Access (SDMA). Thereby, precoding techniques, which are designed to minimize the co-channel interference and to maximize the system sum rate, are promising candidates for signal processing in satellite networks [1]. Full frequency reuse can be used as much as possible, yielding a significant performance improvement in the spectral efficiency.

Precoding, or generally called beamforming, can be carried out either on-board or on-ground to electronically steer the beams [2, 3, 4]. Thus, from the implementation architecture perspective, two beamforming techniques can be identified, namely on-board beamforming (OBB) [5, 6] and on-ground beamforming (OGB) [7, 8, 9, 10, 11, 12]. Several commercial satellites such as Inmarsat 4, Alphasat I-XL, and Thuraya have applied OBB techniques [4]. The OBB is carried out based on an on-board Digital Signal Processor (DSP) and is fixed or programmable, which has a limited capability of suppressing the interference. It is quite challenging to implement adaptive beamforming on-board, especially when a large number of beams are required. Compared to the OBB, the OGB, promises a high flexibility and alleviates the on-board complexity. Some U.S. mobile satellites (i.e., ICO-G1, Terrestar-1 and Skyterra-

1) have adopted OGB techniques [13]. The OGB can be designed dynamically or even adaptively. However, due to the fact that the OGB architecture requires all the feeds' signals to be delivered via the feeder link, independent signals on different frequencies suffer from the amplitude and phase dispersions. Thus, a robust calibration scheme is required to compensate these amplitude and phase variations for all the feed elements. Moreover, OGB also requires certain frequency spectrum for exchanging the feeds' signals through the feeder link. Considering future broadband satellite communications, the satellite supports a significant number of feed elements and the traffic signals may accommodate larger bandwidths. In this regard, a large bandwidth requirement is an obvious drawback of the OGB architecture.

Therefore, hybrid space-ground beamforming, which trades-off the on-board and on-ground complexity, becomes more attractive. It splits the beamforming into two parts, i.e., on-board and on-ground, which not only reduces the feeder link bandwidth, but also alleviates the efforts and complexity on the calibration that is only required for a reduced number of feeder link channels. There are several existing solutions for the hybrid space-ground beamforming [14, 15, 16, 17, 18]. References [14, 15] propose to apply the Discrete Fourier Transformation (DFT) beamspace beamforming for the OBB. Authors in [16, 17] have proposed a hybrid space-ground precoding technique, i.e., beam-level fixed OBB combined with Zero-Forcing (ZF) or Minimum Mean Square Error (MMSE) based OGB, and shown that a large performance degradation is observed as compared to the fully OGB (or feed-level beamforming). A robust optimization OBB approach is designed for the hybrid space-ground architecture in [18]. The OBB weights are calculated based on the non-adaptive Channel State Information (CSI) and the scheme outperforms the one based on the fixed OBB.

All the aforementioned existing solutions for the hybrid space-ground beamforming rely on the full array and the beamforming is carried out for the signals to all the feed elements. As a result, the complexity of the corresponding on-board implementation becomes high for a large number of feed elements of the multi-beam satellite antenna. Furthermore, in practice, not all the feed elements need to contribute to the beamforming design, since the gains of some antenna feeds with respect to a certain served spot beam are trivial.

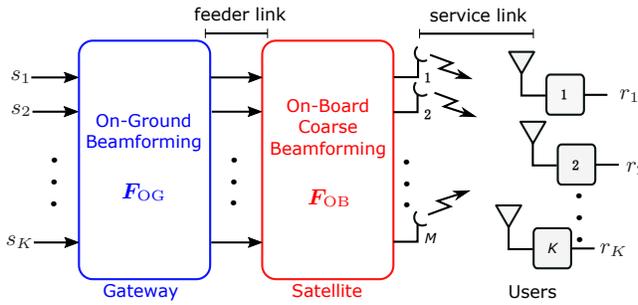
In this paper, we propose a feed selection based hybrid space-ground precoding technique for the forward link in multi-beam MSSs. The proposed beamforming approach consists of a coarse OBB and a reduced-rank OGB. The feed selection ensures that one beam formed on-board requires only a small set of feed elements instead of all the elements in the full-array case, which reduces the complexity of the on-board DSP. A Greedy Sparse Recovery (GSR) algorithm is developed to design the sparse OBB matrix. We show that it can also be generalized to the solution for the full-array case without any modifications. The proposed hybrid precoding tech-

nique is able to support various precoding methods for the reduced-rank OGB, where the linear MMSE precoding scheme is considered due to its better performance compared to the ZF. We analyze the performance of the proposed hybrid space-ground precoding technique in the S-band scenario and compare it to the existing solutions in terms of the system sum rate and the complexity.

*Notation:* The operations  $|\mathbf{X}|$ ,  $\|\mathbf{X}\|_2$ ,  $\|\mathbf{X}\|_F$  denote the determinant, 2-norm, and Frobenius norm of a matrix  $\mathbf{X}$ . The operator  $\text{abs}(\cdot)$  takes the absolute value of a scalar.  $\mathbf{X}(:, a : b)$  is a MATLAB notation, meaning that the columns of the matrix  $\mathbf{X}$  indexed from  $a$  to  $b$  are chosen. The Hadamard product is denoted by  $\odot$ .

## 2. SYSTEM MODEL

Generally speaking, MSSs provide 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 of the MSS, i.e., precoding.



**Fig. 1.** Block diagram of the hybrid space-ground precoding architecture for the multi-beam MSS.

The block diagram of the hybrid space-ground precoding architecture for the multi-beam MSS is shown in Figure 1. We assume that the transmission scheme is based on Time Division Multiplexing (TDM), i.e., one user with a single antenna is active in each spot beam at each given time slot. The total number of spot beams is  $K$  and the number of feed elements is  $M$ , where  $M \gg K$  usually holds for the multi-beam MSSs. The transmitted data from the gateway is denoted as  $\mathbf{s} = [s_1, s_2, \dots, s_K]^T$  and without loss of generality it is assumed that the complex data are independent and identically distributed (i.i.d.) uniformly distributed random variables and  $\mathbb{E}\{\|s_k\|^2\} = 1$ . The received signal  $\mathbf{r} = [r_1, r_2, \dots, r_K]^T$  at all user terminals during a certain time slot is given by

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

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

In the fully OGB case, the full-dimension precoding matrix  $\mathbf{F}_{\text{FD}}$  needs to be designed, for example by MMSE. In the hybrid space-ground architecture, the precoding matrices designed for the coarse OBB and the OGB are denoted by  $\mathbf{F}_{\text{OB}} \in \mathbb{C}^{M \times L}$  and  $\mathbf{F}_{\text{OG}} \in \mathbb{C}^{L \times K}$  with  $L \geq K$ , respectively, where the product  $\mathbf{F}_{\text{OB}}\mathbf{F}_{\text{OG}}$  should be computed to approach the full dimension case  $\mathbf{F}_{\text{FD}}$  as much as possible. For simplicity, we consider the case where  $K = L$ .

## 3. HYBRID SPACE-GROUND PRECODING TECHNIQUES

### 3.1. Problem Formulation

The capacity region of the MIMO broadcast channels can be reached by dirty paper coding (DPC) [19]. It is able to achieve the maximum sum rate of the system and attain the maximum spatial diversity order. However, the corresponding non-linear pre-coding schemes require perfect channel state information at the gateway. As a comparison, linear precoding techniques based on ZF and MMSE are less computationally demanding. Either the instantaneous channel knowledge or the long-term channel statistics can be employed. Even though linear precoding algorithms cannot achieve the maximum sum rate, compared to the non-linear schemes they are less sensitive to calibration and channel imperfections. Thus, for the fully OGB or the feed-level beamforming, ZF and MMSE linear precoding schemes are mainly considered.

In the hybrid space-ground architecture, the on-board and on-ground beamforming matrices are designed so that the system sum rate under the total power ( $P_T$ ) constraint is maximized, i.e.,

$$\max \sum_{k=1}^K \log_2 \left( 1 + \frac{\mathbf{h}_k^T \mathbf{F}_{\text{OB}} \mathbf{f}_{\text{OG}}^{(k)} \mathbf{f}_{\text{OG}}^{(k)H} \mathbf{F}_{\text{OB}}^H \mathbf{h}_k^*}{N_0 + \sum_{i \neq k} \mathbf{h}_i^T \mathbf{F}_{\text{OB}} \mathbf{f}_{\text{OG}}^{(i)} \mathbf{f}_{\text{OG}}^{(i)H} \mathbf{F}_{\text{OB}}^H \mathbf{h}_i^*} \right) \quad (2)$$

s. t.  $\|\mathbf{F}_{\text{OB}}\mathbf{F}_{\text{OG}}\|_F^2 = P_T$

where the precoding matrix for the OGB consists of  $K$  precoding vectors, i.e.,  $\mathbf{F}_{\text{OG}} = [\mathbf{f}_{\text{OG}}^{(1)}, \mathbf{f}_{\text{OG}}^{(2)}, \dots, \mathbf{f}_{\text{OG}}^{(K)}]$  and the channel matrix is denoted by  $\mathbf{H} = [\mathbf{h}_1^T, \mathbf{h}_2^T, \dots, \mathbf{h}_K^T]^T$ . The OBB matrix should be designed that is common to all users. It is not trivial to solve the above optimization problem. Therefore, a more efficient way is to split the hybrid precoding procedure into two phases, i.e., design the coarse OBB and then the OGB according to the equivalent channel. The OBB performs a low-rank transformation from  $K$  signal streams to  $M$  antennas at the satellite which significantly reduces the feeder link bandwidth. The OGB carries out the precoding in a reduced dimension at the gateway to mitigate the interference among data streams from all users and enhances the system performance.

### 3.2. Hybrid Space-Ground Precoding Design

#### 3.2.1. Full Array based Hybrid Space-Ground Precoding

Some precoding algorithms have been proposed to design the OBB and the OGB based on all the feed elements. One method is to utilize the fixed (or channel non-adaptive) OBB and to develop the adaptive linear precoding in the beamspace. The fixed OBB can be achieved by the beamspace beamforming and for the OGB, simple linear precoding methods such as MMSE can be applied according to the effective channel. One popular beamspace beamforming method is the DFT [14]. The DFT approach for generating orthogonal beams can be readily applied to the elements located on a rectangular lattice, but it is not straightforward for arrays with an arbitrary lattice or irregular element locations, unless some techniques such as the spatial sampling lattice based transformation are applied [20]. Thus, in the

following we discuss two OBB generation schemes, i.e., the Discrete Prolate Spheroidal Sequences (DPSS) based beamspace beamforming and the Bartlett beamforming.

**DPSS Beamspace Beamforming:** The principle of generating the DPSS is to maximize the percentage of the total power that is concentrated in a given angular region [21]. It has also been shown that the DPSS outperforms the DFT scheme. The solution of this maximization problem is equivalent to finding the  $K$  dominant eigenvectors of the matrix  $\mathbf{J}$  corresponding to the  $K$  largest eigenvalues. The semi-definite matrix  $\mathbf{J}$  is given by

$$\mathbf{J} = \int_{\Theta} \int_{\Phi} \mathbf{a}(\vartheta, \varphi) \mathbf{a}^H(\vartheta, \varphi) d\vartheta d\varphi, \quad (3)$$

where  $\Theta$  and  $\Phi$  are the angular regions of interest in two dimensions and  $\mathbf{a}(\vartheta, \varphi)$  is the array response at the sampling point  $(\vartheta, \varphi)$ . By applying the Singular Value Decomposition (SVD) on  $\mathbf{J} = \mathbf{U}\mathbf{\Sigma}\mathbf{U}^H$ , we can obtain the DPSS beamspace matrix, which is also the OBB matrix  $\mathbf{F}_{\text{OB}}$ , as

$$\mathbf{F}_{\text{OB}} = \mathbf{U}(:, 1 : K). \quad (4)$$

The DPSS beamformer generates  $K$  orthogonal beams, corresponding to  $K$  related spot beams for the coverage of interest. Thus, in this case, the granularity of the beam is the largest.

**Bartlett Beamforming:** The basic idea of the Bartlett beamformer is to maximize the power collected from the angle of interest [21]. The solution corresponds to the array response at the desired angle. The Bartlett based OBB can be written as

$$\mathbf{F}_{\text{OB}} = [ \mathbf{a}(\vartheta_1, \varphi_1), \mathbf{a}(\vartheta_2, \varphi_2), \dots, \mathbf{a}(\vartheta_K, \varphi_K) ] \quad (5)$$

where  $\vartheta_k$  and  $\varphi_k$  are the azimuth and elevation angles of the user  $k$  with respect to the satellite array. The Bartlett based OBB scheme is user-dynamic and direction oriented, which also has the smallest granularity.

### 3.2.2. Feed Selection based Hybrid Space-Ground Precoding

The existing solutions for the hybrid ground-space beamforming are only considered for the full array, which requires the DSP calculations for all the feed elements. This imposes a high complexity on the payload especially when the number of feed elements is high, i.e., over one hundred. The array of the multi-beam satellite is usually designed to cover a very large area in the continental level via hundreds of spot beams. As a result, some of the feed elements whose geographical projections on ground have trivial contributions to the spot beams that are far away. Therefore, we propose to apply the OBB only for a group of feed elements that have the most significant contribution to one specific spot beam. Accordingly, the computational complexity on the payload can be greatly reduced.

In the feed selection based hybrid beamforming case, the precoding matrix  $\mathbf{F}_{\text{OB}}$  only contains non-zeros where the feed elements are selected and therefore  $\mathbf{F}_{\text{OB}}$  becomes a sparse matrix. This sparse property is an additional constraint for the optimization problem shown in (2). In what follows, we propose a feed selection based Greedy Sparse Recovery (GSR) algorithm to generate the OBB matrix.

**Feed Selection:** The set of  $D$  feed elements with an index vector  $\mathbf{d}_k$  to form a beam  $k$  is selected based on the following criterion:

$$\mathbf{d}_k = \left\{ d_k(j) : \text{abs} \left( a_k^{(s)}(\bar{\vartheta}_k, \bar{\varphi}_k) \right) > \gamma, d_k(j) \in \{1, 2, \dots, M\} \right\} \quad (6)$$

where the angles  $(\bar{\vartheta}_k, \bar{\varphi}_k)$  correspond to the center of the predefined spot beam. Each feed element with the index  $d_k(j)$  is chosen so that its gain at the desired angles is larger than the threshold  $\gamma$ . In practice, the index vector for the feed selection can be obtained and optimized off-line, which is not user-specific or dynamic. The number of feed elements can be adapted and varied for different spot beams.

For simplicity, the implementation of the feed selection according to (6) can also be carried out by fixing the number  $D$  and choosing the  $D$  feed elements with the largest gains at the desired location.

**OBB Design - Exploit Large Array Gain:** The multi-beam satellite takes advantage of a significant number of antennas to achieve a wide coverage and a large array gain. As discussed before, the OBB performs a low-rank transformation from  $K$  signal streams to  $M$  antenna elements. The characteristic of the effective or beamformed channel after the OBB should be as close as possible to the original channel  $\mathbf{H}$ . Therefore, we design  $\mathbf{F}_{\text{OB}}$  so that the effective channel gain or the effective array gain is maximized, i.e.,

$$\max_{\mathbf{F}_{\text{OB}}} \sum_{k=1}^K \left\| \mathbf{h}_k^T \mathbf{F}_{\text{OB}} \right\|_F^2 = \max_{\mathbf{F}_{\text{OB}}} \left\| \mathbf{H} \mathbf{F}_{\text{OB}} \right\|_F^2 \quad \text{s. t. } \mathbf{F}_{\text{OB}}^H \mathbf{F}_{\text{OB}} = \mathbf{I}_M. \quad (7)$$

In the full array case without sparsity constraint on  $\mathbf{F}_{\text{OB}}$ , the optimal solution for the problem (7) can be obtained by performing the SVD on  $\mathbf{R}$

$$\mathbf{F}_{\text{OB}} = \mathbf{V}(:, 1 : K), \quad \mathbf{R} = \mathbf{V} \mathbf{\Lambda} \mathbf{V}^H, \quad \text{with } \mathbf{R} = \sum_{k=1}^K \mathbf{h}_k^* \mathbf{h}_k^T. \quad (8)$$

However, for the feed selection based hybrid precoding technique, the sparsity of  $\mathbf{F}_{\text{OB}}$  makes the problem (7) rather challenging to solve.

**GSR Algorithm:** With the sparsity constraint, (7) becomes a sparse eigenvalue problem, where the direct SVD cannot be applied. Therefore, we propose a GSR algorithm to reconstruct the OBB matrix  $\mathbf{F}_{\text{OB}} = [ \mathbf{f}_1, \mathbf{f}_2, \dots, \mathbf{f}_K ]$  sequentially as shown in Table 1. At the initial step,  $\mathbf{f}_1$  is obtained by solving

$$\max \mathbf{f}_1^H \mathbf{R} \mathbf{f}_1, \quad \text{s. t. } \|\mathbf{f}_1\| = 1 \text{ and } f_1[j] = 0, j \in \bar{\mathbf{d}}_1, \quad (9)$$

where  $\mathbf{f}_1$  contains zeros at the  $j$ -th positions and  $\bar{\mathbf{d}}_k$  is the complementary set of  $\mathbf{d}_k$ , i.e., the index for the unselected feeds' positions. A truncated power method has been proposed in [22] to solve such a sparse eigenvalue problem and its convergence has been proven. At the  $q$ -th iteration, we first update the full vector via  $\bar{\mathbf{f}}_1^{(q)} = \bar{\mathbf{R}} \mathbf{f}_1^{(q-1)} / \|\bar{\mathbf{R}} \mathbf{f}_1^{(q-1)}\|_2$  and then truncate  $\bar{\mathbf{f}}_1^{(q)}$  by restricting the elements indexed by  $\bar{\mathbf{d}}_k$  to zeros. The mask vector  $\mathbf{x}_k$  is used for truncation, where each element is defined as

$$x_k[j] = \begin{cases} 1, & j \in \mathbf{d}_k \\ 0, & j \in \bar{\mathbf{d}}_k \end{cases}. \quad (10)$$

The iteration of  $\mathbf{f}_1^{(q)}$  will be terminated until convergence, where  $\gamma \in \mathbb{R}$  is an arbitrary small number. We then remove the contribution of  $\mathbf{f}_1^{(q)}$  from the matrix  $\bar{\mathbf{R}}$  so that the interference among the beamforming vectors  $\mathbf{f}_k$  is alleviated.

**Table 1.** Greedy Sparse Recovery Algorithm

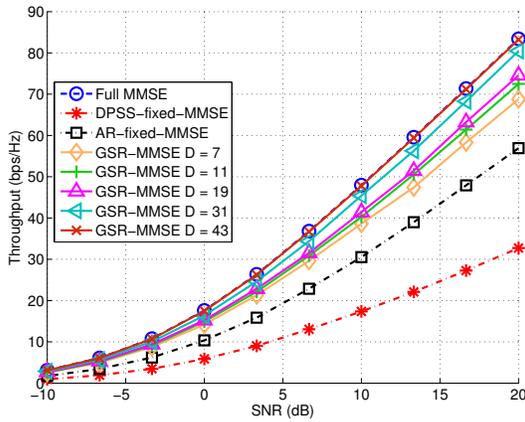
<b>Require:</b> $\mathbf{F}_{\text{OB}} = \text{empty matrix}, \mathbf{R} = \mathbf{R}$
<b>For</b> $k = 1, \dots, K$
<b>Initialize</b> $q = 1, \bar{\mathbf{f}}_k^{(0)} = \mathbf{x}_k$
<b>Repeat</b>
$\bar{\mathbf{f}}_k^{(q)} = \bar{\mathbf{R}} \bar{\mathbf{f}}_k^{(q-1)} / \ \bar{\mathbf{R}} \bar{\mathbf{f}}_k^{(q-1)}\ _2$
$\mathbf{f}_k^{(q)} = \bar{\mathbf{f}}_k^{(q)} \odot \mathbf{x}_k$
<b>Until</b> $\ \mathbf{f}_k^{(q)} - \mathbf{f}_k^{(q-1)}\ _2 < \gamma, q = q + 1$
<b>Return</b> $\mathbf{F}_{\text{OB}} = [ \mathbf{F}_{\text{OB}} \quad   \mathbf{f}_k^{(q)} ]$
<b>Update</b> $\bar{\mathbf{R}} = \left( \mathbf{I}_M - \alpha \mathbf{f}_k^{(q)} \mathbf{f}_k^{(q)H} \right) \cdot \bar{\mathbf{R}}, \quad \alpha = 1 / \ \mathbf{f}_k^{(q)}\ _2^2$
<b>End</b>

**OGB Design:** With the low-rank transformation by  $\mathbf{F}_{\text{OB}}$ , the OGB is carried out in a reduced dimension. Accordingly, compared to the fully OGB, it not only reduces the feeder link bandwidth but

also alleviates the efforts at the gateway such as beamforming and calibration by moving part of the DSP complexity to the satellite. Based on the equivalent channel  $\tilde{\mathbf{H}} = \mathbf{H}\mathbf{F}_{\text{OB}}$ , we apply the MMSE precoding technique for the OGB, i.e.,

$$\mathbf{F}_{\text{OG}} = \beta \left( \tilde{\mathbf{H}}^H \tilde{\mathbf{H}} + \frac{N_0 K}{P_T} \mathbf{I}_K \right)^{-1} \tilde{\mathbf{H}}^H, \beta = \sqrt{\frac{P_T}{\|\mathbf{F}_{\text{OB}} \mathbf{F}_{\text{OG}}\|_{\mathcal{F}}^2}}. \quad (11)$$

*Remarks:* If the full array is considered, the iterative truncated power method in Table 1 turns out to be the traditional power iteration for obtaining the eigenvectors, which approximates the solution in (8). Therefore, even though the proposed GSR algorithm is designed based on the feed selection, it can be directly applied to the full array case without any modifications. The solution in (8) seems to arrive at a similar solution as the robust OBB design in [18]. However, our proposed algorithm is developed based on a simple and completely different optimization criterion, which can be generally applied to both the feed selection and the full array cases, using long-term or non-adaptive CSI to obtain  $\mathbf{R}$ .



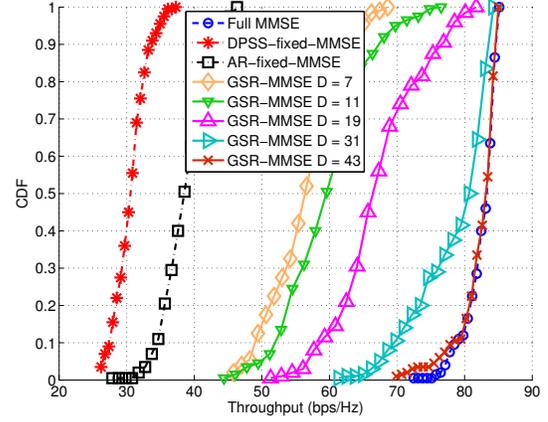
**Fig. 2.** Sum rate performance of various hybrid space-ground precoding schemes for users with fixed locations.

#### 4. SIMULATIONS AND CONCLUSIONS

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 only one user is active in one beam, i.e.,  $K = 11$ . The full frequency reuse and a single polarization of the satellite antenna are considered. According to the channel modeling in [4], the channel of the user service link is modeled by the Rician fading with the Rician factor of 7 dB. In the feed selection case, for simplicity the same number of feed elements is chosen for different spot beams.

*Users at fixed locations:* In this part, we consider that each user is located at the center of its spot beam. Figure 2 shows the sum rate performance of the proposed feed selection based GSR hybrid precoding scheme (denoted by “Hybrid GSR-MMSE”) and compares it with the hybrid fixed OBB & adaptive precoding using the DPSS and Bartlett methods (“Hybrid DPSS-MMSE” and “Hybrid Bartlett-MMSE”) as well as the fully OGB (“Full MMSE”). We can observe that the Bartlett based scheme outperforms the DPSS coun-

terpart mainly due to its smaller granularity and accordingly its dynamic as well as direction-aware nature. Proposed algorithm shows a much better performance than the DPSS or the Bartlett scheme. The performance of the proposed “Hybrid GSR-MMSE” precoding technique varies with the number of selected feed elements  $D$  and approaches that of the full array case when  $D$  is close to  $M$ .



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

**Table 2.** Performance and complexity of the “Hybrid GSR-MMSE” compared to the fully OGB MMSE at SNR = 20 dB

Availability	Performance			Complexity
	5%	50%	95%	$D/M$
$D = 7$	61.8%	67.7%	76.0%	16%
$D = 11$	64.4%	71.3%	82.0%	25%
$D = 19$	73.4%	79.8%	92.0%	43%
$D = 31$	87.2%	96.9%	98.9%	70%
$D = 43$	98.0%	99.8%	99.9%	98%

*Users at random locations:* The Cumulative Distribution Functions (CDFs) of the sum rate performance for various schemes are shown in Figure 3, where users are generated at random locations within their own spot beams. We can observe that the proposed “Hybrid GSR-MMSE” algorithm greatly outperforms the DPSS or Bartlett based hybrid schemes for all availabilities. Its performance for various  $D$  is closer around cell centers (at 95%) but diverges at cell edges (at 5%). We summarize the behavior of the proposed scheme in Table 2, where the performance is computed in percentage with respect to that of the fully OGB at various availabilities and the complexity is simply estimated by  $D/M$  for comparison. It is shown that the proposed hybrid space-ground precoding with  $D = 11 \sim 19$  is suggested, since an affordable performance degradation and a significant complexity reduction are observed.

#### 5. ACKNOWLEDGMENTS

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