On the Performance of Advanced Reflectarray Configurations for Multibeam Satellite Communications

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***Abstract*—The performance of two multiple beam antenna configurations based on reflectarray technology is compared. Both cases, for two-colour and four-colour reuse schemes in satellite coverage, make use of two antennas on-board the satellite, which leads to more compact designs as opposed to more traditional four reflector deployments. The comparison is made in terms of the received signal-to-noise-ratio and signal-to-interference-noise-ratio. In addition, an initial spectral efficiency comparison is performed by assuming single user detection at the terrestrial terminals. The two-colour scheme offers better performance indicators, specially for higher power regimes. Furthermore, the performance of the two-colour scheme can be potentially increased with the application of interference mitigation techniques for those locations with high co-channel interference.**

I. Introduction

Multiple beam antennas (MBAs) have become a key technology to enable broadband satellite communications in Ka-band [1]–[3]. The existing High Throughput Satellites (HTS) provide a cellular coverage formed by a large number of closely-spaced spot beams, which are produced at different frequencies and polarizations according to a multi-colour reuse scheme [1]. The standard MBA architecture consists of four reflectors in single-feed-per-beam (SFPB) configuration that produce a four-colour multispot coverage at transmit (Tx, 20 GHz) and receive (Rx, 30 GHz) frequencies from the satellite [2]. In this configuration, each reflector generates the spots associated to one colour (same frequency and polarization). The main drawback of this MBA system is associated to the accommodation of four large reflectors (between 2 and 2.5 m in diameter) on the satellite. Reflectarray antennas have been recently proposed as an attractive solution for the design of new MBA configurations to produce multispot coverage with a smaller number of main apertures (two instead of four) [4]- [5]. Unlike conventional SFPB reflectors, reflectarrays have the ability to produce separate beams in different polarizations and/or frequencies (different colours) with a single feed [6], making it possible to reuse the same aperture to produce the spots associated to different colours. Single and dual reflectarray configurations have been investigated for this application [4], [5]. In this contribution, the multispot coverage performance of two MBA configurations based on reflectarrays has been analysed and compared. The first MBA architecture consists of a dual-reflectarray antenna that is able to generate a continuous multispot coverage in two colours (two polarizations) for Tx in Ka-band. The second MBA system is based on two single-offset parabolic reflectarrays designed to produce a conventional four-colour multispot coverage (each reflectarray produces all the beams associated to two colours, at both Tx and Rx).

The performance of the two-colour and four-colour deployments, achieved by the proposed MBAs, has been evaluated in a basic scenario by assuming single user detection (SUD). Room is left for further studies in the two-colour case, since high co-channel interference is detected at certain locations: advanced inteference mitigation techniques could be potentially applied, as those presented in [7].

The rest of the paper is organized as follows. First, the two-colour and four-colour MBA are described in Section II. After that, the performance comparison between both schemes is presented in Section III. Finally, some conclusions are given in Section IV.

II. Antenna Configurations

A brief description of the two MBA systems considered in this work is provided below. The two configurations present a significant advantage compared to the four-reflector system, since they are able to generate a complete multispot coverage with a smaller number of main apertures.

A. Dual-Reflectarray Antenna to Produce a Two-Colour Multispot Coverage

The first MBA configuration is based on a bifocal dual-reflectarray antenna with an elliptical flat main reflectarray of dimensions 3.5 m x 1.8 m and a flat sub-reflectarray of 80-cm diameter, see Fig. 1. The bifocal technique has been applied to reduce the beam angular separation in the offset plane by a 50% with respect to the equivalent monofocal antenna [4], so that 0.56° separation is achieved between the beams produced by adjacent feeds. By exploiting the dual-polarization capability of the reflectarray cells, each feed will produce two adjacent beams in orthogonal polarization (two colours) in a plane forming 60°, so a continuous multispot coverage is finally obtained. More details about the design of the bifocal dual-reflectarray antenna can be found in [4].

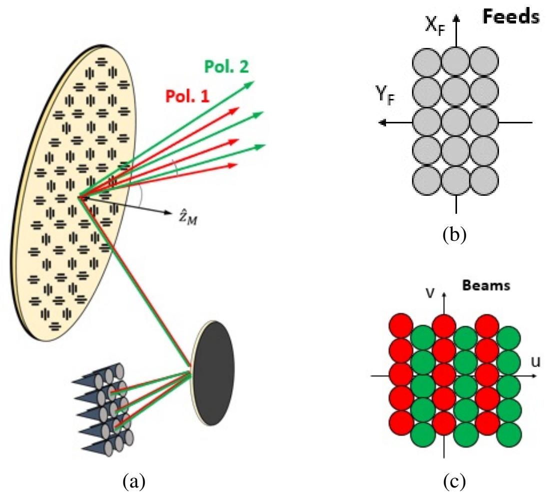

Fig. 1: (a) Representation of the bifocal dual-reflectarray antenna. (b) Feed cluster and (c) beam configuration associated to a two-colour coverage formed by 30 spots.

The designed dual-reflectarray antenna has been used to produce a continuous multispot coverage formed by 30 spot beams in a two-colour scheme at the Tx frequencies in Ka-band (20 GHz). The maximum gain of the spots is between 49 and 50.5 dBi, and the centre-to-centre spot separation is around 0.56°, which are typical coverage requirements for HTS systems in Ka-band [1]- [6]. The performance of this two-colour coverage will be analysed in Section III.

B. Two Single-Offset Parabolic Reflectarrays to Produce a Standard Four-Colour Coverage

The second MBA configuration is formed by two single-offset parabolic reflectarray antennas of 1.8-m diameter. Each parabolic reflectarray is able to produce half of the multispot coverage (two colours) at Tx and Rx frequencies in Ka-band, as shown in Fig. 2. The two antennas must be properly pointed to combine the two sets of beams and produce a complete four-colour multispot coverage. The Variable Rotation Technique (VRT) has been applied to the reflectarray elements in order to produce two spaced beams per feed (separated 0.56°) in orthogonal circular polarization simultaneously at Tx and Rx [5]- [6]. Additional information about the design of the 1.8-m parabolic reflectarray based on VRT can be found in [5].

A four-colour multispot coverage formed by 30 spot beams with the same lattice than the previous two-colour coverage has been generated at the Tx frequencies in Ka-band using the second MBA configuration. The maximum gain of the spots is around 50 dBi, and the spot separation is again 0.56°. The performance of the four-colour coverage will be analysed and compared with that of the two-colour coverage provided by the previous MBA system.

III. Performance Comparison

The two presented antenna configurations will be initially compared in terms of signal-to-noise-ratio (SNR) and signal-to-interference-noise-ratio (SINR). For this purpose, the satellite spot-beam coverage is obtained and presented for the different antenna configurations in Figs. 3 and 4. To proceed

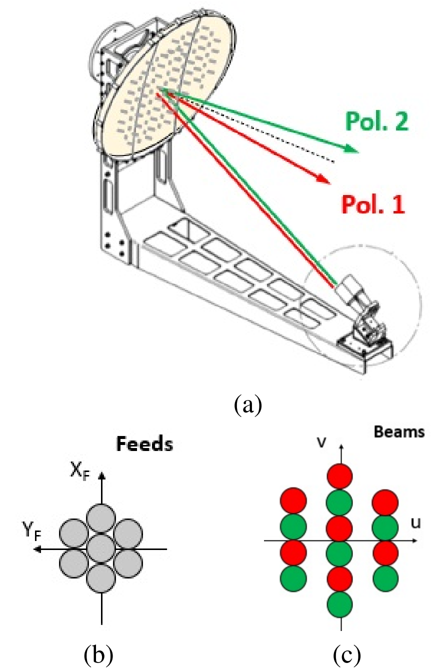

Fig. 2: (a) Representation of one of the two parabolic reflectarray antennas. (b) Feed cluster. (c) Beam configuration corresponding to one half of the multispot coverage (two colours).

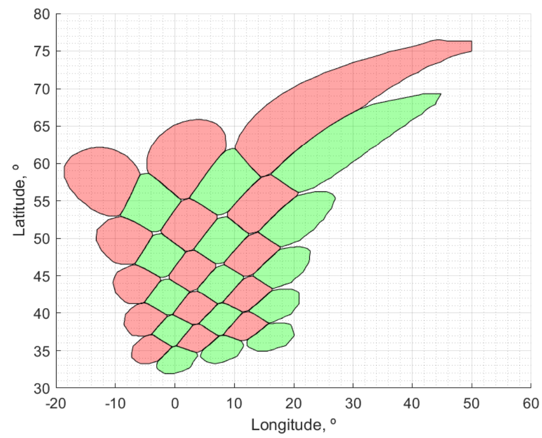

Fig. 3: Diagram pattern of the two-colour reuse scheme with the dual-reflectarray antenna.

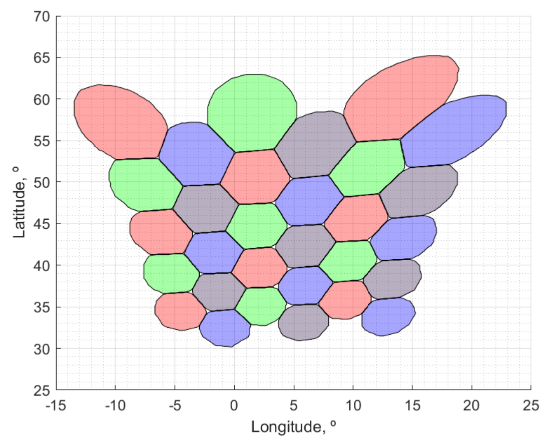

Fig. 4: Diagram pattern of the four-colour reuse scheme with the two single-offset parabolic reflectarrays.

with the comparison, we are going to assume a basic scenario in which the users are only served by its dominant beam. Thus, the SNR of a user within the i-th beam is given by

$$\mathsf{SNR}_i = \frac{P_T}{N_o \cdot BW}|h_i|^2 \tag{1}$$

where P_T is the transmit power, N_o is the noise power density ratio, BW the available bandwidth and $|h_i|$ the channel magnitude. This channel magnitude is obtained with the antenna feed gain as

$$|h_i| = \frac{\sqrt{GF_i}}{4\pi d/\lambda}. \tag{2}$$

Here, the term G refers to the receiver antenna gain, and F_i represents the gain of the i-th feed. As for the rest of the terms, λ is the carrier wavelength, with d the distance from the satellite to the user. On the other hand, the SINR of a user within the i-th beam can be expressed as

$$\mathsf{SINR}_i = \frac{P_T|h_i|^2}{N_o \cdot BW + P_T \sum_{k\in\mathcal{C}} |h_k|^2} \tag{3}$$

where $\mathcal{C}$ is the set of beam indexes that employs the same colour as the i-th beam. With respect to the available transmission power P_T, and for a fair comparison, we are going to assume the same power for both two-colour and four-colour schemes. To set this power value, the system is calibrated to achieve a given value of average SNR at the centers of the beams in the four-colour scheme. Note that the average SNR in the case of the two-colour scheme will be 3 dB lower, due to the additional noise power in twice the available bandwidth per beam.

The empirical probability distribution function (pdf) of the SNR and SINR are presented in Figs. 5-8 for different system calibration points. The four-colour scheme presents lower variation on the SNR values due to the 3-4 dB roll-off [5]. However, the co-channel interference seems to have a severe impact on the SINR as we move to high power settings. On the other hand, the two-colour scheme presents a higher variation on both SNR and SINR. The main reason behind this is the higher roll-off of the radiated power across the beam, around 11 dB [4]. In addition to that, very low SINR values can be found due at those locations with high levels of interference, at the boundary between two spot-beams with the same colour. Due to the more aggressive frequency reuse in the two-colour scheme, we could expect a more severe impact on the SINR with respect to the four-colour scheme as power increases. Interestingly, the impact on the SINR is similar in both cases: the higher roll-off of 11 dB of the two-colour scheme is providing a better overall resilience to the co-channel interference, confining highly interfered users at the boundaries between two spot-beams with the same colour.

For benchmarking purposes, we assume single user detection receivers, by treating the co-channel interfering signals as noise. In this case, the theoretical maximum rate for a given user i is obtained as

$$r_i = \mathsf{BW} \cdot \log_2(1 + \mathsf{SINR}_i). \tag{4}$$

The two-colour scheme happens to perform better in terms of the achievable transmission rates. The corresponding improvement is summarized in Fig. 9 for the different system

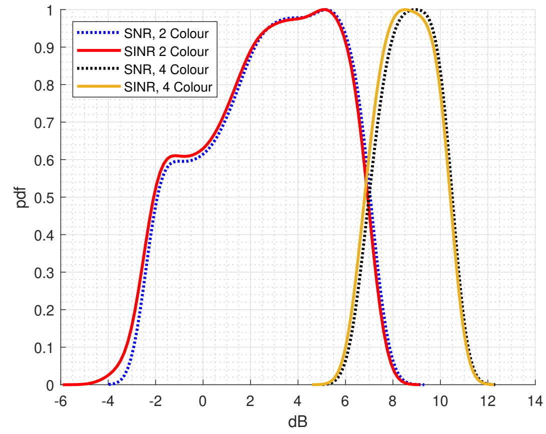

Fig. 5: SNR and SINR probability density distributions for the two-colour and four-colour schemes. Power is calibrated to obtain an average of SNR=10 dB at the center of the beams in the four-colour scheme.

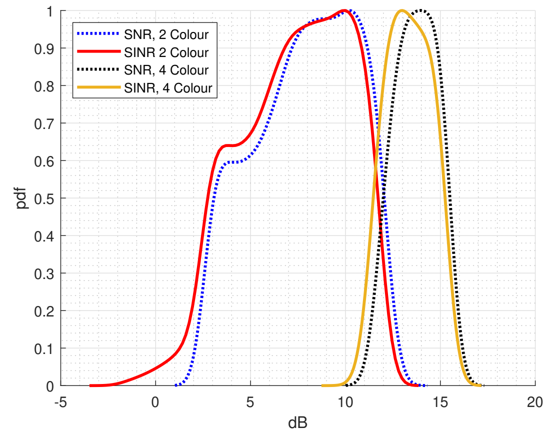

Fig. 6: SNR and SINR probability density distributions for the two-colour and four-colour schemes. Power is calibrated to obtain an average of SNR=15 dB at the center of the beams in the four-colour scheme.

calibration points. The better overall resilience of the two-colour scheme to the co-channel interference results in a better average efficiency with respect to the four-colour scheme as the power increases. However, the overall system fairness of the two-colour scheme is not good due to the locations with very low SINR levels, and consequently, with very low rate values. The application of more advanced transmission schemes to mitigate the co-channel interference can be a solution to try to even the overall performance of the system, and thus, increase the fairness. For example, interference can be mitigated with precoding solutions [8], [9], or with more advanced receivers that perform successive interference cancellation (SIC) [7], [10]. However, the potential improvements with the application of these techniques are made at the cost of increasing the gateway and/or the receivers complexity.

IV. Conclusions

In this paper, two multiple beam antennas for different colour schemes have been compared. A dual-reflectarray and two single-offset parabolic reflectarrays are presented to synthesize two-colour and four-colour reuse schemes, respectively, both providing more compact designs than traditional

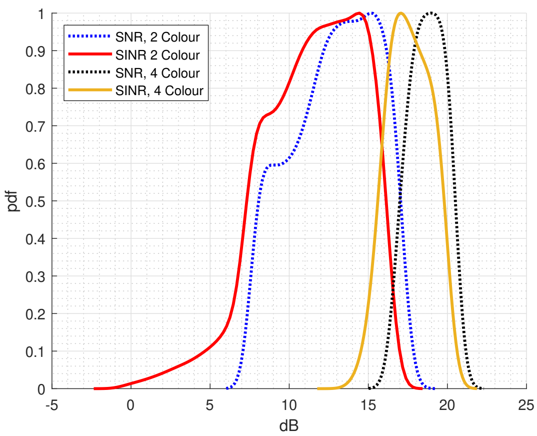

Fig. 7: SNR and SINR probability density distributions for the two-colour and four-colour schemes. Power is calibrated to obtain an average of SNR=20 dB at the center of the beams in the four-colour scheme.

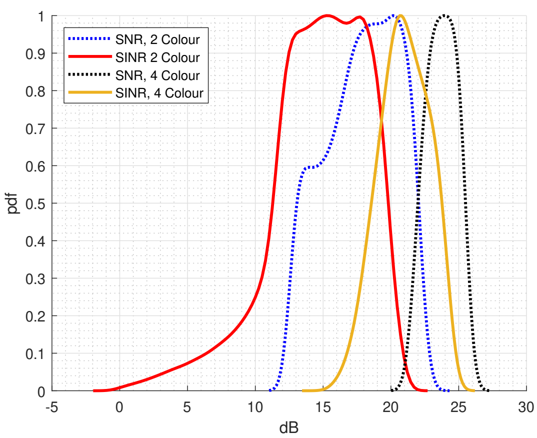

Fig. 8: SNR and SINR probability density distributions for the two-colour and four-colour schemes. Power is calibrated to obtain an average of SNR=25 dB at the center of the beams in the four-colour scheme.

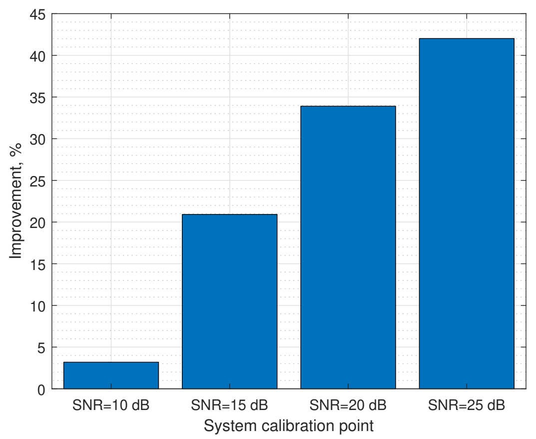

Fig. 9: Improvement on the average rates of two-colour scheme vs. four-colour scheme. Single User Detection is performed at the receivers.

four reflector deployments. The higher co-channel interference suffered with the aggressive two-colour solution is mostly confined at the boundaries of the spot-beams, due to the high radiated power roll-off. Thus, it outperforms the four colour deployment in terms of the overall achievable transmission rate, at the cost of a higher unbalance in the provided rates to the different users. This drawback could be addressed with the application of interference mitigation techniques in future studies. Additionally, the implication on the payload complexity for both antenna configurations should be taken into account for a comprehensive comparison.

Acknowledgements

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