2022 11th Advanced Satellite Multimedia Systems Conference and the 17th Signal Processing for Space Communications Workshop (ASMS/SPSC) | 978-1-6654-7377-4/22/$31.00 ©2022 IEEE | DOI: 10.1109/ASMS/SPSC55670.2022.9914760

Satellite Beam Densification for High-Demand Areas

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***Abstract*—Conventional multi-beam pattern design in Geostationary (GEO) satellite communication systems consists of a regular grid of non-reconfigurable beams, where the beams overlap is typically assumed at the point where the beam edge reaches a 3-dB loss in the antenna pattern (with respect to the beam center). For certain high demand areas, this 3dB loss has a significant impact. To overcome this issue, in this paper we evaluate the potential gain of beam densification, i.e. considering an increased number of beams (keeping the same beam size and shape) to cover hot-spot areas, with the aim to push the beam overlap and increase the beam gain. In particular, we compare two beam patterns (kindly provided by ESA): One with regular beam grid, and one with densification in a particular hot-spot area. We provide a comparison in terms of per-beam average SINR and capacity, as well as an overall system analysis considering the whole densified region.**

***Index Terms*—Multi-beam high throughput satellite systems, beam pattern design, beam densification.**

I. INTRODUCTION

High-density 5G small cell deployments has been identified as a fundamental design direction for a successful rollout in urban settings where demand is high and efficient spectrum reuse is essential [1]. Accordingly, the next generation of cellular systems is implementing a high number of small cells to increase the network capacity and provide the required data rates [2], [3].

High Throughput Satellite (HTS) systems are facing similar challenge to cope with the emerging volume of data traffic, driven by internet data-hungry applications [4], [5]. As in the terrestrial domain, a satellite beam densification strategy can help in optimizing the resource utilization.

Conventional HTS systems operate with a multi-spot coverage with intensive frequency and polarization reuse, typically with the so-called 4 Color Reuse (4CR), i.e. two orthogonal frequency blocks and two orthogonal polarizations [6]. This conventional design does not take into account the spatial distribution of the demand on Earth and aims at providing the same capacity to all spot beams [7].

However, due to rapid population growth and its spatial distribution, the communication traffic is highly non-uniform over the Earth. This has let to hot-spot regions with high capacity requirement over Europe, Eastern and Western United States and South East Asia [8]. Accordingly, traditional method of regular spot-beam grid with spectral reuse of 4 non-interfering frequency resources fails to provide demand satisfaction at these so called high demand hot-spot regions [9]–[11].

Hence, demand-based satellite beam designs try to address such uneven demand distribution in more recent works including [12] and [13]. However, such design would require to change the satellite payload architecture and will increase operational cost. On the other hand, the authors of [14], increase or reduce the signal overlap at beam edge after defining a fixed number of beams and the related beam center locations. However, even though, the numerical assessment revealed better performance in terms of average spectral efficiency, such approach will fail to exploit the spacial isolation in terms of interference mitigation that can be obtained in higher order frequency reuse.

Hence, in this paper, we evaluate the potential benefits of a beam densification strategy, where more beams are generated to cover high demand areas. Furthermore, due to advancements in technologies such as phased array antennas and a digital transparent processors, increasing the number of beams will not majorly impact the complexity.

By increasing the beams overlap, we reduce the beam gain gap between users in beam center and users in beam edge, which typically suffer from a 3-dB loss in the antenna pattern when considering regular beam grid. Furthermore, by retaining the same beam size, we do not increase the complexity of the payload architecture even after densification. Also, unlike previous works, we evaluate different frequency reuse schemes to handle the inter-beam interference introduced by densification.

This work represents a preliminary study, where a specific non-densified beam pattern is compared with a densified beam pattern. However, the preliminary results observed in this comparison are encouraging, with several open research directions that are discussed at the end of this paper.

The rest of the paper is organised as follows: In Section II, the system and channel model employing multi-beam high throughput satellite system and channel is described. In Section III, opportunistic regular beam densification is discussed with pros and cons along with multiple frequency reuse factors such as 4-color frequency reuse, 16-color frequency reuse and full frequency reuse with precoding. Section IV provides the simulation results, and section V concludes the paper with insights of the future work.

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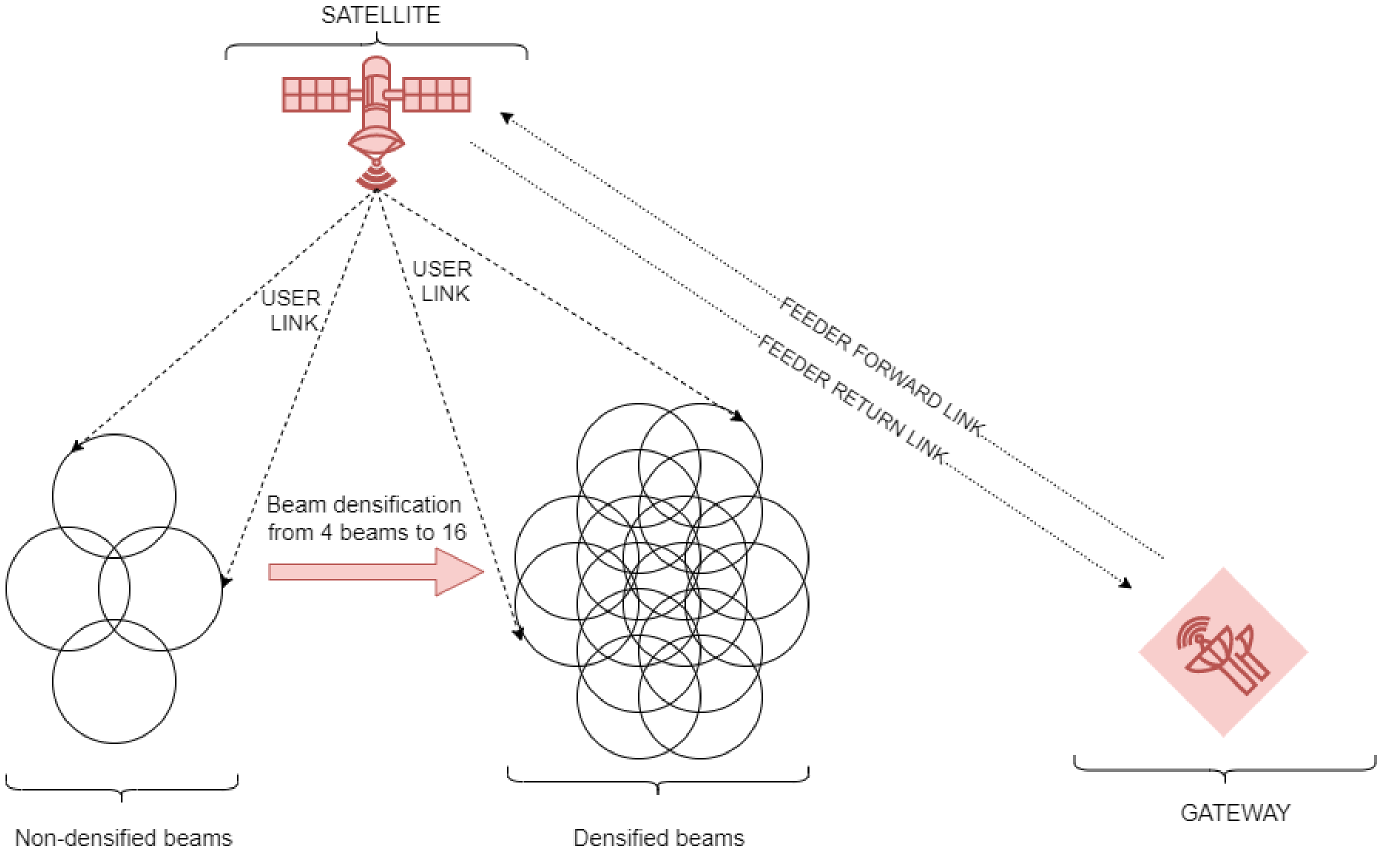


Fig. 1: System Model

II. System and Channel Model

The system model includes a ground segment with an ideal feeder link (single gateway) and a bent pipe space segment (high throughput multi-beam satellite with beamforming capabilities) as shown in Figure 1. The gateway performs the signal processing and sends the transmission signals in the feeder forward link. Also, when precoding is enabled, the gateway computes the precoding matrix using low-complexity linear precoding techniques [15] and sends precoded signals in the feeder forward link.

The satellite receives the signal, amplifies it, translates it to a downlink frequency, amplifies it again, and directs it toward the users on earth in the user link using a high-gain antenna. The user link is per DVB-S2(X) [16] standardization, where Adaptive Coding and Modulation (ACM) ensures the adaptation of transmission parameters for link variations. The user forward link has K spot beams across the coverage area of consideration. We consider unicast scheduling and hence, one user per beam is assumed. The received signal of user n is y_n and is expressed as,

$$y_n = \mathbf{h}_n^T \mathbf{x} + \mathfrak{N}_n, \tag{1}$$

where $\mathbf{h}_n \in \mathbb{C}^{K\times 1}$ is the CSI vector corresponding to this particular user. By rearranging all the users' received signals in a vector $\mathbf{y} = [y_1 \dots y_N]^T \in \mathbb{C}^{K\times 1}$, the above model can also be expressed as,

$$\mathbf{y} = \mathbf{H}\ \mathbf{x} + \mathfrak{N}, \tag{2}$$

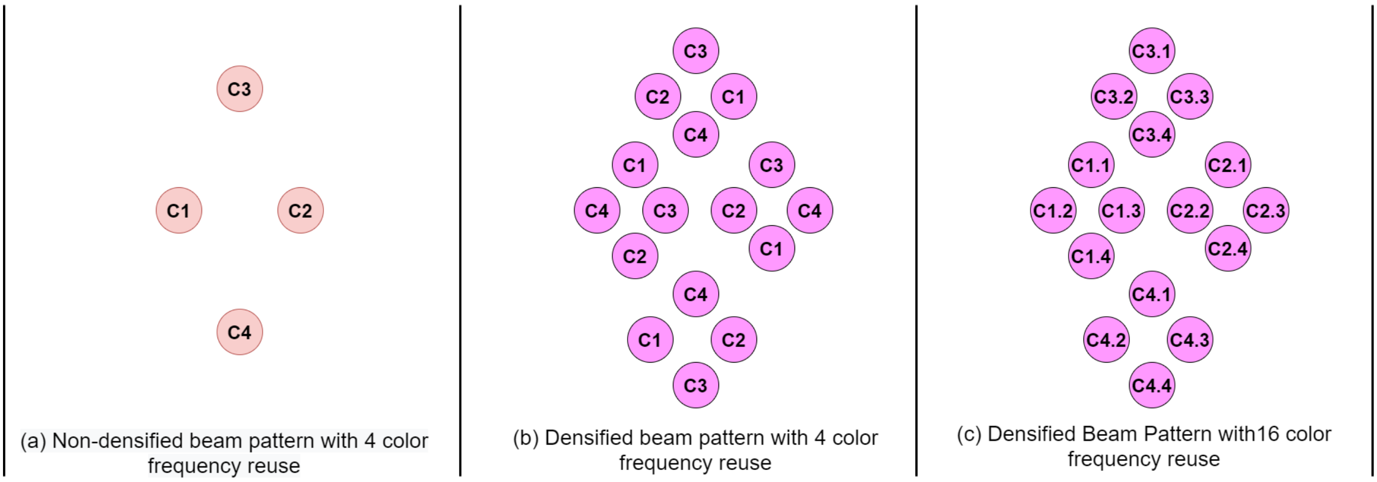
by considering $\mathbf{H} = \Phi^{(LNB)}\Phi^{(prop)}\mathbf{B} \in \mathbb{C}^{K\times K}$, where $\mathbf{B} = [\mathbf{b}_1 \dots \mathbf{b}_N]^T \in \mathbb{R}^{K\times K}$ is the system channel matrix whose the (n, k)th component is given by,

$$[\mathbf{b}]_{n,k} = \frac{\sqrt{G_{Rn}G_{kn}}}{(4\pi\frac{\mathfrak{D}_{nk}}{\lambda})}, \tag{3}$$

where λ is the wavelength of transmission, G_{kn} is the gain of beam k in the direction of user n, G_{Rn} is the user's receive antenna gain and $\mathfrak{D}_{nk}$ is the distance between the satellite transmit antenna and user's receiving antenna. The phase noise due to user terminal (Φ^{LNB}) is introduced by the users' LNB downconverters are modelled as gaussian random variable with zero mean and standard deviation of $\sigma_{RX} = 0.24°$. The phase noise due to RF propagation (ϕ^{prop}) depends on the user-to-satellite distance and is modelled as,

$$\phi^{prop} = \frac{2\pi}{\lambda}\mathfrak{D}_{nk}[rad]. \tag{4}$$

When we evaluate the performance of color coded schemes, we do not perform precoding and **x** represent vector of transmit symbols. However, when we evaluate full frequency reuse with precoding, **x** represents the precoded signal.



(a) Non-densified beam pattern with 4 color frequency reuse

(b) Densified beam pattern with 4 color frequency reuse

(c) Densified Beam Pattern with16 color frequency reuse

Fig. 2: Color coding

III. OPPORTUNISTIC REGULAR BEAM DENSIFICATION

Opportunistic beam densification involves in densifing the high demand hot-spot regions with higher number of beams. However, increasing the number of beams does not necessarily mean increase in total power and bandwidth. The system power and bandwidth distribution remains same before and after densification.

In this work, we consider a non-densified beam pattern with $K = 4$ parent beams, and when densified regularly, we replace the 4 parent beams with 16 child beams as shown in the Figure 1. The positions of the child beams are placed around the parent beam in regular fashion.

Beam densification in this case, does not mean that the child beams are narrow beams or directed beams with higher antenna gain. The child beams will retain the shape and size of the parent beam with an intrest to not increasing the complexity of payload architecture.

Such coverage densification will benefit in two ways.

1) Firstly, beam densification facilitates the users to have better antenna gain. Around the beam edges of non-densified beams, the typical antenna gain reaches a 3-dB loss in the antenna pattern with respect to the beam center. However, upon densification, antenna gain around the beam edges are significantly improved as the beam edges are now at lower loss in the antenna pattern.
2) Secondly, upon densification, we can serve more users simultaneously. In this work, as we consider one user per beam, with the increase in the number of beams, the number of users served simultaneously increases from 4 to 16.

Consequently, on the downside, opportunistic regular beam densification translates into more overlapping coverage areas causing considerable interference levels among different beams. Hence, we perform a system design trade-off analysis to evaluate the performance of beam densification for two different frequency coloring / reuse, including full frequency reuse with and without linear precoding.

TABLE I: Bandwidth allocation

Beam Pattern	Frequency Reuse Factor	Bandwidth per beam
Non-densified	4CR	250 MHz
	FFR with precoding	1000 MHz
Densified	4CR	250 MHz
	16CR	62.5 MHz
	FFR with precoding	1000 MHz

A. Color coding

Frequency reusing allows us to use the same radio transmission frequencies for multiple spot beams, provided that they are separated by considerable distance. The geographical isolation between beams that use same frequencies ensures that they cause minimum interference for each other.

In 4-color frequency reuse (4CR), the total available bandwidth is divided into 4 parts. When allocating the frequencies to the beams, we ensure that no two beams that are adjacent to each other are been assigned with same transmission frequencies/colors. However, as orthogonality can also be obtained by polarization (right circular and left circular polarization can provide additional two colors), in practice, the total bandwidth is divided into two parts to obtain two colors and the other two colors are obtained by polarization. Figure 2a shows the 4CR coding for non-densified 4 beam centers. Figure 2b shows the 4CR coding for densified 16 beam centers.

Similarly, in case of 16-color frequency reuse (16CR), the available system bandwidth is divided by 8 to obtain 8 colors and the remaining 8 colors are obtained by polarization. Figure 2c shows the 16CR coding for densified 16 beam centers.

Table I provides the frequency allocation for different color codes. In the non-densified case with 4CR, the bandwidth allocated per beam is 250 MHz. Similarly, in densified case with 4CR and 16CR, the bandwidth availability per beam is 250 Mhz and 62.5 MHz respectively. Hence, higher the frequency reuse factor, lower will be the available bandwidth per beam.

B. Full frequency reuse with MMSE precoding

Full frequency reuse (FFR) implies that we use same transmission frequencies for all the spot beams of the system. Hence, as shown in Table I, the total system available bandwidth will be the available bandwidth per beam. Furthermore, as we had considered the advantages of polarisation in color coding cases, for fair comparison, the available bandwidth per beam while using FFR is 1000 MHz. However, as there is no geographical separation or isolation between beams of the same color, FFR introduces high inter beam interference in all the beams. Hence, we use precoding as an effective interference mitigation tool.

The precoded signal is given by,

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

where $\mathbf{W}$ is the precoding matrix and $\mathbf{s}$ is vector of transmit symbols that satisfies $\mathbb{E}[\mathbf{s}\mathbf{s}^H] = \mathbf{I}$. The precoding matrix $\mathbf{W}$ is obtained with the well-known MMSE design, which can be expressed as,

$$\mathbf{W}_{RZF} = \eta \boldsymbol{H}^{\boldsymbol{H}}(\boldsymbol{H}\boldsymbol{H}^{\boldsymbol{H}} + \alpha_r \boldsymbol{I})^{-1}, \tag{6}$$

where α_r is a predefined regularisation factor which is equal to the standard deviation of noise and η is the power allocation factor defined as,

$$\eta = \sqrt{\frac{P_{tot}}{\text{Trace}(\mathbf{W}\mathbf{W}^{\dagger})}}, \tag{7}$$

with P_{tot} being the total available power.

IV. SIMULATION PARAMETERS AND RESULTS

The considered antenna pattern corresponds to a GEO 13°E satellite operating at the Ka exclusive band 19.7 to 20.2 GHz. Out of 108 beams under study, we consider 4 non-densified beams that convert into 16 densified beams.

We consider unicast scheduling with K users scheduled in K beams where each of the user position is randomly selected. Accordingly, before densification, we schedule 4 users in the high demand region using 4 beams. After densification, we use 16 beams to schedule 16 users in the same high demand region.

For fair comparison, we consider equal power before and after densification. At target hot-spot area, the Satellite total radiated power is considered as 166.67 W. This power is shared between 4 beams in the case of non-densified scenario and furthermore, it is shared between 16 beams in the densified case. The other simulation parameters can be found in Table II.

TABLE II: Simulation Parameters

Satellite longitude	13° East (GEO)
Satellite total radiated power, P_T	166.67 W
Total Number of Beams, N_B	4 (non densified), 16 (densified)
Beam Radiation Pattern	Provided by ESA
User link bandwidth, B_W	500 MHz
Roll-off Factor	20%
Antenna Diameter	0.6
Terminal antenna efficiency	60%
DL wavelength	0.01538 m
Number of symbols duration, T	100

A. Performance Metrics definition

1) Signal to Interference plus Noise Ratio (SINR): The Signal to Interference plus Noise Ratio (SINR) is defined as the power of a certain signal of interest divided by the sum of the interference power (from all the other interfering signals) and the power of some background noise. The mean SINR value is defined using the expression below, where K denotes the number of beams.

$$SINR_{Mean} = \frac{\sum_{k=1}^{K} \frac{\sum_{t=1}^{T} SINR^{(k,t)}}{T}}{K}. \tag{8}$$

2) Capacity based on DVB-S2X: DVB-S2X [16] defines a table to map SINR to Spectral Efficiency (SE) based on ACM vales. The offered capacity obtained using SE (in DVBS2X defined table) can be analysed for more practical systems. The system capacity based on DVB-S2X is defined using,

$$C_{DVB-S2X} = \frac{\sum_{k=1}^{K} \frac{\sum_{t=1}^{T} C_{DVB}^{(k,t)}}{T}}{K}. \tag{9}$$

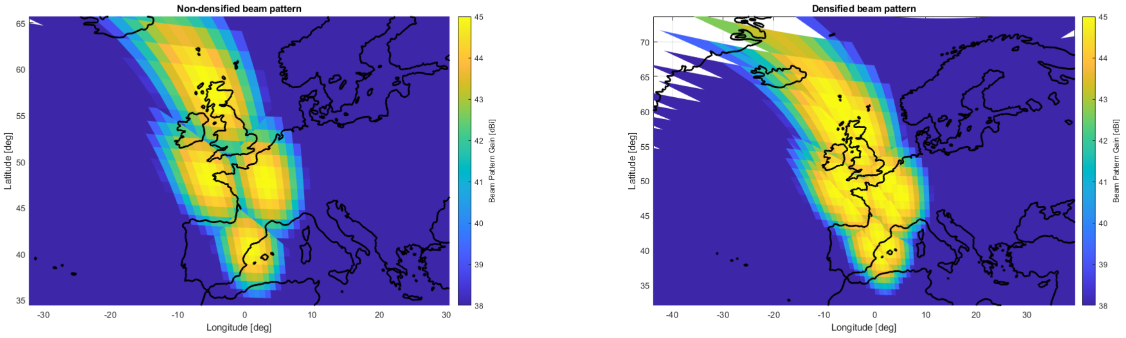
3) System Capacity based on DVB-S2X: Similarly, system capacity based on DVB-S2X is expressed as,

$$C_{DVB-S2X}^{sys} = \sum_{k=1}^{K} \frac{\sum_{t=1}^{T} C_{DVB}^{(k,t)}}{T}. \tag{10}$$

B. Performance evaluation

The Figure 3 shows the comparison between beam pattern gain values before and after densification. Upon beam densification, the gain values in the high demand hot-spot regions have improved considerably. In Figure 3a, which represents the non-densified beam pattern, there are more regions with lesser values of beam pattern gain (near the beam borders). Furthermore in Figure 3b, most of the regions show higher values of beam pattern gain. Hence, densification improves the beam pattern gain values.

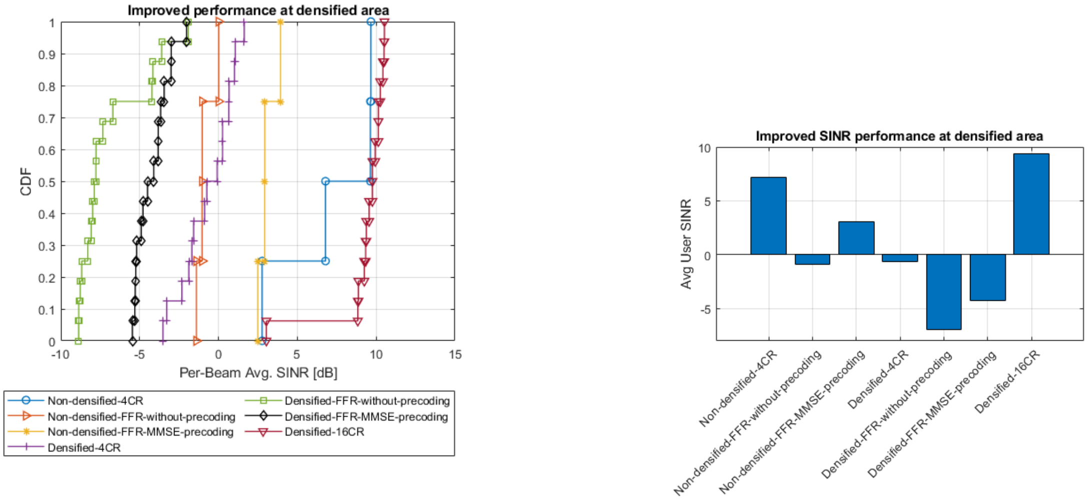
Figure 4 shows the results achieved in terms of per-beam SINR and average user SINR. Figure 4a shows the CDF of the per-beam average SINR. We can observe that SINR values of 16CR-densified has increased considerably, which was expected. This can be more simply understood using the Figure 4b which provides the average user SINR. The gains in SINR comes from the fact that the worst user in the coverage is at higher beam gains after densification. Furthermore, using a 4CR scheme in the densified beam pattern results in low SINR values due to the increase in inter-beam interference.



(a) Non densified beam pattern.

(b) Densified beam pattern

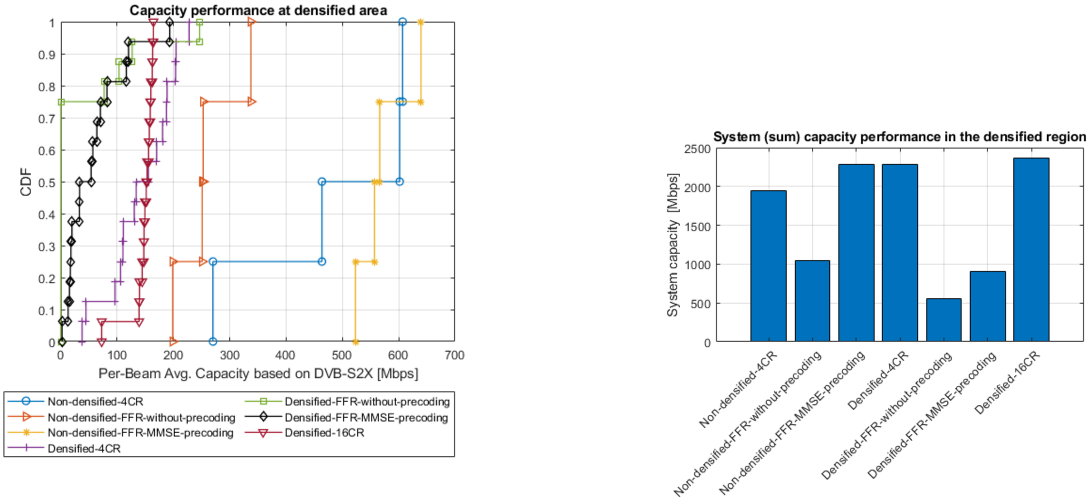
Fig. 3: Improved antenna gain values after densification



(a) CDF plots of per-beam avg SINR.

(b) Avg user SINR.

Fig. 4: Improved SINR at densified region



(a) Per beam average capacity.

(b) System capacity.

Fig. 5: Capacity performance at densified region

Figure 5 shows the offered DVB-S2X defined system capacity. It is fair to compare non-densified-4CR with densified-16CR because they are of same complexity without any additional complexity introduced by precoding. From both the plots 5a and 5b, it is evident that upon densification with 16CR, we gain more in comparison to non-densified 4CR. Furthermore, it should be noted that, in non-densified cases, we are serving only 4 users but in densified case, we are able to serve 16 users simultaneously.

Densified 16CR performs similar to non-densified-FFR-MMSE-precoded case. Nevertheless, precoding comes with additional complexity. Also, from 5b densified-4CR performs very well in terms of system capacity. However, even when the offered system capacity is higher, from Figure 4, 4CR-densified does not perform at user SINR level.

When considering FFR, we can observe that the SINR achieved with densified-FFR-MMSE-precoding is poor. The justification for such poor performance can be the fact that the inter-beam interference is very high and precoding has problems in mitigating such interference. Therefore, it seems that the particular densification applied in this scenario is degrading the performance of FFR.

V. SUMMARY AND FUTURE WORK

Beam densification has been identified as a key development for the next generation of satellite systems. While beam densification facilitates to increase the number of users served simultaneously, it also benefits from providing better antenna gain for the users. From the design trade-off analysis conducted in this paper, densification increases the beam pattern gain in the densified region. Furthermore, as densification also increases the inter-beam interference, it has to be combined with an appropriate frequency reuse scheme. For example, in this work, 16CR frequency reuse scheme performs well after densification. Also, particular densification considered herein, full frequency reuse performs poorly in terms of offered capacity. This may be justified by a too aggressive densification, which generates strong levels of interference.

As an extension of this work, possible future works include, evaluation of the impact of densification on the neighbouring beams. Furthermore, the beam densification considered in this report is regular, such that the child beam centres are placed in a defined order around the parent beam. However, the position of the densified child beams can be optimized for ideal beam densification. Furthermore, we can optimize over the number of required child beams based on the demand requisites in the parent beam. This approach shall lead do more dynamic demand based design. Lastly, while using more colors, we can achieve less inter beam interference (SINR), but, by using less colors, we can gain in transmission bandwidth (in turn improve offered capacity). Hence, for a given densified beam pattern, instead of selecting fixed frequency reuse factors (like 4 or 16), we can find the optimized number of colors required for maximum demand satisfaction. In addition, we can also jointly find optimized color-beam association that result in least inter beam interference.

VI. ACKNOWLEDGEMENTS

The beam patterns used in this work was kindly provided by European Space Agency (ESA). This work was supported by the Luxembourg National Research Fund (FNR) under Industrial Fellowship Scheme with industrial partner SES S.A., project REGAL," grant FNR14147087 and under the project FlexSAT (C19/IS/13696663)."

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