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Interference in Cellular Satellite Systems

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1. Introduction

In cellular satellite communications systems, a given coverage area is typically filled with a network of contiguous spot beams, which carry concentrated radiation along preferred directions. The coverage regions for such applications are typically large areas, such as continents and many beams need to be generated.

Due to bandwidth limitations in cellular communications, the same bandwidth is allocated to beams which are isolated spatially. This is known as frequency reuse, and the beams operating at the same frequency are referred as co-channel beams. While this approach allows a large coverage area with limited bandwidth, the co-channel beams have the potential to interfere with each other. This is known as co-channel interference and its nature and how it could be reduced is the focus of this chapter.

The interference in multiple beam satellite communications systems will be investigated under two different approaches. First approach, which is the conventional way of defining beam coverage on earth, is discussed in Section 2. This will be referred to as spot beam coverage as explained in further detail later. The interference will be investigated for two cases; first is the uplink where interference at the satellite antenna is the main concern, and the second is the downlink where interference at the user terminal is calculated. Section 3 discusses a new method of defining beam coverage on earth, referred to as sub-beam coverage. The motivation is to keep the coverage on earth identical but reduce the satellite antenna size as much as 50% (Kilic & Zaghloul, 2009). The advantages and overall performance of the sub-beam approach in terms of interference is the subject of Section 3.

2. Interference in Cellular Satellite Systems

In multibeam satellite systems, the coverage area is divided into a number of beams often referred to as spot beams, which are much smaller in size and cover the area contiguously.

Since satellite systems are bandwidth limited, the sub-division of beams into smaller portions allow for frequency reuse to increase capacity. The available bandwidth is shared among these beams as depicted in Figure 1 for reuse factor of n.

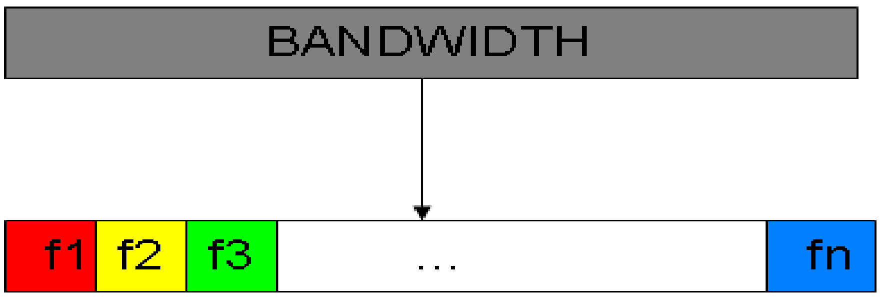

Fig. 1. Frequency reuse in multi-beam satellite communications

The size of the antenna that generates these beams on earth is related directly to the peak gain at the center of the spot beams and the smallest spot beam size. The spot beams are typically defined by the contours at 3 or 4 dB down from the peak power at the center of the beam.

2.1 Coverage on Earth

Achieving a contiguous coverage is important so that there are no regions without service in the coverage area. Since the beams are defined by the projection of antenna patterns on earth at a certain contour value, they tend to be close to circular shape. These circles on earth need to be structured so that they overlap with each other to avoid any gaps in the coverage area. In order to have a systematic approach, these can be represented by various geometric lattices that tessellate. A few such possibilities are shown in Figure 2. It is often the hexagon that is used in the system design as it closely represents a circle, i.e. for the same distance from the center to the edge, the hexagon area is closest to that of the circle that circumscribes it. Therefore the hexagon represents the beam which circumscribes it as shown in Figure 3. This assures that there are no gaps between beams. Then the system is designed based on this artificial hexagonal geometry on earth as depicted in Figure 4.

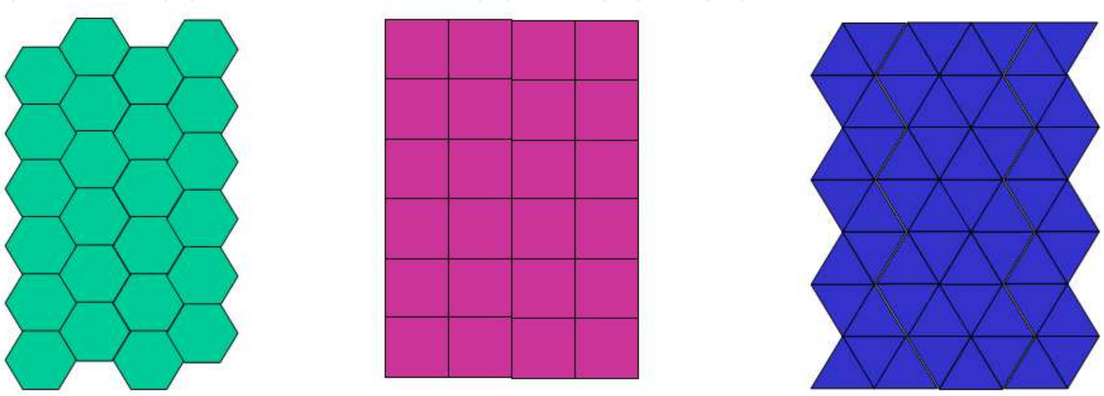
Fig. 2. Contiguous coverage on earth using tessalating shapes – hexagonal, square and triangular lattices

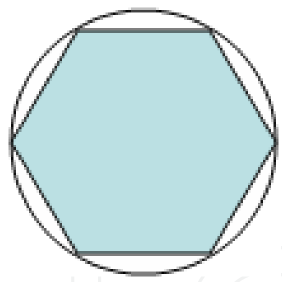

Fig. 3. Hexagonal representation of a circular beam

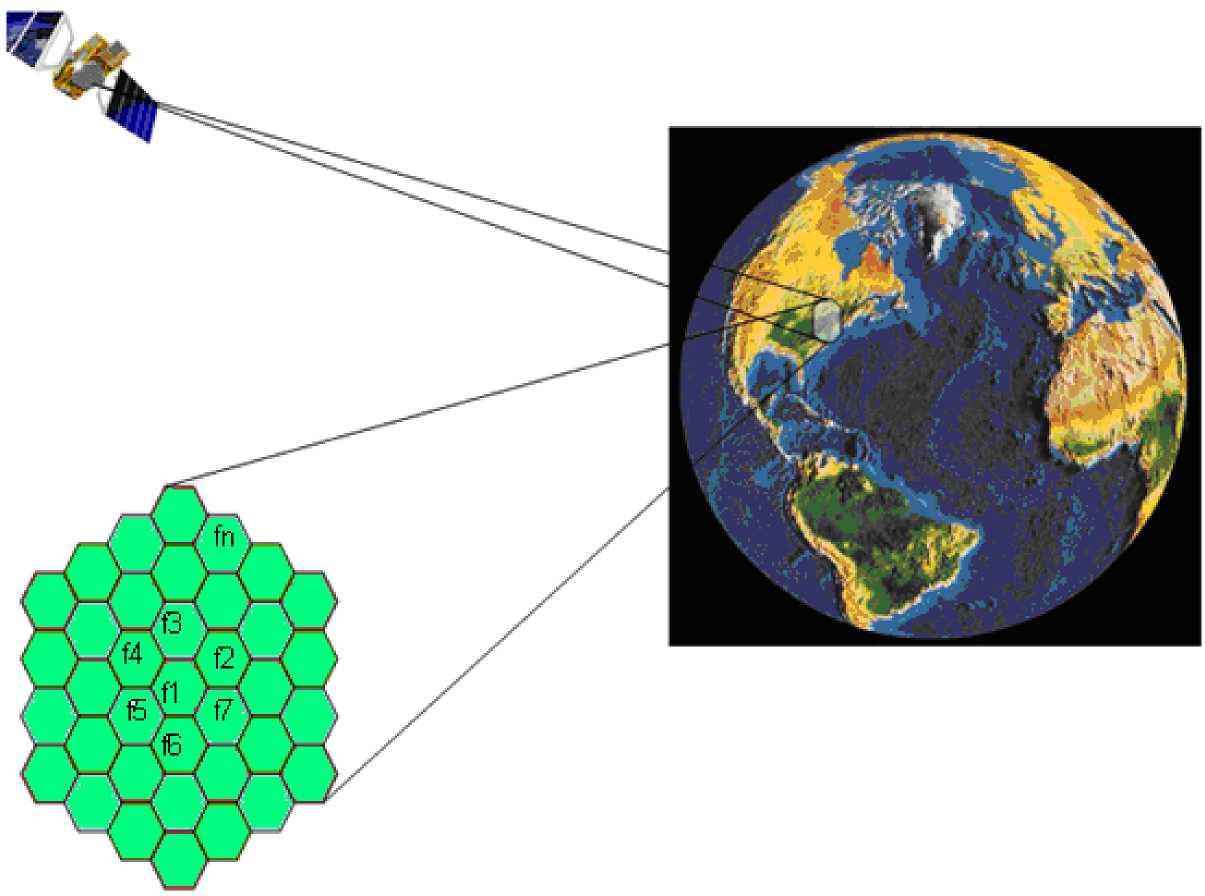

Fig. 4. Hexagonal Coverage on Earth

2.2 Frequency Reuse

Since the satellite systems typically serve large ares such as countries or continents, a large number of beams need to share the available bandwidth. Therefore, the available bandwidth within a beam becomes a very limited resource, as is implied in Figure 1 earlier. To circumvent this, a frequency reuse scheme is often utilized. This is based on reusing the same frequencies in spatially isolated beams. Therefore, the available bandwidth is divided into a smaller number of beams than the total number of beams in the coverage area. The set of contiguous beams that share the total available bandwidth is known as a cluster. The clusters are then repeated in the coverage area relying on the fact that the beams operating at the same bandwidth will be separated from each other sufficiently so that they do not interfere with each other.

There are only a discrete set of possible cluster sizes, N, to accommodate a contiguous coverage for a hexagonal geometry [Mehrotra, 1994]. The possible number of beams in a cluster which would form a tessalating shape is given by:

$$N = i^2 + j^2 + i \times j \tag{1}$$

where N, is the number of beams in the cluster; i.e. the number of beams that share the total bandwidth, and i, j are non-negative integer numbers. This results in possible cluster sizes of 3, 4, 7, 9, etc. An example of how these clusters are formed is shown in Figure 5.

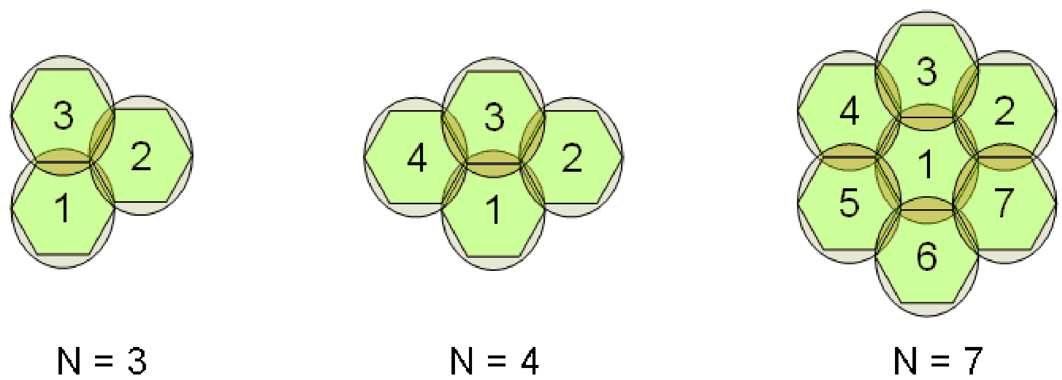

Fig. 5. Different cluster options for hexagonal lattice

2.3 Co-channel Beams and Tiers

The clusters as depicted in Figure 5 for reuse factors of 3, 4 and 7, are repeated to fill the required coverage area on earth. An example of how a cluster size of three (i.e. i=1, j=1) would be used to fill a given area is shown in Figure 6. A cluster size of three implies that the total available bandwidth is shared between three beams. The numbers 1, 2, 3 are used to identify the beams using the corresponding bandwidth segments. Therefore, beams with the same number imply that they use the same frequency.

Beams operating at the same frequency are known as co-channel beams. In Figure 6, the co-channel beams are shown in the same color and labeled with the same bandwidth segment number. It can be observed that the location of co-channel beams follow a pattern. They can be grouped by their distance with respect to a reference beam. The set of co-channel beams which have same distance from a reference beam are said to fall on a tier. Therefore tiers define a set of beams equidistant from a reference point. In a hexagonal geometry, each tier consists of six or twelve beams. Figure 7 shows the first four tiers for the frequency reuse of three.

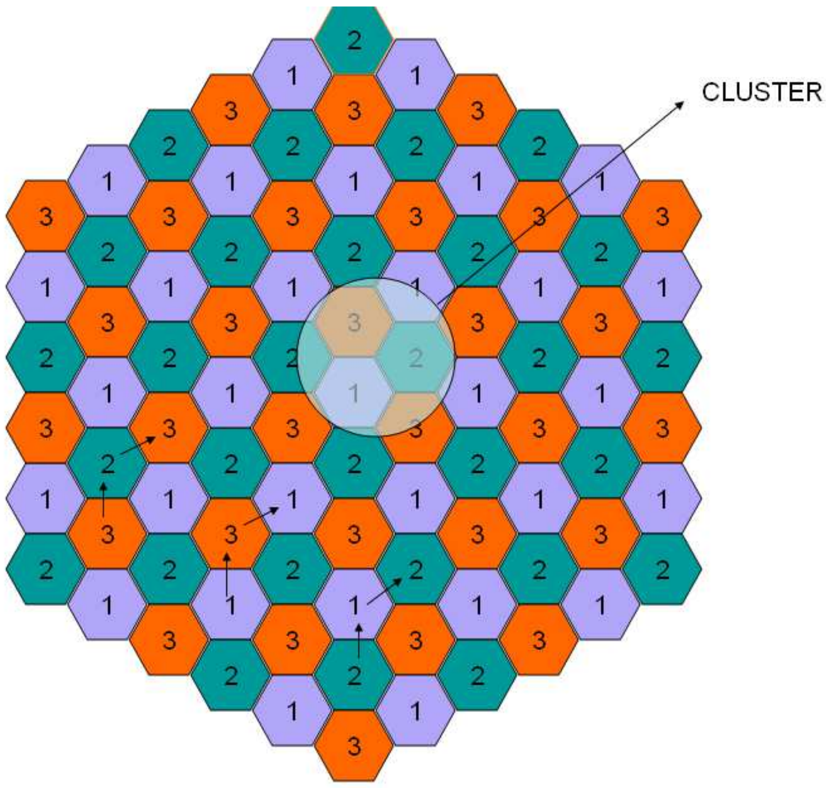

Fig. 6. Cluster coverage, N=3

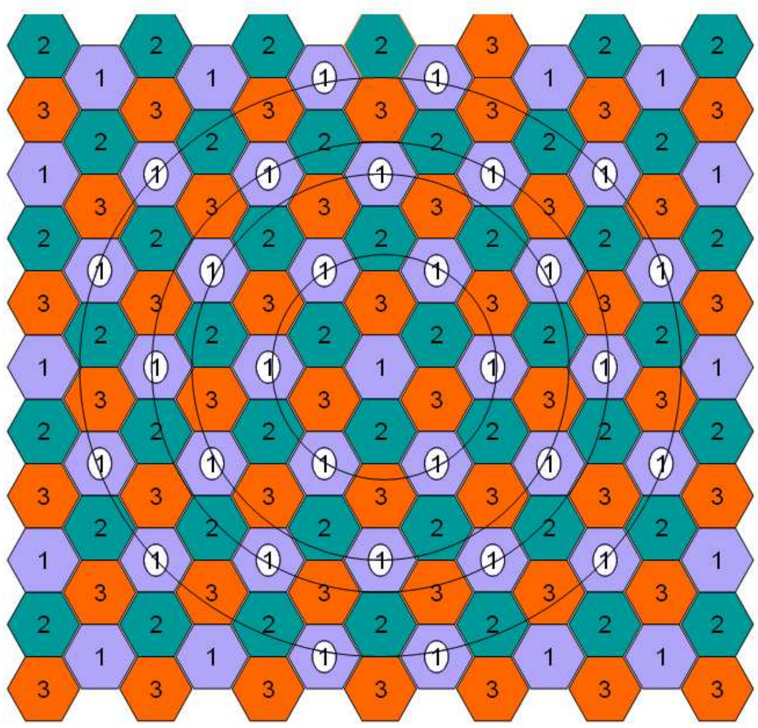

Fig. 7. Tiers in frequency reuse

The beams that lie on a tier are equidistant from the beam at the center of the tier, and for an azimuthally symmetric power distribution, beams on a tier would contribute the same amount of interference. As the tier's number increases, the diameter hence the distance from the center beam increases, reducing the contribution from the beams in that tier compared to the beams on closer tiers assuming the radiation decreases away steadily from the antenna peak.

As can be observed from Figures 6 and 7, higher frequency reuse numbers result in tiers with larger diameters, thereby increasing the distance between co-channel beams and reducing the total number of beams operating at the same frequency. However, this is done at the expense of reduced bandwidth within a beam, a trade off which needs to be decided by system engineers based on the requirements of a particular system.

2.4 Antenna Pattern and Spot Beam Generation

Due to their ability to generate multiple beams simultaneously, phased arrays are a natural choice for multi-beam satellite antennas. Each beam in the coverage is generated by electronically scanning the beam. A key parameter in satellite antenna design is the directivity of antenna, which defines how well the antenna focuses the power in the desired direction.

The radiation pattern of an array antenna depends on the array factor. For a MxN planar array, the array factor is given by (Balanis, 2005)

$$AF = \sum_{m=1}^{M}\sum_{n=1}^{N} I_{mn} e^{j(m-1)(kd_x \sin\theta\cos\phi+\beta_m)} e^{j(n-1)(kd_y \sin\theta\sin\phi+\beta_n)} \tag{2}$$

where I_{mn} are the voltages that feed the mn^th^ element in the array. The array factor is related to the antenna directivity which measures how well the input power is focused along a given direction and can be computed as follows (Stutzman, 1998)

$$D_0 = \frac{4\pi[AF(\theta_0,\phi_0)][AF(\theta_0,\phi_0)^* |_{max}}{\int_0^{2\pi}\int_0^{\pi}[AF(\theta_0,\phi_0)][AF(\theta_0,\phi_0)]^* \sin\theta\cdot d\theta\cdot d\phi} \tag{3}$$

In the case of a large array with uniform excitation, this equation can be approximated by

$$D_0 = \frac{\pi^2}{\Omega_A} \tag{4}$$

where the denominator is the subtended beam angle defined by

$$\Omega_A = \frac{\theta_{x0}\theta_{y0}\sec\theta_0}{\left[\sin^2\varphi_0 + \frac{\theta_{y0}^2}{\theta_{x0}^2}\cos^2\varphi_0\right]^{\frac{1}{2}}\left[\sin^2\varphi_0 + \frac{\theta_{x0}^2}{\theta_{y0}^2}\cos^2\varphi_0\right]^{\frac{1}{2}}} \tag{5}$$

In equation (5) the angles φ_0 and θ_0 represent the direction at which the directivity is computed, and θ_{x0} and θ_{y0} denote the half power beamwidths of the array along the directions x and y, the plane on which the array resides. In this chapter we will assume a 40x40 square planar array with isotropic elements separated by half wavelength as shown in Figure 8.

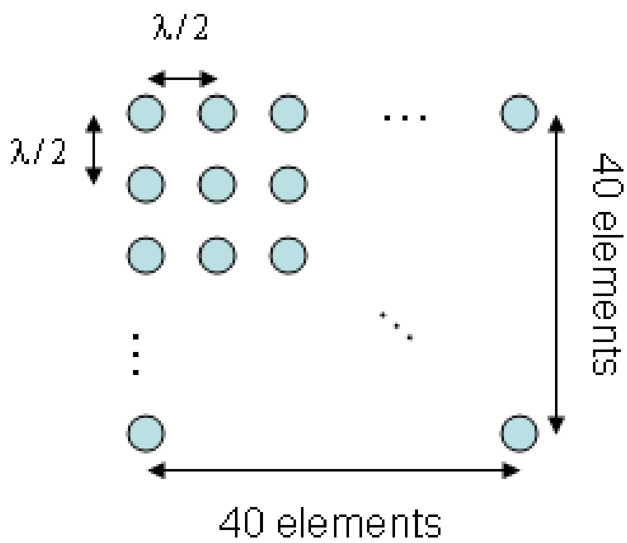

Fig. 8. A uniformly spaced 40x40 element planar array

The plot of the directivity in two different planes for this particular array is shown in Figures 9-10. The 40x40 element antenna is sized to have an edge gain of 36 dB defined at its -4dB contour relative to the peak. Thus, the peak gain of the antenna is 40 dB, with a beamwidth of 1.44 degrees at the - 4 dB down contour from the peak gain. The spot beam in the coverage area is defined by this contour. The contour plot for the same antenna is shown in Figure 11. The beam is generated at the center as denoted by the white circle.

As seen in the contour plot, the energy is radiated to the whole coverage area even though most of the power is focused in the spot beam. This "leak" into other regions is not a problem for beams operating at different frequencies as filtering will eliminate this energy. But for co-channel beams; i.e. beams operating at the same frequency, this leaking energy creates the interference which is the focus of this chapter.

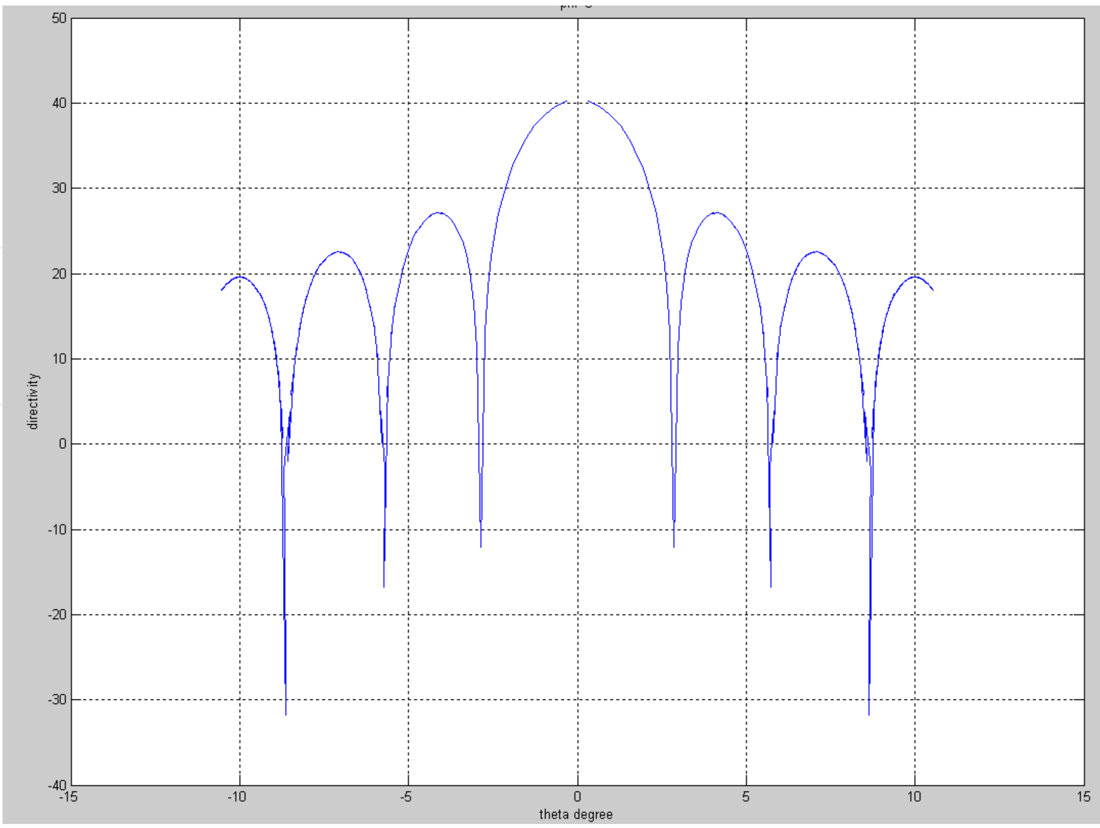

Fig. 9. Array factor for the 40x40 element array, φ = 0 plane

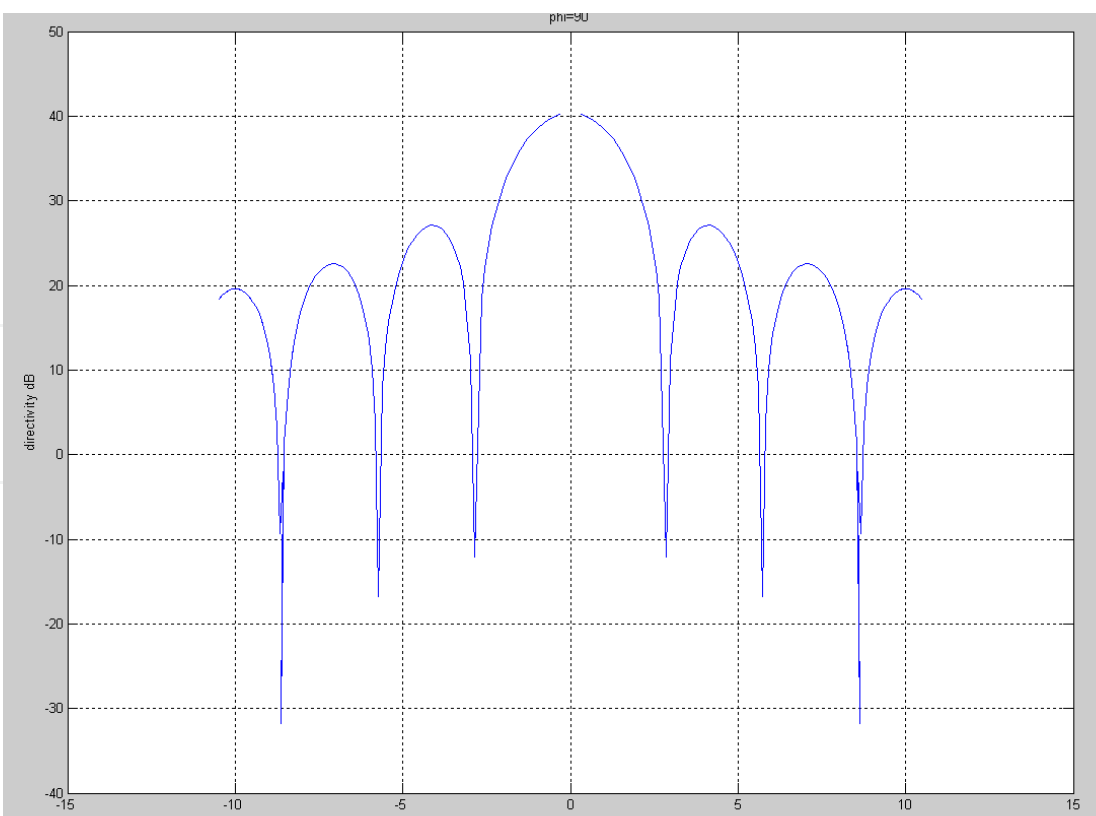

Fig. 10. Array factor for the 40x40 element array, φ = 90 plane

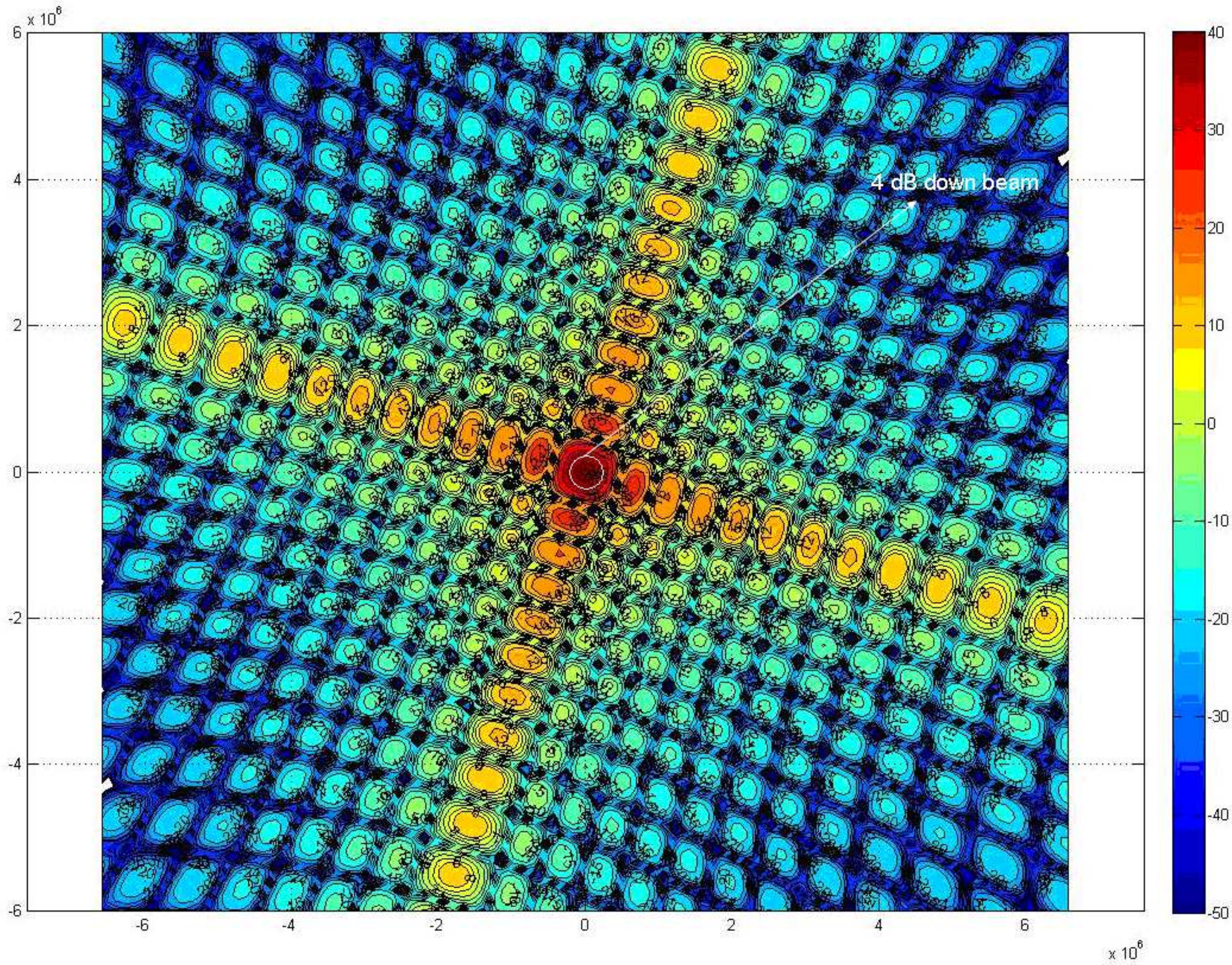

Fig. 11. Contour plot of directivity for 40x40 element array

2.5 Co-channel Interference

The energy leak from a beam into other beams operating at the same frequency causes co-channel interference. Figure 12 shows a simplistic diagram of the co-channel interferers in both the uplink and the downlink. The downlink interference is primarily a function of the reuse number and of the aggregate power due to the power in the side lobes of the interfering co-channel spot beams that is received in an earth station receiver. On the other hand, the uplink co-channel carrier-to-interference ratio is dependent upon the reuse number and the number of co-channel users transmitting simultaneously and received at the side lobes of the interfered beam. This section will focus solely on the downlink interference.

The farther the co-channel beams are separated from each other, the lower is the expected interference levels as the antenna pattern gradually tapers off with increasing angles away from the peak point. However, this gradual taper in the antenna pattern is oscillatory due to the side lobes. Therefore, the co-channel interference in a multiple beam system depends on the antenna pattern as well as the cluster configuration.

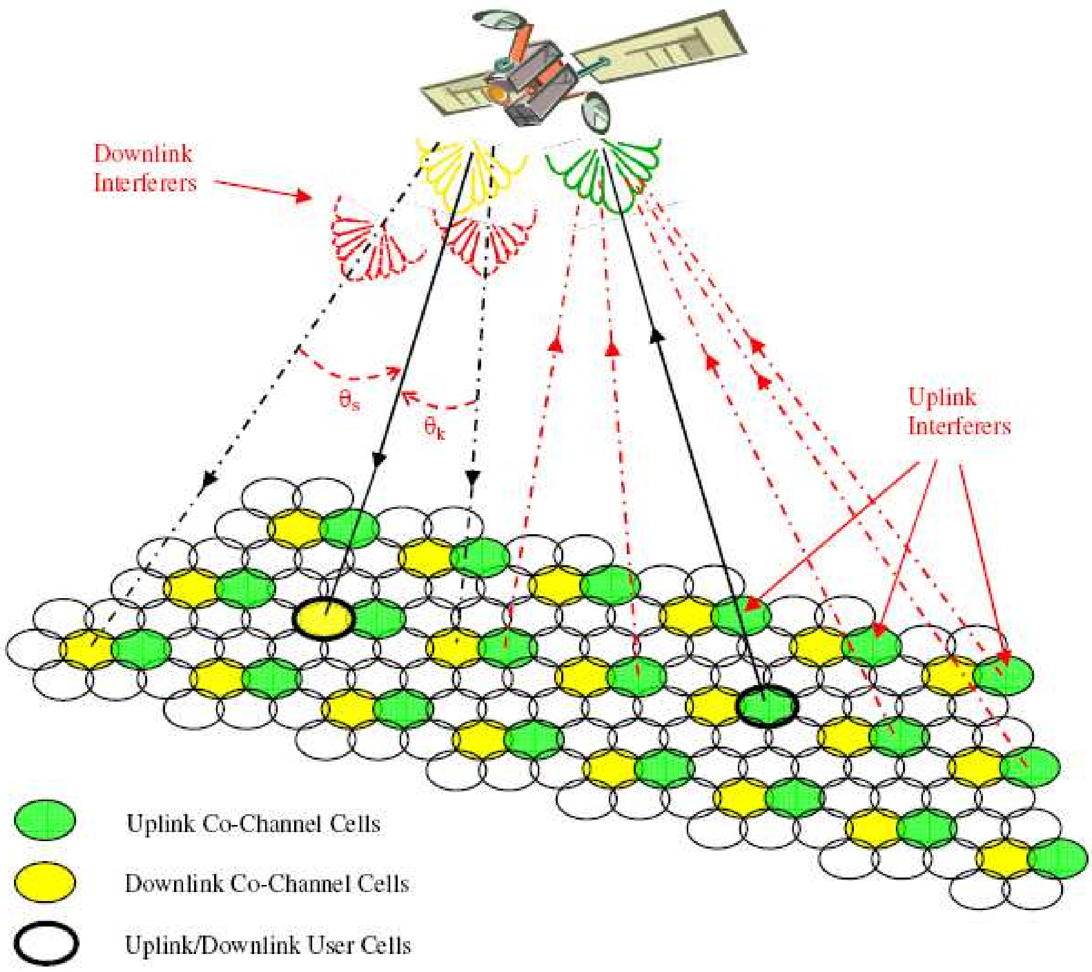

Fig. 12. Co-channel interference concept in multibeam satellite communication systems

A parameter for the system performance is the carrier to interference ratio, which defines how much better the intended signal is compared to the interfering signals:

$$\left.\frac{Carier}{Interference}\right|_{\text{at beam center}} = \left.\frac{C}{I}\right|_{\text{at beam center}} = \frac{D_{Max}}{D_{Interference}} \tag{6}$$

where the interference term is the sum of powers received from all co-channel beams. We can express equation (6) equivalently in dB as:

$$10\log(\frac{C}{I}) = 10\log(D_{\max} - \log D_{Interference}) \tag{7}$$

For an azimuthally symmetric antenna pattern, the co-channel beams lying on the same tier would result in equal interference levels as they are equidistant from the reference point. Therefore, categorizing all co-channel beams by their tier number helps simplify the interference calculations. Although the square array does not produce an azimuthally symmetric pattern, the power levels tend to decrease as the tier number increases, i.e. as the co-channel beams are farther from the reference point. This concept is shown in Figures 12 and 13 for frequency reuse factors of 3 and 7. We observe that for the larger size cluster (i.e. N=7), the diameter of the tiers are larger for the same tier number. This implies that, larger cluster sizes will likely have less co-channel interference.

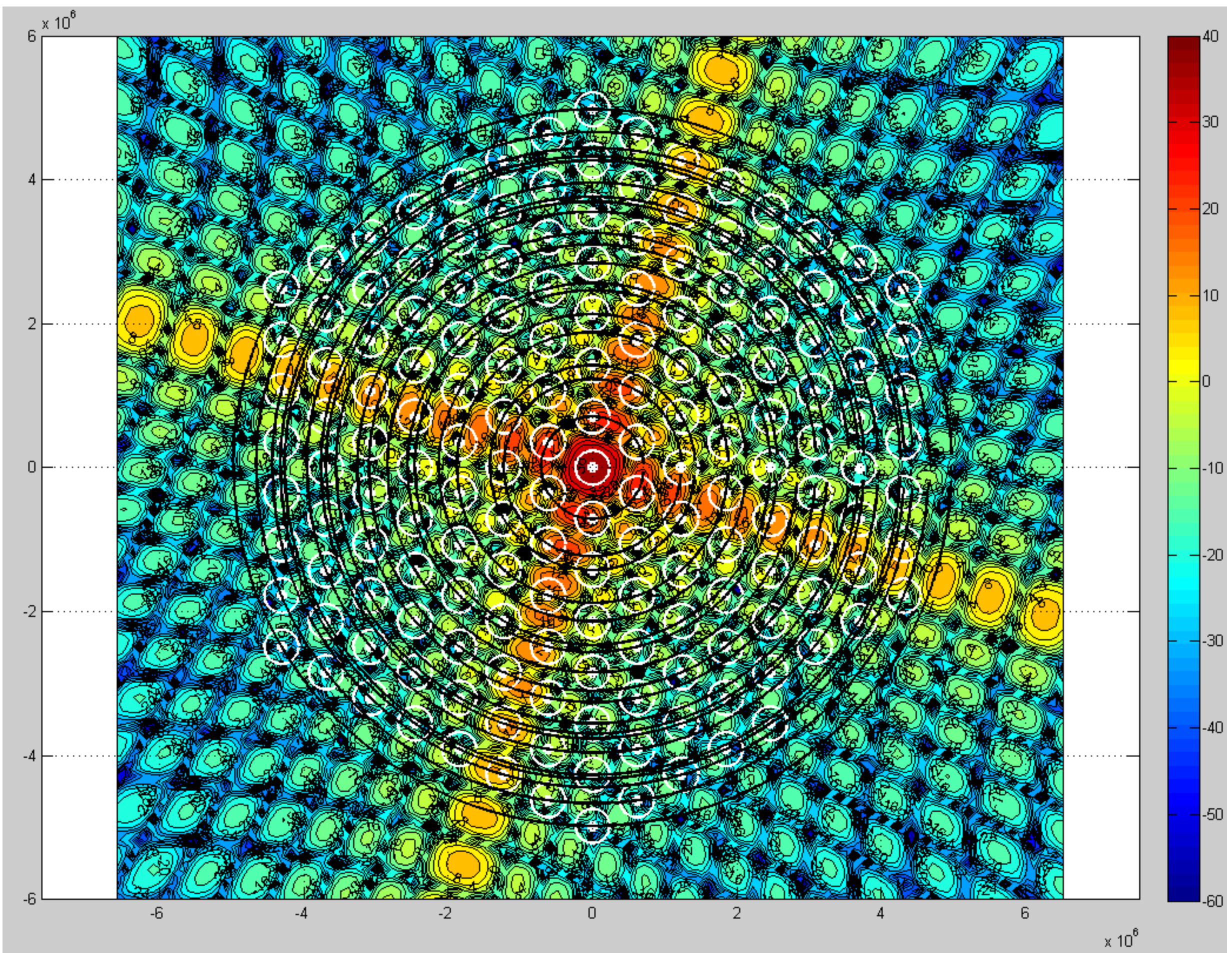

Fig. 13. Tiers for reuse factor = 3 overlaid on the contour plot of the 40x40 array

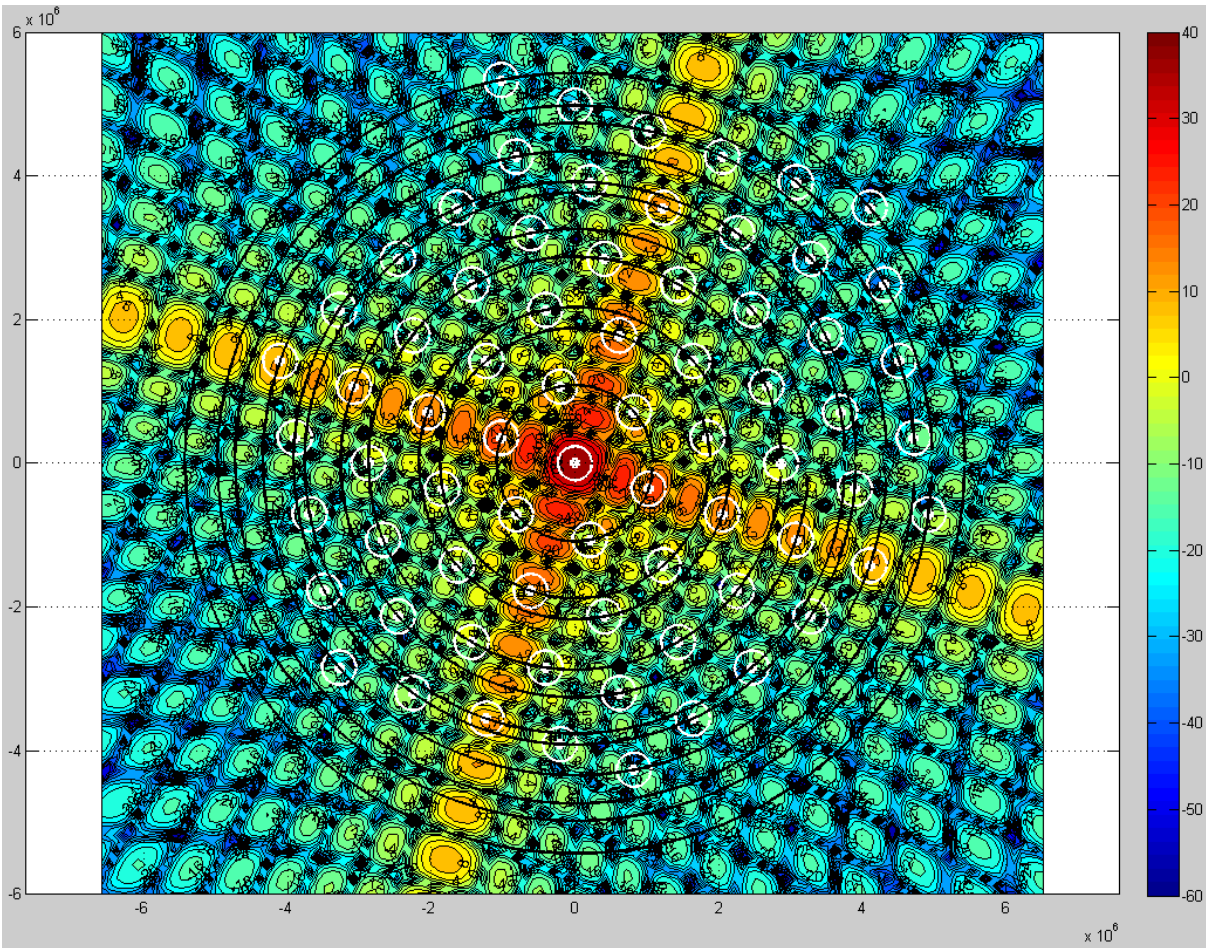

Fig. 14. Tiers for reuse factor = 7 overlaid on the contour plot of the 40x40 array

2.6 Example – LEO System Downlink Interference

In this section we calculate the total downlink interference in using a Low Earth Orbiting (LEO) satellite system. The relevant parameters of the system are as follows:

Altitude = 9400 km
Peak Gain = 40.0 dB
Spot Beam edge @ 4dB (36.0 dB)
Frequency = 1.9 GHz
Minimum elevation angle = 22^o
Number of beams on earth = 500

The spot beams generated by the 40x40 element phased array antenna for frequency reuse of three are shown in Figure 15. The radii of all spot beams are assumed equal to that of the center spot beam, and are computed using the beam width at -4dB relative to the peak gain and the altitude as follows:

$$Radius = H(altitude) * \tan(\theta_{4dB\_down}) \tag{8}$$

For the 40x40 element array antenna, the beam width is 0.0252 radians (1.44 degrees), resulting in a radius of 236km. The beam coverage on earth for this system for reuse factor of 3 is shown in Figure 15. The red lines depict the different tiers for this reuse factor, and same numbers denote the same bandwidth of operation, hence co-channel beams.

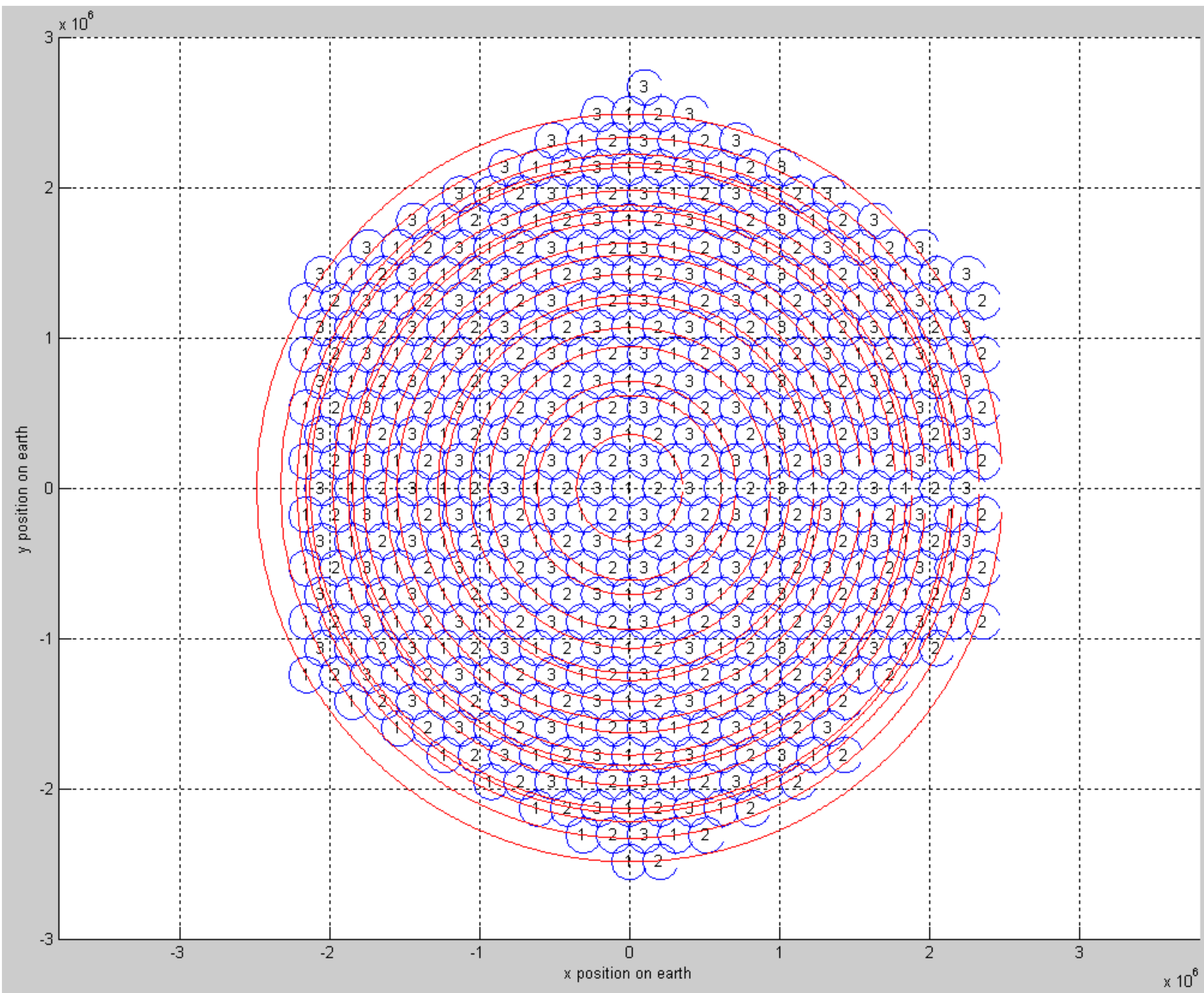

Fig. 15. LEO system, reuse of 3

The total interference from each tier for the center beam is shown for different reuse factors in Figure 16. We observe that there are fewer tiers for the same coverage when a higher frequency reuse factor is used. It is also observed that the interference levels are higher (hence the carrier to interference ratio is lower) from the tiers closest to the beam of interest. Since the square array is not azimuthally symmetric, we observe oscillations in the interference levels between tiers due to the side lobe level variations. We also observe that higher frequency reuse factor results in lower interference as there are fewer co-channel beams in the coverage area and they are spread farther apart.

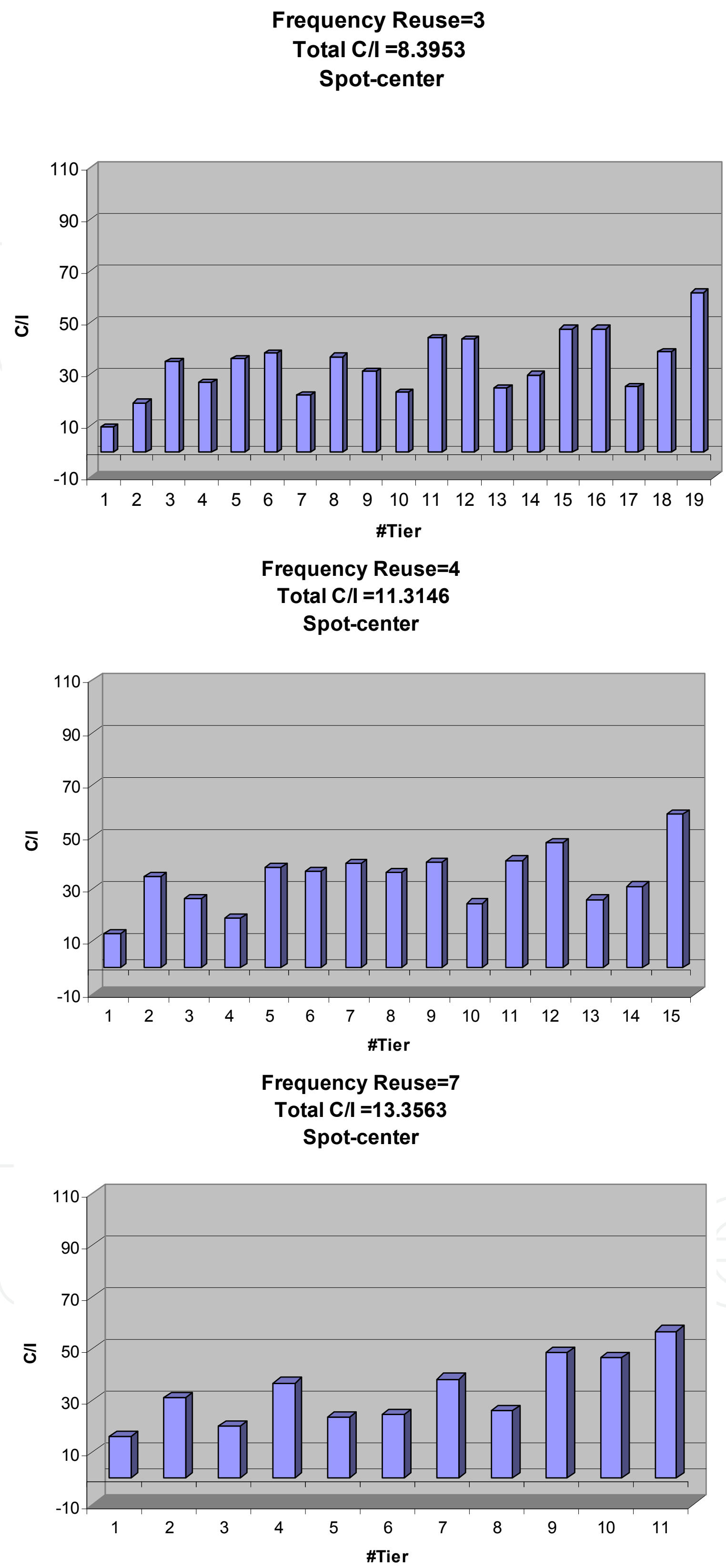

Fig. 16. Interference versus tier number (a) reuse = 3 (b) reuse = 4 (c) reuse = 7

3. Sub-Beam Concept

As we have seen so far, the coverage area in multibeam satellite systems is divided into a number of beams often referred to as spot beams, which are much smaller in size. As discussed before, since satellite systems are bandwidth limited, the sub-division of beams into smaller portions allow for frequency reuse to increase capacity. The size of antenna that generates these beams on earth is related directly to the peak gain at the center of the spot beam and the smallest spot beam size. The spot beams are typically defined by the contours at 3 or 4 dB down from the peak gain at the center of the beam. While it is the edge gain requirement which needs to satisfy the communication link, the satellite antennas have to be sized for the maximum gain to achieve the 3-4 dB drops around the perimeter of the spot beam. Therefore it can be argued that the satellite antenna is typically oversized as lower gain levels within the spot beam would satisfy the link requirements. Having a larger sized antenna leads to higher cost. To achieve 3 dB higher gain levels, one needs to double the aperture size, which directly translates to cost.

Recently a new method has been presented for reducing the cost of satellite antennas by sizing the antennas for lower power levels than the conventional approach, while maintaining the edge gain requirements, (Kilic and Zaghloul, 2009). This approach relies on the partitioning of the spot beam into a number of sub-beams. The basic idea behind the sub-beam partitioning approach is to replace the spot beams with a number of smaller sub-beams with lower peak gain and same edge gain values. This translates to an increase in the total number of beams to be generated by the antenna. However, since the sub-beams have lower peak gain, the antenna size can be reduced significantly. The increase in the number of beams results in a more complex beamforming structure, but this can be handled digitally without significant cost effects. Therefore the sub-beam partitioning results in significant reduction in the cost of the antenna compared to the spot beam approach.

Although the antenna cost is reduced in sub-beam approach a key issue which remains to be addressed is the interference effects in the new beam configuration. It is necessary to satisfy the carrier to interference ratio throughout the coverage area for this approach to be of practical value.

The objective of this section is to investigate interference performance of the sub-beam approach in comparison to the spot beam configuration. First the definition of the spot beam concept is presented and the sources of interference in a multiple beam communication system are identified. Then the sub-beam concept is introduced. Finally, the performance of the conventional spot beam approach with the sub-beam partitioning technique is compared in terms of co-channel beam interference.

3.1 Partitioning of spot beams into sub-beams

The sub-beam design reduces the peak gain requirements at the beam center while maintaining the edge gain requirements. In order to do this, each spot beam in the coverage area is divided into a number of smaller beams defined by contour levels less than the typical 3 or 4 dB, as depicted in Figure 17, where four sub-beams are used to replace a spot beam. For an edge gain requirement of 36 dB, it is observed that the sub-beam approach provides a more uniform gain distribution within a beam's coverage area (36-37 dB) compared to the spot beam approach (36-40 dB). A group of these smaller sub-beams, i.e. "sub-beam clusters," represent each spot beam.

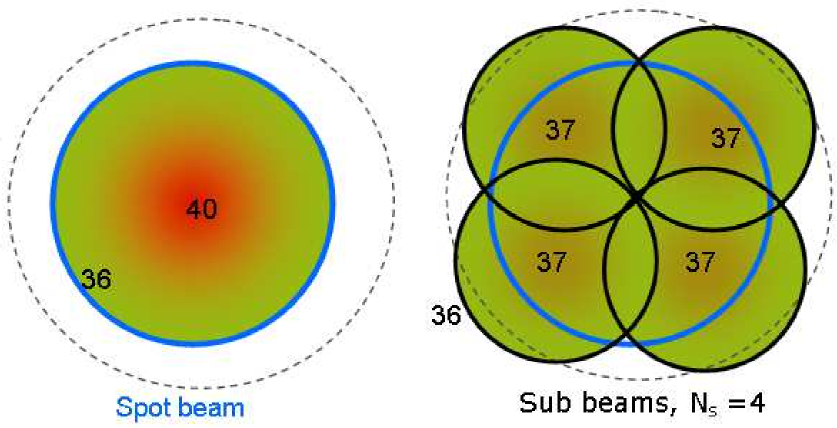

Fig. 17. Sub-beam representation of a spot beam

To satisfy the contiguity requirements of the coverage, the sub-beams intersect at the boundaries of the spot beam. Figure 18 demonstrates the sub-beam concept, where the hexagons correspond to the spot beams in the coverage area. The numbers at the center of each hexagon denote the frequency band assigned in each beam. A frequency reuse index (or spot beam cluster size) of seven is depicted in the figure. The large circles encompassing sets of seven hexagons represent the spot-beam clusters based on this reuse factor. The sub-beams are shown for the center spot beam of each cluster. A sub-beam cluster size of four is assumed in the demonstration.

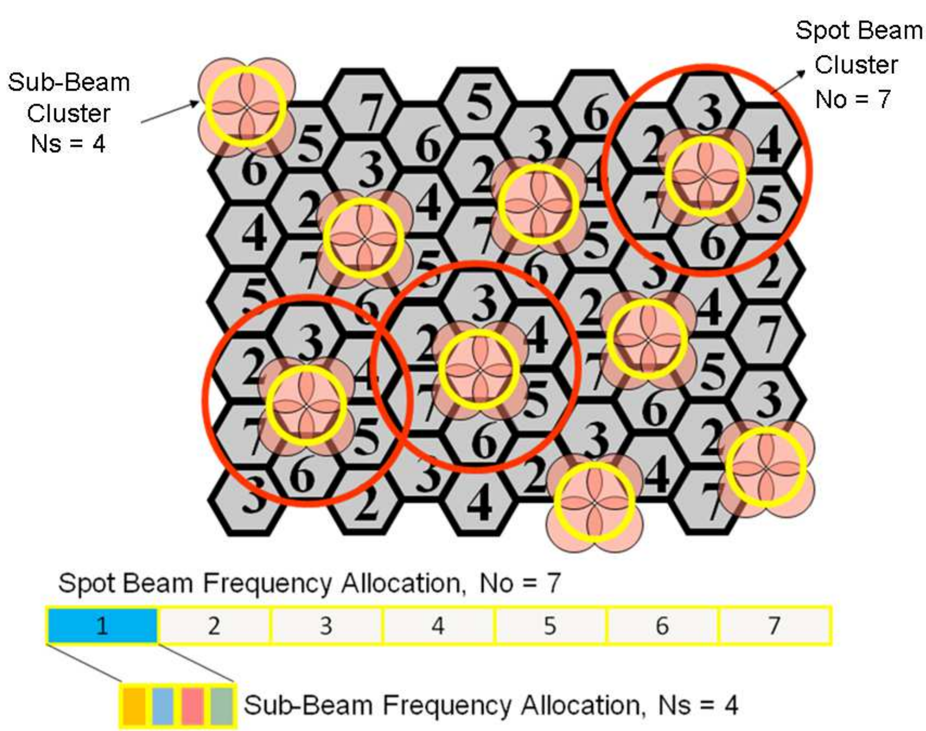

Fig. 18. Sub-beam partitioning for spot beams, reuse =7

As a result of this approach, the antenna is required to generate four times more beams than the conventional spot beam design. However, the sub-beams do not need to satisfy the peak gain requirements of the spot beam. Since only the edge gain needs to be satisfied, the sub-beam peak gain is lower and the overall antenna size is reduced as explained in the following sections.

3.2 Spectrum Subdivision with the Sub-beams

The frequency reuse configuration is conserved with the sub-beam approach. The allocated bandwidth per spot beam is shared among the sub-beams in a sub-beam cluster. As Figure 18 suggests, each sub-beam in a sub-beam cluster uses the bandwidth allocated to the spot beam they represent. While each sub-beam is designated a smaller portions of the bandwidth, the bandwidth allocation for the entire spot beam remains the same. Hence, the capacity per spot beam is conserved. Furthermore, this approach makes it possible to have a non-uniform distribution of the available bandwidth in a spot beam to address local high traffic areas. Depending on the sub-beam cluster size, some areas are served by more than one sub-beam from different spot beams, adding to the flexibility of traffic assignment.

3.3 Gain Reduction Concept of the Sub-beam Approach

The amount of reduction in the antenna size depends on the edge gain relative to the peak, and beam width requirements of the coverage. The sub-beam cluster generates an equivalent coverage to the spot beam by using a higher number of smaller beams. This enables using smaller antennas. The number of beams in a sub-beam cluster needs to be chosen such that a contiguous coverage is achieved. This results in values such as 3, 4, 7 …etc.

The relationship between the relative edge gain of the spot beam and the relative edge gain of the sub-beams can be determined as a function of the number of sub-beams that make up a sub-beam cluster. In the derivations that follow, the subscripts 'o', and 's' denote the spot beam and sub-beams, respectively. The sub-beam edge contours are defined by x_s dB down relative to the peak gain of G_s dB. The spot beam contours are assumed to be x_0 dB lower than the peak gain, which is denoted by G_0 dB. Since the edge gain requirements are satisfied for both cases, the gain relationship can be written as follows:

$$\mathrm{G_o - x_o = G_s - x_s} \tag{9}$$

This equation can be rewritten in terms of gain reduction as:

$$\Delta G \equiv G_o - G_s = x_o - x_s \tag{10}$$

It is observed that the reduction in gain is directly proportional to the difference of the beam contour levels of the spot beam and the sub-beams. While the typical contour level to define a spot beam is 3-4 dB, the sub-beam configuration is flexible, and the choice is based on increasing the gain reduction. As equation (10) suggests, defining the sub-beams at a low level would increase the reduction in gain. However, the sub-beam cluster size, Ns, constrains the beam width of the sub-beams, and the value of x_s cannot be assigned arbitrarily. The choice will depend on the edge gain of the spot beam as well as the partition size, N_s.

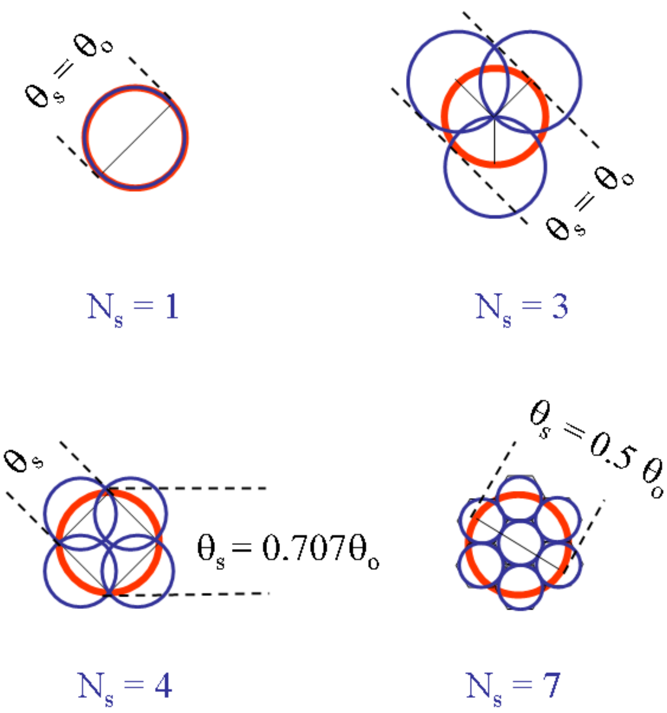

Fig. 19. Possible Sub-beam Partitions for Contiguous Coverage

3.4 Defining the Sub-beams to Achieve Desired Gain Reduction

A contiguous coverage of the sub-beam clusters can be obtained by satisfying Equation 1, in which case the number of sub-beams that define a spot beam are restricted to values such as 1, 3, 4, 7, …, etc. Examples of the geometry for different cluster sizes are shown in Figure 19, where the circle at the center corresponds to the spot beam and the surrounding circles denote the sub-beam contours. The beam width ratio, θ_s/θ_o depends on the sub-beam cluster geometry, and is equal to 1, 1, 0.707 and 0.5 for sub-beam cluster sizes of 1, 3, 4 and 7, respectively. The higher sub-beam clusters approximate the spot beam better and reduce the overlap of sub-beams from different clusters. Higher cluster sizes also reduce the sub-beam peak gain that is needed to satisfy the spot beam edge gain requirement.

An empirical relationship has been obtained to relate the beam width of a phased array at an arbitrary contour level, x to its HPBW by using the definition of the array factor as:

$$\frac{\theta_X}{\theta_3} = 0.59x^{0.4806} \tag{12}$$

where x is in dBs, (Zaghloul , et. al. 2000). This empirical relationship assumes isotropic radiating elements, which combine in space to form the directive pattern, and has been verified for large array sizes for broadside radiation. The expression is determined by fitting a curve to different size square arrays that range from 20x20 to 50x50 elements with half wavelength spacing between them. The results of the simulations and the agreement with the empirical relation above are shown in Figure 20.

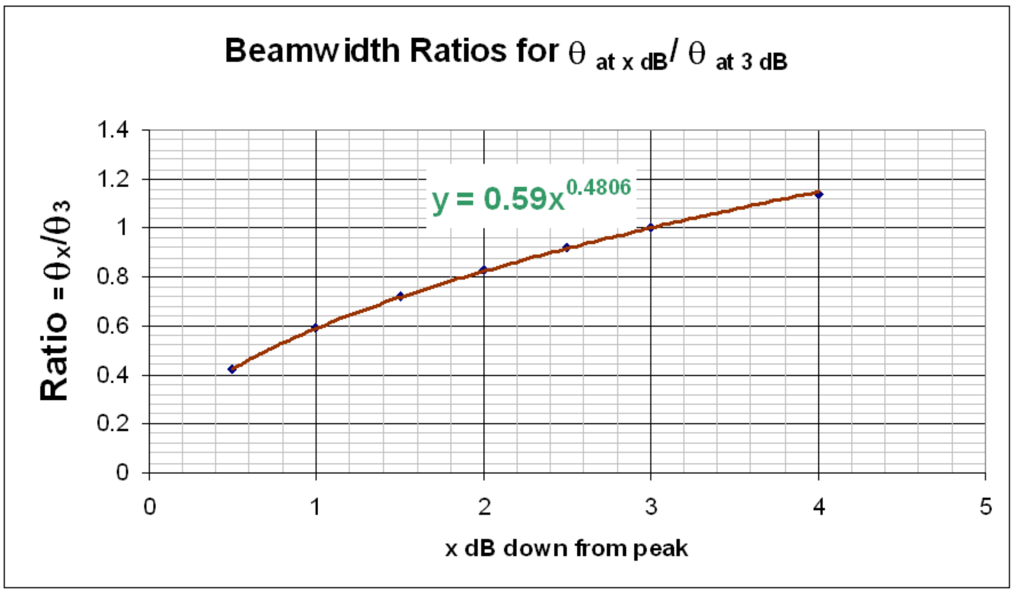

Fig. 20. Beam width at arbitrary contour levels for large arrays

Using equation (12) in (2), the contour levels of the spot and sub-beams can be related to their beam widths, and as follows:

$$9.612\log\left(\frac{x_s}{x_o}\right)+x_o-x_s=20\log\left(\frac{\theta_s}{\theta_o}\right) \tag{13}$$

Equation 13 can be rewritten in terms of gain reduction, using (10) as

$$9.612\log\left(\frac{x_s}{x_o}\right)+\Delta G=20\log\left(\frac{\theta_s}{\theta_o}\right) \tag{14}$$

where $\Delta G = G_o - G_s$ is the gain reduction achieved by using the sub-beam concept and the beam width ratio on the right is a constant determined by the sub-beam cluster configuration. Thus, for a given sub-beam configuration, the peak gain reduction and the ratio of the relative edge gains are uniquely related. In other words, if two of the parameters ΔG, x_c and x_s are given, the third is uniquely determined for a specific sub-beam cluster configuration.

The relation between reduction in gain and beam contour levels is demonstrated in Figure 21. Two cases are plotted for comparison. The blue line corresponds to the sub-beam cluster size of 4, while the red line represents the sub-beam cluster size of 7. The dashed lines show the contour level for the sub-beams as a function of gain reduction, and the solid line describes the relation between spot-beam contour levels and the gain reduction. It is observed that, for a desired amount of gain reduction, the beam contour levels for both sub-beam and spot beam are uniquely defined for each sub-beam cluster size.

Since the sub-beam approach is offered as a solution to reduce the antenna aperture size, it is worth investigating the improvement by assuming that the spot beam contour levels and the peak gain are already defined for the system to be replaced. For instance, if a spot beam width at 4 dB contour levels is being replaced with sub-beams of lower contour levels, the graph in Figure 21 suggests that a gain reduction of 3dB can be achieved for Ns = 4 by defining the sub-beam contours at 1 dB down from the sub-beam peak gain. Similarly, for Ns = 7, a gain reduction of 3.6 dB is achieved by defining the sub-beams at 0.4 dB down from their peak gain.

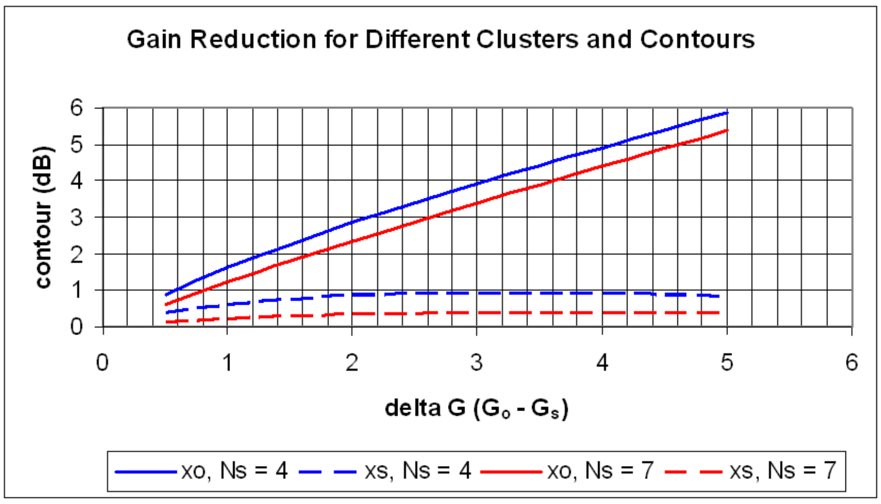

Fig. 21. Contour levels of spot beams and sub-beams as a function of gain reduction.

This example implies that for a given spot beam configuration, the larger sub-beam clusters can offer higher gain reduction, which is associated with a corresponding reduction in the antenna aperture size and cost. However, since the higher cluster sizes define beams at lower contour levels, a legitimate concern is to make sure the energy in the main beam of these antennas do not adversely affect the co-channel interference levels.

The reduction in peak gain results in a reduction in the aperture size and correspondingly a reduction in the number of elements in the array. This is illustrated in Figure 22 where a 28 x 28 or 784-element array for a conventional spot beam (corresponds to Ns =1) is replaced with arrays of fewer elements as the number of sub-beams increase in the cluster. It is observed that the limit case is approached for sub-beam cluster sizes of 7, where less than 300 elements are required.

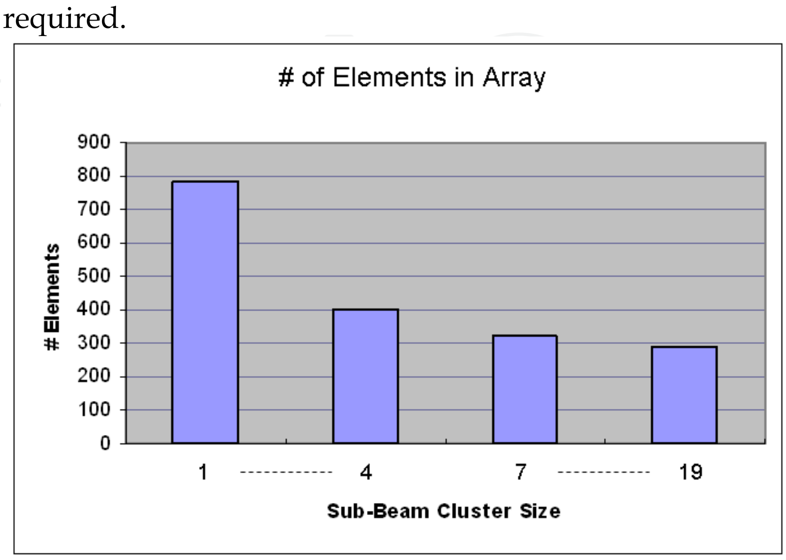

Fig. 22. Array size reduction with sub-beam partitioning

The reduction in the receive and transmit antenna aperture sizes result in fewer components. However, the generation of sub-beam clusters requires further de-multiplexing and increase in the size of the digital traffic router. Corresponding multiplexing on the transmit side is also required. However, the added complexity occurs in the software-driven processor on board the satellite, with minimal addition to the hardware.

3.5 Interference in Sub-beam Partitioned Coverage

The same LEO system as in section 2.5 is considered for the interference analysis of the sub-beam partitioned coverage. A comparison of beam coverage on earth for spot beam and sub-beam configuration with partition size of 3 is shown in Figure 23. The beams are overlaid on the contour plot of the antenna pattern that generates the center beam, the beam of interest for interference calculations.

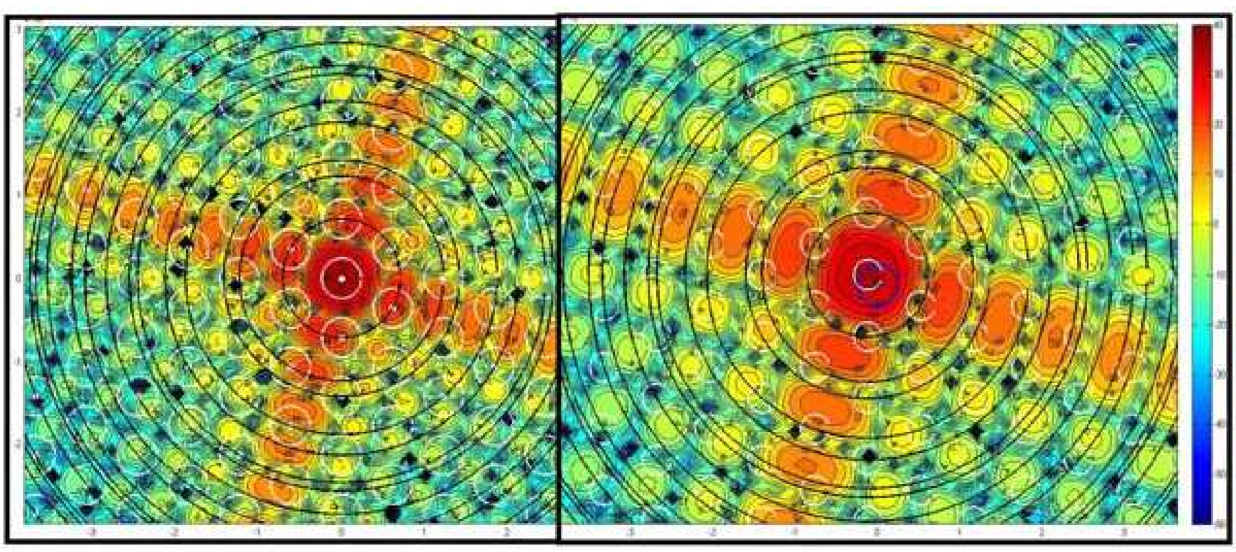

Fig. 23. Coverage on Earth – Spot beam pattern (left) versus Sub-beam pattern (right)

Sub-beam partition sizes of four and seven will be considered for the interference analysis. Figure 24 shows a zoomed in depiction of which one of the sub-beams that replace a spot beam are used for interference calculations. The spot beam to be replaced is the blue circle, while the red circles are the sub-beams for a partition size of four (left) and seven (right). The green circle is the sub-beam that will be selected in the interference analysis.

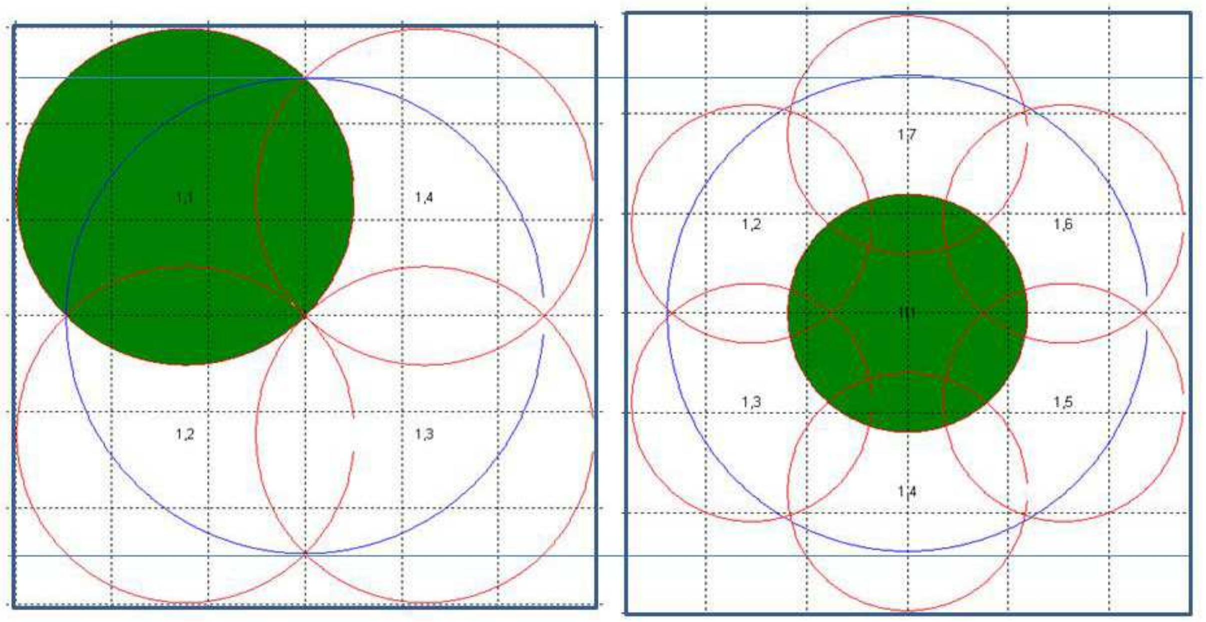

Fig. 24. Sub-beam selection for interference calcualtions, Ns = 4

The carrier to interference ratio and total interference are shown for frequency reuse of 3, 4, 7, 9 and 13 in Figure 25 for sub-beam partition sizes of four and seven. It is observed that the C/I at the center of the beam (where carrier power is maximum) are better for the spot beam configuration for large cluster sizes (i.e. N > 9). However in certain cases such as No = 3 and No = 9, the performance of the sub-beam approach is better or comparable to the spot beam configuration. It should be noted that this comparison presents a best case scenario for the spot beams as the carrier power is at its peak value. The total interference shown in Figure 25(b) indicates that sub-beams may have lower interference values relative to the spot beam cases of the same frequency re-use number. A large cluster size separates co-channel cells, and the highly directive spot beam antenna tends to have lower sidelobe levels at these separations.

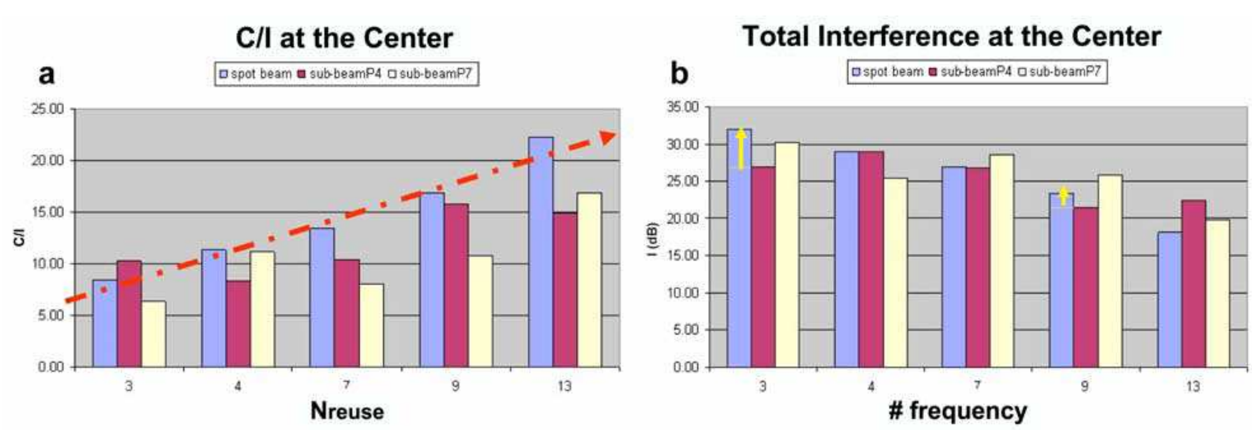

Fig. 25. Interference at the center by tier for sub-bem partition=4, 7 and frequency reuse 3, 4, 7, 9, 13. (a) C/I (b) Total interference

To better understand the sub-beam performance, a better analysis is calculating C/I as one moves within the spot beam to be replaced by the sub-beams as depicted in Figure 26. The spot beam shown at the center with the blue circle is replaced by 4 sub-beams. The C/I is calculated at discrete distances from the center (d) and at angular positions (α). The chart on the right shows the C/I for the spot beams (blue lines) and sub-beams (red lines) for different d and α values. The x-axis shows the ratio of the distance from the center to the spot beam radius, R.

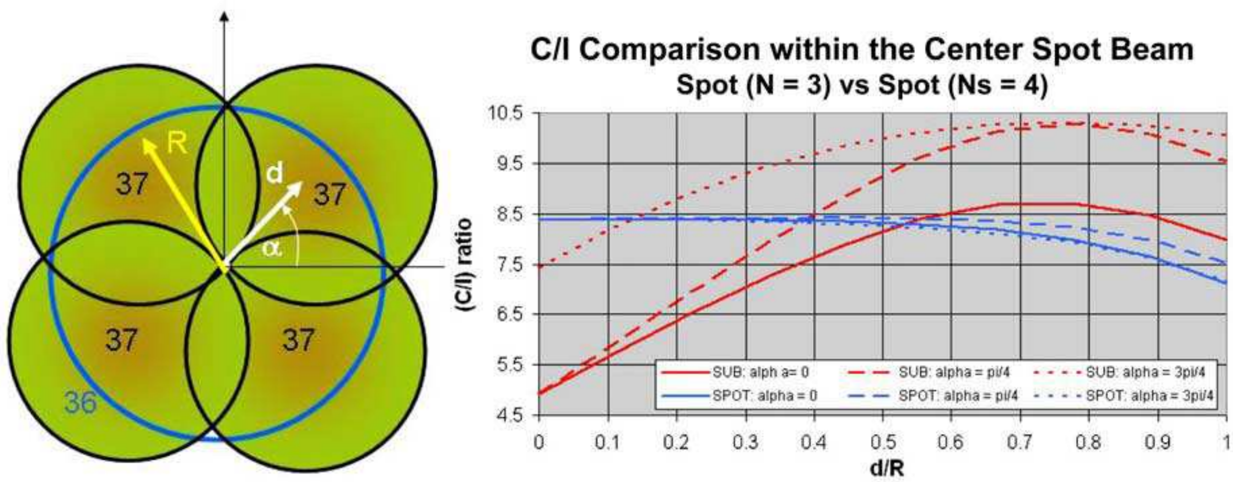

Fig. 26. C/I performance comparison within the spot beam

It is observed that partitioning the spot beam into sub-beams performs superior towards the spot beam edge because the carrier power in the sub-beam gets stronger. This is typically where the spot beam performs worst and a significant advantage for the sub-beam approach results. The main region where the spot beam seems to perform better is at the center of the beam as expected due to the high carrier power levels in the spot beam. In the regions near the beam center, it is observed that the sub-beam approach performs worst where the spot beams have the best performance. As expected, this is due to the high carrier power the spot beam has at the center. Typically the C/I value at the beam center has a higher margin as the systems are designed for the edge gain and the degraded performance of the sub-beam at the center may not pose a problem. To mitigate the relatively poor performance at the center, it would be possible to optimize the sub-beam antennas to perform better at the beam centers. If necessary a further step could be to modify the frequency allocation. However, this could result in lower system capacity, and should be attempted only if the antenna size and cost is the primary concern. Overall, the findings suggest that the sub-beam approach holds promise as its C/I is mostly not degraded compared to the spot beam approach, while its peak gain is lower and thus requires smaller antenna aperture.

4. Conclusion

Co-channel beam interference in multi-beam satellite communications systems was investigated particularly for the downlink. Concept of frequency reuse was explained and the role of satellite antenna size and pattern was examined. Conventional spot beam coverage and its impact on determining the antenna size on board was discussed.

A method was presented to reduce the array antenna aperture on board the satellite for multiple-spot-beam cellular coverage. The overlapped spot beams have edge gain that is determined based on link budget, coverage requirement, frequency band allocations, and corresponding channel capacity allocations. The edge gain relative to the peak gain of the spot beam determines the size of the required antenna aperture. Dividing the spot beam into a number of sub-beams that overlap at the same gain level as the spot beam but with lower gain taper over the sub-beam results in lower peak gain and consequently smaller aperture. The frequency band allocated to the spot beam is divided among the constituent sub-beams and can be assigned with enough flexibility to meet projected traffic demands.

The reduction in the antenna aperture with this approach translates into significant reductions in number of array elements, RF components, and A/D and D/A converters. These savings are obtained at the expense of more complex digital beam forming and traffic routing algorithms. Analysis has shown that in spite of the smaller aperture and the broader beams of the sub-beams, the co-channel interference between sub-beams using the same frequency segment is not adversely affected.

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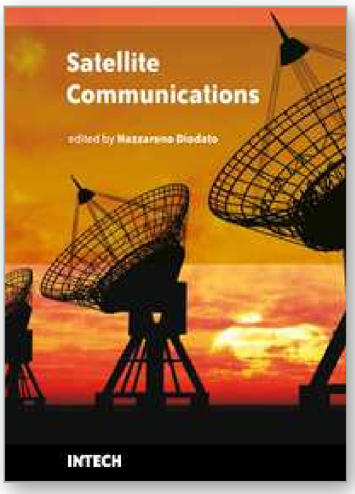

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This study is motivated by the need to give the reader a broad view of the developments, key concepts, and technologies related to information society evolution, with a focus on the wireless communications and geoinformation technologies and their role in the environment. Giving perspective, it aims at assisting people active in the industry, the public sector, and Earth science fields as well, by providing a base for their continued work and thinking.

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