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LETTER

Performance evaluation of planar antenna arrays onboard low earth orbit satellites

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Abstract

Earth orbit satellite (LEOS) systems offer continuous service using constellations, which stand out for their global coverage capacity, broadcast and ability to support user mobility. However, the low gain offered by omnidirectional antennas, as well as the large number of handovers within the satellite footprint due to the use of sector and spot beam antennas, along with the short satellite viewing time from the earth stations (ES), waste satellite power and degrades communications link quality. In this paper we present the use of a planar array antenna to establish communication links between LEOS and ES, allowing a more efficient use of satellite power and an increase in digital communications performance. The continuous steering of the antenna array radiation pattern (direction of arrival, DOA), adaptively directs the main lobe onboard the satellite towards the desired direction over the earth, allowing longer visibility time. A more directive downlink beam is obtained, increasing antenna gain and improving the bit error rate (BER) probability within quality of service (QoS) limits.

Keywords: Low earth orbit satellite; Direction of arrival; Quality of service; Planar array antenna; Chebyshev synthesis

1. Introduction

The demand for satellite broadband services is growing rapidly, so low earth orbit satellite (LEOS) systems are being designed and developed to provide such global communications services. Due to limited available frequency spectrum for global LEOS communications, it is very important to improve spectrum efficiency in order to enhance system capacity [1]. Many satellite communication systems use contiguous satellite constellations to provide worldwide continuous services. However, the service areas are usually quite large to be covered by a single beam.

Currently there are systems that employ multiple spot-beam antennas, where the footprint of each satellite is divided into smaller areas called cells. The basic concept of partitioning the satellite footprint into small cells comes from the same idea used in current terrestrial cellular systems [2]. The iridium LEOS network is currently using this technology, with onboard antennas generating antenna gain. However this process may cause multiple signal handovers within the satellite footprint as well as many inter-satellite links (ISLs) between contiguous and adjacent satellites. Another disadvantage is that the adjacent beams must use different frequency bands from one beam to another in order to avoid interbeam interference, a drawback since it requires earth terminals to quickly change frequency as the satellites pass above them [3].

Thus, the smart antenna technology becomes one of the most promising approaches to improve the capacity of wireless communications systems. An adaptive array differs from conventional arrays in the sense that they adapt to changing channel or user conditions. An adaptive array is actually a phased array antenna capable of adjusting the phasing of

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elements automatically, thus dynamically controlling its own pattern [4].

2. Natural response of the antenna arrays

The array antennas considered in this work are based on planar arrays with a constant element spacing d. The array factor of planar arrays can be written multiplying two factor linear arrays S along the x- and y-axes, according to the principle of pattern multiplication shown in Fig. 1, from [5],

$$S_n = \sum_{n=0}^{N-1} I_n \, e^{jn(kd \sin\theta \cos\phi + \alpha_n)} \tag{1}$$

$$S_m = \sum_{m=0}^{M-1} I_m \, e^{jm(kd \sin\theta \sin\phi + \alpha_m)} \tag{2}$$

where k is the free space propagation constant, I_n, I_m, denote de amplitude of the n-th and m-th element excitation, respectively. The progressive phase shifts between elements along the x-, y-axes are represented by α_n, α_m, respectively. These last variables are important when used to evaluate the scanning array performance, where the main beam has been steered to θ_0, ϕ_0, and are given by the following equations:

$$\alpha_n = -kd \sin\theta_0 \cos\phi_0 \tag{3}$$

$$\alpha_m = -kd \sin\theta_0 \sin\phi_0 \tag{4}$$

The array factor for the entire planar array is the product of two linear array factors, written as

$$AF(\theta, \phi) = S_n S_m \tag{5}$$

For an array with uniform amplitude, the amplitudes shown in (1) and (2) can be replaced by I_0, i.e. $I_n = I_m = I_0$, as mentioned in [6].

3. Chebyshev planar arrays

Chebyshev planar arrays have the important property of providing equal magnitude sidelobes in their radiation patterns [7–9]. They are optimized such as a specified sidelobe level (SLL) they have the smallest beamwidth, and for a specified beamwidth they produce the lowest SLLs.

For Chebyshev planar arrays design, the array factor in (5) is represented as the product of two Chebyshev polynomials, which is given by [9] as

$$AF(u, v) = \frac{1}{R} T_{N-1}(w_0 \cos u) T_{N-1}(w_0 \cos v) \tag{6}$$

where

$$u = \frac{\pi d}{\lambda}(\sin\theta \cos\phi - \sin\theta_0 \cos\phi_0) \tag{7}$$

$$v = \frac{\pi d}{\lambda}(\sin\theta \sin\phi - \sin\theta_0 \cos\phi_0) \tag{8}$$

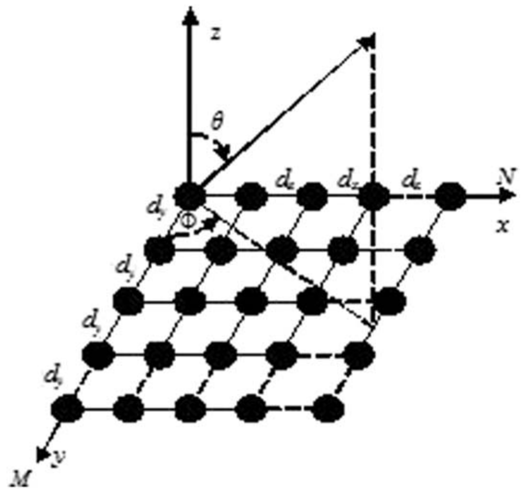

Fig. 1. Structure of a uniform planar antenna array.

In (6), R represents the main lobe to SLL ratio, and w_0 is a parameter for controlling the SLL, given by

$$w_0 = \cosh\left[\frac{1}{N-1}\cosh^{-1}(R)\right] \tag{9}$$

T_{N-1} denotes a Chebyshev polynomial of the $(N-1)$th order, and is given by

$$T_{N-1}(w) = \begin{cases} \cosh[(N-1)\cosh^{-1} w] & w > 1 \\ \cos[(N-1)\cos^{-1} w] & w \leqslant 1 \end{cases} \tag{10}$$

where

$$w = w_0 \cos u \cos v \tag{11}$$

In order to make the radiation pattern a Chebyshev pattern in any cross section, (6) can be replaced by a single Chebyshev polynomial. Thus, we can write Eq. (12), taken from [10]

$$AF(u, v) = \frac{1}{R} T_{N-1}(w_0 \cos u \cos v) \tag{12}$$

A 29 × 29 element planar array antenna was simulated, in order to validate our results with those presented in [6], and then the Chebyshev model was used on an LEOS planar array.

Fig. 2 shows the natural response radiation pattern for a 29 × 29 element planar array, with SLLs around −13 dB (first sidelobe) and −17 dB (second sidelobe) with respect to the maximum gain of the main beam. Fig. 2 shows the main beam steered by −53° off-center, as described in [11,12].

Fig. 3 shows similar a Chebyshev radiation pattern for a 29 × 29 element planar array, with even SLLs around −17.5 dB with respect to the maximum gain of the main beam, thus reducing first sidelobe interference of more than 4.5 dB with respect to the natural response behavior.

Although this improvement in array antenna power distribution strongly increases the behavior of the outer SLL due

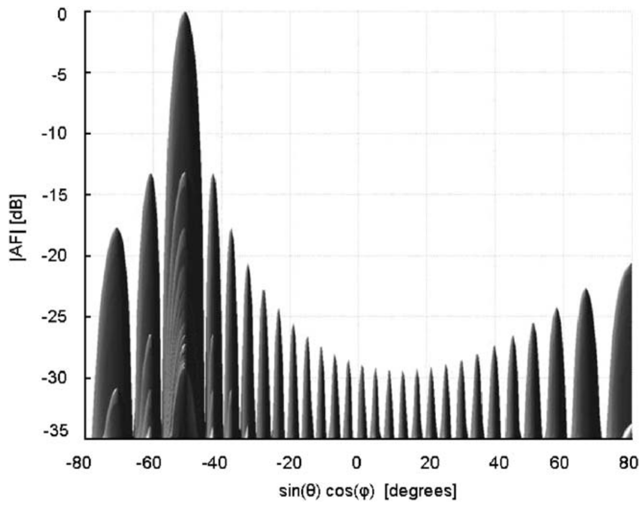

Fig. 2. Natural response radiation pattern of a 29 × 29 element planar array for different angular steerings of its main lobe.

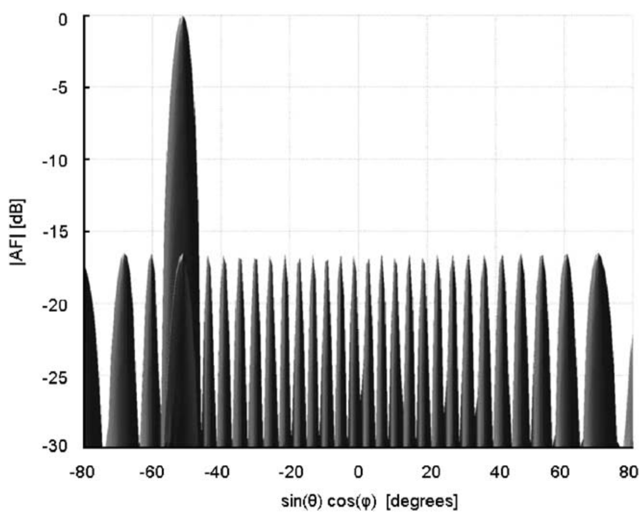

Fig. 3. Chebyshev radiation pattern of a 29 × 29 element planar array for different angular steerings of its main lobe.

to antenna radiated power redistribution, Chebyshev synthesis allows a better performance from the main lobe, increasing its total gain by an order of two and isolating its main beam angular directivity. This process allows a more precise and selective angle of arrival from a satellite smart antenna.

4. Simulation considerations in LEOS constellations

In order to apply the smart antenna technology, as mentioned in [13], we consider an LEOS constellation with an orbital height of 1400 km and a minimum elevation angle (ξ_{min}) of 19.28 from the earth station (ES). With this data it is possible to know the satellite footprint over which the main lobe of the array antennas will be steered. For the satellite link budget, 128 kbps are considered to analyze quality of service (QoS) in function of the bit error rate (BER) and maximum main lobe steering for the antenna array, considering two cases:

(a) A worst-case scenario with 10^{-3} BER probability when the satellite-ES distance is at maximum.
(b) A best-case scenario with 10^{-6} BER probability when the satellite-ES distance is at minimum.

In addition, we consider QPSK modulation with a $\frac{1}{2}$ forward error correction. The error probability for this modulation scheme is given by [14] as

$$P_e = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \tag{13}$$

where E_b is the bit energy, N_0 is the noise-power spectral density and $Q(x)$ is the complementary error function. Since error probability depends on the E_b/N_0, value, (14) relates the error probability with the link budget as follows:

$$\frac{E_b}{N_0}(\mathrm{dB}) = \left.\frac{C}{N}\right]_{tot}\left(\frac{B_N}{R_b}\right) \tag{14}$$

where B_N is the RF signal noise bandwidth in Hz and R_b is the information bit rate in bps.

The half-power beamwidth (HPBW) of the radiation pattern main lobe measures the range of angles around the maximum radiation intensity, as described in [11]:

$$HPBW = \theta_{h_{1,2}} = \cos^{-1}\left(\cos\theta_0\frac{\lambda}{Nd}\right) \tag{15}$$

where θ_0 determines the direction of the maximum array factor described by (5), N is the number of antenna elements, d is the separation between antenna elements and λ is the received signal wavelength. For a planar antenna array of $M \times N$ elements, when $M = N$, we have

$$\theta_{x_0} = \theta_{y_0} \tag{16}$$

The HPBW (θ_h) on the x–y plane array will be

$$\theta_h = \theta_{x_0}\sec(\theta_0) = \theta_{y_0}\sec(\theta_0) \tag{17}$$

where θ_{x_0} is the HPBW in broadside mode of the M element linear array antenna and θ_{y_0} is the HPBW in broadside mode of the N element linear array antenna.

Considering Eqs. (13)–(17), and according to [15], the main lobe shift or beam steered, in function of antenna gain G_{sat}, is given by

$$\theta_0 = \cos^{-1}\left(\frac{\Theta_{x0}^2}{10^{(4.511-0.1\,G_{sat})}}\right) \tag{18}$$

The BER of a satellite link results from its carrier-to-noise ratio C/N), and it is directly related to the satellite antenna gain through its link budget. With smart antennas, the gain varies dynamically along its radiation pattern through its directional angle shifts.

Since the antenna array is located onboard the satellite, Eq. (18) is a function of the satellite antenna gain G_{sat}, given by

$$G_{sat} = C/N)_{downlink} + \beta \tag{19}$$

where $C/N)_{downlink}$ is the downlink carrier-to-nose ratio. Similarly, we have that

$$\beta = -G/T)_{ES} + kB_N + L_{od} - P_{sat} \tag{20}$$

where $G/T)_{ES}$ is the receiving ES figure of merit, k is Boltzman's constant, B_N is the receiver noise bandwidth, L_{od} is the downlink propagation loss and P_{sat} is the satellite transmitting power, all unit numerical values normalized to dB.

Simplifying typical downlink expressions from a satellite link budget, and considering values of $C/N)_{uplink} = 24.77$ dB and $C/I = 16.5$ dB, the satellite gain is obtained from

$$G_{sat} = \frac{\left.\dfrac{C}{N}\right|_{tot}}{1 - 0.02573\left.\dfrac{C}{N}\right|_{tot}} + \beta \tag{21}$$

which, when substituted in (18), leads to

$$\theta_0 = \cos^{-1}\left(\frac{\Theta_{x0}^2}{10^{\dfrac{(1-ax)(b-\beta)-x}{x}}}\right) \tag{22}$$

In (22), a and b are constant values obtained from the link budget, equal to $a = 0.02573$ and $b = 4.511$, while x is the total carrier-to-noise value, $x = C/N)_{tot}$.

Thus, Eq. (22) allows the calculation of the main beam direction of a planar array antenna radiation pattern, considering BER $C/N)_{tot}$. Eq. (23) shows how the total carrier-to-noise ratio $C/N)_{tot}$ is a function of the error probability P_e:

$$P_e = \frac{1}{2} erfc\left(\frac{\left.\dfrac{C}{N}\right|_{tot}}{\sqrt{2}}\right) \tag{23}$$

5. Simulation and numerical results

5.1. Error rate (BER)

To find the maximum main lobe steering allowed to maintain a BER between 10^{-3} and 10^{-6}, we consider a planar

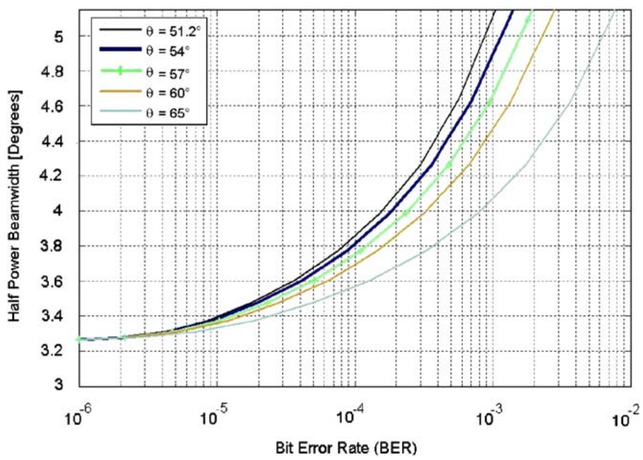

Fig. 4. BER and HPBW of a 29 × 29 Chebyshev planar array for several main lobe steerings in an LEO network with ξ_{min} 19.28 at 1400 km.

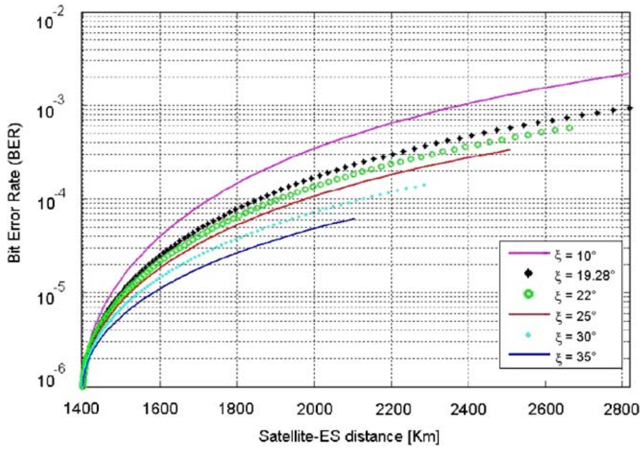

Fig. 5. Error probability of a 1400 km satellite network considering minimum ES elevation angles of 10, 19.28, 22, 25, 30 and 35.

array antenna of 29 × 29 elements with $\lambda/2$ uniform element spacing, in order to validate our results with [6].

Fig. 4 shows that the maximum main lobe steering allowed for a similar 29 × 29 element planar array employing Chebyshev synthesis in the same constellation should be ±51.2 for maintaining a QoS between 10^{-3} and 10^{-6}. In addition the HPBW may be seen varying from 3.27 to 5.17 during the satellite viewing time. With Chebyshev synthesis we can reduce the HPBW of the main lobe of 0.23 when the error probability is 10^{-6}, and 0.53 when the error probability is close to 10^{-3}.

Fig. 5 displays BER curves based on the minimum ES elevation angle for a satellite network with an orbital height of 1400 km. It can be observed that all elevation angles satisfy the error probability in the best case scenario, although for a BER of 10^{-3}, only $\xi_{min} \geqslant 19.28$ satisfies this QoS. If

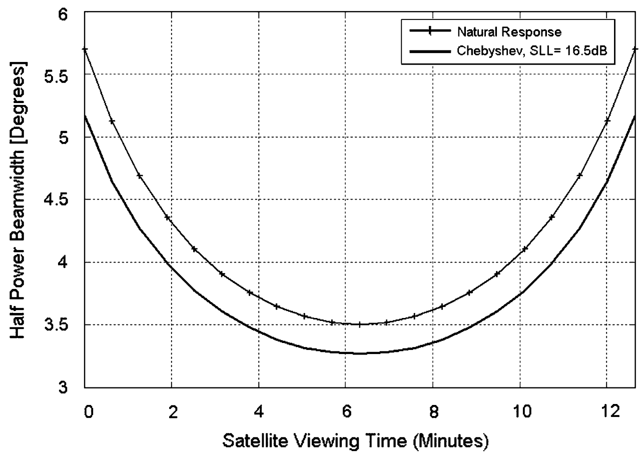

Fig. 6. Satellite viewing time for a 1400 km LEO satellite network with a 29 × 29 planar array antenna with its natural response and Chebyshev synthesis.

this angle is increased, the margin of error in the worst case improves, although it does not fulfill the maximum BER established for a 10^{-3}, making the satellite network more complex.

5.2. Satellite viewing time

There are also differences in the performance of the HPBW of a 29 × 29 element planar array regarding satellite viewing time. Fig. 6 shows HPBW main lobe variations for a 29 × 29 planar array antenna while it reshapes its radiation pattern during the satellite viewing time. Fig. 6 shows a HPBW of 5.7 for the natural response and 5.17 using Chebyshev synthesis from beginning to end of the satellite viewing time (0 and 12.64 minutes, respectively), with the narrowest HPBW at 6.32 minutes of satellite viewing time, well inside the HPBW minimum visibility angles.

6. Conclusion

This paper introduces the concept of using smart antenna technology onboard moving LEOS in order to improve the use of satellite power by modifying its radiation pattern. It dynamically focuses its main lobe towards a fixed user on the surface of the earth, improving satellite link capacity while keeping a good satellite QoS downlink performance. The onboard smart antenna technology steers the radiation pattern within the satellite footprint within its visibility angle. This papers shows how satellite antenna lobes are also focused and optimized, increasing real traffic capacity and used power, improving overall satellite link performance.

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