Fade Compensation in Antenna Optimization

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1. Introduction. Contoured beam satellite antennas are usually designed by optimizing the antenna gain pattern over the desired coverage such that the minimum gain is maximized and the ripple throughout the region minimized. Furthermore, if frequency reuse is applied by means of spatial isolation between different regions, the antenna gain pattern may also be kept below a specified level over adjacent coverages.

Once the gain has been optimized, the link performance is calculated from the usual link equations taking into account free space losses, receive antenna gain and noise temperature as well as propagation path characteristics such as depolarization, rain attenuation and scintillation. Rain attenuation is determined using statistical methods, and results in a site specific attenuation depending on the required service availability. Since the propagation effects by nature are localized, there is no correlation between antenna gain and the propagation losses, and the link performance may therefore vary considerably from place to place within the coverage. For satellite networks with a few, large ground stations this is of less importance, since each station may be designed specifically for its intended location. However, for other services such as broadcast and mobile communications where the number of ground terminals may be in the order of thousands, there is a strong interest in being able to use identical ground antennas throughout the service area.

An attempt has been made to provide a more homogeneous link performance in the recent design of the DirectTv satellite antenna (Ramanujan et al, 1993), where the continental US is divided up into three regions with different rain attenuation according to the CCIR model. The spacecraft antenna is optimized to reflect these different climatic regions, providing higher gain in the regions with higher rain attenuation.

The European Space Agency (ESA) has developed an even more advanced statistical model for the prediction of rain attenuation over Europe based on a large number of observation sites (Watson et al, 1987), for high-availability services. It is possible to predict the attenuation at any longitude/latitude coordinate in Europe, and thus generate contour maps of the attenuation. During an on-going contract with the University of Bradford and Ticra, the method is being extended to low-availability services. The tool is immediately applicable to the antenna designer since it is now possible to predict the attenuation at each of those stations where constraints are placed on the antenna gain. These can easily be modified to reflect the path attenuation thereby improving the link performance. In the following we will illustrate this by means of an example, and demonstrate the potential improvements to satellite link design.

2. Antenna design for a European coverage. We consider the scenario shown in Figure 1, which represents a typical European coverage seen from a spacecraft location at 13°E. The coverage is represented by a number of stations, 241 in total, each of which will be used in the antenna optimization. The fade margin, or attenuation, is predicted at each point and a contour map is generated as shown in Figure 1 (b). A few comments are relevant: First, the contours towards the corner of the plot are not realistic, since extrapolation is employed in these regions. Second, the actual dB-levels on the contour are not strictly the attenuation, because also the relative path attenuation, the free-space loss, is included and set to 0 dB where it is maximum. Thus the plot shows the relative variations which the antenna gain pattern should exhibit in order to optimize link performance.

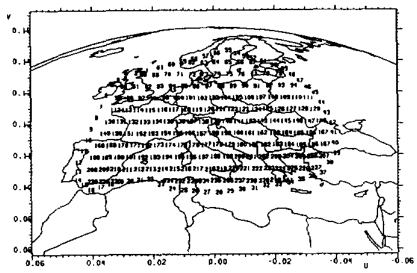

Figure 1 (a). European coverage represented by 241 stations. Orbital location is 13°E.

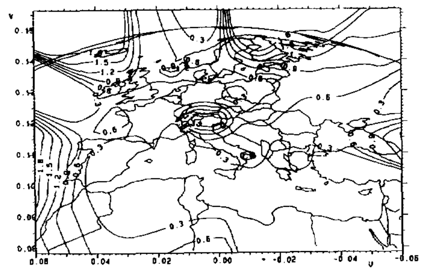

Figure 1 (b). Contour plot of attenuation function based on point prediction at the stations in (a).

The contours are derived for a 99% service availability at 12.1 GHz, circular polarization. An antenna size of 80λ diameter has been chosen, but rather than optimizing a specific antenna, shaped or multi-feed, we have employed the concept of an ideal aperture distribution. This was presented by Sørensen et al (1991) and has been found extremely useful in parametric studies where many optimizations of different size antennas are required. The results are in general better than for both shaped and multi-feed antennas since there is no spill-over, but very indicative of the expectable performance of a given size aperture. Briefly, the complex aperture field is expressed in Zernike polynomials, the maximum order of which is determined from the aperture size and coverage extent. Using a minimax optimization, the coefficients of the expansion are then determined to fulfil the antenna gain requirements.

To fully exploit the advantages of the proposed approach, we have performed optimizations both for the varying gain constraints shown in Figure 1, and for the traditional, uniform gain constraints. Plots of the two cases showing contour levels in steps of 0.5 dB starting at 0.5 dB below peak are presented in Figure 2. Obviously, the uniform case has a very flat pattern with less than 1 dB of ripple inside the coverage. The other case reflects the varying constraints: the central portion extending from northern Italy towards southern Norway is emphasized due to the high attenuation values in precisely these two regions. The ideal pattern would be one which would image the attenuation pattern of Figure 1 and have two peaks, one over Italy and one over Norway, but due to the limited size of the antenna this is not possible.

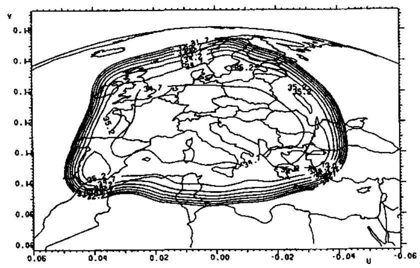

Figure 2 (a). Contour plot of antenna gain, when optimized for uniform constraints

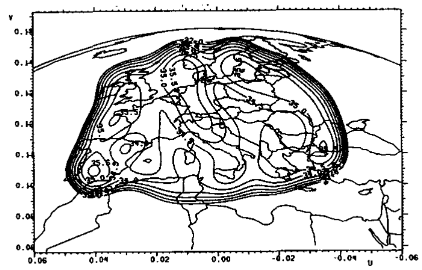

Figure 2 (b). Contour plot of antenna gain when optimized for varying constraints

The minimum antenna gain values over all stations in the two cases are 34.4 dBi for the uniform case and 33.8 for the varying case. This could imply that the uniform case was better, but that comparison is not correct. Instead we must subtract the attenuation data from the antenna gain at all stations and find the minimum of these data. The difference between these numbers for the two cases will indicate the difference in transponder power needed to provide the same worst-case link performance, and thus truly reflect the improvements obtained by optimizing for varying requirements. In this case we obtain a difference of 1.4 dB in favour of the new approach, a number which is very indicative for the magnitude of the improvements. We have found increases in the order of 1-2.5 dB depending on coverage, traffic requirements and antenna size.

3. Noise temperature considerations. In the above we have implicitly assumed the ground station antenna noise temperature to be constant when we have discussed optimum link performance. However, this is not the case, and in fact the noise temperature is correlated to the rain attenuation: when the atmospheric attenuation increases so does the antenna noise temperature. Let us assume the system noise temperature at any point of the Rx chain, consists of 3 contributions:

$$T = T_1 + T_2 + T_3$$

where

T_1 = noise temperature of low noise converter
T_2 = clear sky temperature (typically 50K)
T_3 = noise temperature due to atmospheric attenuation

It is the third contribution which varies with the atmospheric attenuation and can be estimated as

$$T_3 = (1 - 10^{-\alpha/10}) \cdot (T_4 - T_5)$$

where

T_4 = the physical temperature of the rain cloud (typically 290K)
T_5 = background temperature (typically 15K)
α = predicted attenuation (in dB) as shown in Figure 1

We have performed one further optimization of the 80λ aperture for gain constraints where the additional contribution to noise temperature is included, assuming a noise figure of 1 dB for the receiver. Such modified constraint would result in equal availability at the ground terminal, independant of the actual variation in G/T. The contour plot in Figure 3 shows a greater ripple since the constraint variations are more pronounced.

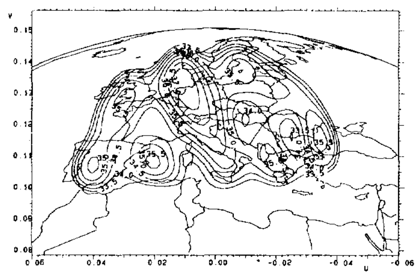

Figure 3. Contour plot of antenna gain pattern when optimized for varying gain constrains including not only propagation losses but also increase in ground station noise temperature.

A comparison of realized minimum gain values shows that the last design achieves a further 1.0 dB improvement in link performance.

4. Conclusions. The inclusion of link statistics for the attenuation into antenna gain optimization can improve the link by several dB over the traditional approach of optimizing for a uniform gain over the coverage region. The method hinges on the ability of predicting the attenuation for a given service availability at any point within the coverage. A further advantage is obtainable if the increase in noise temperature at the ground terminal due to the rain attenuation is also included. The present example has considered a static antenna design in which the attenuation function is derived based on the worst-month performance; with a reconfigurable antenna and means for monitoring the actual link performance it would be possible to incorporate dynamic compensation for fade, thereby improving the link performance dramatically.

5. References.

Ramanujam, P., et al," A shaped reflector design for the DirecTv direct broadcast satellite for the United States", Proceedings of the IEEE AP-S, Ann Arbor, pp. 788-791, 1993.

Watson, P.A., et al, "Prediction of attenuation on satellite-earth links in the European region", IEE Proceedings, Vol. 134, Pt.F, No. 6, October 1987.

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