Optimizing an Antenna Array for Satellite Communications

Randy L. Haupt
Electrical Engineering and Computer Science
Colorado School of Mines
Golden, CO, USA

***Abstract*—Phased arrays steer their main beam electronically rather than by mechanical means. An array that communicates with satellites must have the ability to maintain contact with the satellite from horizon to zenith. The array, in particular its tilt angle, size, frequency, transmit power, and element spacing, determines the amount of signal received from the satellite during its orbit. This paper shows how to optimize the array design for a given satellite system using computational intelligence: a genetic algorithm.**

I. Introduction

Phased array antennas are ideal for tracking, controlling, and communicating with satellites. Most arrays are either linear (antenna elements lie along a line) or planar (antenna elements lie in a plane). Sometimes, phased arrays are made to conform to the surface of a structure, such as a sphere (Fig. 1) [1]. The beam of a spherical array can follow satellites from the horizon to the zenith. Spherical arrays have uniform patterns and gains over the hemispherical coverage but suffer from expensive high fabrication and assembly costs [2].

An alternative to the spherical array is the multi-faced planar array [3]. Each planar array scans a specified region of the hemisphere. There needs to be enough array faces that have a sufficient scan region in order to cover the hemisphere. The PAVE PAWS radar is an excellent example of a multi-face phased array (Fig. 2) that scans over a large region [4].

Typically, large tracking radars have the 20^o tilt angle exhibited by PAVE PAWS (Fig. 2) and Cobra Dane (Fig. 3). Although these examples are all radars, communications arrays must use the same concepts to communicate with satellites. The arrays for communications do not have to be as large as for radars due to the $1/R^4$ propagation loss in radar compared to the $1/R^2$ propagation loss in communications system. The push for multi-function apertures, however, will find radar and communications functions on the same antenna aperture.

The spacing between elements in the elevation plane is limited by grating lobes that result when the element spacing is too large and the highest frequency in the signal is not sampled enough. In addition, the gain of the antenna in a given direction is proportional to the projected area in that direction. These constraints have been used to estimate an optimum tilt angle for an array [6]. Further research included amplitude tapered arrays as well [7].

This paper addresses horizon to zenith coverage of a communications system by optimizing a phased array that results in sufficient power transfer to a satellite as it orbits from horizon to zenith. Computational intelligence methods are needed to optimize the complex design of an antenna array. A genetic algorithm finds the optimum array tilt angle, size, frequency, transmit power, and element spacing given the orbit of the satellite. The formulation in this paper differs from previous results, because a communications system rather than a radar is considered. In addition, the satellite orbit is a factor and the number of elements and element spacing are optimized in addition to the tilt.

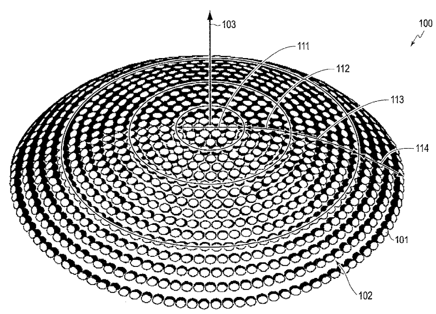

Fig. 1. An array on a spherical surface [1].

Fig. 2. PAVE PAWS array [2].

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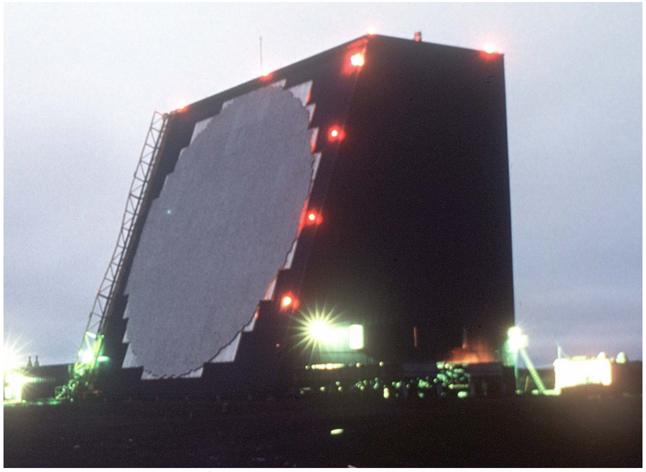

Fig. 3. PAVE PAWS array [5].

II. PROBLEM FORMULATION

A crude approximation to optimizing the tilt angle combines the well-known element spacing limit to restrict grating lobe formation [2]

$$d \le \frac{\lambda}{1+\sin\theta_{s\max}} \tag{1}$$

with the gain of an antenna approximately equaling it projected area

$$G(\theta) \propto \cos\theta \tag{2}$$

where θ is measured from boresight and $\theta_{s\max}$ is the maximum scan angle. These two conditions combine into an approximation for the antenna gain [6].

$$G(\theta) \approx \frac{\cos\theta}{1+\sin\theta_{s\max}} \tag{3}$$

The formulas for the antenna gain were improved by incorporating low sidelobe amplitude tapers [7].

A phased array maintains contact with a satellite by electronically scanning the beam as the satellite moves from horizon to horizon. Unfortunately, a phased array scan region is much less than $\pm 90^o$. Usually, a planar array scan region is limited to $\pm 60^o$ but is often less due to the element pattern and mutual coupling. In order to track and maintain contact with the target, the phased array is tilted, so the array can transmit/receive more power at the horizon (satellite is farthest away) than at the zenith (satellite is closest). Previous results were for radar which has targets that are much lower in altitude than satellites.

Fig. 4 shows a diagram of a satellite in orbit and a tilted phased array on the surface of the earth. The distance from the ground antenna to the satellite is given by

$$R = -r_e\cos(\gamma) + 0.5\sqrt{\left[-2r_e\cos(\gamma)\right]^2 - 4\left[r_e^2 - (r_e+h)^2\right]} \tag{4}$$

$r_e =$ radius of earth

$h =$ height of orbit

$\gamma =$ satellite angle measured from zenith

This distance determines the propagation loss of the signal. The satellite antenna points at the ground station at all points in the orbit.

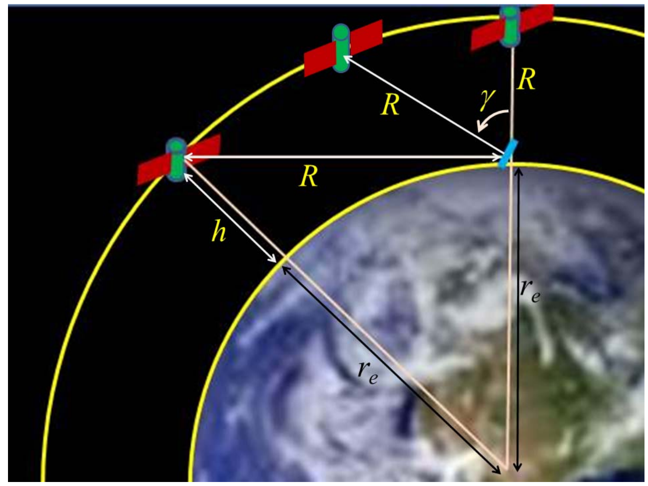

Fig. 4. Satellite in orbit and passing over a phased array that is tilted to maximize the power received by the satellite.

Fig. 5 shows the space loss as a satellite moves from zenith to horizon. Three orbits were considered: geostiationary (GEO), medium earth orbit (MEO), and low earth orbit (LEO). A higher orbit has a greater loss than a lower orbit. The loss varies as the satellite travels along the orbit with the greatest loss at the horizon. Low orbits have large variations whereas the geostationary orbit is nearly flat. The angle γ is measured from the zenith to the satellite (Fig. 4).

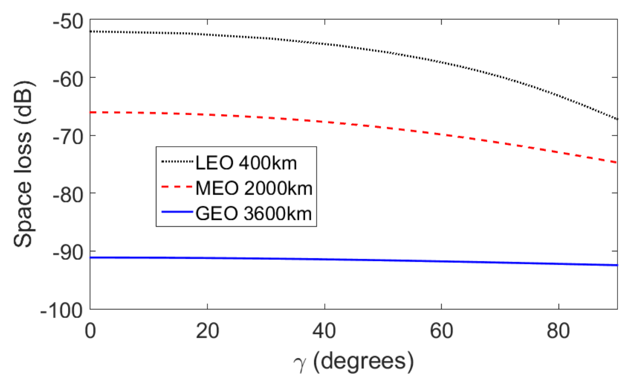

Fig. 5. Space loss as a function of angle for LEO, MEO, and GEO satellites.

Fig. 6 is a close up of the array in Fig. 4. The z-axis is orthogonal to the array and points in the direction of boresight. The tilt angle (θ_{tilt}) is the angle between the z-axis and the horizon. Since the array is assumed to scan from horizon to zenith, the maximum scan angle is the angle from the z-axis to the zenith.

$$90^o = \theta_{s\max} + \theta_{tilt} \tag{5}$$

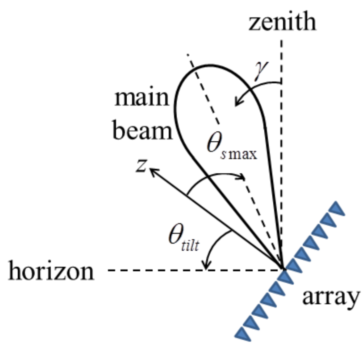

Fig. 6. Satellite in orbit and passing over a phased array that is tilted to maximize the power received by the satellite.

III. Cost Function and Genetic Algorithm

The antenna has many design variables. In this paper, only the following variables are optimized by the genetic algorithm:

θ_{tilt} = angle between boresight and horizon
N = number of elements
P_t = transmit power (W)
f = frequency $4 \le f \le 5$ GHz
d = element spacing (cm)

The satellite antenna is assumed to have the following characteristics:

- G_r = gain of receive antenna = 20 dB
- Satellite antenna points at transmit antenna
- Mimimum received signal level = -120 dB

The goal is to have the transmit signal exceed the minimum power level at the satellite from horizon to zenith while minimizing the cost of the antenna which is proportional to N and P_t.

The cost function is based on the Friis transmission formula [2].

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \tag{6}$$

where

P_r = power transmitted
G_t = gain of the transmit antenna
G_r = gain of the receive antenna
λ = wavelength
R = distance between transmit and receive antennas

The resulting cost is given by

$$\text{cost} = \begin{cases} \max\{P_r - P_{\min}\} & P_r \ge P_{\min} \text{ for all } \gamma \\ 2\max\{|P_r - P_{\min}|\} & P_r < P_{\min} \text{ for any } \gamma \end{cases} \tag{7}$$

For the examples here, the receiver sensitivity ($P_{\min}$) is set at --120 dBW.

Local optimization does not work well with this cost function. Variables have to be constrained, many local minima exist, and discontinuities discourage the use of derivatives (e.g. $P_r > -120$ dBW). Computational intelligence approaches to optimization overcome the limits of traditional derivate based local optimization algorithms. The genetic algorithm was selected to perform the optimization. For this project, the genetic algorithm has a population size of 8, a mutation rate of 10%, and used uniform crossover. These parameters were selected based upon experience and suggestions in [8]. The genetic algorithm ran for 100 generations and the resulting best solution was further refined with a Nelder-Mead downhill simplex algorithm (which avoids taking derivatives of the cost function).

IV. Optimized Array

This section presents three examples of communicating with satellites in GEO, MEO, and LEO orbits. Fig. 7 shows the convergence of the genetic algorithm/Nelder-Mead optimization. Optimization benefited the GEO orbit the most and the LEO orbit the least.

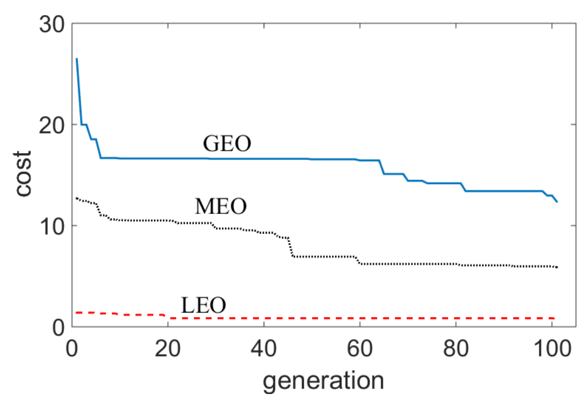

Fig. 7. Satellite in orbit and passing over a phased array that is tilted to maximize the power received by the satellite.

In the first example, the satellite is assumed to be in a GEO orbit at h = 36,000 km. The percent difference between R at the horizon and at the zenith is small, so the received power at various positions in the orbit is nearly the same. Since the distance to the satellite is greatest in this orbit, the transmit power and size of the array are the largest. This design also had the highest frequency. An array tilt of 36.6° insures that enough power reaches the satellite, while variation in received power is minimized for all γ.

The lower MEO orbit at 2,000 km has less loss than the GEO orbit, so it requires less transmit power and fewer elements. The tilt and maximum scan angles are similar to the GEO orbit example. Element spacing is slightly larger. An array tilt of 36.6° insures that enough power reaches the satellite, while variation in received power is minimized for all γ.

The final example is a satellite in a LEO orbit at 400 km requires the smallest antenna and the least amount of transmit power. It also has the lowest frequency of operation and the largest element spacing. The tilt and scan angles are close to that of the other cases. An array tilt of 38.0° insures that enough power reaches the satellite, while variation in received power is minimized for all γ.

Table 1 summarizes the optimization results for each of the orbits. The last three rows shows the receive power at three different angles. An optimized design will have $P_r(\theta = \theta_{tilt})$ and $P_r(\theta = 0^o)$ about the same. A nearly constant P_r for an orbit becomes more practical as h increases.

Table 1. Array design features.

Variable	GEO	MEO	LEO
h (km)	36,000	2000	400
f (GHz)	4.48	4.27	4.06
N	93	22	18
d (λ)	0.553	0.576	0.588
θ_{tilt}	36.6°	36.1°	38.0°
$\theta_{s\max}$	53.4°	53.9°	52.0°
P_t (W)	6007	378	75
$P_r(\theta = 0)$ (dBW)	-119.2	-114.4	-108.5
$P_r(\theta = \theta_{tilt})$ (dBW)	-120.0	-120.0	-120.0
$P_r(\theta = 90^o - \theta_{tilt})$ (dBm)	-119.8	-114.1	-107.5

V. Conclusions

Designing a communications antenna array based on the orbit of the satellite saves on the cost of building the array, while significantly improving ground communication with the satellite. This paper explained how to computational intelligence to optimize the signal received by the satellite in orbit by varying the tilt angle, the size of the array, the frequency, and the transmitted power. Results show that the standard 20^o tilt for radar phased arrays is not ideal for phased arrays that communicate with satellites. Instead, a tilt between 36 and 38 degrees insures that enough power reaches the satellite, while variation in received power is minimized for the entire orbit.

The next step is to include mutual coupling in the design and perform the optimization. Since the cost function will be much more time-consuming, the genetic algorithm parameters will need to be tuned to reduce the number of function calls. Linear arrays are a start for analyzing this problem, but planar arrays must be used for a more realistic design.

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