Concentric Ring Shaped Cellular Configuration for High Altitude Platforms using Particle Swarm Optimization

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ABSTRACT
In this paper a high altitude platform (HAP) based vertical one dimensional (1D) antenna array is used to generate a concentric ring shaped cellular configuration. The geometry and the design of the ring shaped cells are explained. Different types of weights for the linear array, e.g. the Dolph-Chebyshev weights, Hamming weights, and optimized weights by The Particle Swarm Optimization PSO algorithm are used for beamforming of the linear array. Calculations of the link budget are introduced for evaluating the signal to interference ratio SIR of a user in the HAP system. The study of the coverage performance for the three different types of weights is introduced. Results indicate the superior performance of PSO in improving the coverage performance than Dolf-Chebyshev and Hamming windows.

General Terms
High Altitude Platforms, Linear antenna arrays, Particle Swarm Optimization, and Window functions.

Keywords
High Altitude Platforms (HAPs), Particle Swarm Optimization (PSO), Signal to interference ratio (SIR), and coverage performance

1. INTRODUCTION
High Altitude Platforms HAPs refer to aircrafts or airships operating in the stratosphere at an altitude in the range 17-22 km [1]. HAPs can play a great role in mobile communications because of their superior advantages compared to terrestrial systems or satellite systems [2]. The terrestrial mobile systems need large numbers of base stations to cover the required area. Satellite systems have many problems, e.g. limitations on the minimum cell size which appear in GEO satellite systems and handover problems provided by LEO satellites [1]. Also radio coverage in platform wireless communications is superior to both terrestrial and satellite systems because of the availability of line of sight communications as in satellite but with low propagation loss due to the reduced altitude [1-5].

Easy deployment, flexibility, low cost operation, and broad coverage are major advantages that may encourage fast deployment of HAP communication systems [1], [4]. HAPs can provide a wide range of broadband services like broadband internet access, video conferencing, voice telephony, voice over IP, entertainment services (i.e., radio and TV broadcasting and video on demand), distance learning, and telemedicine [1]. The main disadvantage is the instability of HAP position which requires frequent stabilization of the HAP antenna [6]. The rotation of the HAP around its central axis is a major problem especially for outer cells in the hexagonal configuration which requires either redirecting all the beams forming the cells or performing high rate handoff techniques [6]. The novel ring shaped cellular configuration is used to overcome this problem [7]. It affords many advantages like the reduction of the required motion monitoring and the needed corrections. Also, it allows power reduction and implementation of TDMA techniques. It is provided by a two dimensional rectangular planar array which has the disadvantages of the large payload and the large number of elements [6], [8]. To compromise between the advantages of the ring shaped cells and the system complexity arises from the 2D antenna array, a 1D vertical antenna array is used to construct the concentric ring shaped cells [6]. This approach shows a reduction of both antenna payload and implementation complexity.

In this paper, the weights of the antenna elements are provided by Hamming window [9], Dolph-Chebyshev window [9], and PSO algorithm [10]. Hamming window improves the first sidelobes level. Dolph-Chebyshev achieves the narrowest main-lobe width for a given desired side-lobe level. PSO algorithm is a power optimization tool for antenna designing problems. PSO is preferred than other evolutionary algorithms like genetic algorithms or the sequential Quadratic programming SQP algorithm because it is much easier to understand and implement, and it requires minimum mathematical processing [10-12]. The coverage area was divided into concentric ring shaped cells [6]. Then, the link budget calculations were used to provide the value of the power received by a user in this coverage area [8]. Additionally, the frequency reuse plane was used to calculate the signal to interference ratio SIR and provide a comparison of the coverage performance for the three different cases of the linear array weights [13].

The paper is organized as follows: section 2 illustrates the geometry of the concentric ring shaped cells. Section 3 illustrates the linear vertical array and three different types of weights. Section 4 shows calculations of SIR. Section 5 shows the Numerical results and, finally, conclusions are included in section 6.

2. NUMBER AND SIZE OF RING SHAPED CELLS

Figure1 illustrates a communication scenario with a HAP at an altitude of h (km) covering a circular area with a radius of R (km) [6]. A vertical linear array was used to cover the area with concentric ring shaped cells. Applying a different steering angle to the beam produces the needed cells with different areas as a result of the nonequal beamwidth.

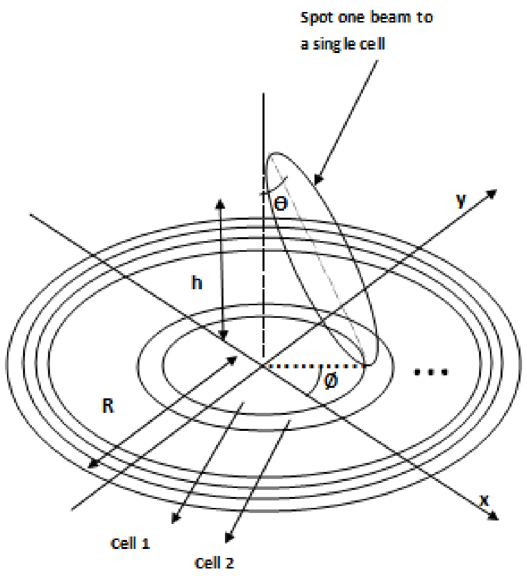

Fig 1: Vertical antenna array and concentric ring-shaped cells for HAP communications [6].

The number of cells in a specific coverage area depends on the beamwidth of the array which can be controlled by the number of array elements, distance between elements, and the feeding of each element. The following algorithm defines the position and width of each cell [6]:

1. For the 1st cell, the center is zero $(\text{center}(1) = 0)$ and the equivalent steering angle is zero $(\text{pho}(1) = 0)$.
2. The 3 dB beamwidth was considered as $(WN(1))$.
3. The right and left boundary of the cell were $\text{WR}(1)$ and $WL(1)$ respectively

   $\text{WR}(1) = \text{h} * \tan(\text{phir}(1))$ where

   $$\text{phir}(1) = \text{pho}(1) + \text{WN}(1)/2 \qquad (1)$$

   $\text{WL}(1) = \text{h} * \tan(\text{phil}(1))$ where

   $$phil(1) = pho(1) - WN(1)/2 \qquad (2)$$

   where h is the altitude of HAP.
4. For the next cells, the initial center was started by zero $(center(NOC) = 0)$, the equivalent steering angle was found by $pho(NOC) = a\tan(center(NOC)/h)$, the equivalent beamwidth and the right and left boundary of the cell number (*NOC*) were determined respectively.
5. The difference between the left boundary of the current cell (*NOC*) and the right boundary of the previous cell (*NOC-1*) was evaluated as following $diff = WL(NOC) - WR(NOC-1)$.
6. The value of overlap $(diff)$ was checked, when it was within the acceptable range the simulation proceeded to the next cell, if not the center was updated once again.
7. For the same cell, every time $diff(i)$ was compared to the previous value $diff(i-1)$, if $diff(i) < diff(i-1)$ the value of $diff(i)$ was set to $diff(i-1)$ and if not, the value of σ (the step size or the shift in center of the cell) was updated to the half for the convergence of calculations.
8. When the required overlap was not reached, updating of the center of the cell was done by shifting it by σ

   $$center(NOC) = center(NOC) + \sigma \qquad (3)$$

   when $WL(NOC) < WR(NOC-1)$

   $$\text{center(NOC)} = \text{center(NOC)} - \sigma \qquad (4)$$

   when $\text{WL(NOC)} > WR(\text{NOC} - 1)$. Then; all the preceding calculations were reevaluated. For each cell, the value of i (number of iteration to reach the optimum position of the cell) and the value of σ were initialized.
9. The algorithm proceeded outwardly till the whole coverage area is covered.

The final number of cells depends on the shape of the beam originating from the array. Each beam steered toward a certain direction (the center of the cell), had a specific beamwidth which determines the boundaries of the cell. This beamwidth decreases with increasing the steering angle. The area of cells differs with moving away from the center of the coverage area. The outermost cell was found to be the largest cell. The geometry of the concentric ring cells obtained here can be produced by the analysis developed in [14].

3. LINEAR ARRAYS

In this study, the coverage area needs to be covered with a suitable number of concentric ring shaped cells generated by scanning the area with different steering angles. The characteristics of the beam were controlled through the feeding (weights) of the array elements. The array factor of N elements linear array was evaluated as following [6]:

$$A(\theta) = \sum_{u=0}^{N-1} w(n) e^{Jk_o ulcos\theta} \qquad (5)$$

$$w(n) = |w(n)| e^{-Jk_o ul \cos\theta_o} \qquad (6)$$

Where u takes the values of 0 to N-1, $k_o = 2\pi/\lambda$ is the wavenumber, λ is the wavelength and l represents spacing between array elements. $W(n)$ represents a complex weight, $|w(n)|$ is amplitude weighting, θ is the complementary elevation angle of a point in the coverage area and θ_o is the beam steering angle. Controlling the weights, by applying different window functions or optimizing them through PSO, defines the array factor and the gain of the array. The Dolph-Chebyshev, Hamming, and PSO optimized weights were introduced as follows:

- The Dolph-Chebyshev window samples were evaluated by taking the inverse z transform after computing the z transform of the Dolph-Chebyshev array factor from its zeros [7].

  $$w(z) = z^{-(N-1)/2} \prod_{j=1}^{N-1} (z - z_j) \qquad (7)$$

  N is the number of array elements and z_j are zeros of the Dolph-Chevyshev polynomial. The inverse z transform of $w(z)$ are the window coefficients $|w(n)|$.
- Hamming window provides a narrow mainlobe but the sidelobes level is changing from the best level of the first sidelobes to a higher level of the rest.

  $$w = 0.54 - 0.46\ cos\left(\frac{2\pi c}{N-1}\right) \qquad (8)$$

  where $c = (0:N-1)$
- Particles Swarm Optimization algorithm: The PSO algorithm is used here to optimize the amplitude of the

excitation of each element in the linear array to improve SIR and yield a better coverage performance. The PSO algorithm is introduced in 1995 by Kennedy and Eberhart [10] as a population based self-adaptive optimization technique, which depends on the social interaction between particles. The concept of fitness is used by particles to get the optimum solution. The PSO algorithm proceeds with the following steps:

1. The solution space and the fitness function were defined.
2. The position and velocity of each particle of the swarm were randomly initialized.

$$X_m = (x_{m1}, x_{m2}, \dots\dots\dots, x_{mY})$$
$$V_m = (v_{m1}, v_{m2}, \dots\dots\dots, v_{mY}) \quad 1\#m\#M \qquad (9)$$

M is the number of the particles in the swarm.

3. For Y dimensional problem, the iterative formula of particle's velocity updating equation was arranged

$$V_{my}^{k} = w.\, v_{my}^{k-1} + c_1.\, u_{y1}^{k}.\, (p_{my}^{k} - x_{my}^{k-1}) + c_2.\, u_{y2}^{k}(g_y^{k} - x_{my}^{k-1}) \qquad (10)$$

and the particle's position updating equation

$$X_{my}^{k} = x_{my}^{k-1} + s.\, v_{my}^{k} \qquad (11)$$

The superscripts k and $k-1$ refer to the time index of the current and the previous iterations. p_{my}^{k} is the personal best position. It defines the position of the best fitness value attained by each particle of the swarm up to the present iteration. g_y^{k} is the global best position which specifies the position at which the best fitness values was achieved by particles, u_{y1} and u_{y2} are two random numbers of uniform distribution in the interval [0, 1]. c_1 and c_2 specify the relative weights of the personal best position versus the global best position. w is the inertial weight in the range [0-1]. Finally, s specifies convergence speed.

4. EVALUATION OF SIGNAL TO INTERFERENCE RATIO (SIR)

In order to determine the value of SIR, the link budget for the HAP earth link was considered to calculate the power (in dB) received by a mobile from a HAP at an angle (θ) (the complementary elevation angle of the user position) in a cell of number NOC [8], [13].

It can be obtained by:

$$P_r(\theta) = P_t + G_r(\theta) + G_t(\theta) - L_s(\theta) \qquad (12)$$

Where P_t is the transmitted power from the HAP, $G_r(\theta)$ is the mobile antenna power gain, $G_t(\theta)$ is the HAP array power gain and $L_s(\theta)$ is the free space path loss which is calculated as:

$$L_s(\theta) = 20 \log 10 \left(\frac{4\pi h}{\lambda\, cos(\theta)}\right) \qquad (13)$$

SIR for a particular user at an angle θ is defined by the following equation [13]:

$$SIR(\theta) = \frac{P_{rmax}(\theta)}{-P_{rmax}(\theta) + \sum_{t=1}^{N_c} P_{rt}(\theta)} \qquad (14)$$

Where N_c is the number of steered beams toward co-channel cells, $P_{rt}(\theta)$ is the power received by the user from these beams (*t=1,…* *,Nc*) and the maximum of these values is $P_{rmax}(\theta)$ which represents the power received by the user from his cell. For a specific user at an angle (θ) connected to one of the cells according to his position, the gain of the beam steered to form the cells was evaluated at the angle(θ). Then, this gain was used in the link budget equation as $G_t(\theta)$ to compute the received power by the user from this cell. This process was repeated for each cell of the co-channel cells which depends on the selected frequency reuse plan. The maximum received power is the power directed to the user from his cell and represents the signal. The summation of all the received power values excluding the maximum represents the interference. The preceding steps were developed for the evaluation of SIR. Users were randomly positioned in the coverage area with one user in each cell. Coverage performance is evaluated by the following probability distribution function [15]:

$$c(\mu) = P_r\{SIR_{NOC} > \mu\} \qquad (15)$$

5. NUMERICAL RESULTS

The proposed communication scenario was as follows [15]: the platform height h=20 km, the radius of coverage area R=32.7 km and the number of array elements N=171. The selected frequency is 30 GHz. The coverage area is divided into 61 ring shaped cells with reuse factor of 2 for the three types of weights (30 cells /channel). The study of coverage performance of 80 to 100% of cells was evaluated.

Figure 2 shows the coverage performance obtained with a vertical linear antenna array with Hamming window and a linear antenna array of weights optimized by semidefinite programming SDP [15]. Results show a good coverage performance of approximately 37 dB at 100% coverage to 41 dB at 80% coverage. SDP improves coverage performance by approximately 15 dB more than Hamming.

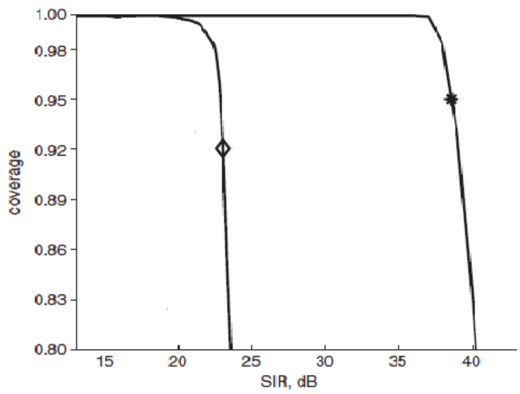

Fig 2: Coverage performance of a linear vertical antenna array showing results for SDP and Hamming window [15].

In this paper, the results were provided using Hamming window, Dolph Chevyshev window, and PSO algorithm as shown in figure 3**.** The comparison between figure 2 and figure 3 regarding hamming window coverage performance shows rapprochement of the results. Dolph-Chebyshev weights show an improvement in the coverage performance than Hamming weights by 13 dBs. PSO improves the coverage performance than Dolph-Chevyshev by a variable level starting from 17 dB at 100% coverage to 11 dB at 80% coverage. PSO provides a better coverage performance than SDP by 7 dBs. So, PSO provides a better control of the sidelobes level more than SDP.

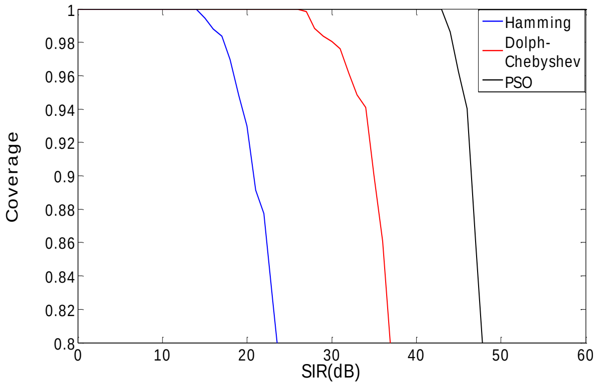

Fig 3: Coverage performance of a linear vertical antenna array

6. CONCLUSIONS

In this paper, our target was to achieve the best coverage performance in a coverage area divided into concentric ring shaped cells. Three beamforming techniques were utilized, Hamming window, Dolph-Chebyshev window, and PSO algorithm. For the same number of cells per channel, PSO algorithm produced the best coverage performance. Beamforming of the vertical linear antenna array with PSO provided a great reduction of sidelobes level. So, the values of interference of co-channel cells were reduced and SIR increased.

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