Accepted Manuscript

Regular paper

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PII: S1434-8411(17)32950-3
DOI: https://doi.org/10.1016/j.aeue.2018.05.002
Reference: AEUE 52323

To appear in: *International Journal of Electronics and Communications*

Received Date: 14 January 2018
Accepted Date: 1 May 2018

Please cite this article as: A.M. Ismaiel, E. Elsaidy, Y. Albagory, H.A. Atallah, A.B. Abdel-Rahman, T. Sallam, Performance Improvement of High Altitude Platform Using Concentric Circular Antenna Array Based on Particle Swarm Optimization, *International Journal of Electronics and Communications* (2018), doi: https://doi.org/10.1016/j.aeue.2018.05.002

Performance Improvement of High Altitude Platform Using Concentric Circular Antenna Array Based on Particle Swarm Optimization

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Abstract—This paper proposes a beamforming technique based on finding the optimum current weights using comprehensive learning particle swarm optimizer (CLPSO) for side-lobe level (SLL) reduction. In a wireless communication network operated by high altitude platforms (HAPs), the key factor for the carrier to interference ratio (CIR) improvement is the antenna SLL reduction. The antenna array configuration is chosen as concentric circular antenna array (CCAA) and the HAPs cellular system is consisting of 169 cells. Compared to other techniques, the proposed method can significantly suppress SLL and this can reduce the co-channel interference for HAPs cellular networks design which leads to a significant improvement in CIR.

Keywords— ***Comprehensive learning particle swarm optimizer (CLPSO); concentric circular antenna array (CCAA); High altitude platforms (HAPs).***

1. Introduction

With a growing demand for the broadband multimedia and higher data rate applications, service providers are looking for utilizing high altitude platforms (HAPs) to introduce broadband wireless access which has the benefits of both satellite and terrestrial communication systems [1]. HAPs are airplanes or airships which are located at stratospheric altitudes of 17-22 km. In HAPs, the line-of-sight (LoS) paths can be efficiently achieved, so that fewer infrastructures are used to serve the same coverage area compared to the terrestrial services. HAPs also have important benefits over the satellite communication systems because of their low propagation delay and small free space path loss [2]. According to these merits, HAPs have been used in many applications such as communication services and other cost effectively applications [3] like broadband communications, remote sensing, navigation, event servicing, and emergency services. In [4], an efficient traffic monitoring and control system using HAPs is proposed. The system has a worthy performance compared to other systems which makes HAPs more convenient to establish wireless sensor network for traffic monitoring applications. Irrigation control system is achieved using HAPs to manage the amount of fresh water with high quality performance which cannot be attained by traditional smart irrigation techniques [5]. Digital video and audio broadcasting (DVB/DAB) is another application that is proposed using HAPs with enhanced link performance compared to terrestrial systems [6].

The space and weight on a HAP are limited, the HAP antenna constitutes a significant part of the payload, and as a consequence designing the antenna with optimized parameters is vital [7]. Interference is a severe issue in any communication system. In a HAPs system, the interference is provided by antennas serving cells by intersecting the main lobes or the side lobes [8]. The level of the carrier to interference ratio (CIR) in a HAP cellular system, assuming LoS links, is a result of spatial spectrum reuse and is dominated by the antenna radiation pattern. The improving in the CIR will increase the system capacity and will allow the provision of new services.

Many antenna configurations are applicable for HAPs. A set of different aperture antennas are used in [9] to provide one spot-beam per cell. Although HAP has high system capacity resulting from low side lobe levels, the antenna size and weight could be considerably large and improper. With beamforming, the antenna array provides higher directivity and capability to track users on the ground. The antenna array may be linear or planner. A linear array permits beam steering in one dimension. Therefore, this array configuration will not be suitable for HAPs. On the other hand, a two-dimensional array (TDA) can steer the beam in any direction. However, the SLL for this array is very high for practical applications in HAPs cellular system [10]. The concentric circular antenna array (CCAA) is a variant array configuration that has widespread applications [11]. The uniform concentric circular array (UCCA) leads to an SLL which is lower than that of the square TDA for a high number of rings at the expense of the wider beamwidth [10].

Many attempts to reduce the SLL of CCAA have been done. In [12], the existence of the central element in UCCA lowers the SLL while a minor increase is achieved in the beamwidth. This method is only sufficient for small-size arrays. The proposed technique to control the SLL of CCAA is presented in [13]. All elements in any ring have equal excitations. However, the different rings are weighted with different excitations through a Gaussian window. In this technique, the SLL can be decreased by increasing the number of rings and decreasing the number of elements in the inner rings. Recently, genetic algorithms (GAs) [14] and particle swarm optimizer (PSO) [15] have been examined for analysing the CCAA by optimizing the element spacing or the excitation weights of rings to minimize the maximum SLL. In [16], another approach is based on the improved discrete cuckoo search algorithm (IDCSA) has been used to suppress the maximum SLL with a specific half power beam width. Generally, IDCSA is proposed to solve the problem of CCAA by turning off certain array elements. In [17], a Symbiotic Organisms Search (SOS) algorithm has been used for sidelobe reduction. Unlike other methods, SOS algorithm is free of tuning parameters which makes it an attractive optimization method. In these studies, The PSO algorithm has achieved better performance than other evolutionary algorithms.

The core shortage of the traditional PSO algorithm is the early convergence, especially with the multimodal problems. Different PSO algorithms were proposed to improve the PSO's performance when dealing with multimodal problems. Many antenna design problems are multimodal. Consequently, there is a need for an optimization method that does not get trapped in a local optimum such as the comprehensive learning PSO (CLPSO) [18].

In the previous work [11], a technique was developed for the synthesis of CCAA with central element. The comprehensive learning PSO (CLPSO) is used for obtaining the optimum current excitation weights and positioning of the rings.

In this paper, a new technique which is based on the CLPSO is used to optimize the current excitation weights of the rings for SLL reduction. Therefore, the optimized CCAA, as well as the applied beamforming techniques, will help in improving the HAPs cellular performance regarding the levels of the CIR.

The paper is organized as follows: In Section 2, the problem formulation is presented and discussed. In Section 3, the CCAA beamforming technique is discussed. Section 4 illustrates the performance of the HAPs cellular communications using CCAA. Finally, Section 5 concludes the work.

2. Problem Formulation

2.1 Geometry of CCAA

The CCAA has elements organized in multiple concentric circular rings which differ in radius and number of elements as shown in Fig. 1. The array composed of M concentric circular rings where the m^{th} ring has a radius r_m and N_m is the number of elements in each ring where $m = 1, 2, 3, .. M$. The elements in the array are assumed to be isotopic sources so the radiation pattern of array can be formulated in terms of the array factor only. When a single element is placed at the center of the CCAA as shown in Fig. 1, the array factor is given by [19]:

(1)

where M and N_m are the number of rings and the number of elements in each m ring, respectively, w_m is the excitation current of elements at the m^{th} ring, r_m is the radius of the m^{th} ring, k is the wave number, θ and $\emptyset$ $(\theta, \emptyset \in [-\pi, \pi])$ are the zenith angle from the positive *z*-axis and the azimuth angle from the positive *x*-axis respectively, and $\emptyset_{mn}$ is the element angular separation calculated from the positive *x*-axis [19]:

$$\emptyset_{mn} = 2\pi\left(\frac{n-1}{N_m}\right); m = 1,2,3,\ldots,M; n = 1,2,3,\ldots N_m \quad (2)$$

α_{mn} is the phase difference between the elements in the CCAA [19]:

$$\alpha_{mn} = -kr_m \sin\theta_o \cos(\emptyset_o - \emptyset_{mn}) ; m = 1,2,3,..,M; n = 1,2,3,..N_m \quad (3)$$

where θ_o and $\emptyset_o$ are the main lobe angles. A broadside radiation pattern is formed in case of θ_o = 0 and $\emptyset$ = constant. The array factor can be written as:

$$AF(\theta,\emptyset) = 1 + \sum_{m=1}^{M}\sum_{i=1}^{N_m} w_m e^{j(kr_m \sin\theta \cos(\emptyset - \emptyset_{mn}))} \quad (4)$$

The array factor is normalized to dB and written as follows:

$$AF(\theta,\emptyset) = 20log_{10}\left[\frac{|AF(\theta,\emptyset)|}{|AF(\theta,\emptyset)|_{max}}\right] \quad (5)$$

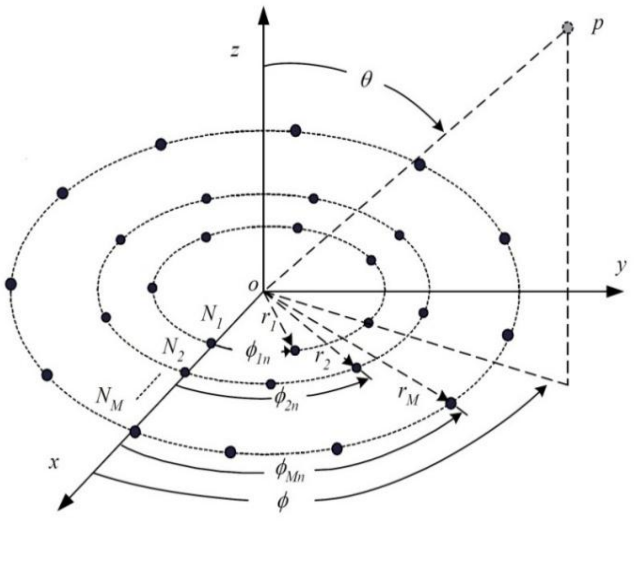

Fig. 1 CCAA.

2.2 Cost Function

After defining the CCAA, the next step in the design procedure is the formulation of the cost function or fitness function that should be minimized to achieve the highest reduction of the maximum SLL and try to maintain the HPBW of the proposed design closed to the HPBW of the uniform excitation antenna array. To achieve these goals, the cost function (CF) is written as:

(6)

where SLL_{max} is the magnitude of the maximum side-lobe level, W_1 *and* W_2 are positive weighting factors which are used to control the obtained results, $FNBW_c$ is the angel in radian of the computed first null beamwidth for the non-uniform excitation case, and $FNBW_u$ is the angel in radian of the first null beamwidth for the uniform excitation case $(w_m = 1)$, where w_m is the excitation current of elements of the m^{th} ring.

In this problem, the values of W_1 and W_2 are chosen to preserve the reduction of SLL_{max} more dominant than the optimization of the HPBW of the array. In addition, the CF never becomes negative. Consequently, the values of W_1 and W_2 are selected according to the experiment to be 18 and 1, respectively. In equation (6), the minimization of the CF guarantees a maximum reduction of the SLL_{max} as well as reducing the difference between the $FNBW_c$ and the $FNBW_u$.

3. Proposed Beamforming Technique

3.1 PSO

PSO is a developmental algorithm that simulates the swarm behaviour of bird flocking. In PSO, each swarm member (particle) represents a candidate solution which starts with random solutions. The particles position and velocity are updated in a search direction by learning from its own experience and the other particle's experiences. Each particle velocity is modified by two optimum values called *pbest* and *gbest*. The first one is the best solution (fitness) that has been achieved so far. While the second one is the global best value obtained so far by any particle in the swarm [20]. The updated velocity and position equations of each particle in PSO are given by [18]:

$$V_{i,d}^{k} = V_{i,d}^{k-1} + c_1 * rand1_{i,d}^{k} * \left(pbest_{i,d}^{k} - X_{i,d}^{k-1}\right) + c_2 * rand2_{i,d}^{k} * \left(gbest_{d}^{k} - X_{i,d}^{k-1}\right) \quad (7)$$

$$X_{i,d}^{k} = X_{i,d}^{k-1} + V_{i,d}^{k} \quad (8)$$

where $V_{i,d}^{k}$ and $V_{i,d}^{k-1}$ are the current and previous velocities of the i^{th} particle in the d^{th} dimension, respectively, c_1 and c_2 are the acceleration constants reflecting the weighting of stochastic acceleration terms that pull each particle toward $pbest_{i,d}^{k}$ and $gbest_{d}^{k}$ positions, respectively, $rand1_{i,d}^{k}$ and $rand2_{i,d}^{k}$ are two random numbers in the range [0, 1], $X_{i,d}^{k}$ and $X_{i,d}^{k-1}$ represent the current and previous position of i^{th} particle in the d^{th} dimension, respectively.

3.2 CLPSO

The CLPSO is an updated version of the conventional PSO to guarantee that the diversity of the swarm is preserved to reduce the occurrence of premature convergence. In the CLPSO algorithm, any particle will learn from best solution (*pbest*) of another particle. Each particle's velocity vector is updated by its own *pbest* and the other particle's *pbest* to enhance the population diversity. The updated velocity equation of each particle in CLPSO is given by [18]:

$$V_{i,d}^{k} = w * V_{i,d}^{k-1} + c * rand_{i,d}^{k} * \left(pbest_{f_i(d),d}^{k} - X_{i,d}^{k-1}\right) \quad (9)$$

where w and c are the inertia weight and acceleration constant, respectively, $fi = [f_i(1), f_i(2),\ldots, f_i(D)]$ defines which particles' *pbest* the i^{th} particle should follow, $pbest_{f_i(d),d}^{k}$ can be the corresponding dimension of any particle's *pbest* including its own *pbest*, and the decision depends on probability P_c, which is a learning probability that uses different values for different particles. For each dimension of the i^{th} particle, a random number has been generated. If this random number is larger than P_c of the i^{th} particle, the corresponding dimension will learn from its own *pbest*; otherwise, it will learn from another particle's *pbest*. When a particle learns from another particle's *pbest*, the following selection procedure is used:

- Two particles are chosen out of the population using a uniform random distribution excluding the particle whose velocity is modified.
- The two particles fitness (*pbests)* are compared and the best one is chosen.
- In the previous step, the selected particle's *pbest* will be used as the exemplar to learn from for that dimension.

If all exemplars of a particle are its own *pbest*, then randomly one dimension is chosen to learn from another particle's *pbest* for that dimension. The details on how to choose f_i(d) and further details on CLPSO are given in [18].

4. COMPUTATIONAL RESULTS AND PERFORMANCE OF HAPS CELLULAR COMMUNICATIONS USING CCAA

4.1 Computational Results

This section gives the simulated results for CCAA designs which are obtained by CLPSO technique. For CLPSO algorithm, the population size is set to 120, with 1000 iterations, and c = 1. The simulation is done by MATLAB.

The CLPSO algorithm is used to optimize the current excitation weights for ten rings (M = 10) using the cost function in (6) for the two cases: (a) CCAA with a central element and (b) CCAA without a central element. We assume that the innermost ring N_1 has 3 elements and the element increment is 6 elements per ring outwardly. The inter-element spacing d_m in any individual ring is half wavelength. For this case, θ_o = 0 and $\emptyset_o$= π/4.

Table 1 shows the output current excitation weights, SLL, and the HPBW for the two cases (a) and (b). These results show that SLL is substantially reduced in the optimized UCCA compared to the non-optimized one at the expense of increasing HPBW. The side-lobe level reduced to - 47.0442 dB in the case of CCAA without central element at the expense of a little increase in HPBW.

Table 1: Excitation current weights (w_m), SLL, and HPBW for non-optimized and optimized CCAA (with and without central element).

	Current excitation weights w_m $(w_1, w_2, \ldots. w_{10})$	**SLL (dB)**	**HPBW (degrees)**
non-optimized UCCA	1	- 17.5365	6.18^o
Case (a) Optimized array with central element	0.4493 0.9981 0.8130 0.7320 0.5886 0.4503 0.3097 0.2190 0.1126 0.0757	- 45.887	8.26^o
Case (b) Optimized array without central element	0.8538 0.9601 0.8480 0.7227 0.5892 0.4512 0.3089 0.2076 0.1152 0.0730	- 47.0442	8.3^o

Figure 2 illustrates the radiation pattern of the ten-ring CCAA with the excitation current weights obtained by CLPSO for the two cases (a) and (b). The side-lobe level of the case (b) is a little bit lower than that of the case (a) with almost the same HPBW.

Figure 3 shows the radiation patterns of the optimized CCAA (case (b)) and the one obtained using Gaussian window (δ = 2.5) [10,13]. It is obvious that the radiation pattern of the optimized CCAA using CLPSO is nicer than that of the Gaussian window function. The optimized CCAA reduces the SLL to – 47.0442 dB compared to the –41.6239 dB level of the Gaussian window function with almost same HPBW. Another comparison is made when using Dolph-Chebyshev window (R_o = 80 dB) [21] and the results of the SOS algorithm are summarized in Table 2. The SOS leads to a maximum SLL of − 42.40 dB for a ten-ring CCAA with a total number of 440 isotropic radiators [17]. In [16], IDCSA is a technique depends on sparse array synthesis (switching elements on and off). A CCAA with 10 rings needs to be optimized and the array has 440 antennas distributed uniformly along the rings. Generally, the maximum SLL obtained by IDCSA is – 22.17 dB and the number of switched-off elements is 211. Whereas, CLPSO is used to optimize current excitation weights of the rings for SLL reduction. It can be noticed that the CLPSO technique achieves the lowest value of SLL.

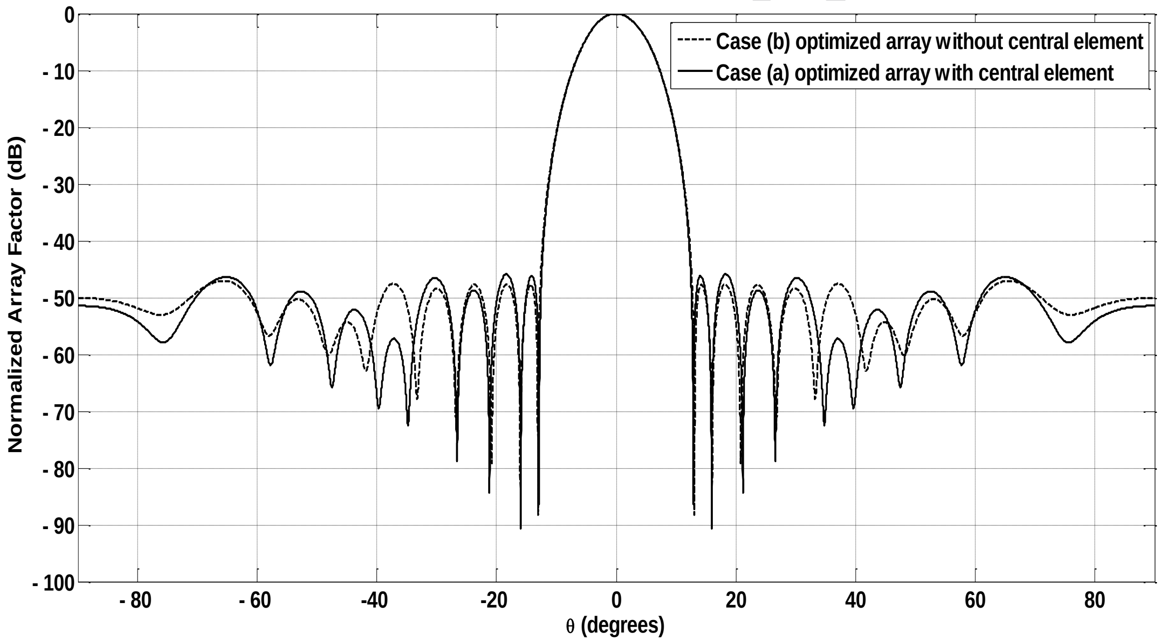

Fig. 2 Radiation pattern for the optimized CCAA for the two cases: (a) CCAA with central element and (b) CCAA without central element.

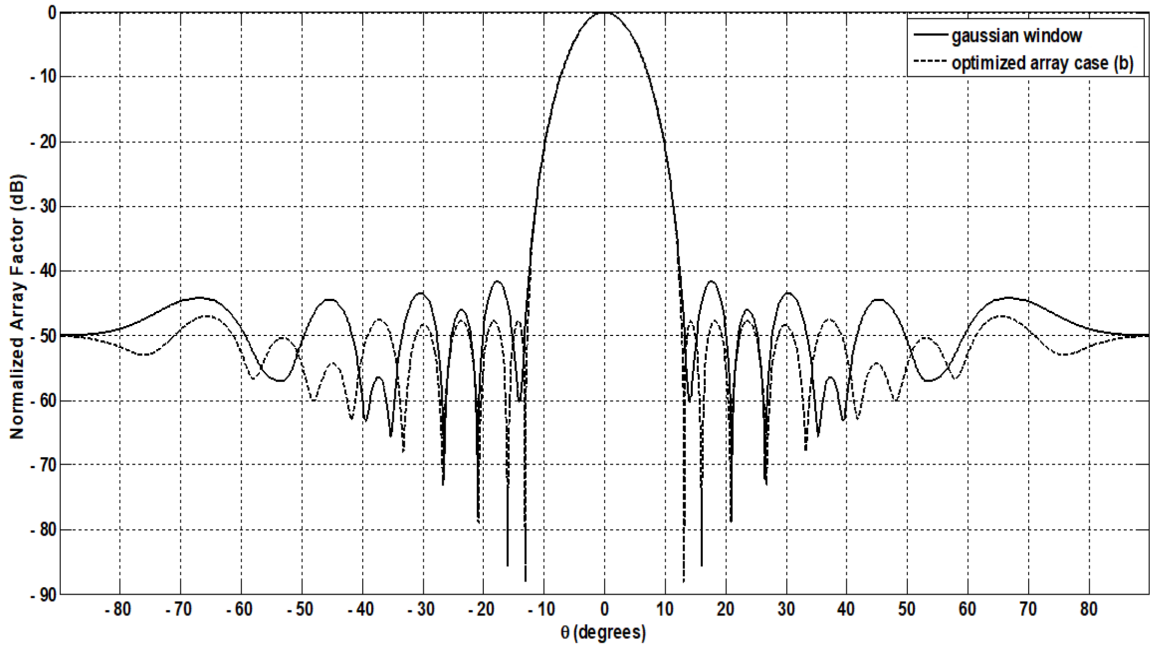

Fig. 3 Radiation patterns of the optimized CCAA (case (b)) and the CCAA using Gaussian window weights [10,13].

Table 2: SLL and HPBW for Gaussian window, Dolph-Chebyshev window, SOS, and CLPSO techniques.

Technique	**SLL (dB)**	**HPBW (degrees)**
Gaussian window	- 41.6239	8.24^{o}
Dolph-Chebyshev window	- 42.3186	10.3^{o}
SOS	- 42.40	---
CLPSO	- 47.0442	8.3^{o}

4.2 Performance of HAPs Cellular Communications Using CCAA

This section discusses the performance of HAPs cellular communications using CCAA in terms of CIR when applying the proposed approach. We assume a cellular system consisting of 169 cells, as shown in Fig. 4, is deployed. The model that shown in Fig. 4 is generated by flat-earth coverage model [22] where the cell is ellipse and antenna beam pointing angle algorithm [23]. In this model, the cells that labeled with "*c*" are the co-channel cells. The coverage diameter is typically 60 km and the average cell diameter is 3 km. Channel reuse number (cluster size) is set to 4. From the results in Section 3, the 3 km diameter is generated by a beamwidth of about 8.2^o at 21 km high and this can be generated by utilizing the CCAA with the proposed beamforming technique.

For a given co-channel cell group, the CIR at each ground position (*x*,*y*) can be calculated as [8]:

$$CIR(x,y) = \frac{P_{max}(x,y)}{(\sum_{i=1}^{n} P_i(x,y)) - P_{max}(x,y)} \quad (10)$$

where P_{max} $(x,\ y)$ is the power of the beam having the maximum power from a set of n co-channel beams, and therefore it is defined as the carrier (the wanted signal). The sum in (10) is

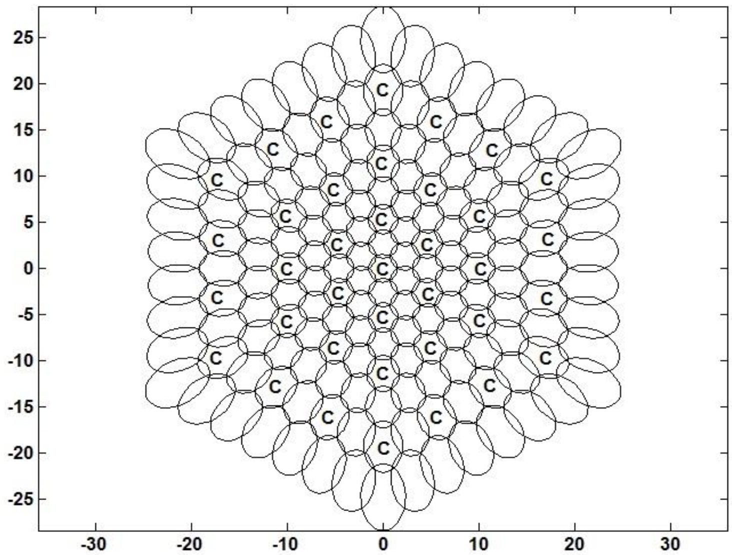

Fig. 4 A HAP cellular system layout consisting of 169 cells generated from a platform at 21 km high where the axes represent the distance from the central cell in km.

the sum of powers of all other beams, which is the aggregate interference. The received power calculated using [24] is:

$$P_r = P_t G_r(\theta, \emptyset) \left(\frac{\lambda}{4\pi h}\right)^2 |AF(\theta, \emptyset)|^2 \cos^2(\theta) \quad (11)$$

where P_t is the transmitted HAP cell power, $G_r(\theta,\emptyset)$ is the mobile antenna gain, h is the HAP altitude, and $AF(\theta,\emptyset)$ is the antenna array factor.

The array size required to approximately fit the 8.2^o beamwidth for the UCCA, the Gaussian Window method [10,13], and the proposed approach is 7, 10, and 10 rings, respectively. We assume that the inner ring has 3 elements and the element increment is 6 elements per ring outwardly. The inter-element spacing in any individual ring is half wavelength. In [10], the Gaussian window tapered beamforming is applied to the UCCA and compared to the TDA showing an improvement in the value of CIR.

Figure 5 compares the proposed approach to the Gaussian window tapered beamforming. It depicts the cumulative distribution function (CDF) for both approaches. As shown, in our proposed approach, the CIR has increased due to the reduction of SLL, compared to the Gaussian window and UCCA techniques.

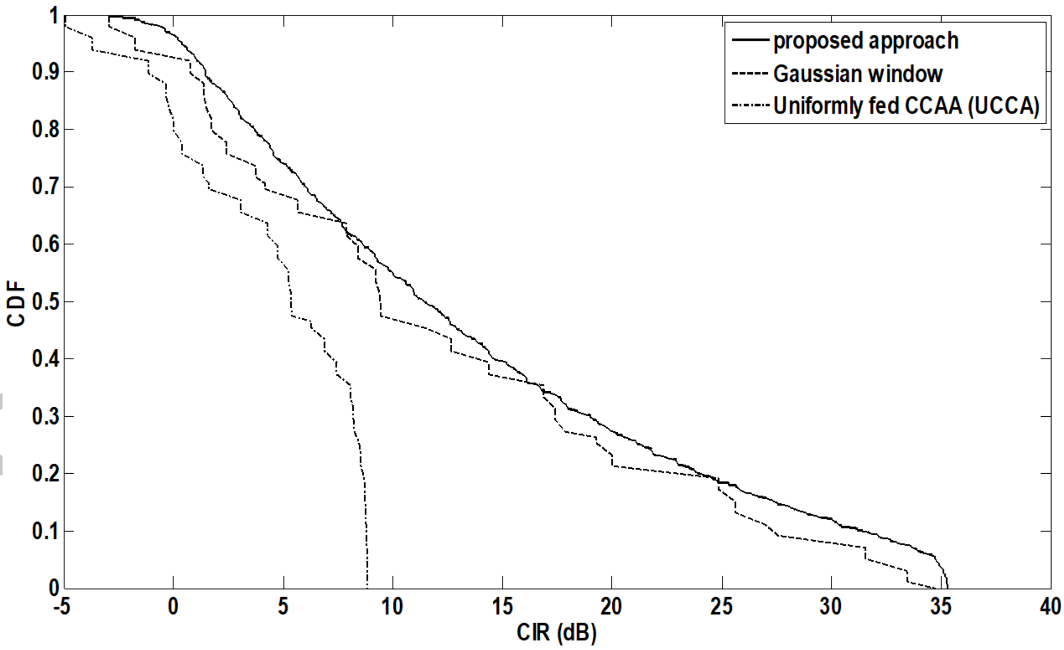

Fig. 5 The CDF of CIR across coverage area for one channel of four.

5. Conclusion

In this study, a cellular planning technique for broadband services delivered from HAPs has been proposed. The achieved CIR patterns highly depend on the antenna beamwidths. The radio coverage from a HAPs station may be accomplished by either spot beam antennas or antenna arrays which introduces more flexibility in controlling the ground cells. CCAA has more advantages than other configurations for HAPS. In this paper, a CLPSO based technique for designing a CCAA with and without central element is given. In this method, current excitation weights of rings are optimized. The computational results show that the CCAA without central element achieves a side-lobe level of – 47.0442 dB which is lower than that of the one with central element. In addition, the optimized CCAA has shown to have the lowest maximum SLL compared to the CCAAs with Gaussian and Dolph-Chebyshev windows. The CIR variation for a typical cellular layout of 169 cells utilizing a frequency reuse of 4 is depicted and shows an improvement in the value of CIR using the proposed beamforming method compared to the Gaussian window method.

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