

Research Letter

A Novel Beamforming Technique for Highways Coverage Using High-Altitude Platforms

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This paper proposes a novel beamforming technique to form an arbitrary-shaped cell for the high-altitude platforms (HAPs) mobile communications. The new technique is based on pattern summation of individual low-sidelobe, narrow beams which constitute the desired cell pattern weighted by an amplitude correcting function. The new cell pattern can be adapted to cover the main highways forming worm-shaped cells which may cover the highway for long distances up to 100 km and it will have an important role in reducing frequent handoffs and signaling traffic of location updating from moving users over the long highways.

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1. INTRODUCTION

There is an increasing demand for broadband mobile communications which has led to the rapid development of the conventional terrestrial and satellite wireless communication systems. In recent years, another competitive system has attracted the attention for providing mobile communications which is based on quasistationary platforms operating in the stratosphere known by high-altitude platforms (HAPs), and located 17–22 km above the earth's surface [1–3]. The most important advantages of HAP communication system are their low cost, low propagation delay, high elevation angles, easy and incremental deployment, flexibility in operation, broad coverage, broadcast and broadband capability, ability to move around in emergency situations, and so forth [3]. An important feature in HAPs at their altitudes is that it can see better the coverage area than the conventional terrestrial or satellite systems, and that any desired cell shape can be designed utilizing adaptive antennas with a suitable beamforming technique [4, 5]. This is very important in optimizing the radio coverage from HAPs especially when the users are concentrated in some regions than others as in highways. For example, in most world capital cities, there are main heavy traffic highways surrounding these cities like Washington DC, London, Paris, and so forth, where the moving users result

in frequent handoffs as well as high location updating signaling traffic. In terrestrial systems, this problem was calmed by forming elongated cells but still limited to cover straight parts in these highways. Therefore in this paper, the coverage of highways from an HAP station is discussed and a new beamforming technique is proposed to design a novel worm-shaped cell to improve the radio coverage. This technique utilizes the uniform concentric circular antenna arrays (UC-CAs) with low sidelobe levels [6–9] to form the desired cell pattern; and a coverage simulation has been performed for some main highways in London as a case study. The paper is arranged as follows: Section 2 demonstrates the coverage footprint of HAPs, Section 3 introduces the new beamforming technique, Section 4 demonstrates a coverage design case study, and finally Section 5 concludes the paper.

2. RADIO COVERAGE FROM HIGH-ALTITUDE PLATFORMS

Figure 1 demonstrates the footprint of a beam directed from an HAP station on the earth's surface forming a single elliptical cell. Assuming that this beam has a pointing direction of (θ_o, ϕ_o) and cross-section half-power beamwidths of B_θ and B_ϕ in the θ and ϕ directions, respectively. The footprint of

this beam is in general an ellipse which can be defined by its major and minor axes (b_C and a_C , resp.) given by [4]

$$b_C = R \left(\sin^{-1} \left(\left(1 + \frac{h}{R} \right) \sin \left(\theta_o + \frac{B_\theta}{2} \right) \right) - \sin^{-1} \left(\left(1 + \frac{h}{R} \right) \sin \left(\theta_o - \frac{B_\theta}{2} \right) \right) - B_\theta \right),$$

$$a_C = 2R \tan \left(\frac{B_\phi}{2} \right) \left(\left(1 + \frac{h}{R} - \frac{1}{2} (\cos(\gamma_1) + \cos(\gamma_2)) \right)^2 + \frac{1}{4} (\cos(\gamma_1) + \cos(\gamma_2))^2 \tan^2(\gamma_o) \right)^{1/2}, \quad (1)$$

where R is the earth's radius, h is the platform altitude, and γ_1 , γ_2 , and γ_o are given by [4]

$$\gamma_1 = \sin^{-1} \left(\left(1 + \frac{h}{R} \right) \sin \left(\theta_o - \frac{B_\theta}{2} \right) \right) - \theta_o + \frac{B_\theta}{2},$$

$$\gamma_2 = \sin^{-1} \left(\left(1 + \frac{h}{R} \right) \sin \left(\theta_o + \frac{B_\theta}{2} \right) \right) - \theta_o - \frac{B_\theta}{2}, \quad (2)$$

$$\gamma_o = \frac{1}{2} (\gamma_1 + \gamma_2).$$

This beam can be formed by using either directional antennas or adaptive antenna arrays. Directional antennas have the advantages of its simplicity and practical implementation while adaptive antenna arrays provide more flexibility and reconfigurability in the design of such beams. In this paper, the uniform concentric circular arrays (UCCAs) shown in Figure 2 will be adopted, which has several applications including radar, sonar, direction finding, and mobile communications [7]. This array has M concentric circular sub-arrays having an element separation of half the wavelength, and the number of elements for the m th ring is N_m , where $m = 1, 2, \dots, M$. The elements are weighted in amplitudes and phases by a weighting matrix $W(\theta, \phi)$, which controls the beam footprint on the ground to have the desired coverage. This matrix can be composed of two parameters; the first reduces the sidelobe level and denoted as α_m while the second part is responsible for the cell shape and denoted by $d_m(\theta, \phi)$. In general, it may be written as

$$W(\theta, \phi) = [w_1(\theta, \phi), w_2(\theta, \phi), \dots, w_m(\theta, \phi), \dots, w_M(\theta, \phi)], \quad (3)$$

where

$$w_m(\theta, \phi) = \alpha_m d_m(\theta, \phi), \quad m = 1, 2, \dots, M, \quad (4)$$

is the m th column in $W(\theta, \phi)$ which represents the weighting vector of the m th ring, α_m is a window function used for sidelobe reduction [7–9], and $d_m(\theta, \phi)$ is the m th column in the cell-shaping matrix given by

$$D(\theta, \phi) = [d_1(\theta, \phi), d_2(\theta, \phi), \dots, d_m(\theta, \phi), \dots, d_M(\theta, \phi)]. \quad (5)$$

The array factor $AF(\theta, \phi)$ can be defined by determining the array steering matrix $AS(\theta, \phi)$, which is given by [8]

$$AS(\theta, \phi) = [S_1(\theta, \phi) S_2(\theta, \phi) \cdots S_m(\theta, \phi) \cdots S_M(\theta, \phi)], \quad (6)$$

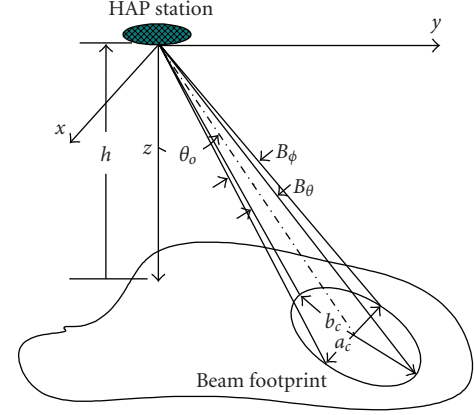


FIGURE 1: Footprint of a HAP cell.

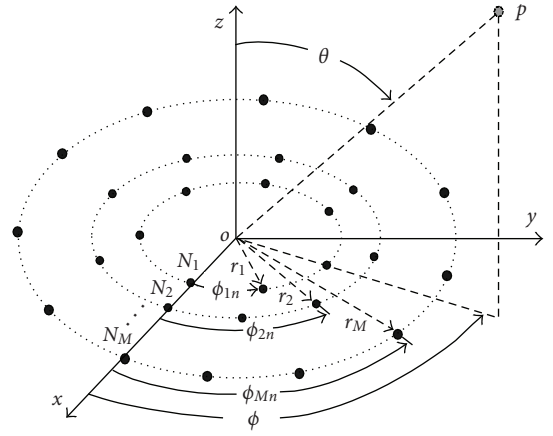


FIGURE 2: Uniform concentric circular arrays (UCCA).

where each column in the array steering matrix represents the corresponding ring steering vector which, in general, for the m th ring is given by [8]

$$S_m(\theta, \phi) = [e^{jkr_m \sin \theta \cos(\phi - \phi_{m1})} e^{jkr_m \sin \theta \cos(\phi - \phi_{m2})} \dots e^{jkr_m \sin \theta \cos(\phi - \phi_{mn})} \dots e^{jkr_m \sin \theta \cos(\phi - \phi_{mN_m})}]^T, \quad (7)$$

where the m th ring has a radius r_m and its elements azimuth angle is given by

$$\phi_{mn} = \frac{2\pi n}{N_m}, \quad n = 1, 2, 3, \dots, N_m, \quad (8)$$

and $k = 2\pi/\lambda$.

Therefore, the array factor $AF(\theta, \phi)$ can be written as

$$AF(\theta, \phi) = \text{SUM}\{W(\theta, \phi)^H AS(\theta, \phi)\}, \quad (9)$$

where the operator SUM is the summation of all elements in the resulted matrix. Assuming free-space propagation scenario between the HAP and mobile users, therefore we can write an expression for the received power P_r given by

$$P_r = P_t G_r(\theta, \phi) G_t(\theta, \phi) \left(\frac{\lambda}{4\pi d(\theta)} \right)^2, \quad (10)$$

where P_t is the transmitted power of the HAP cell, $G_r(\theta, \phi)$ is the mobile antenna gain, $G_t(\theta, \phi)$ is the HAP array power gain given by

$$G_t(\theta, \phi) = |\text{AF}(\theta, \phi)|^2, \quad (11)$$

and $d(\theta)$ is the line-of-sight distance between the HAP and the mobile determined from the following equation:

$$d(\theta) = \frac{h}{\cos(\theta)}. \quad (12)$$

Therefore, the received power can be rewritten as

$$P_r = P_t G_r(\theta, \phi) \left(\frac{\lambda}{4\pi h} \right)^2 |\text{AF}(\theta, \phi)|^2 \cos^2(\theta). \quad (13)$$

The received power in the last equation depends on the array factor and the mobile location with respect to the HAP station assuming all the other quantities constant. Therefore, we may rewrite the last equation as

$$P_r = P_t G_r(\theta, \phi) \left(\frac{\lambda}{4\pi h} \right)^2 \rho(\theta, \phi), \quad (14)$$

where

$$\rho(\theta, \phi) = |\text{AF}(\theta, \phi)|^2 \cos^2(\theta) \quad (15)$$

which may be denoted by the power gain profile function where it represents the variation in the received power level due to the array factor and the mobile location.

3. THE PROPOSED BEAMFORMING TECHNIQUE

In most capital cities, there is a need to design a highway that surrounds the city to bypass the traffic which does not intend to enter it. Also in the city itself, there will be almost long highways that carry high traffic of mobile users. Terrestrial mobile radio cells are designed to cover the straight parts of the main roads by using directed antennas along these roads [10] while this can be easier in the case of using HAPs. The cells can be adapted to cover very long distances of the highways through careful radiation pattern synthesis which must have continuous radio coverage without holes or droppings in the received power. This specialized cell pattern which follows the highway terrains forms a ‘‘wormy’’ cell structure which can be formed by summing up contiguous footprints of low-sidelobe beams footprints as in the mosaic pictures. These constituting beams are centrally separated by one major axis, and any desired pattern can be obtained by controlling their numbers, amplitudes, and beamwidths.

In this respect, the desired pattern can be formed by setting the cell shaping matrix as

$$D(\theta, \phi) = \sum_{i=1}^{N_c} \zeta(\theta_i, \phi_i) \text{AS}(\theta_i, \phi_i), \quad (16)$$

where N_c is the number of spot beams needed to constitute the desired wormy cell pattern and $\zeta(\theta_i, \phi_i)$ is an amplitude

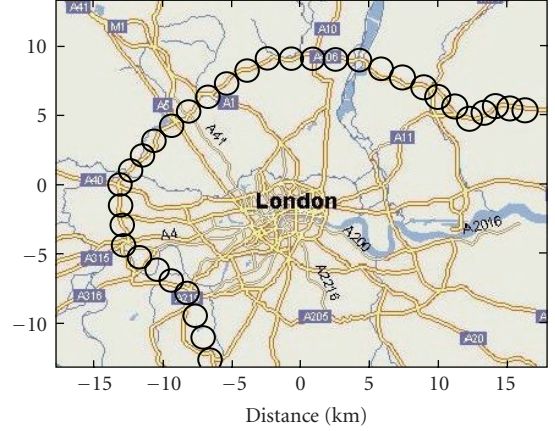


FIGURE 3: 34 footprints of individual spot beams constituting a wormy cell for one of the major London highways. These beams are formed using Dolphen-Chebyshev UCCA of $N_1 = 5$ and $M = 20$.

correcting function for the i th beam which is needed to reduce the unwanted amplitude variations after summing the individual spot beams patterns. This function is proposed to be the inverse of the array factor at the main individual beams directions, and for the i th beam it is proposed to be

$$\zeta(\theta_i, \phi_i) = \begin{cases} \frac{1/\sqrt{2}}{\left| \text{SUM} \left\{ \sum_{l=1}^{N_c} \text{AS}(\theta_l, \phi_l)^H \text{AS}(\theta_i, \phi_i) \right\} \right| \cos(\theta_i)}, & i = 1, N_c \\ 1, & 2 \leq i \leq N_c - 1 \\ \frac{1}{\left| \text{SUM} \left\{ \sum_{l=1}^{N_c} \text{AS}(\theta_l, \phi_l)^H \text{AS}(\theta_i, \phi_i) \right\} \right| \cos(\theta_i)}, & \end{cases} \quad (17)$$

which results in mostly uniform coverage and half-power contour, noting that the cosine term in the denominator compensates for the attenuation due to distance variations between the mobile and the HAP station. To improve the sidelobe performance, the array may be tapered in amplitude with a suitable window such as Dolph-Chebyshev [8] or the Gaussian [9] windows and this is very important as it will reduce the amount of out-of-cell radiated power.

4. SIMULATIONS AND DISCUSSIONS

Assuming a highway coverage in London city is to be designed as shown in Figure 3 utilizing a Dolph-Chebyshev UCCA [8] of $N_1 = 5$ and $M = 20$ onboard a HAP station at 20 km high. Therefore, we may need about 38 individual beams separated by a half-power beamwidth which equals 5.2 degrees. Adopting the amplitude correction function given in (17) and plotted in Figure 4 for the different 34 spot beams provides the required wormy cell. Figure 5 depicts the normalized received power profile in dB from an HAP station while in Figure 6; the half-power contour is plotted.

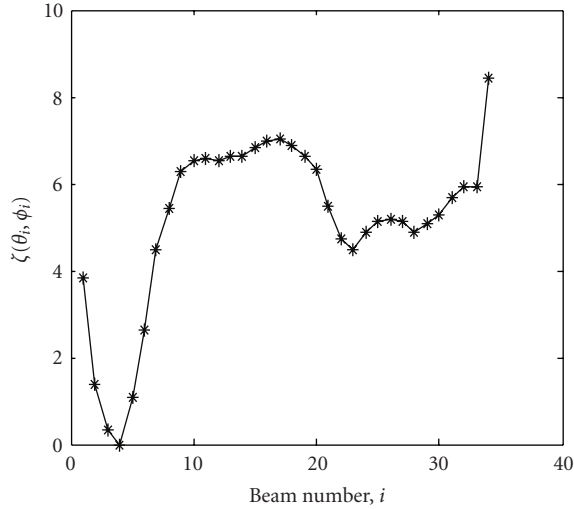


FIGURE 4: The amplitude correcting function for the design in Figure 3.

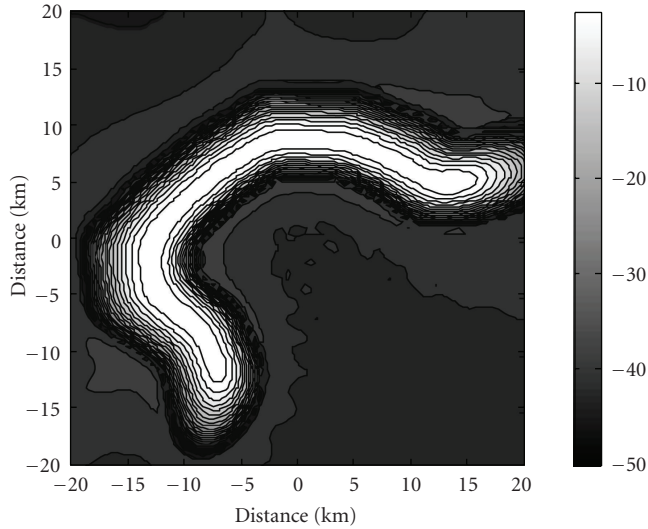


FIGURE 5: Normalized received power pattern in dB for the design in Figure 3.

Wormy cellular structure for HAP mobile communications system will improve the system performance especially in covering long highways carrying mobile users for the following reasons.

- (1) The handoff will be reduced because the cell is very long even if the mobile users are talking for long periods of time.
- (2) The location updating rate and its corresponding signaling traffic will be reduced for users moving along the wormy cell.
- (3) The wormy cells can be designed to optimize the coverage depending on the terrains of the covered regions.
- (4) It can be adapted in shape to accommodate any change in the highways design due to the varying traffic or population conditions.

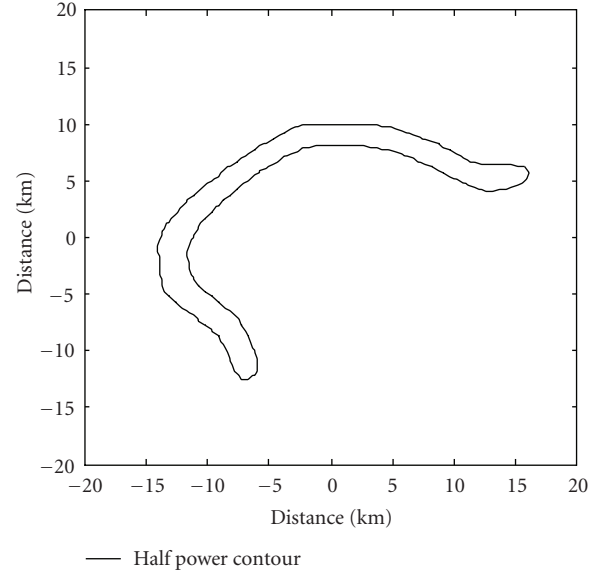


FIGURE 6: The half-power contour of the wormy cell designed in Figure 3.

- (5) Adopting the tapered UCCA beamforming will reduce the radiation in other uncovered regions which reduces the interference to the cochannel cells allowing frequency reuse.

On the other hand, this cellular structure needs a careful frequency planning to have the desired carrier-to-interference ratio as the cells are not distributed uniformly.

5. CONCLUSIONS

The coverage of highways is examined and a wormy cell shape for the radio coverage is proposed. This novel cell structure can cover very long distances along the highways and has several advantages like reduced handoff rate as well as reduced signaling traffic due to location updating. This cellular structure can be designed by a beamforming technique adopting tapered uniform concentric circular arrays in which the total desired radiation pattern can be obtained by summing the patterns of individual contiguous beams weighted by an amplitude correction function to equalize the pattern to have mostly uniform coverage without holes over the highway.

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