3D Lens Antenna Array for Tbps Communications

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***Abstract*— Recently a base station concept at 120 GHz has been proposed, capable of providing 12 Tbps wireless data rate to serve 80.000 users. The antenna consists of a 3D array of 1500 lenses in semispherical arrangement, where each lens generates a directive beam covering a group of users. The base station overall RF transmitted power was estimated to be 50 W, which is orders of magnitude smaller than current base station solutions. In this paper we present the base station concept and the feasibility study of its fabrication, proposing some approaches which could improve significantly the system cost efficiency.**

Keywords—base station, lens array, high speed wireless.

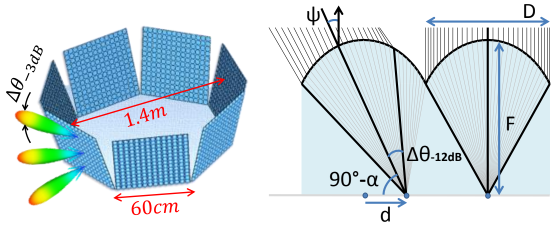
I. INTRODUCTION

Increasing customer demand makes wireless communications become more and more challenging for both software and hardware developers. New features such as 360° and VR videos might require at least 100 Mbps in download, and the posting of HD photos and videos 50 Mbps in upload for each user. In order to transfer this high-speed data stream, new revolutionary concepts need to be developed in all system layers. These demanding specifications can only be reached when moving to much higher frequencies, as the realizable RF bandwidth increases. The initial scenario considered to dimension our antenna concept is a football stadium with a capacity of 80.000 people, one of the most demanding scenarios for mobile carriers nowadays. In this case, data rate requirements of 12 Tbps could be reached, which is 300 times more bandwidth than current stadium solutions. Our base station concept can be easily scaled for other user dense scenarios such as concerts, conference halls, etc. [1].

II. BASE STATION CONCEPT

We propose a compact system based on a central base station which generates multiple-directive beams to divide the Field of View (FoV) into a number of angular cells. The base station could be suspended above the center of the stadium, covering a FoV of 360° in azimuth and 50° in elevation. The proposed dimensioning will be based on a RF bandwidth of 24 GHz centered at 120 GHz, but it could be scaled to another frequency band, depending on the required data rate. The antenna solution consists of a 1.4m diameter spherical array of 1500 lenses arranged in a fly's eye configuration (see Fig. 1a). Each lens has 4 cm ($16\lambda_0$) diameter *D*, resulting on a beam-width $\Delta\theta_{-3dB}$ of 3.6° in azimuth and elevation, which covers an angular spatial cell of 54 users. We propose to use a SDMA/FDMA scheme with four 6 GHz channels assigned to alternating cells. This provides each user with 112 MHz of RF bandwidth.

For the link-budget calculations we have considered a line-of-sight link of 100 m. The chosen modulation scheme is QPSK, very efficient when moving to higher frequencies. The single lens directivity results to be 34 dB, while 10 dB should be achieved in the user terminals. In both directions, transmitted power is assumed to be 14 dBm and noise figure 10 dB, which could be accomplished with one RX/TX chipset per lens such as presented in [2]. Employing TDM technology, 100 Mbps in downlink and 50 Mbps in uplink can be reached per user, assuming a BER of 10^{-6}.



(a) (b)

Fig. 1. a) Base station antenna array. b) Lens with off- and on-focus feed.

III. 3D ANTENNA ARRAY FABRICATION

The assembly of the front-end on a spherical surface would be, if possible, very costly. Instead, we propose to approximate the lens sphere described in [1] through several planar sectors, getting to a polyhedral configuration (Fig. 1a). In this way several lenses could be fabricated on a single dielectric panel, making the fabrication, assembly and integration much easier. In order to achieve separated angular cells over the FoV with this polyhedral antenna, we need to introduce progressive beam steering in the panels, which could be achieved by using off-focus feeds [3]. The required 50° elevation FoV could be reached with one single panel, instead the 360° azimuthal FOV results into a 7 panel division. Each of the 7 panels contains an array of 15x15 lenses, leading to 1575 antenna beams. The manufacturing of the array panels could be carried out via injection molding or 3D printing, which are cost-efficient standard industrial processes. Both of them require the use of plastic materials for the lenses, which would lower the material cost as well. There is a wide range of materials with low losses and low dielectric permittivity, instead plastics with higher ε_r (5-10) are ceramic filled and have typically more dielectric loss. If we extend the concept to higher frequencies, the use of silicon micro-fabricated lenses could lead to a cost effective solution as well [5].

IV. LENS ARRAYS WITH BEAM STEERING

In this section we study the achievable antenna efficiency of the mentioned array panels. For high frequencies, integrated elliptical lenses (see Fig. 1b) with $e = 1/\sqrt{\varepsilon_r}$ is preferred to avoid substrate mode losses [3]. The considered lenses are made of hypothetical dielectrics with low and high dielectric permittivity (ε_r). Our simulations use ray tracing and physical optics techniques.

A. Design considerations

The design of the lens array requires the choice of an optimum focal distance F to lens diameter D ratio $f_\#$. The elliptical lenses are characterized by a minimum $f_\#$

$$f_\#^{min} = \frac{1+\sqrt{\epsilon_r}}{2\sqrt{\epsilon_r - 1}} \tag{1}$$

associated to the presence of the critical angle. The lower the ε_r, the larger the $f_\#^{min}$. In order to keep the reflection and spillover loss small, the $f_\#$ should be larger than $f_\#^{min}$ and, consequently, the feed beam-width (i.e. $\Delta\theta_{-12dB}$) narrower. The implementation of directive low-loss feeds can get challenging at high frequencies [4]. A promising solution can be the use of compact feed designs such as leaky wave enhanced antennas [5].

The beam steering angle ψ on each lens depends linearly on its feed displacement d (Fig. 1b), provided there is not significant phase error losses. The geometrical approximated steering angle for the central ray is

$$\psi[deg] \approx \Delta\theta_{-3dB}\frac{d}{\lambda_d f_\#} \tag{2}$$

where λ_d is the wavelength inside the substrate. By displacing the feed along the lens focal plane, some of the rays may reach the total reflection area. This effect can be avoided, in the whole range of d, if $f_\# \gg f_\#^{min}$. Therefore it seems convenient to use always very large $f_\#$. However this could lead to large d compared to D. Indeed to avoid spill over problems, $d < D/4$. This condition imposes a maximum quote for the optimum $f_\#$

$$f_\#^{max} = \frac{D}{4\lambda_d N} \tag{3}$$

where $N = \psi/\Delta\theta_{-3dB}$ is the number of steered beams. For large ε_r, it is possible to find an optimum $f_\#$ in between the two quotes where the same feed pattern could be used in all lenses, keeping a good spillover efficiency along the whole array, which can minimize the fabrication cost. Instead, when ε_r decreases, $f_\#^{max}$ becomes at some point actually lower than $f_\#^{min}$. In this case an efficient lens illumination is only possible by steering the feed pattern to a certain angle α (see Fig. 1b).

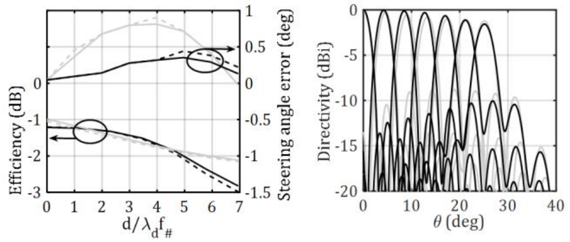
B. Simulated performances

Reaching a compromise between feed design complexity and lens efficiency, two examples of 15x15 lens arrays with low and high permittivity have been dimensioned (Table 1), considering the same loss tangent (tan δ) for both dielectrics. In the aperture efficiency calculation (Fig. 2a) we account for the taper efficiency (achieved directivity w.r.t a uniform aperture), reflection loss with matching layer, spill over loss and dielectric loss. The loss in directivity (Fig. 2b) can be compensated increasing the panel length by 15%, becoming this 70 cm.

We observe that choosing $f_\#$ = 1.25 in both configurations, we arrive to comparable and acceptable performances in terms of aperture efficiency and steering angle error (Fig. 2a), as $f_\# > f_\#^{min}$ for both dielectrics. In case of ε_r=10, since $f_\# < f_\#^{max} = 1.8$, the same feed $\Delta\theta_{-12dB}$ could be used over the whole array and only slight feed beam steering would be needed in the outer elements. In contrast, for the lower ε_r, $f_\# > f_\#^{max} = 0.9$, and therefore a feed beam steering α is needed to avoid spill over, as shown in Fig. 1b. Moreover the required feed $\Delta\theta_{-12dB}$ changes over d to avoid the total reflection area for off-focus cases, leading to more complex and possible lossy feed designs.

TABLE I. LENS FEED REQUIREMENTS

ε_r	tan δ	D	$f_\#$	d_{max}	Feed $\Delta\theta_{-12dB}$	Feed α_{max}
2.5	4e-5	16 λ_0	1.25	5.49 λ_0	±30° to ±20°	25°
10	4e-5	16 λ_0	1.25	2.75 λ_0	±25°	10°



(a) (b)

Fig. 2. a) Aperture efficiency and ψ error versus d. ε_r = 10 (black), ε_r = 2.5 (grey). H plane (solid line), E plane (dashed line). b) E-plane directivity steered beams (half panel).

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