A Simple Beamforming Technique for Intelligent Reflecting Surfaces in 5G Scenarios

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***Abstract*—This contribution proposes a simple closed-form formula to compute the phase-shift distribution on Intelligent Reflecting Surfaces (IRS), which can be implemented using metasurfaces or reflectarray panels. The proposed technique is based on introducing a quadratic phase correction to the phase distribution that generates a collimated beam. The phase correction allows to independently control the half-power beamwidth (HPBW) in azimuth and elevation for low-cost passive IRS panels. The capabilities of the technique have been demonstrated by computing the phase distribution and radiation patterns of a 40 cm × 40 cm IRS that redirects the beam in azimuth and elevation and broadens the beam from 2º to 4º in elevation and from 2º to 18º in azimuth. This technique is very useful to the design of low-cost passive IRS panels.**

Keywords—reflectarray, intelligent reflecting surface, IRS, metasurface, mm-wave 5G, 5G scenarios.

I. INTRODUCTION

The fifth generation of mobile communications (5G), as well as future generations (Beyond 5G and 6G) are driving the use of new frequency bands in the millimeter-wave (mm-wave) spectrum (27 GHz, 39 GHz, 100 GHz) to provide high-speed wireless access in cellular networks, taking advantage of the increased bandwidth available [1], [2]. However, the propagation in mm-wave communications is characterized by higher losses and is more sensitive to blockage by physical barriers [3], [4]. In both outdoor and indoor scenarios, the presence of obstacles can result in areas with poor coverage, known as "blind" or "dead" zones.

Blind zones can be reduced by increasing the number of base stations (BS), although it would significantly increase the cost in equipment and infrastructure, also aggravating the interference problem [4]. An alternative solution is based on the deployment of Intelligent Reflective Surfaces (IRS) [5]-[7], which reflect the signal generated from a BS in the direction of the blind zones. An IRS is a planar surface formed by an array of phasing cells that are optimized to generate a reflected beam according to the users' requirements. In most previous works, IRSs are designed to redirect the signal in a prescribed direction [8], to maximize the power transmission [9], to improve the signal-to-interference ratio [10], or to generate multiple simultaneous beams for different users [11].

In many mm-wave 5G scenarios, as shown in Fig. 1, the IRS should provide a shaped coverage to illuminate the blind zone by redirecting and shaping the reflected beam. Passive IRSs made of a printed pattern of conductive elements on a PCB are a low-cost and efficient solution, with no energy consumption. In recent works, a reflectarray panel has been proposed to deviate and shape the reflected beam [12], [13]. The required shaping and redirection of the secondary beam produced by the IRS can be achieved by applying the efficient *Phase-Only* pattern synthesis technique based on *Intersection Approach* algorithm [14], which has been successfully demonstrated in reflectarray antennas [14 – 17]. The shaping of the beam, which in general has to be broadened in azimuth to cover the user's area, was achieved in [13] by using a generalized *Intersection Approach* [18], with satisfactory results. Note that in general the pattern synthesis must be carried out for each IRS location, requiring a large number of designs for the deployment of mmWave 5G networks. As an alternative to the more cumbersome pattern synthesis techniques, we propose in this work a very simple approach to obtain the phase distribution on the IRS that produces a reflected beam with the prescribed requirements of the half-power beamwidth (HPBW) in azimuth and elevation.

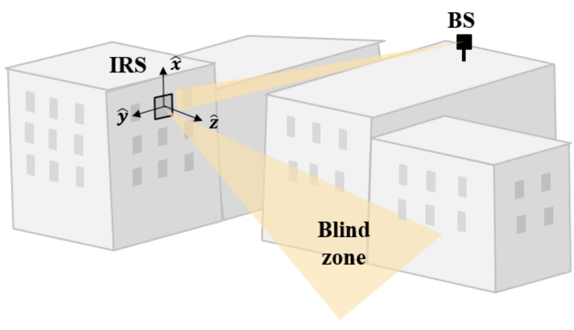

Fig. 1. Typical mm-wave 5G scenario with a BS and an IRS (installed on the wall of a building) to illuminate a blind zone.

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II. SECENARIO

A 5G scenario including a BS and an IRS, as shown in Fig. 1, is considered. The IRS of dimensions $L_x \times L_y$ is illuminated by the BS antenna located at a distance *d*. The beam reflected by the IRS must be redirected in a prescribed direction, defined either by spherical coordinates (θ_b, φ_b), or by azimuth and elevation (Az, El) angles, as shown in Fig. 2. In general, to illuminate the blind zone efficiently, the beam should be wider in azimuth than in elevation.

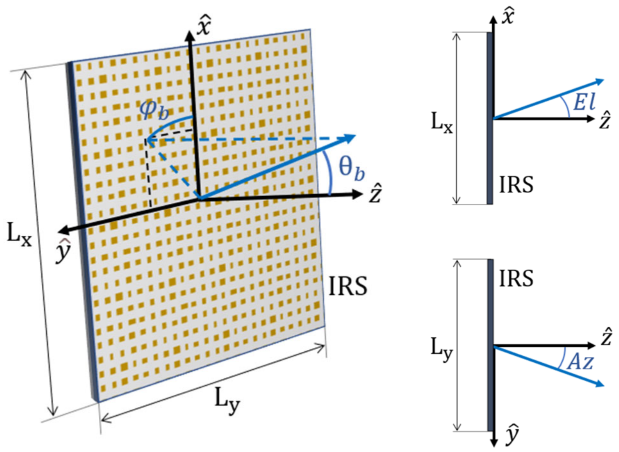

Fig. 2. Passive IRS panel and coordinate system.

The IRS is defined as a metasurface or a reflectarray panel made of small phasing cells, capable to produce an individual adjustment on the phase of the reflected field, for each polarization of the incident field (Vertical and Horizontal). Note that the phase of the reflected field in the IRS should be identical for both linear polarizations to ensure that the polarization of the reflected beams is not modified [13].

III. CLOSED-FORM COMPUTATION OF PHASE-SHIFT ON IRS

The IRS should introduce a phase-shift distribution to deflect the beam in a specific direction and to shape the beam in azimuth and elevation. To generate a collimated beam in the direction (θ_b, φ_b), corresponding to the center of the coverage area, the required phase-shift distribution on the IRS, as it is well-known from reflectarray antennas [19], can be expressed as follows:

$$\phi_{cb}(x_l,y_l) = k_0\,(d_l - (x_l \cos\varphi_b + y_l \sin\varphi_b)\sin\theta_b), \qquad (1)$$

where d_l is the distance from the BS to the *l*th element and k_0 is the wave-number. The phase-shift distribution given by (1) will generate a beam with the highest gain for the defined IRS size. Note that high gain is desirable to increase the signal level but reduces the coverage angular range. According to the scenario requirements, the beam should be broadened in azimuth and sometimes also in elevation. To broaden the beam, a quadratic phase term is added to independently control the beamwidth in azimuth and elevation, as follows:

$$\phi_{bb}(x_l,y_l) = \phi_{cb}(x_l,y_l) + A_x(x_l) + A_y(y_l) \qquad (2)$$

where the second and third terms are:

$$A_x(x_l) = k_0 \cdot \left(\alpha_x \cdot \left((L_x/2)^2 - x_l^2\right)\right) \qquad (3)$$

$$A_y(y_l) = k_0 \cdot \left(\alpha_y \cdot \left((L_y/2)^2 - y_l^2\right)\right), \qquad (4)$$

where α_x and α_y are coefficients that are adjusted to control the degree of broadening of the beam in *x* and *y* directions, respectively. The values of α_x and α_y can vary from 0.0 to 0.5, producing a higher defocusing and broadening of the beam for larger values of coefficients α_x and α_y. Note that when $\alpha_x = 0$ and $\alpha_y = 0$, the phase in (2) corresponds to that of a collimated beam. Note also that the phase correction is zero at the reflectarray center and increases to the panel edges.

IV. SIMULATED RESULTS

To demonstrate the effectiveness of the previous closed-form formula, a 40 cm × 40 cm IRS panel has been considered, which is formed by 80 × 97 phasing cells arranged in a rectangular lattice of 5 mm × 4.1 mm. The IRS is illuminated by a BS located at 10 meters, impinging with an incidence angle of 30º and 5º in the azimuth and elevation planes, respectively. The reflectarray IRS is designed to deviate the signal from the BS in both azimuth and elevation planes. Furthermore, the reflectarray panel must provide a HPBW of 18º in azimuth and 4º in elevation, operating at 28 GHz in an 800 MHz bandwidth, with the same performance in horizontal (H) and vertical (V) polarization. The main requirements of the system are summarized in TableTABLE I.

TABLE I. SPECIFICATIONS OF THE SYSTEM

Parameter	Value
Incidence angle in azimuth	−30º
Incidence angle in elevation	5º
Radiation angle in azimuth	50º
Radiation angle in elevation	−2º
HPBW in azimuth	18º
HPBW in elevation	4º
Polarization	Dual-linear

The phase-shift distribution obtained to generate a collimated beam (Eq. 1) is shown in Fig. 3.a; while the phase distribution that produces 18º beamwidth in azimuth and 4º beamwidth in elevation is shown in Fig. 3.b, using the parameters $\alpha_x = 0.18$ and $\alpha_y = 0.35$ in (3) and (4).

Fig. 4 shows the computed radiation pattern for the corrected phase distribution in the normalized angular coordinates ($u = \sin\theta\cos\varphi$, $v = \sin\theta\sin\varphi$). This figure shows clearly how the beam has been broadened in the azimuth plane ($u = -\sin(2º) = -0.035$) significantly more that in the elevation plane ($v = \cos(2º)\sin(50º) = 0.766$).

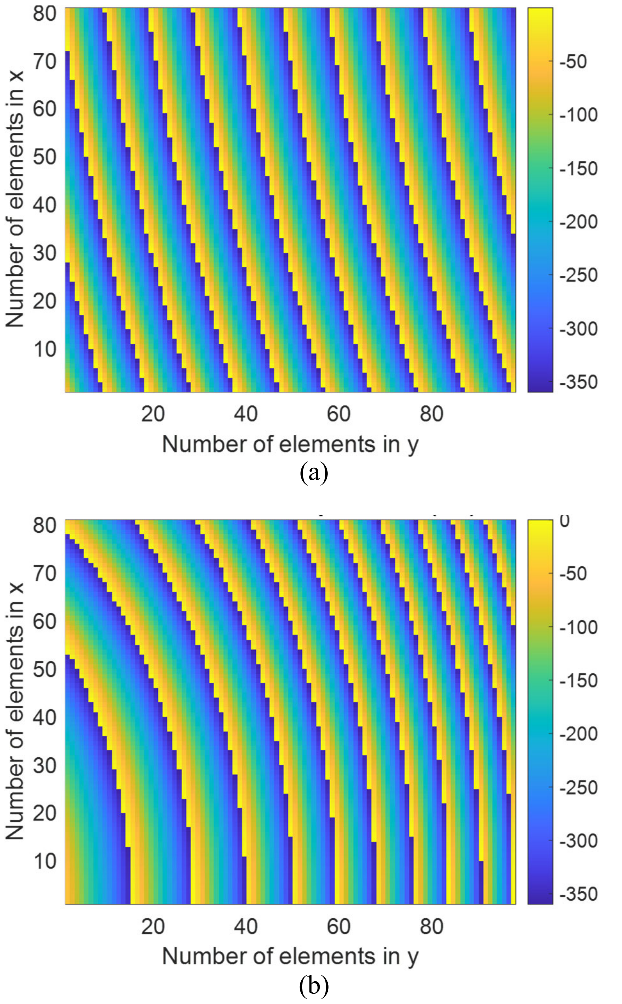

Fig. 3. Phase distribution on the IRS (deg.) for a collimated beam (a) and for a broadened beam in both azimuth and elevation (b).

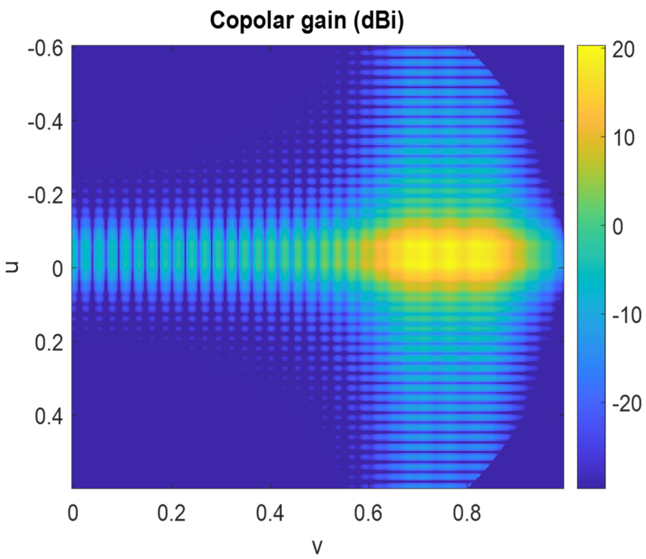

Fig. 4. Radiation pattern of the beam with 18º HPBW in azimut and 4º HPBW in elevation in normalized (u,v) angular coordinates.

The co- and cross-polar radiation patterns in the elevation (−2º) and azimuth (50º) planes are shown in Fig. 5. The co-polar radiation pattern associated to the phase distribution given in Fig. 3.a, which corresponds to the collimated beam produced by an aperture of 40 cm, is also included as reference. The beam in elevation is radiated at −2º and broadened from a HPBW of 2º to 4º. On the other hand, the beam in the azimuth plane is redirected in the prescribed angle (50º) and broadened to 18º with a ripple lower than 3 dB (HPBW =18º). These simulations show that the proposed simple phase correction allows to broaden the beam in elevation from 2º to 4º and in azimuth from 2º to 18º at the cost of reducing the maximum gain in 14 dB (from 34 dBi to 20 dBi). The cross-polar discrimination is around 30 dB for the broadened beam. Note that the closed-form formulas allow to independently broaden the beam in azimuth and elevation.

These results have been obtained assuming ideal phasing cells. The design and manufacturing of the IRS will be accomplished by using reflectarray cells made of three parallel dipoles for each linear polarization printed on a single layer PCB, where the orthogonal sets of dipoles are shifted half-a-period one from each other to be accommodated in the same layer, as reported in [12], [13].

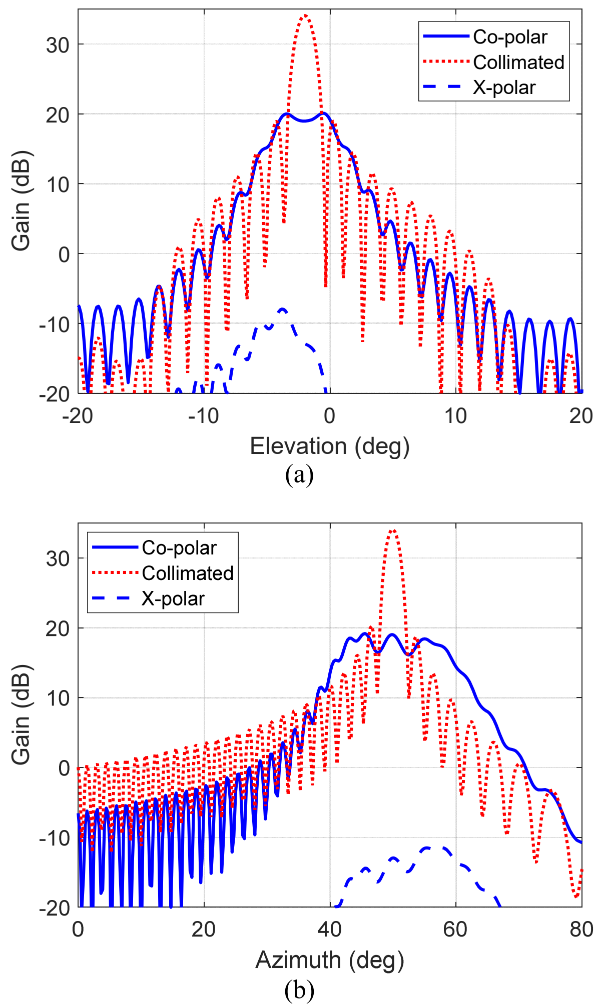

Fig. 5. Comparison of radiation patterns at 28 GHz in the principal planes between the broadened beam (with HPBW of 18º in azimut and 4º in elevation) and the collimated beam. (a) Elevation cut for 50º azimuth angle and (b) azimuth cut for -2º elevation angle.

V. CONCLUSIONS

A simple closed-form correction has been proposed to independently control the HPBW in azimuth and elevation for low-cost passive IRS panels. The phase distribution has been computed for a 40 cm × 40 cm reflectarray panel. The results demonstrate that the HPBW has increased from 2º to 4º in elevation and from 2º to 18º in azimuth.

The phase-shift distribution obtained for directing and broadening the beam in elevation and azimuth can be realized by a metasurface or by a reflectarray panel, using the techniques that have been experimentally demonstrated in previous works.

The use of passive metasurfaces or reflectarrays as IRSs provides a zero energy consumption solution with low manufacturing and mounting costs (the flat surface of the reflectarray can be easily installed on walls). Thus, passive reflectarrays would allow the mass deployment of advanced IRSs with a minimal visual impact, due to their flat surface.

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