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***Abstract*—In this paper some numerical and experimental results on the design of multi-beam antennas, suitable for their possible use as base-station antennas in the next generation of 5G communication systems, are presented and their main features are discussed.**

***Index Terms*—5G communication system, antennas, arrays, transmitarrays**

I. INTRODUCTION

To obtain the expected revolutionary performances of the 5th Generation (5G) of communication systems, that are supposed to be able of transmitting a total amount of data almost 1000 times larger then the present one, with improved data rate, very low latency and reduced costs and energy consumption [1], [2], innovative and highly performing technologies are needed.

For what concerns base station antennas, the most promising solution seems to be that of using a Multiple-In Multiple-Out (MIMO) configuration [3], [4] able to transmit and to receive multiple beams, to exploit multipaths to enhance the spectral efficiency, with a consequent increase of the throughput capacity, to reduce the latency and to increase the communication system robustness against possible interferences. Some of the technologies for the realization of a multi-beam antenna to be use in MIMO architectures are presented in [5], [6]; even if the most assessed solution is that of using a phased array, other alternatives are considered, as that of adopting a passive aperture antenna illuminated by the field radiated by a feed-array: in this case, the most traditional configurations use a shaped reflector or a dual reflector system to improve the antenna performances, even if especially this last has the disadvantage to be quite bulky and heavy. The metallic reflector could be substituted either by a planar Reflectarray (RA) [7], or else by a collimating device working in transmission, i.e. a lens or a planar Transmitarray (TA) [8], [9], presenting, with respect to configurations working in reflection, the advantage to not suffer for feed blockage even when it is not off-set.

In this paper, some preliminary results on the design of two different configurations, one consisting in a planar array and the other using a transmitarray, both suitable for the realization of a multi-beam antenna, are discussed. Moreover, since expecially the second solution considered needs the use of a proper approach for its design, able to enhance its features, an innovative approach for its optimization, named M_QC_{10}-BBO is also described.

II. MULTI-BEAM PHASED ARRAY

Phased arrays [10], [11] represent the traditional technology for the multi-beam antenna system; in phased array systems, the high-power generation for transmitting and low-noise amplification on the receiving end are distributed, as is the phase control at each radiating element. On the other hand, planar printed antennas have gained interest for phased array applications due to their features of low cost, ease of fabrication, and potential for high-efficiency operation [12] – [14]. Recently, the planar phased-array antennas have been received much attention for designing multi-beam 5G antennas.

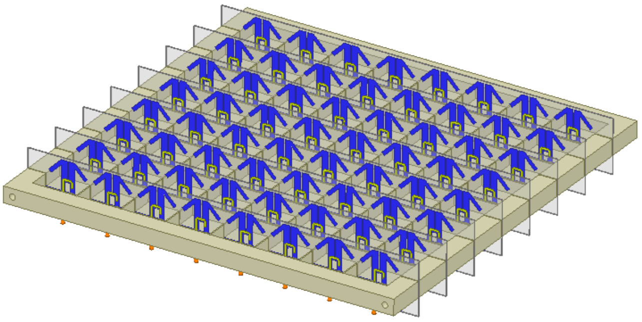

Fig. 1: Geometry of 8×8 array with the cavity-backed angled dipole antenna.

This section presents a two-dimensional phased array with 8×8 cavity-backed angled-dipole antennas for multi-beam applications. Fig. 1 shows the geometry of the array, which consists of 64 cavities and 64 printed angled-dipole. The angled-dipole was designed on both sides of a Rogers RO4003 substrate ($h_s = 0.508$ mm, $\epsilon_r = 3.38$ and $\tan\delta = 0.0027$) and fed by an integrated balun consisted of a folded microstrip line and a rectangular slot. The dipole was angled at $\alpha = 45°$ for a compact size and a wide-beam radiation. The center-to-center spacing between adjacent elements is 25 mm ($\sim 0.48\lambda \times 0.47\lambda$ at 5.8 GHz). The cavity-backed angled-dipole antenna was first optimized through several parametric HFSS simulations to obtain a wide-band and wide-beam radiation at 5.8 GHz, and then arrayed for the wide scanning angle in both E- and H-planes.

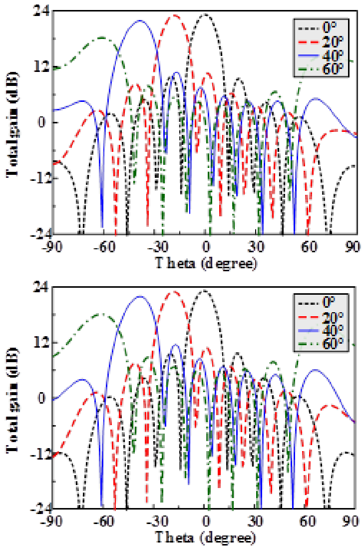

Fig. 2: The scanning performance of the phased array in (Top) E- and (Bottom) H-planes.

Fig. 2 shows the scanning performance of the array at 5.8 GHz, which was obtained by using HFSS simulations. It is observed that the array yields a wide scanning angle and a stable scanning performance in both E- and H-planes. At 5.8 GHz, in both principle planes, the array achieves a scan angle up to 60° and a gain of 18.0 – 23.5 dBi.

III. MULTI-BEAM TRANSMITARRAY

Transmitarrays are promising solutions for the realization of high gain, low cost and high efficiency antennas (see e.g. [15] and references therein). They mimic the behavior of a lens, where the curvature is substituted by a planar surface, divided in unit-cells with size equal or lower than half wavelength at the working frequency. In order to collimate the beam in a desired direction, one or more parameters of each unit-cell is varied, so that the transmission coefficient S_{21} and in particular its phase locally changes.

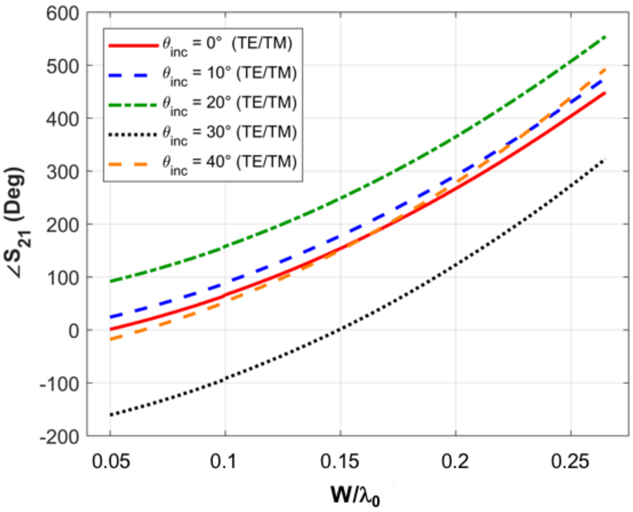

Fig. 3: Variation of S_{21} phase as a function of W/λ_0, computed for different values of θ_{inc}

The behavior of the unit-cell depends on the angle of arrival of the incident field radiated by the feed: in single beam TA, this is not a problem, since the design is carried out considering a fixed position of the feed. If, as in the present case, it is necessary to generate several beams pointing in different directions, a multi-feed system can be used, able to radiate several beams impinging on the surface of the transmitarray with different angle of incidence. In this way, also the direction of maximum radiation of the entire antenna changes, and it forms an angle θ_{max} with the normal $\hat{n}$ to the TA surface that is proportional to the incidence one, i.e. θ_{max} = BDFθ_{inc}, where θ_{inc} is the angle between $\hat{n}$ and the direction of arrival of the incident field, and BDF is the beam deviation factor, representing how much θ_{max} differs from θ_{inc}. Unfortunately, due to the dependence of the unit-cell from θ_{inc}, the performances of the antenna does not stay the same for all its value, but they degrades as well as the difference between the considered value of θ_{inc} and that used for the antenna design increases.

To reduce this effects, two strategies can be adopted, possibly jointly: to chose a proper unit-cell, with a low sensitivity to the angle of incidence, and to define an ad-hoc procedure for the entire antenna design. While some results on the first requirement are presented in this section, the consideration relative to the second one are postponed to the next one. An exhaustive analysis of different types of unit-cell highlights the good characteristics of that introduced in [16], consisting in three layers of the same dielectric material: the central one presents a square hole, whose size W is varied to control S_{21}, while the two identical layers present a truncated pyramid hole and they act as wide band matching circuits. In addition to the excellent frequency behaviour, this unit-cell is also slightly sensible to the direction of arrival of the impinging field, as can be proved by the curves in Fig. 3, representing the variation of the transmission coefficient phase with W/λ_0 (being λ_0 the wavelength computed at the design frequency f_0), for different values of θ_{inc}: the curves are almost parallel and they keep their linearity for all the considered angles of incidence.

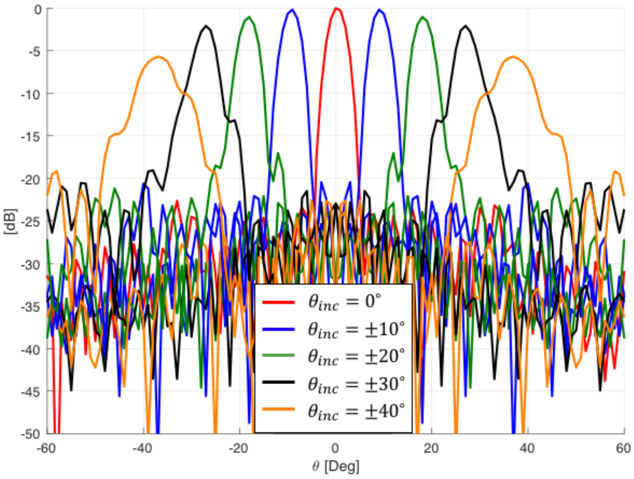

Fig. 4: Normalized radiation patterns in the E-plane, measured at f_0 and for different values of θ_{inc}

A medium size (approximately $20\lambda_0 \times 20\lambda_0$) transmitarray prototype has been manufactured, using a 3D printing technique, and the effective behaviour of the unit-cell has been tested, just changing the position of a single feed-horn that was allowed to move along a circular arc. The normalized radiation patterns in the E-plane, measured for several values of θ_{inc} in the interval $[-40°, +40°]$ are plotted in Fig. 4: it can be noticed that the main beam minimally changes for angles of incidence between $-30°$ and $-30°$, in correspondence of which the side lobes starts to increase, even if not significantly. In this range the reduction of the gain is not greater than 2 dB, while it decreases more than 5 db for θ_{inc}=$\pm 40°$, when the main beam enlarges and the side lobes are much higher. Note that, as expected, the direction of maximum direction is not equal to θ_{inc}: here the value of BDF is approximately 0.9.

IV. OPTIMIZATION-BASED ANTENNA DESIGN

The results summarized in the previous sections prove the possibility to use the considered technologies for the design of a multi-beam antenna for a MIMO system, but also point out the necessity to adopt a proper, non-conventional design technique to further improve their performances. For this purpose, the use of a global optimization approach seems to be a convenient solution. The algorithms most widely applied to the optimization of antenna systems are the Genetic Algorithm (GA) [17] and the Particle Swarm Optimization (PSO) [18], that are both well-established methods. However, the increasing complexity of the problems to be optimized pushes the development of new approaches with improved features, in terms of convergence, computational cost and reliability. Here, a most recent algorithm is considered, the $\mathrm{M}_Q\mathrm{C}_{10}$-BBO, an enhanced version of the Biogeography Based Optimization (BBO) introduced in [19], particularly suitable for antenna problems.

The $\mathrm{M}_Q\mathrm{C}_{10}$-BBO is a population-based method, in which the possible solutions of the problem are represented by “islands” or “habitats”. They evolve to the optimum thank to mutation and migration, regulated by the emigration (μ) and immigration (λ) rates. These two quantities depend on the goodness of each solution, i.e. by its fitness score, here named Habitat Suitability Index (HIS). The relation between μ, λ and the HIS could be linear (L), as in the standard BBO, quadratic (Q) or cosine-type (C), as indicated by the subscript of “M” in the algorithm name. Moreover, to increase its exploration capability, a further quantity controlling the evolution of the algorithm has been added, the “cataclysm”, with the aim of destroying all the population except the best elements (elitism) and to generate randomly a new one when the convergence does not improve after 5n following iterations. The number n is also coded in the algorithm name, through the subscript of “C”.

Application of the $\mathrm{M}_Q\mathrm{C}_{10}$-BBO to several antenna test problems has proved its effectiveness; as an example, the results relative to the optimization of a planar thinned array are reported. The considered array consists in 15×15 elements, while the control parameters are the number and the positions of the elements switched off. The aim of the optimization is to keep as lower as possible the side lobes, generally higher in thinned array than in full ones. A population size equal to 50 has been adopted and the performances of the $\mathrm{M}_Q\mathrm{C}_{10}$-BBO have been compared with those of the standard BBO and the GA. The minimum value of the side lobe level (SLL), averaged over 10 independent trials and obtained with the three approaches after 50 iterations, is reported in Table 1: the comparison among these data confirms the improved capabilities of the $\mathrm{M}_Q\mathrm{C}_{10}$-BBO with respect to the other considered algorithms.

TABLE I: Comparison among the performances of the $\mathrm{M}_Q\mathrm{C}_{10}$-BBO, the GA and the BBO, applied to the design of a planar thinned array

Algorithm	**GA**	**BBO**	**$\mathrm{M}_Q\mathrm{C}_{10}$-BBO**
Side Lobe Level	-14.4 dB	-16.1 dB	-17.3 dB

Results of the application of the $\mathrm{M}_Q\mathrm{C}_{10}$-BBO to the antennas considered here will be presented at the Conference.

V. CONCLUSIONS

Some preliminary results of two different multi-beam antenna configurations, including a planar phased-array and a transmitarray, have been presented and discussed. The planar array is a two-dimensional phased array with 8×8 cavity-backed angled-dipole antennas, which achieved a wide scanning angle and a stable scanning performance in both E- and H-planes. Characterization using ANSYS HFSS indicate that at 5.8 GHz, in both principle planes, the array achieves a scan angle up to 60° and a gain of 18.0 – 23.5 dBi. The transmitarray configuration has been manufactured and experimentally characterized. It shows lower scanning angles capabilities with respect to the phased-array, that can be however improved with the aim of an optimized design.

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