A Beamforming Network for 5G/6G Multibeam Antennas Using the PCB Technology

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***Abstract*—This paper presents the design of a 4×4 Blass matrix for enabling beamforming operations in a four-element uniform linear antenna array (ULAA) operating at 3.5 GHz, corresponding to the first frequency band reserved for the forthcoming fifth and sixth generation (5G/6G) systems. To obtain a simple and inexpensive device, the proposed feeding network, which provides to the ULAA beam pointing capabilities towards four different directions, is entirely implemented using printed circuit board technology. The design procedure is realized adopting an extended iterative mathematical framework accounting for losses control and providing the pointing angles and the matrix coefficients. The performance of the conceived architecture is numerically investigated through full-wave simulations. The versatility, low losses, and low price of the developed microstrip network makes it suitable for both 5G/6G air/terrestrial femtocell base stations and Internet of Things (IoT) cluster-head sensors/actuators.**

I. Introduction

The evolution of the network society has necessarily led to a scenario where everyone and everything are almost already connected everywhere at every time. In addition, the data size, the quality requirements, and the application domains have exponentially grown over the years, thus calling researchers and operators to answer to novel challenging demands of pervasive connectivity [1]. As a first step, the International Telecommunication Union has allocated a larger spectrum to the fifth generation (5G) system [2], with frequencies up to 6 GHz used to match the reliability/coverage purposes of critical machine type communication (MTC), and those beyond 24 GHz to satisfy the ultra-high throughput requirements of massive MTC [3]. Unfortunately, the high frequencies have many limitations, such as high path-loss, low object-penetration, and supplementary rain attenuation. These drawbacks can be effectively overcome by adopting multibeam antennas (MBAs), which, beside the coverage and data security improvements, are able to guarantee high signal-to-interference-plus-noise ratio levels to multiple coexisting communications between the users and their serving base station (BS) [4]. MBAs have in fact the capability to cover a predefined number of angular sectors employing a beam switching approach, which is realized by exciting the elements of an antenna array through a proper beamforming network (BFN). With reference to the 5G ecosystem, and also to the future sixth generation (6G) one, it is expected that energy saving will play a key role during the design process of the radio-communication interfaces. This makes passive MBAs (PMBAs), which avoid the usage of active components, as ideal candidates for large-scale low-cost power-limited antenna feeding architectures. Within this context, the proposals of BFNs for PMBAs available from the literature can be classified in two main categories: those based on beamforming circuits and those based on lenses. The BFNs of the first type consist of millimeter-wave circuit components, such as switches, power dividers, directional couplers, phase shifters, and crossovers. In this category, the most known solutions are the Blass matrix [5], [6], the Nolen matrix [7], and the Butler matrix [8]. The BFNs of the second type are instead based on Rotman lens [9], which implement a quasi-optical beamforming strategy relying on the transmission of input signals through a lens, whose output face is properly connected to the antenna terminals.

An overview of the most relevant characteristics of the four listed PMBA design approaches is reported in Table I, while Table II lists some relevant state of the art proposals. In general, the circuit-based BFNs have the considerable advantage of being fully integrable into a single substrate together with the antenna array radiating elements and other RF circuits, thus keeping small the overall dimension of the final device. In addition, the use of the printed circuit board (PCB) technology makes the BFN very easy to fabricate, inexpensive, light-weight, and simpler to design with respect to the lens-based approach. Within the circuit-based BFN category, the Blass matrix offers a major versatility, since it allows one to generate an arbitrary number of beams without constraints on the pointing directions. Conversely, the Butler matrix can generate only orthogonal beams, whose number must be, similarly to the number of antenna elements, a power of two and proportional to the number of hybrid couplers and phase shifters, thus limiting the actual size of the structure. Some modified versions have been proposed in the literature to overcome this issue [8], but maintaining the beams orthogonality limit. The main disadvantage of the Blass matrix is its inherent losses due to the rows/columns termination by matched loads, which dissipate the incoming power. However, with a proper design, these losses may be maintained low. The Nolen matrix may be seen as a special case of the Blass one with (ideally) no losses, but its flexibility is reduced because the number M of inputs must be lower than that N of outputs. For these reasons, the circuit-based Blass matrix approach is widely diffused, since it represents a really satisfactory tradeoff

TABLE I
MOST RELEVANT CHARACTERISTICS OF PASSIVE BFN TECHNOLOGIES.

	Advantages	Disadvantages
Blass matrix	Flexibility: pattern shape, number of ports. No crossover. Ease of fabrication.	Low efficiency. Many components. Spurious paths.
Nolen matrix	Theoretically lossless. No crossover. Ease of fabrication.	Less inputs than outputs. Spurious paths.
Butler matrix	Theoretically lossless. Few components. Simple structure. Ease of fabrication.	Crossover. Multi-layer design. Limited number of ports, Beam directions.
Rotman lens	Flexibility: beam direction, numbers of ports.	Low efficiency. Complex structure. Large size.

between complexity and versatility.

According to the above discussed issues, this paper proposes a new Blass matrix solution completely conceived using the PCB technology and operating at a center frequency of 3.5 GHz. The presented BFN, which is composed by $4+4$ transmission lines interconnected by 4×4 directional couplers, is developed to allow beam pointing to a composite uniform linear antenna array (ULAA) with four radiating elements towards $M = 4$ arbitrary desired directions, thus without constraints on beam orthogonality or pattern shape. In order to obtain a simple and inexpensive device, a copper metallized Roger 5880 substrate is firstly chosen and an extended iterative mathematical framework is implemented, with the aim of calculating the pointing angles and the related Blass matrix coefficients. The performance of the derived structure is validated by CST full-wave simulations by modeling the input/output ports through connectors and adopting 50 Ω loads. The results show the satisfactory behavior of the proposed feeding architecture in terms of pointing versatility and design simplicity, revealing its suitability for the low-losses and low-cost requirements of 5G/6G communication interfaces.

The paper is organized as follows. Section II describes the design procedure. Section III shows the numerical validation. Finally, Section IV summarizes the most relevant conclusions.

II. DESIGN PROCEDURE

The Blass matrix is a multiplex transmission line network introduced in the Sixties by Jude Blass as a method to feed a ULAA composed by N elements when it is required to steer the beams of the generated pattern towards M different directions, so as to obtain a multidirectional antenna [5]. Fig. 1 shows an $M \times N = 4 \times 4$ Blass matrix, which is a series feeding structure, composed by $M+N = 8$ transmission lines interconnected by $M \times N = 16$ directional couplers.

The principle of operation can be described as follows. To steer a beam towards the mth desired direction, a traveling wave is injected from the mth input port (on the left). This wave travels towards the N output ports (on the top), which

TABLE II
STATE OF THE ART PROPOSALS.

Ref.	Technology	$M \times N$	Pointing	Frequency [GHz]
[6]	Blass/waveguide	5×32	$30° \div 50°$	11.5
[10]	Blass/microstrip	2×8 3×8	$0°, 30°$ $0°, 30°, 45°$	5.3
[8]	Butler/microstrip	8×8	$\pm 90°$	2.4
[11]	Rotman/microstrip	5×5	$\pm 20°$	28.0
[12]	Rotman/SIW	3×8	$\pm 25°$	11.5

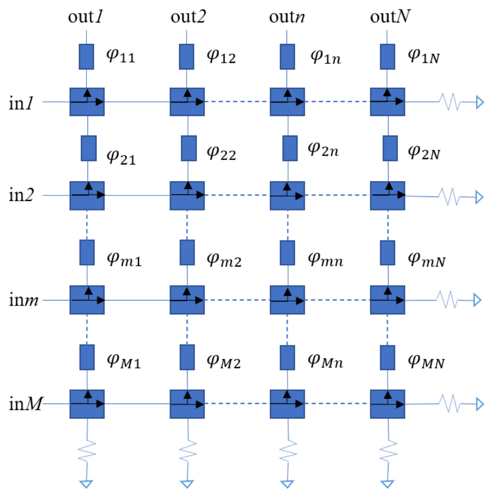

Fig. 1. $M \times N = 4 \times 4$ Blass matrix.

are connected to the radiating elements of the ULAA. The interconnections are realized by directional couplers, which properly divide the incoming power among the output ports. The sidelobe level of the array factor of a ULAA is mainly determined by the magnitude distribution of the element excitations, which here correspond to the transmission coefficients $T_{m,n}$ between the mth and the nth ports. Besides, the pointing direction is mainly controlled by the excitation phases $\alpha_{m,n}$, which can be properly adjusted by designing the length of the paths and/or by adopting phase shifters [5]. Finally, rows and columns are terminated on matched loads. Therefore, the overall design procedure of a Blass matrix consists in determining and implementing the phase shifter values, the coupling values, and the matched terminations so as to obtain proper transmission coefficients at the antenna terminals with minimal losses. The technique proposed to achieve this result is described in detail in the following subsections.

A. Directional couplers

Directional couplers are four-port components characterized by an input port (Port 1), a coupled port (Port 2), a direct port (Port 3), and an isolated port (Port 4) [13]. For the generic coupler $\mathcal{C}_{m,n}$ inserted between the mth and the nth ports of the Blass matrix, the input power at Port 1 is directed towards Port 2 with a coupling factor $C_{m,n}$ and towards Port 3 with a coupling value $\sqrt{1 - C^2_{m,n}}$. Ideally, no power should flow through Port 4, which should be perfectly isolated. Couplers are critical elements in the Blass matrix design.

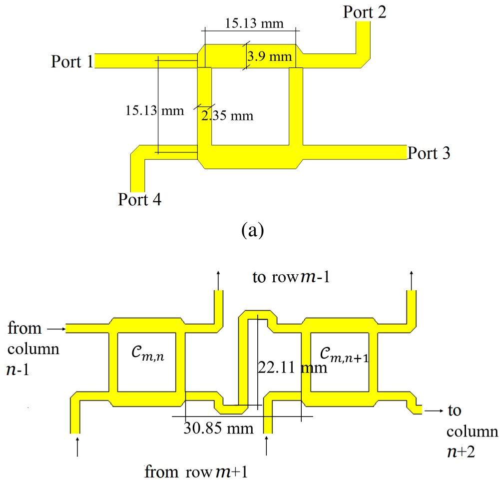

Fig. 2. Directional coupler: (a) dimensions of the single element; (b) consecutive couplers on the matrix row.

Although they might be separately optimized, the usage of identical components is widely considered, since this second choice makes the final device extremely simple and suitable for mass production. Moreover, a trade-off exists between circuit efficiency, which is increased by high coupling values, and influence of spurious paths, which is instead mitigated by lower coupling values. For these reasons, the here developed couplers are identical and characterized by $C_{m,n} = C = \sqrt{1 - C^2} = 1/\sqrt{2}$ for $m = 1, ..., M$ and $n = 1, ..., N$. To satisfy these requirements, the formulas in [13] are initially used and subsequently optimized through the CST simulation tool, thus deriving the final geometry reported in Fig. 2a. Of course, this choice of adopting identical couplers, which is advantageous for the final device realization, also comports some drawbacks, which are actually related to the reduction of the degrees of freedom of the problem. The most relevant are the lower control of the amplitude of the excitations at the antenna terminals, and of the power delivered to the matched terminations. However, results of simulations prove that the beam pointing is realized and good efficiencies are obtained with the adopted choice.

Then, since in a Blass matrix, the couplers connect transmission lines, a second relevant aspect must be taken into account. In fact, when a given row of the matrix is considered, four couplers result concatenated. It is evident that the distance between consecutive branch lines influences the overall dimension of the Blass matrix and that a reduced distance is preferable to make the device more compact. This reduction must be however imposed by taking care that the input signals are maintained in-phase at all the input ports. This requirement is satisfied by numerically optimizing the length of the transmission line connecting Port 3 of $\mathcal{C}_{m,n}$ to Port 1 of $\mathcal{C}_{m,n+1}$, thus obtaining the structure shown in Fig. 2b. If $\mathcal{C}_{m,n}$ lies at the end of a row, it is terminated on a matched load, whose design will be described in Subsection II-C.

TABLE III
DESIRED DIRECTIONS θ_m.
EXCITATION PHASES AND PHASE SHIFT VALUES: $\alpha_{m,n}/\varphi_{m,n}$.

m	θ_m	$n = 1$	$n = 2$	$n = 3$	$n = 4$
1	60°	0°/270°	255°/345°	150°/60°	45°/134°
2	110°	0°/180°	72°/354°	144°/180°	215°/335°
3	85°	0°/180°	341°/93°	323°/339°	305°/269°
4	140°	0°/180°	161°/358°	322°/178°	123°/13°

B. Phase shifters

In the Blass matrix architecture, a phase shifter $\varphi_{m,n}$ is placed between any pair of consecutive couplers lying in the same column (Fig. 1). These $M \times N = 16$ components are fundamental to properly synthesize the phases of the transmission coefficients at the antenna terminals, so as to control the pointing angles. Therefore, the $\varphi_{m,n}$ values must be calculated to produce the desired excitation phases $\alpha_{m,n}$ at the antenna array terminals. To this aim, consider first a ULAA composed by $N = 4$ radiating elements placed on the x-axis of a Cartesian system $O(x, y, z)$ at positions $x_n = nd$, where d denotes the inter-element distance and $n = 1, ..., 4$ identifies the antenna element. The array factor of this ULAA can be expressed as [14]:

$$\mathrm{AF}(\theta) = \sum_{n=1}^{4} a_{m,n} \exp\left(jnkd\cos\theta\right), \qquad (1)$$

where j is the imaginary unit, $k = 2\pi/\lambda_0$ is the free-space wave number, θ is the angle from the array axis and $a_{m,n} = |a_{m,n}|\exp(j\alpha_{m,n})$ is the complex excitation of the nth element required to radiate the mth desired beam.

The literature offers several synthesis techniques for ULAAs [15]–[19]. One of the simplest and most widely diffused is the progressive phase method [14], according to which the excitation phases can be related to the desired directions by:

$$\alpha_{m,n} = \angle a_{m,n} = -(n-1)kd\cos\theta_m. \qquad (2)$$

As a possible example, Table III lists the values obtained from (2) for $d = 50$ mm and for the four desired directions in the second column when $f = 3.5$ GHz. These pointing angles will be from now on assumed in order to illustrate the performance of the proposed design method in a realistic situation characterized by not regularly distributed desired directions.

Now, with reference to Fig. 1, it is evident that $a_{m,n} = T_{m,n}$. Therefore, the evaluation of the phase shifts $\varphi_{m,n}$ can be carried out by firstly imposing the following condition on the phase of each transmission coefficient:

$$\angle T_{m,n} = \alpha_{m,n}. \qquad (3)$$

The procedure to find the phase shift values then evolves iteratively by starting with $m = 1$. When considering the first row of the Blass matrix, the transmission coefficients, for $n = 1, ..., 4$, can be written as:

$$T_{1,n} = C(1 - C^2)^{(n-1)/2}\exp[-j(\varphi_{1,n} + \xi_{1,n})], \qquad (4)$$

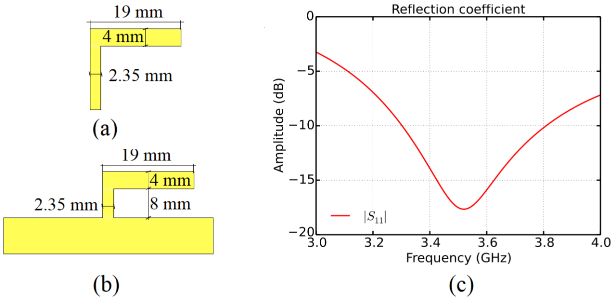

Fig. 3. Matched termination (dummy antenna): (a)-(b) top and bottom view; (b) reflection coefficient.

where $\xi_{1,n}$ is the phase shift introduced by the branch lines connecting input 1 to antenna n, which can be easily inferred recalling that all couplers are identical. By imposing condition (3), one can then derive the phase shift corresponding to the first row ($n = 1, ..., 4$) as:

$$\alpha_{1,n} = -(\varphi_{1,n} + \xi_{1,n}). \tag{5}$$

For $m, n > 1$ the complexity increases because of the presence of secondary paths that connect the generic mth input to the generic nth output. However, proceeding row-by-row, it is possible to express the transmission coefficient $T_{m,n}$ as:

$$T_{m,n} = t_k + t_u(\varphi_{m,n}), \tag{6}$$

where the term t_k depends on the sole already known phase shift values, while the term $t_u(\varphi_{m,n})$ depends on the sole unknown phase shift value $\varphi_{m,n}$. By adopting the procedure developed in [20] to solve (6) with respect to $\varphi_{m,n}$ when (3) is imposed, one obtains the values reported in Tab. III. These phase shifts are implemented by properly designing the corresponding lengths of the transmission lines that connect Port 2 of $\mathcal{C}_{m,n}$ with Port 4 of $\mathcal{C}_{m-1,n}$.

C. Matched terminations

In the Blass matrix, each row/column is terminated by a matched load. In the proposed design, this component is developed adopting a dummy antenna consisting of an antipodal dipole, which is a cheap, easy to fabricate, and very compact radiator, thus its selection is in the agreement with the low-cost approach adopted for the realization of the entire Blass matrix. Of course, the name dummy antenna refers to its very poor radiation performance. In fact, its design is realized in such a way as to provide matched terminations for rows and columns, while not interfering with the radiation of the adopted antennas. The dimensions of the antipodal dipole, still matched at $f_0 = 3.5$ GHz, are calculated combining the model with the CST optimization tool. The resulting structure is illustrated in Fig. 3, along with its $|S_{11}|$ curve. This last task concludes the overall design procedure of the developed Blass matrix, whose achievable performance is explored in the next section.

III. Results

The obtained Blass matrix architecture, including directional couplers, branch lines, phase shifters, matched terminations,

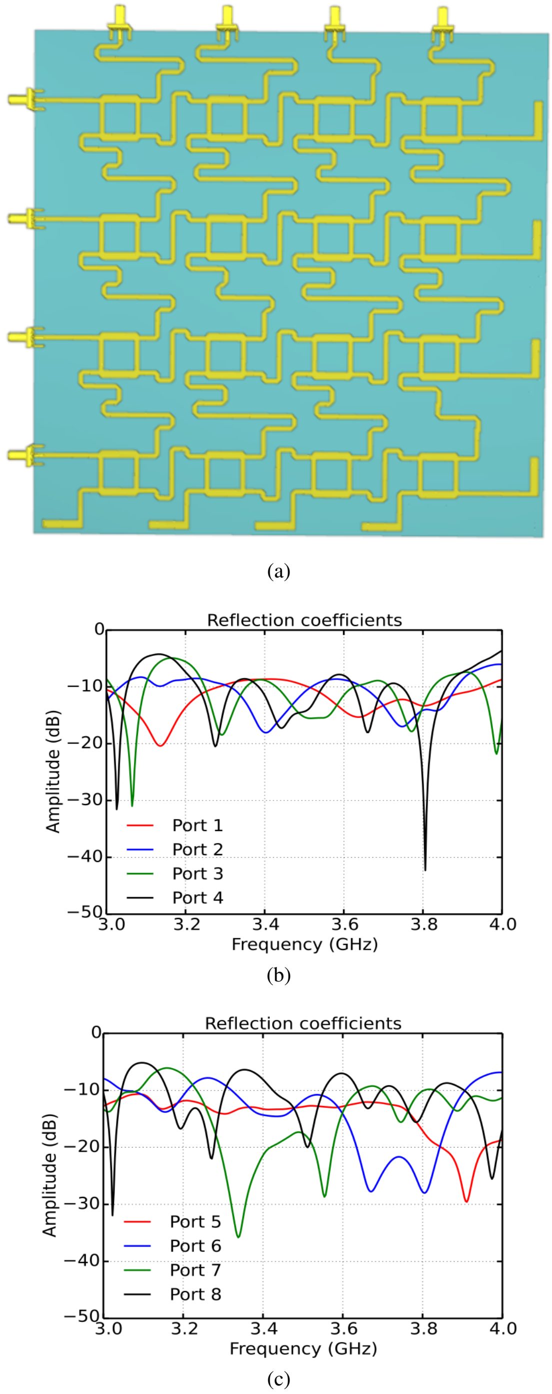

Fig. 4. (a): Designed Blass matrix. Reflection coefficients: (b) input ports 1–4, (c) output ports 5–8.

and connectors, is shown in Fig. 4a. As specified in the previous section, $M = 4$ desired beams pointing at the angles $\theta_1 = 60°$, $\theta_2 = 110°$, $\theta_3 = 85°$, and $\theta_4 = 140°$ are chosen considering a ULAA consisting of $N = 4$ elements having an inter-element distance $d = 50$ mm. Such a distance allows one to consider, for example, rectangular patches as radiating elements, which might eventually be printed on the same board where the Blass matrix is realized. In this case, the output

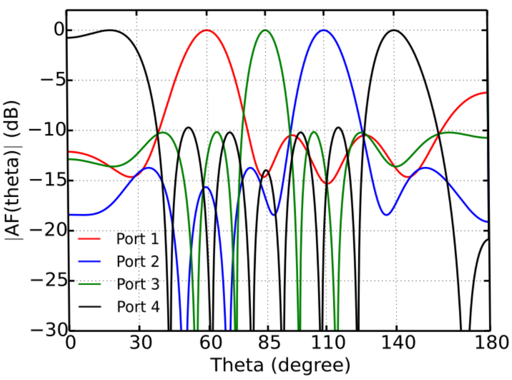

Fig. 5. Final array factors.

TABLE IV
TRANSMISSION COEFFICIENTS $T_{m,n}$ AND EFFICIENCIES η_m.

m	$n=1$	$n=2$	$n=3$	$n=4$	η_m
1	$0.7\angle 0°$	$0.5\angle -105°$	$0.4\angle 150°$	$0.2\angle 45°$	77%
2	$0.5\angle 0°$	$0.7\angle 72°$	$0.2\angle 144°$	$0.3\angle -145°$	73%
3	$0.4\angle 0°$	$0.2\angle -18°$	$0.7\angle -37°$	$0.5\angle -55°$	73%
4	$0.2\angle 0°$	$0.4\angle 161°$	$0.5\angle -39°$	$0.7\angle 123°$	65%

connectors would not be necessary and the overall dimension would be kept as small as possible. The entire structure is implemented in CST to perform full-wave simulations and hence prove the validity of the proposal. Figs. 4b and 4c show the reflection coefficients of the input and output ports, respectively. In particular, the numbering refer to Fig. 4a, with the input ports (on the left) numbered from 1 to 4 and the output ones (on the top) from 5 to 8. As it may be observed from Figs. 4b and 4c, all the $|S_{nn}|$ values from $n = 2$ to $n = 8$ are lower than -10 dB at $f_0 = 3.5$ GHz, while, at the same frequency, the remaining coefficient is just slightly higher ($|S_{11}| \cong -9.73$ dB). This represents a significant result, since the reflections are very limited. Finally, Fig. 5 shows the array factors evaluated by Matlab with the transmission coefficients reported in Tab. IV, which, in turns, represent the excitations of the radiating elements. This puts into evidence a satisfactory level of accuracy for the proposed device. Last column of Tab. IV also lists the efficiencies obtained by the full-wave simulations, which are quite acceptable, when the power is not a critical issue.

IV. CONCLUSION AND FUTURE DEVELOPMENTS

A novel 4×4 Blass matrix design entirely realized using PCB technology for providing beamforming capabilities to a four-element ULAA has been proposed. The developed structure, which operates at 3.5 GHz, enables beam pointing towards four different arbitrary directions by a proper realization of all required components, including directional couplers, phase shifters, and matched terminations. To this aim, an iterative procedure is extended to account for the transmission coefficients and the line lengths to finally derive the necessary phase shifts. Preliminary results, based on full-wave simulations combined with Matlab simulations, reveal a satisfactory performance in terms of limited reflections, pointing capabilities, structure efficiency and size compactness. These advantages, combined with the low-cost of the adopted technology, the simplicity of the basic components, and their integrability with the circuitry of the radio interface, makes the presented architecture suitable for several 5G/6G systems, including cluster-head IoT nodes and femtocell BSs. Fabrication of a prototype for further validation will be realized in the next future.

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