Multibeam Network Design and Measurement for Triangular Array of Three Radiating Elements

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***Abstract*— Nowadays, more a more base stations are equipped with active conformal antennas. These antenna designs combine phase shift systems with multibeam networks providing multi-beam ability and interference rejection, which optimize multiple channel systems. GEODA is a conformal adaptive antenna system designed for satellite communications. Operating at 1.7 GHz with circular polarization, it is possible to track and communicate with several satellites at once thanks to its adaptive beam. The antenna is based on a set of similar triangular arrays that are divided in subarrays of three elements called 'cells'. Transmission/Receiver (T/R) modules manage beam steering by shifting the phases. A more accurate steering of the antenna GEODA could be achieved by using a multibeam network. Several multibeam network designs based on Butler network will be presented.**

I. INTRODUCTION

The antenna GEODA is a smart, conformal, multi array system design for satellite communications. Its structure consists of a hemispherical dome placed on a cylinder of 1.5 meters height. Both cylinder and dome are made of 30 triangular arrays. Each of those triangular arrays contains 15 'cells' of three radiating elements. Hence, the total number of radiating elements is 2.700.

The radiating element consists of two stacked circular patches. The principal patch is fed in quadrature in two points separated 90º, in order to get circular polarization. The coupled patch, which has smaller size, is used in the aim of improving the bandwidth. As it is shown in figure 2, the bandwidth of the radiation pattern of a single radiating element is on the order of 60º.

An electronic control module will govern the T/R modules of each radiating element. By setting phase shifts between the radiating elements, the steering direction of a triangular array will be controlled. Finally, the desired beam shape will be obtained by using the digital adaptive system of the signal of each triangular array.

The steering capability of the antenna GEODA could be increased by using a multi beamforming network (MBFN) at each cell, providing greater versatility. Butler matrix is the easiest and smallest lossless MBFN that can be implemented on printed circuit embedded within a 2D substrate. Generally, the number of inputs in Butler matrix is a power of two, which do not fit with the triangular subarray under study, thus, modify Butler network must be studied to obtain a 3 inputs network.

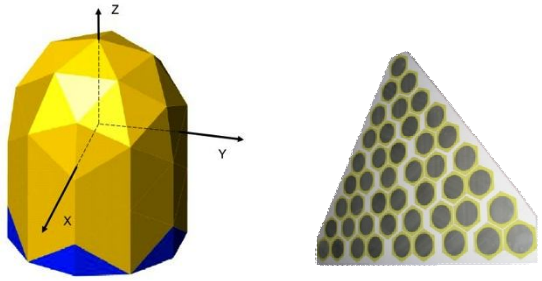


Fig.1. General geometric GEODA structure (Left). Triangular panel configuration (Right).

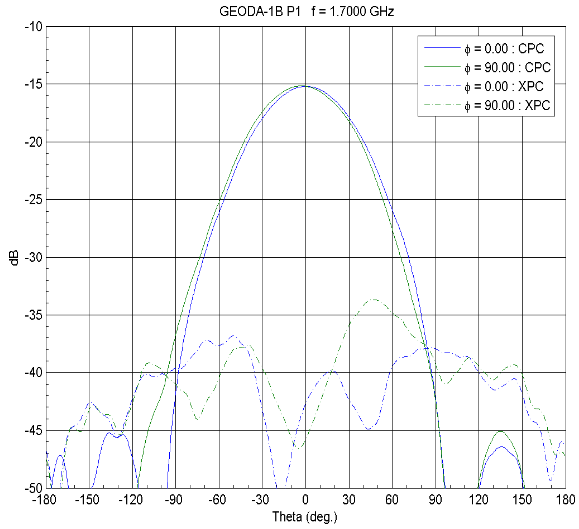


Fig.2. Radiation pattern of a single radiating element

II. GENERAL MBFM SCHEME

Usually, passive multi beamforming networks are a set of inputs related to the system outputs, which are connected to the radiating elements. Terms input or output depends on the working way, transmission or reception. In this document, MBFN will be associated to a transmission antenna. The reception network behaviour will be the same through network reciprocity.

Regarding the classification, we only distinguish between lossless and lossy networks. Though real networks are lossy, we will consider lossless those that would be not dispersive if elements that form them were ideals.

Considering inputs and outputs adapted and isolated from each other, a MxN network responds to the scattering matrix defined in (1),

$$[S]=\begin{bmatrix} 0 & \cdots & 0 & s_{1,M+1} & \cdots & s_{1,M+N} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & s_{M,M+1} & \cdots & s_{M,M+N} \\ s_{N+1,1} & \cdots & s_{1,M+1} & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ s_{M+N,N+1} & \cdots & s_{M+N,M} & 0 & \cdots & 0 \end{bmatrix}=\begin{bmatrix} 0 & S_R \\ S_T & 0 \end{bmatrix} \tag{1}$$

Each matrix elements represent the mutual coupling between each M input and N output. Scattering matrix can be summarized in a pair of matrices, S_T and S_R. However, if the network is reciprocal, S_T and S_R^t will be the same.

On scattering parameters terms, a network is reciprocal and lossless when the product of the scattering matrix and its transpose conjugate is the identity matrix. In the case under study,

$$[S][S]^H=\begin{bmatrix} [S_R][S_R]^H & [0] \\ [0] & [S_T][S_T]^H \end{bmatrix}=[I] \tag{2}$$

This implies that vectors related to the columns of each matrix S_T and S_R have to be orthonormal to each. Hence,

- The number of input and outputs must be the same. Otherwise, matrices would be non-square matrices and one of them would have more vectors than matrix range wherewith it would be impossible to obtain orthogonal beams to each.
- Unitary excitations indicate that the output power is equal to the input power.
- Vectors are orthogonal. When an input port is excited, the radiation pattern obtained will be orthogonal to any other one generated by any other input port.

Once network parameters have been established, the radiation pattern depends on both radiation pattern of the single radiating element and the distribution of each radiating element on the array.

III. BASIC EQUATIONS

In order to analyse a 'cell', it is assumed patches are located over vertices of an equilateral triangle with 'd' side length. Figure 3 shows an scheme where $x_1=\frac{d}{2\sqrt{3}}$, $y_1=\frac{d}{2}$, $x_2=\frac{d}{2\sqrt{3}}$, $y_2=-\frac{d}{2}$, $x_3=-\frac{d}{\sqrt{3}}$, $y_3=0$.

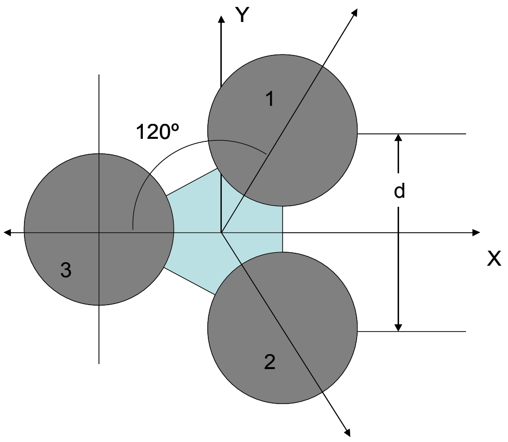


Fig.3: Subarray distribution

Assuming that the steering direction of the first beam is θ=θ$_0$, ϕ=0, and taking into account that the array factor is given by $AF(\theta,\phi)=\sum_{i=1}^{3}A_i e^{-j\alpha_i}e^{-jk\hat{r}r_i}$, if we bear in mind the fact that feeding phases must satisfy the condition of adding the contributions of each array element in the steering direction, then, $k_0\hat{r}r_1-\alpha_1=k_0\hat{r}r_2-\alpha_2=k_0\hat{r}r_3-\alpha_3$. Hence, it is shown that,

$$\begin{aligned} S_{4,1}&=S_{5,1}=ae^{j\alpha} \\ S_{6,1}&=be^{j(\alpha-\beta)} \end{aligned} \tag{3}$$

Where $\beta=\sqrt{3}\frac{\pi d}{\lambda}\sin(\theta_0)$

The other two beams will keep a rotational symmetry steering at the same elevation angle and changing the azimuth angle between 0º, 120º or 240º. Rotating S parameters studied will form three different beams.

Imposing the orthogonal condition $[S_T][S_T]^H=[I]$, then

$$\sin(\theta_0)=\frac{\lambda}{\sqrt{3}\pi d}\arccos\left(-\frac{a}{2b}\right) \tag{4}$$

Main steering directions, θ$_0$, depends on distance and feeding relation between elements. Table I shows θ$_0$ for different distances between elements, d, and different amplitude/phase feeding relation, not taken into account the radiation pattern of the radiating element.

TABLE I. STEERING DIRECTION AND PHASE SHIFTS

		d/λ			
		0.5	**0.6**	**0.7**	**0.8**
a/ b	**β**	**θ$_0$**	**θ$_0$**	**θ$_0$**	**θ$_0$**
0.5	104.5	42.1	34.0	28.6	24.8
0.7	110.5	45.1	36.2	30.4	26.3
1.0	120.0	50.3	39.9	33.4	28.8
1.3	130.5	56.9	44.3	36.7	31.6
1.5	138.6	62.8	47.8	39.4	33.8

Should be noted that when the feeding amplitude is the same for the three elements then it is needed a 120° feeding phase shifts.

IV. NETWORK DESIGNS

Different 3x3 MBFN schemes will be described. Designs will be based on hybrid couplers and fixed phase shifters.

A. Butler Network with odd number of inputs

As Shelton studied in [3], one of the possible Butler matrices may consist of a combination of three coupler circuits and two fixed phase shifters. Figure 5 shows a scheme when uniform amplitude is applied. Two equilibrated coupler and another non equilibrated can be seen. Hereby, if a uniform output power is desired, a coupler non equilibrated (2/3 direct and 1/3 coupled) is needed.

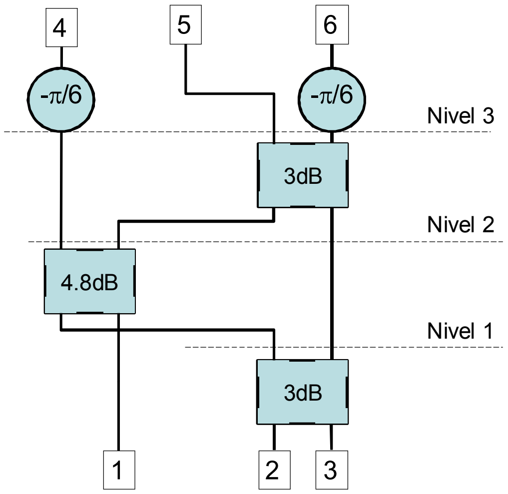


Fig.4: Scheme of a three-port network

Output power distribution will have constant amplitude, 1/3, and relative phase as shown bellow in Table II,

TABLE II. RELATIVE PHASE BETWEEN OUTPUTS

	PO4	PO5	PO6
PI1	0°	-120°	0°
PI2	-120°	0°	0°
PI3	0°	0°	-120°

Taking into account the element radiation pattern and the distance between elements, which is 0.56λ, the radiation pattern coverage is presented in figure 5,

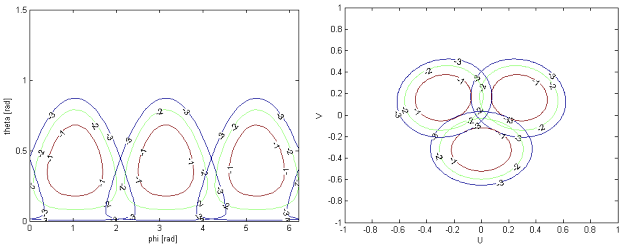


Fig.5: Radiation Pattern Coverage of a cell fed uniform amplitude and 120° relative phase shift

According to Table I, elevation of the main lobe should be about 40° if radiation pattern of the radiating element were isotropic. Since radiation pattern beamwidth of the radiating element is about 60°, elevation angle of the main lobe is reduced, being in this case about 23°.

B. Three-Port Symmetric Network

A rotation symmetric scheme can be set in order to get a perfectly symmetrical behavior between inputs and outputs. Figure 3 shows a scheme of the network with non equilibrated 90° couplers.

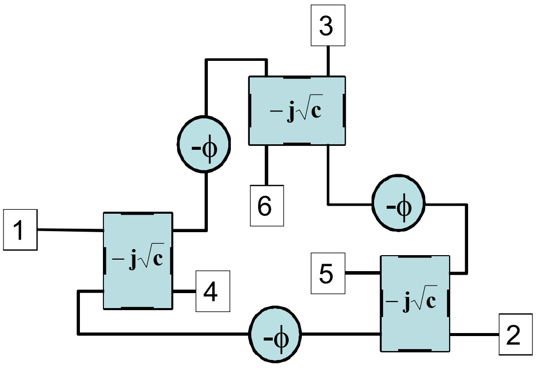


Fig.6: Scheme of a three-port symmetric network

In particular, if we use -3dB hybrid couplers (c=0.5), 20.7° or 159.3° and 45° or 135° phase shifts are obtained. Amplitude and phase relations with their radiation pattern coverage are:

Case a) 0.707_{0° 0.707_{0° $1_{110.7^\circ}$

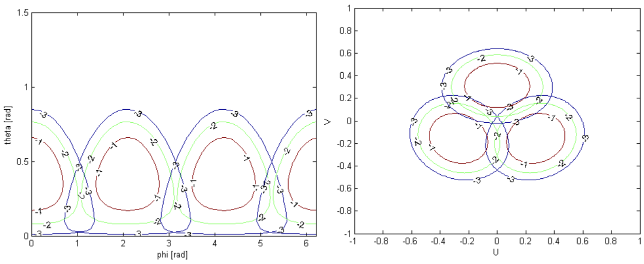


Fig.7a: -1, -2 and -3 dB radiation pattern curves of a cell fed as case a

Case b) 1_{0° 1_{0° 0.707_{-135°

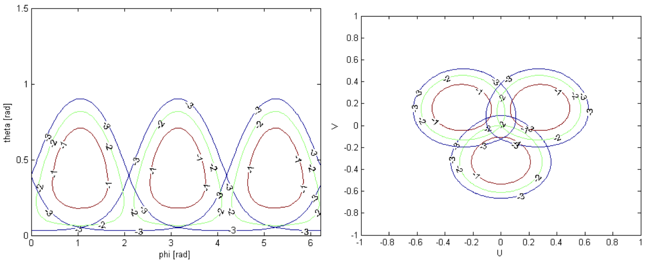


Fig.7b: -1, -2 and -3 dB radiation pattern curves of a cell fed as case b.

The main beam elevation in both cases is about 23°, which is the same as in the previous design.

It could be interesting to study networks that provide us a fourth beam steering to broadside.

C. Scattering Networks with non Orthogonal Pattern

When the number of beams is higher than the number of elements of the array, it is needed to work with scattering networks that have no orthogonal restriction between output vectors.

If we need to get four beams using only a triangular array of three radiating elements, one of which have a normal steering direction to the array and the other three are equidistant with respect to the principal steering direction which have and angle θ_0 respect to the normal direction. In order to get this network we can design a 4x4 Butler matrix loading one of the outputs with the adaptive load as shown in Figure 5.

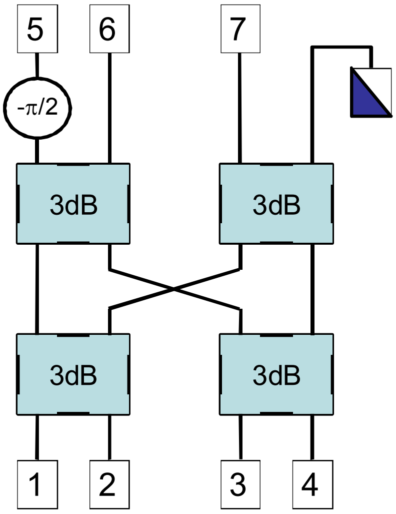


Fig.8: 4x4 Butler matrix

The output power distribution associated to this network is uniform and relative phase shifts as presented in Table III,

TABLE III. RELATIVE PHASE BETWEEN OUTPUTS

	PO5	PO6	PO7
PI1	0º	0º	0º
PI2	0º	0º	180º
PI3	0º	180º	0º
PI4	180º	0º	0º

Relative pattern coverage related to this network is,

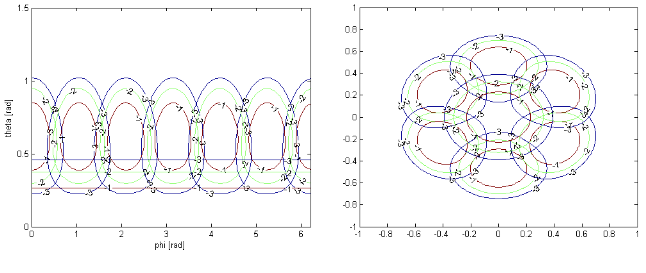


Fig. 9. -1, -2 and -3 dB radiation pattern curves of a cell fed as Table III

The best advantage of this design is that the area covered is much greater than the others presented lately. Inputs 2, 3 and 4 generate a double symmetric beam steering about 36º elevations, which means two main lobules are obtained per those inputs. Furthermore, it is possible to obtain a broadside angle thanks to fed provided by input 1. This network should not be used when a good isolation between coupled pairs beams is needed.

V. BEAM-FORMING NETWORK IMPLEMENTATION

A prototype of a Butler matrix with odd number, shown in figure 5, has been built in microstrip technology. Both, fixed phase shifters and hybrid coupled has been designed in microstrip transmission lines. Figure 9 shows the 3x3 beamforming network board.

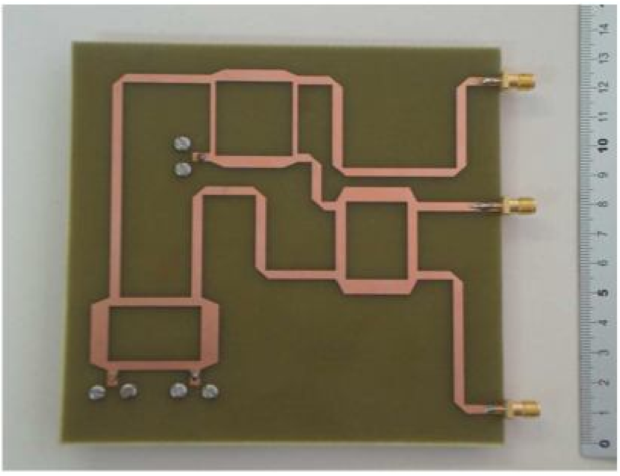
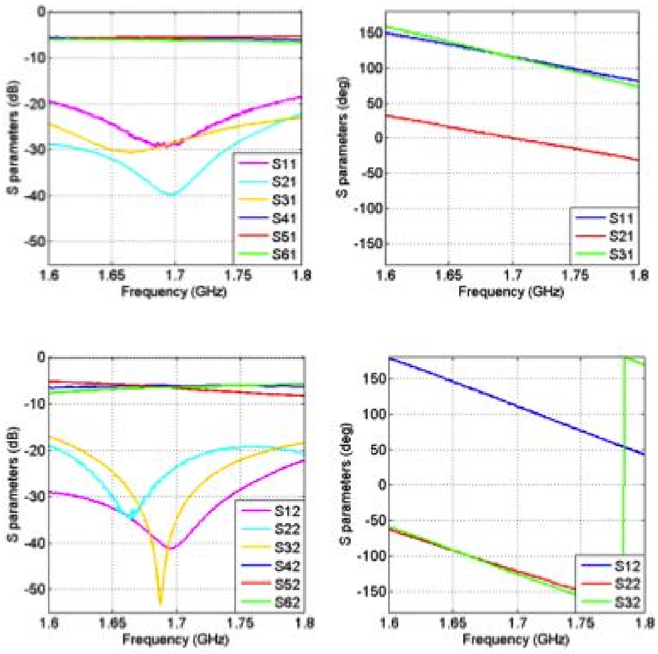


Fig.10: 3x3 odd Butler matrix

VI. BEAM-FORMING NETWORK MEASUREMENTS

Firstly, adaptation and coupling ports are measured. In the figures bellow it is shown the scattering parameters at the output when the beam-forming network is fed by port 1 (a), port 2 (b) and port 3 (c),



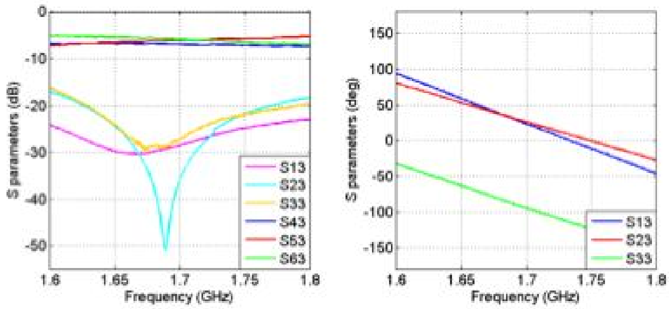


Fig.11: Scattering parameters

As expected, amplitude power at 1.7 GHz is the same for all the three output ports, -6dB. It presents a good adaptation and isolation between ports, better than -20dB. Besides, a 120º phase shift is found as desired.

This network has also been connected to a subarray of three elements, cell, and it has been measured. A spherical compact range has been used to acquire a full field acquisition for the three input ports. The radiation pattern obtained is shown in figure 12 (azimuth) and 13 (elevation).

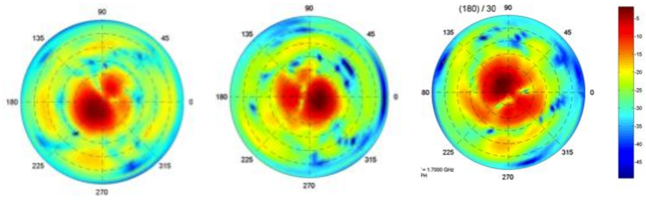


Fig.12: Azimuth radiation pattern

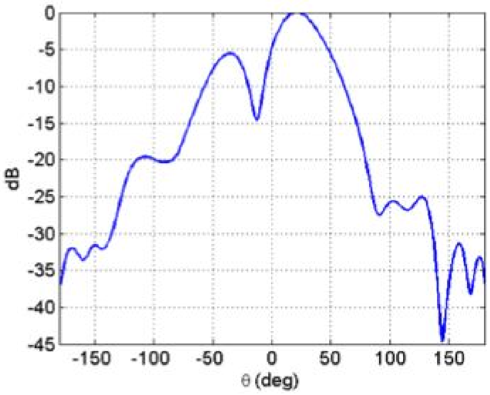


Fig.13: Elevation radiation pattern

As it is seen in figures 12 and 13 a multi-beam forming network has been designed. Steering directions for the three beams are 0º, 120º and 240º azimuth for each of them and 23º elevation grades for the three of them. Thus, radiation patterns obtained are the expected and therefore the implemented network is working properly.

VII. CONCLUSIONS

A general 3 inputs networks study has been presented, showing and analysing different scheme networks designed. Furthermore a 3x3 network has been built and measured successfully, showing behaviour similar to analysis.

VIII. ACKNOWLEDGMENT

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IX. REFERENCES

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