

Study of an Electronic Steering Antenna with a Staggered Phase Shifter Configuration

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Abstract— This paper presents a study of three possible solutions that can be taken into account to control the phase shift between elements in an antenna array. Because commercial digital phase shifters have become a strategic element by U.S. Government, these elements have increased their price. For this reason, it is necessary to adopt some solutions that allow us to deal with the design and construction of antenna arrays.

Keywords - Beam steering; phase shifters; microwave circuits; phased arrays; multi-beam forming networks.

I. INTRODUCTION

In satellite communications or tracking telemetry and control (TT&C) applications, to dispose of a fixed beam, rotation systems are required. The mechanical structure is sensitive to failures and determines scanning speed. Therefore, the need to have an electronic steering that allows the mean beam to be switched arises [1]

In the literature, there are many systems that implement multi-beam networks. Butler Matrix [2] is characterized for using 3 dB and 90° hybrid couplers with fixed phase shifters. There are 2ⁿ inputs/outputs and the same quantity of orthogonal beams. Blass Matrix [3] uses transmission lines and directional couplers which introduce a temporal phase shift, ideal for wide band applications. Wullenweber Array [4] is a circular array that is used in direction of arrival (DoA) outlines. Other fixed networks are Rotman [5] and Luneburg [6] lenses.

As it is explained previously, it is necessary to find alternatives to digital phase shifter devices. Therefore, three possible solutions have been investigated. The first one consists in the construction of our digital phase shifters with switches and transmission lines and it will be shown in Section III. The second one is presented in Section IV expounds a multi-beam switched network. Finally, the last one is a novel proposal design, which mixes previous solutions with a staggered phase shifter configuration, is presented in Section V.

The novel proposal solution can be extrapolated to any array distribution and frequency. The limitation consists in finding commercial devices that work at the desire frequency band and scaling up or down the transmission lines length.

II. ANTENNA SPECIFICATIONS

An example of design, with the specifications shown in Table I, will be presented. The objective is to develop an array antenna system with electronic steering in elevation and azimuth. Additionally, maximum depointing losses are specified as a quality factor.

For this design, six-by-six radiating elements are considered. As seen, the basic array antenna structure is shown in Fig. 1.

TABLE I. ARRAY ANTENNA SPECIFICATIONS

Specification	Value
Horizontal radiating elements	6
Vertical radiating elements	6
Electrical distance between elements	0.5λ
Horizontal scanning	$\pm 50^\circ$
Vertical scanning	0 to 40°
Maximum depointing losses	0.5 dB

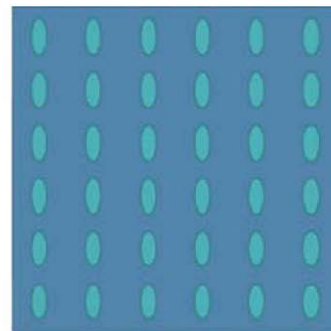


Figure 1. Antenna Array

In phased array antennas, each of the radiating element has a typical transmission/reception (T/R) module like it is shown in Fig. 2.

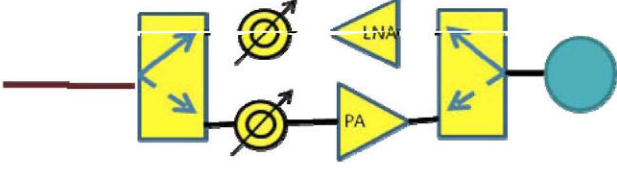


Figure 2. T/R Module

III. DIGITAL PHASE SHIFTERS

Until last year, commercial digital phase shifters were the most used devices because of their reduce size and their wide frequency band. Manufacturers like MA-COM or Hittite supplied components with four or six control bits, with 0° to 360° phase covered and steps of 22.5° (for four bits) and 5.625° (for six bits).

A cheaper solution consists in designing a phase shifter with transmission lines and double-port double-throw (DPDT) switches, as it is illustrated in Fig. 3.

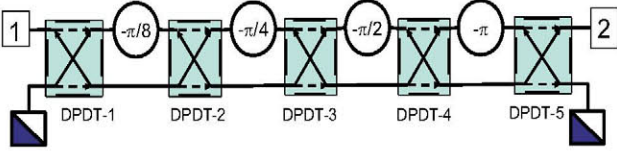


Figure 3. Four bits digital phase shifter

The number of bits corresponds with the number of transmission lines used for phase shift. Other important point is that the phase step decreases when the bits increase and it is related with the maximum steering error. In general, maximum error phase (1).

$$\Delta\phi = \frac{\pi}{2^n}. \quad (1)$$

If the phase error of the radiating elements is random and uniform around the nominal value with a width $\Delta\phi$ [7], then, it is possible to estimate the gain loss in array antenna.

Mean gain loss (2) is presented where ϕ is the phase error of each radiating element.

$$\frac{E\left(|F(\theta_0, \phi_0)|^2\right)}{|F_{\max}|^2} = \frac{E\left(\left|\sum_i \sum_k a_i a_k^* \exp(j(\phi_i - \phi_k))\right|\right)}{\left|\sum_i a_i\right|^2}. \quad (2)$$

If the amplitude of each radiating element is the same, i.e., a_i is equal for all values (3).

$$\frac{E\left(|F(\theta_0, \phi_0)|^2\right)}{|F_{\max}|^2} = \frac{1}{N} + \left(1 - \frac{1}{N}\right) E\left(\exp(j(\phi_i - \phi_k))\right). \quad (3)$$

The phase error is a uniform distribution; accordingly, probability density function (p.d.f.) is a triangular function (4)

$$f(\phi) = \frac{\left(1 - \frac{|\phi|}{\Delta\phi}\right)}{\Delta\phi}; \quad -\Delta\phi < \phi < \Delta\phi \quad (4)$$

Finally, the approximation of gain loss produced by phase error is shown in (5)

$$GL = 1 - \left(1 - \frac{1}{N}\right) \frac{\Delta\phi^2}{2} \cong 1 - \frac{\Delta\phi^2}{2} \quad (5)$$

Table II compiles the relation between gain loss and number of bits in the phase shifter.

TABLE II. GAIN LOSS VERSUS NUMBER O BITS

Bits	Maximum Error Phase	Gain Loss (dB)
3	$\pi/4$	1.6
4	$\pi/8$	0.34
5	$\pi/16$	0.07
6	$\pi/32$	0.02

According with Table II, it will be necessary at least four bits to fulfill a gain loss equal or less than 0.5 dB.

IV. MULTIBEAM SWITCHED NETWORK

Radiation pattern, with elevated radiation elements, is approximately the array factor (AF) (6) and the visible region (7) where the phases α_x and α_y are the differential phases between consecutives radiating elements on each axis. The angles (θ_0, ϕ_0) are the steering direction.

$$F(\theta, \varphi) = \frac{1}{36} \frac{\sin(3\psi_x)}{\sin(\psi_x/2)} \frac{\sin(3\psi_y)}{\sin(\psi_y/2)} \cos^m(\theta) \quad (6)$$

$$\begin{aligned} \psi_x &= \pi \sin(\theta) \cos(\varphi) + \alpha_x \\ \psi_y &= \pi \sin(\theta) \sin(\varphi) + \alpha_y \end{aligned} \quad (7)$$

For this case, with Butler Matrix, the number of inputs matches with the number of different beams synthesized and

determines the radiation pointing angles in elevation and azimuth.

A reduction of depointing loss involves a close direction beams, therefore, it prevents the orthogonality condition for multi-beam lossless networks [2].

With a simulation in MatLab and considering (6) and scanning angles shown in Table II, it is possible to determine the minimum number of beams required. Table III presents positive beams because negative ones are symmetrical.

TABLE III. PROGRESSIVE BEAM PARAMETRES

Steering (°)	Feeding (°)	Band Width 3 dB (°)	Band Width 0.5 dB (°)	Error (°)
0	0	16.8	7.0	0
7	-21.9	17.0	7.2	0.3
14.2	-44.1	17.3	7.4	0.6
21.5	-66.0	17.9	7.7	1.0
29.3	-88.1	18.9	8.5	1.6
37.7	110.0	20.4	9.7	2.6
47.2	132.0	22.7	12.3	4.1

It is enough to use fourteen beams to cover $\pm 50^\circ$ azimuth scanning with feeding steps of 22° . It is considered a power of two to simplify the sketch, in this case, sixteen beams.

With sixteen beams, the progressive phase step is $2\pi/16$, i.e., 22.5° ; approximately that is what is needed to form planned beams. It is possible to work with a 16-by-16 Butler Matrix. As described by H.J.Moody [8], sixteen Butler Matrix is presented in Fig. 4.

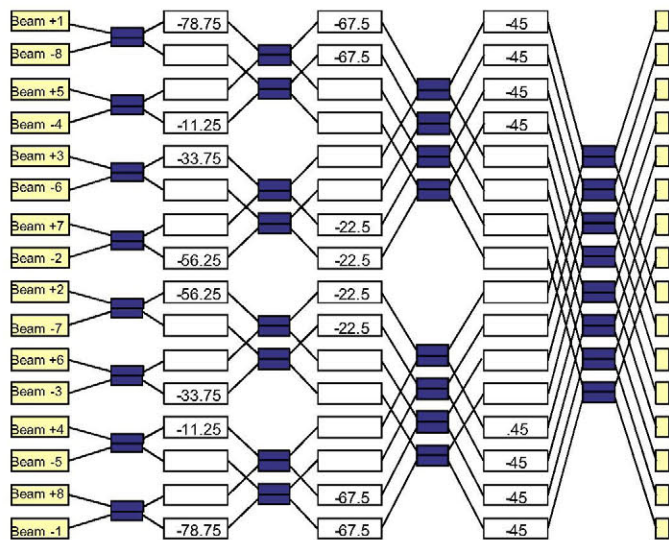


Figure 4. 16-by-16 Butler Matrix

The blue boxes are hybrids with a phase difference of 90° between its outputs and 3 dB power splitter. The white boxes are fixed delay lines in degrees. Finally, the number of beams are on the left and outputs/radiating elements are on the right.

Only six (radiating elements in a row or column) of sixteen possible output will be used and the other ones will be matched (Fig. 5).

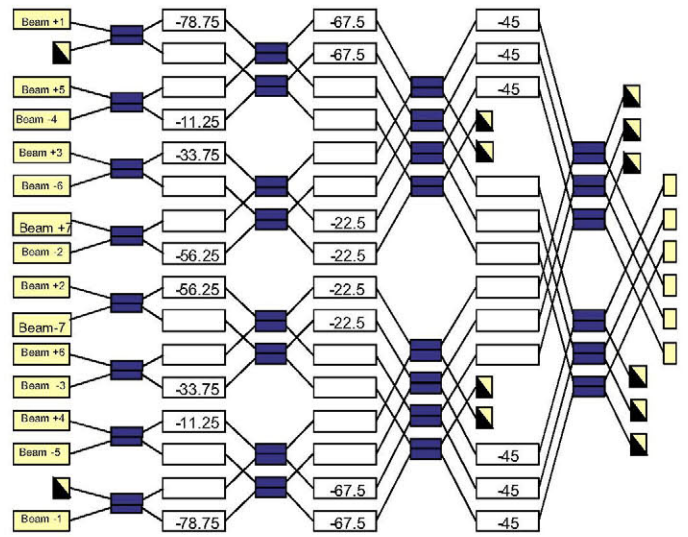


Figure 5. Horizontal network diagram

As expected, all the beams synthesized are close and reduce depointing losses. The simulation corresponding to Fig. 5 is shown in Fig. 6. As can be seen, fourteen beams are together and as shown in enlargement of Fig. 6, the value of the crossing points between beams is around 0.4 dB (Fig. 7), better than 0.5 dB specified in Table I

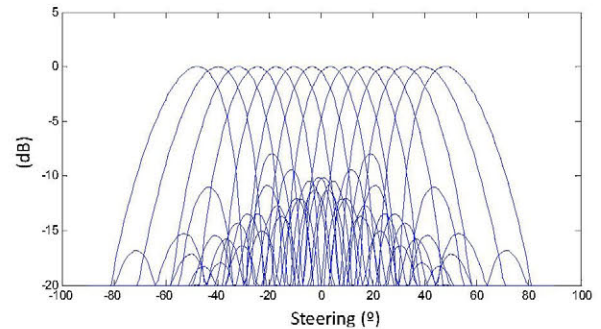


Figure 6. Fourteen beams and six radiating elements

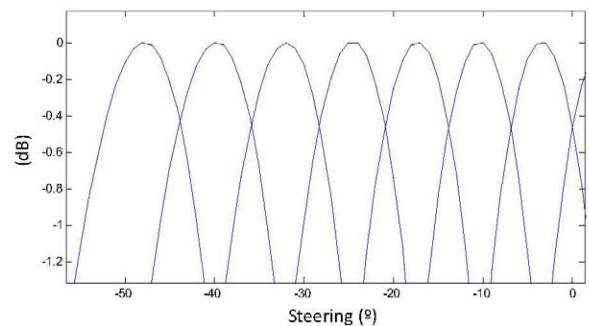


Figure 7. Crossing point detail

Until now, it deals with horizontal diagram. The solution for the vertical diagram is easier because scanning angles are

lower than azimuth requires. According with Table III, the number of beams necessary to cover 0° to 40° is positive five (Fig. 8).

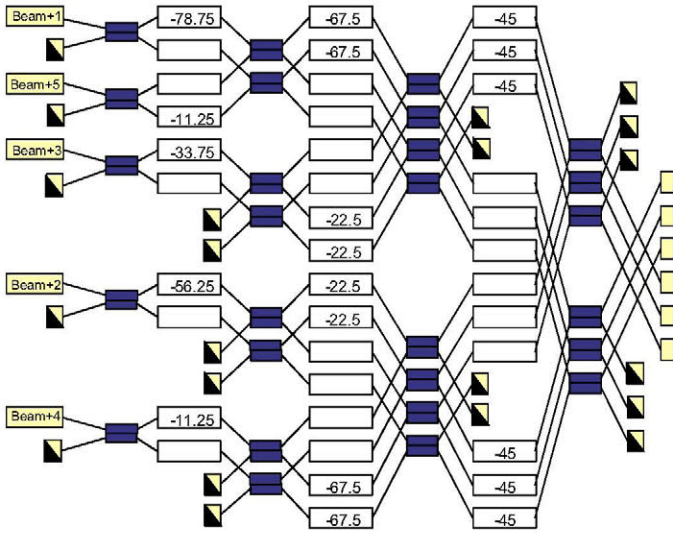


Figure 8. Vertical network diagram

The main problem is that if the antenna size increases, the network becomes more complex with the possibility of line crossings.

V. STAGGERED PHASE SHIFTER CONFIGURATION

As a general rule, networks with phase shifters hold digital control near the radiating elements, while Butler matrix has the control before power splitter networks.

The implemented solution covers both cases offering a greater versatility because it can fit the antenna structure. The principal idea is to establish a relative phase between elements.

For this purpose, the antenna is divided into a modular system with nine sub-arrays of 2-by-2 radiating elements. The idea is to make a phase shift within each sub-array and then execute an appropriate combination of sub-arrays signals.

According to the sub-array design and similar synthesis with sixteen beams that was shown in the preceding Section with the cross point at 0.5 dB, the differential phases are: $\pm\pi/16$, $\pm3\pi/16$, $\pm5\pi/16$, $\pm7\pi/16$, $\pm9\pi/16$, $\pm11\pi/16$, $\pm13\pi/16$ and $\pm15\pi/16$. With these phases a device with 0° to 360° cover and steps of 22.5° is obtained.

With the diagram illustrated in Fig. 9 this purpose is achieved.

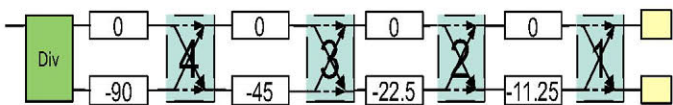


Figure 9. Switching between two consecutive radiating elements

For a complete sub-array, the network uses three phase shifters like it is shown in Fig. 9. In this way, the commutation of rows and columns is controlled as it is presented by Fig. 10.

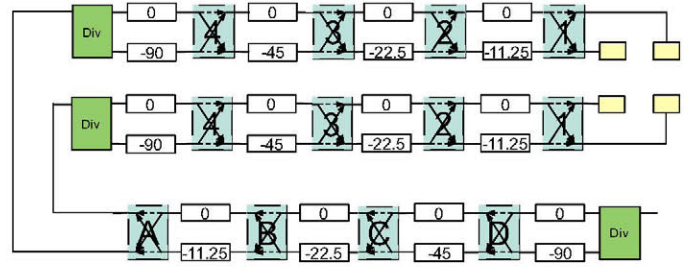


Figure 10. Switching between sub-array's radiating elements

Now, the objective is to govern sub-arrays phases. The complete antenna has 3-by-3 sub-arrays, then, it is necessary to have a network with one input and three outputs (one for each column of antenna). This time, the needed progressive phases are $\pm2\pi/16$, $\pm6\pi/16$, $\pm10\pi/16$, $\pm14\pi/16$, $\pm18\pi/16$, $\pm22\pi/16$, $\pm26\pi/16$ and $\pm30\pi/16$. In addition, it can be simplified because, e.g., $30\pi/16$ is the same phase than $-2\pi/16$. In terms of the delays associated to positive phases, those depend on the reference phase which is equal to the sum of all phases. In this way, the design with transmission lines is guaranteed, as it is shown in Fig. 11.

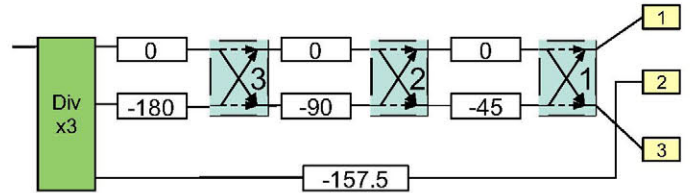


Figure 11. Switching between sub-array

In this case, the cover goes from -180° to 180° with 45° steps because it has three bits of control.

VI. IMPLEMENTED DESIGN

The case developed throughout Section V is the proposal solution using commercial devices for the construction.

A. Hybrids: 3 dB and 90°

The principal advantage is its reduced size. A lower insertion loss (0.5 dB), great isolation (25 dB), and unbalance phase of $\pm1^\circ$, make hybrid an important device.

B. Swithes DPDT

As well as hybrids their operation is good, with 0.4 dB of insertion loss and rough isolation of 20 dB.

C. Relative differential phases

The delays are generated with transmission lines of an appropriated length (related to the working frequency) to obtain desired delays. The transmission lines are designed with microstrip technology.

D. Sub-array's radiating elements

As shown in Fig. 12, the circuit has one input and two outputs, with four DPDT, transmission lines and hybrid.

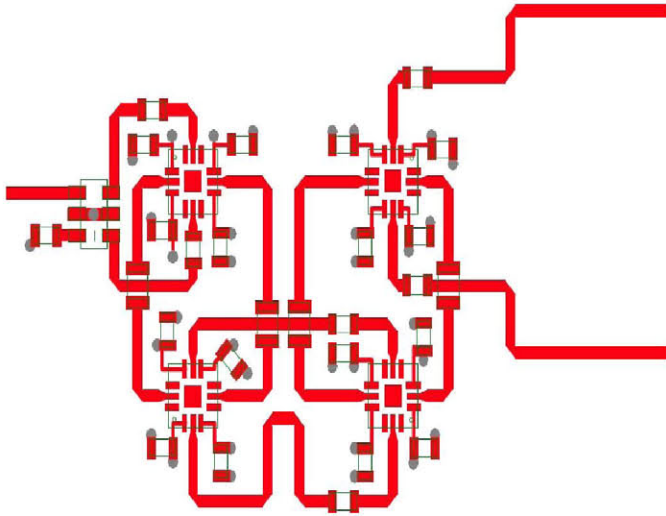


Figure 12. Switching between sub-array's radiating elements

E. Sub-arrays

As shown in Fig. 13, the circuit has one input and three outputs, with three DPDT, transmission lines and hybrids.

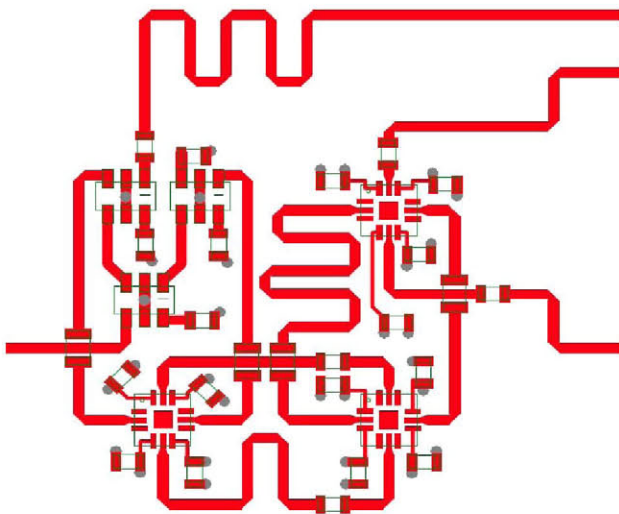


Figure 13. Switching between sub-array's radiating elements

F. Advantage and drawback

The most important advantage is getting a low cost staggered phase shifter configuration that adapts to any antenna structure. Besides, it includes splitter/combination power into the phase shifter network.

The main drawback is the size compared to the devices that previously supplied.

VII. CONCLUSIONS

Three possible alternatives to the digital phase shifter chips have been presented. A discrete phase shifter and Butler matrix have been analyzed. Finally, the proposal solution mixed the other two into a staggered phase shifter configuration so that includes the power splitting and phase shifter networks.

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