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A SCHEMATIC FOR BROADBAND BEAM FORMATION USING TIME-DELAY TECHNIQUE

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Abstract—Simultaneous multiple beam generation by phased array antennas have great importance in recent time, e.g., multiple access satellite communication systems, MIMO (multiple input and multiple output), target tracking radars etc. Here in this article a novel yet simple wideband multiple beam formation network (BFN) has been proposed. Unlike the conventional phase shifter based system, this scheme is based on true time-delay units which is potential for wideband application.

1. INTRODUCTION

One of the most important tasks in a phased array antenna design is designing the beam forming network (BFN). In particular, for a multiple-beam array, designing an appropriate BFN is essential in order to distribute (combine) the signals to the radiating ports. The simplest type of beam former utilizes power dividers, power combiners and phase shifters etc. Multiple beamformer is used where the antenna array needs to transmit multiple beams simultaneously in prefixed directions.

For understanding the principle of multiple beamforming, here one basic BFN having multiple beams is briefly explained with the help of Fig. 1. Suppose the BFN produces four simultaneous beams $V1$, $V2$, $V3$ and $V4$ corresponding to the feeds at beam port respectively. Necessary condition to generate these multiple beams is that, the beams must be mutually orthogonal is mentioned later in this section.

Let us consider the excitation weight vectors at the array port are $[w_1, w_2, w_3, w_4]$, $[x_1, x_2, x_3, x_4]$, $[y_1, y_2, y_3, y_4]$ and $[z_1, z_2, z_3, z_4]$ corresponding to beams $V1, V2, V3$ and $V4$ respectively.

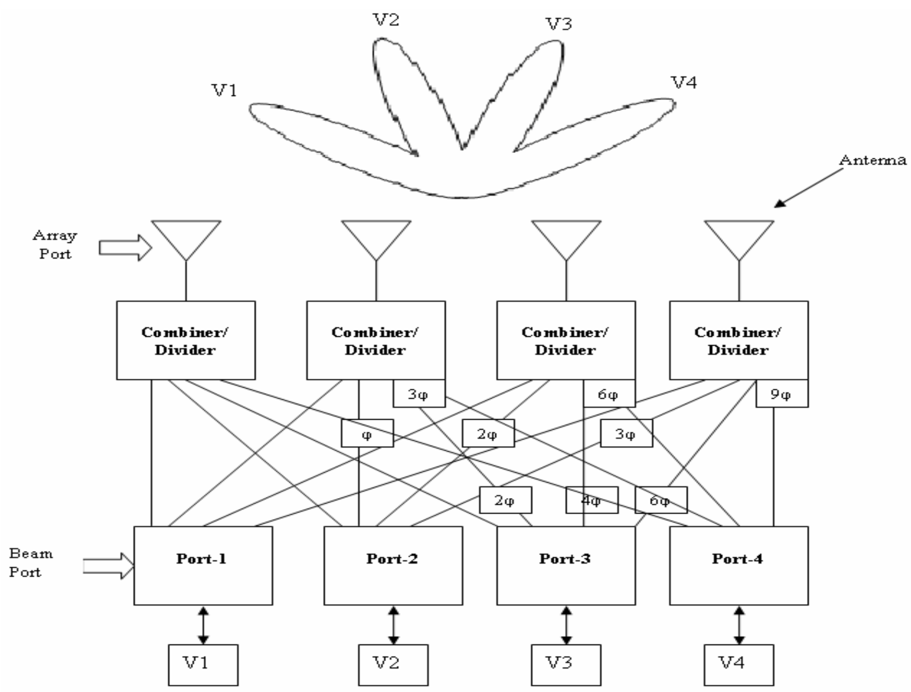

Figure 1. Basic beam forming network.

The beams will be mutually orthogonal if it satisfies the following condition.

$$\sum_{i=1}^{4} w_i x_i* = \sum_{i=1}^{4} w_i y_i* = \sum_{i=1}^{4} w_i z_i * \ldots = 0 \tag{1}$$

Without any loss of simplicity, excitation vectors at each beam port can be expressed by the Eq. (2) to Eq. (5) considering their amplitude as uniform.

$$[w_1, w_2, w_3, w_4] = [1, \exp(-j\phi_w), \exp(-j2\phi_w), \exp(-j3\phi_w)] \quad (2)$$
$$[x_1, x_2, x_3, x_4] = [1, \exp(-j\phi_x), \exp(-j2\phi_x), \exp(-j3\phi_x)] \quad (3)$$
$$[y_1, y_2, y_3, y_4] = [1, \exp(-j\phi_y), \exp(-j2\phi_y), \exp(-j3\phi_y)] \quad (4)$$
$$[z_1, z_2, z_3, z_4] = [1, \exp(-j\phi_z), \exp(-j2\phi_z), \exp(-j3\phi_z)] \quad (5)$$

where ϕ_w is the phase difference between the adjacent antenna elements for beam $V1$. Similarly, ϕ_x, ϕ_y and ϕ_z are the phase difference for the other three constituent beams, $V2, V3, V4$ respectively.

It can be shown [1] that, putting these values of excitation vectors in Eq. (1) generates the criteria for orthogonality, as followed by Eq. (6) to Eq. (8).

$$\phi_x = \phi_w + \frac{1}{2}\pi \quad (6)$$
$$\phi_y = \phi_w + \pi \quad (7)$$
$$\phi_z = \phi_w + \frac{3}{2}\pi \quad (8)$$

It is clear form the above formulations that, for the four beam case, the phase gradient between any two beam ports is $\frac{\pi}{2}$. More generally, for N numbers of orthogonal beams, the phase difference between any two consecutive ports is $\frac{2\pi}{N}$. It can be implemented by phase shifters, power divider/power combiner etc. but simple beam forming increases the size of the array antenna.

Few important factors are to be considered while designing a BFN; are RF loss, size, bandwidth, cost, complexity etc. Various research papers [2–13] and [17–27] are dedicated for single beam and multiple beamforming methods. Among them one of the most popular method is Butler matrix [2] beam former (after J. L. Butler, 1961), which reduces the number of elements in the beam forming network and generates multiple orthogonal beams. Actually it reduces the number of phase shifters by exploiting equivalent analog FFT algorithm. But as the Butler matrix uses phase shifters, which restricts it in the use for wideband application. In [3] and [4] Butler matrix is respectively modified for high power and low power application. Previously wideband Blass matrix [5] uses a set of transmission lines which intersects a set of beam port lines, with a directional coupler at each intersection. But it is lossy and bulky in size due to large number of directional coupler and repeated use of transmission lines. In [6] Blass matrix has been modified systematically to reduce power loss. There are several digital beam forming techniques [7–13], which mainly discuss adaptive beamforming.

Here in this communication, a phase-shifterless schematic is explained for the purpose of orthogonal beam formation. Instead of using phase-shifter, time delay units (delay lines) are judiciously exploited in order to make the system bandwidth efficient and less complex.

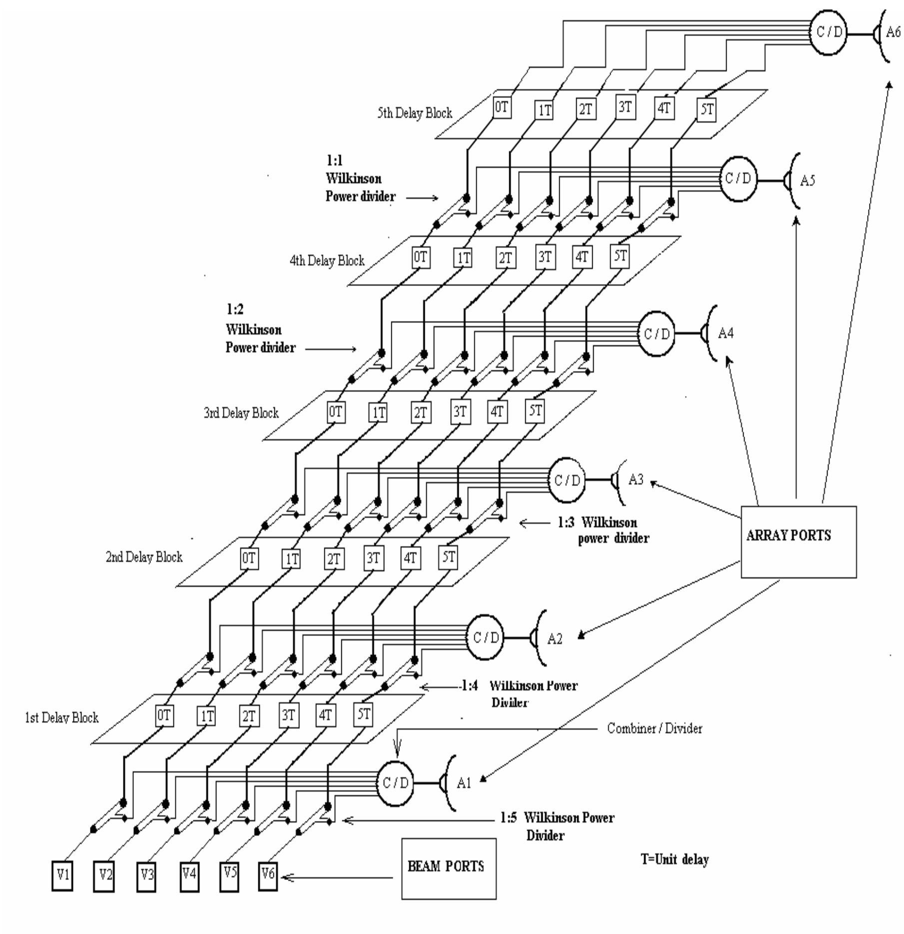

Figure 2. Schematic of multiple beam forming network using delay lines.

2. IMPLEMENTATION WITH TIME DELAY

Consider a linear array of six (6) isotropic radiating elements ($A1 - -A6$) fed by six different signals ($V1$, $V2$, $V3$, $V4$, $V5$ & $V6$) to the beam ports in the transmitting mode as shown in the Fig. 2.

Conventionally, signals fed in each port are to be equally subdivided into numbers of antenna elements so that they can be fed to the each array element. According to the orthogonality criteria (derived in the previous section), the phase difference between the equally divided signals in each port must be $2\pi/6$ and also the same is true for in-between any two ports.

Unlike the phase-shifters, delay line of unit delay T is chosen (calibrated) to provide phase difference of $\pi/3$. In Table 1, the required delays (in terms of unit delay T) for the antenna elements are given in matrix form.

Table 1. Required delays for multiple beam formation.

Unit delay $T = \pi/3$

Beam port	**Signal Power**	**Antenna Elements**					
		$\boldsymbol{A}1$	$\boldsymbol{A}2$	$\boldsymbol{A}3$	$\boldsymbol{A}4$	$\boldsymbol{A}5$	$\boldsymbol{A}6$
1	$\boldsymbol{V}1$	$0\,T$	$0\,T$	$0\,T$	$0\,T$	$0\,T$	$0\,T$
2	$\boldsymbol{V}2$	$0\,T$	$1\,T$	$2\,T$	$3\,T$	$4\,T$	$5\,T$
3	$\boldsymbol{V}3$	$0\,T$	$2\,T$	$4\,T$	$6\,T$	$6\,T$	$10\,T$
4	$\boldsymbol{V}4$	$0\,T$	$3\,T$	$6\,T$	$9\,T$	$9\,T$	$15\,T$
5	$\boldsymbol{V}5$	$0\,T$	$4\,T$	$8\,T$	$12\,T$	$12\,T$	$20\,T$
6	$\boldsymbol{V}6$	$0\,T$	$5\,T$	$10\,T$	$15\,T$	$15\,T$	$25\,T$

It is obvious from the above table that, realization using time delay requires long section of delay lines which may make the system bulky and lossy.

Hence in this proposition, instead of equally subdividing the power at the beam port, they are unequally divided into suitable power ratios and then passed through the delay lines $0\,T$, $1\,T$, $2\,T$, $3\,T$, $4\,T$, $5\,T$ and $6\,T$ (for six elements), so that each antenna element gets the share of 1/6 of power from each beam port, as depicted in Fig. 2. At first, using 1 : 5 power divider, 1/6 of the power from all the beam ports are fed to the antenna element-$A1$ and remaining 5/6 power is passed to the 1st delay block. After passing through the 1st delay block the power is now divided into 4 : 1 ratio, where 1/5 power (of 5/6) is fed to the antenna $A2$ and remaining 4/5 power is passed to the 2nd delay block. In this way, before reaching the 5th element the power is equally (3 dB) divided into two parts, one is fed to the 5th element and other is to 6th element. Here, Wilkinson divider [14–16] is proposed for unequal power division as they have better port to port isolation and provide zero (0) degree phase difference between through port and coupled port. Moreover it is simple to design and shows broadband property in operating frequency range. Finally, power from all the beam ports with different phase shift are combined to provide multiple beams in the space. The same is also valid for receiving antenna, where Wilkinson power dividers acts as an asymmetric combiner who combines the power is coming from two arms. As a result, the signal powers impinging from different prefixed direction are collected by the beam ports. In the array port combiners are replaced by the dividers.

3. RESULTS

Justification of the proposed scheme is shown by the results obtained in the Matlab© simulation. Simulation is performed for six beam ports and an array of six antenna elements. The radiation pattern by the array is shown in Fig. 3.

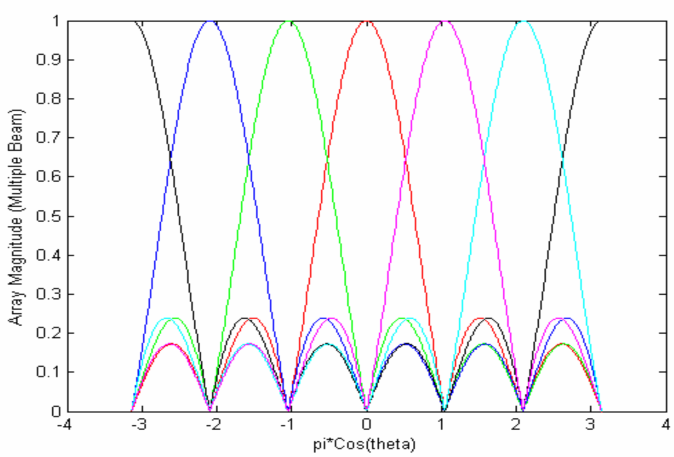

Figure 3. Array pattern for six individual sources.

Signals fed (received) from (to) all the ports simultaneously generates multiple beams as shown by the normalized scalloped pattern in Fig. 4.

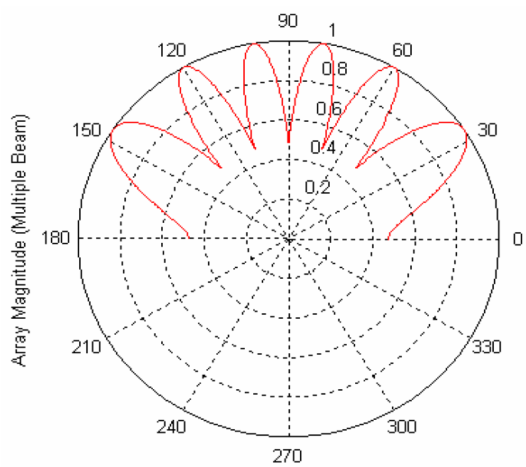

Figure 4. Scalloped pattern (polar plot).

4. PERFORMANCE OF DELAY LINE TECHNIQUE AND CONCLUSION

For a long time, Butler matrix realized with phase shifters has been widely used for analog beam formation. But as said earlier the phase shifters are inherently narrowband and so this matrix is not suitable for broadband operation.

Though the proposed scheme is comparatively bulky with respect to the Butler matrix but its main advantage is that, delay lines made with phase shifter compensate with varying frequency and does not shifts the main beam direction, or suitable for wideband application.

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