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Phase-Controlled Beamforming Network for Continuous Beam-Steering in Conformal Arrays

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Abstract

This paper describes a reconfigurable beamforming network that can be connected to a four-element circular array to perform continuous beam-steering on the azimuthal plane of the array. The network, which consists of a four-way power divider, four 90° hybrid junctions, two 90° fixed phase shifters and four variable phase shifters, is able to feed each couple of adjacent radiating elements with arbitrary power ratios, without spoiling the matching conditions of the other ports. That way, the maximum of the radiation pattern can be steered arbitrarily on the azimuthal plane only by varying the phases of the variable phase shifters of the network.

1 Introduction

With the advent of next-generation wireless telecommunication standards, phased arrays are attracting a renewed attention [1]. Besides their traditional application areas, ranging from avionics to satellite communications, phased arrays are currently finding application even in terrestrial telecommunications. Indeed, with the adoption of millimeter-wave frequencies, antenna arrays can be used not only in base-station front-ends, but also in hotspots and mobile devices [3], [5]. Planar and conformal phased-arrays can be used to steer the beam toward the desired recipients, thereby reducing interference and improving the throughput with space-division multiple-access techniques.

However, to develop low-power antenna topologies able to achieve long-range communications, the feed networks must be designed to reconfigure beams without degrading the signal level, which can be achieved increasing power transmission efficiency and reducing mismatch loss. The latter aspects are particularly challenging, especially if not only the phase, but also the magnitude of the array excitations must be changed over time. Magnitude weighting, which is used in linear arrays to perform side lobe reduction and beam shape control, is essential in conformal arrays, where it allows also for beam-steering [2]. Magnitude weighting is usually achieved using attenuators/amplifiers, although they introduce losses in the circuit and can compromise the port matching when high power ratios must be achieved.

In this paper a 1×4 feed network is proposed, which can be used to perform beam steering on the azimuthal plane of a conformal array. The network was firstly presented in [4], where, however, it was used either to activate single output ports or couples of adjacent output ports with in-phase equal-magnitude signals. Here, the proposed network is used to activate couples of adjacent output ports with arbitrary power ratios. In Sec. 2 the network is theoretically analyzed; then, in Sec. 3 the simulated radiation patterns obtained feeding a four-element circular array with the proposed matrix are shown and discussed, and, finally, the conclusions are drawn.

2 Feed network

The feed network consists of one four-way power divider, four variable phase shifters, two fixed 90° phase shifters and four 90° hybrid couplers, connected as shown in Fig. 1 (see also [4]).

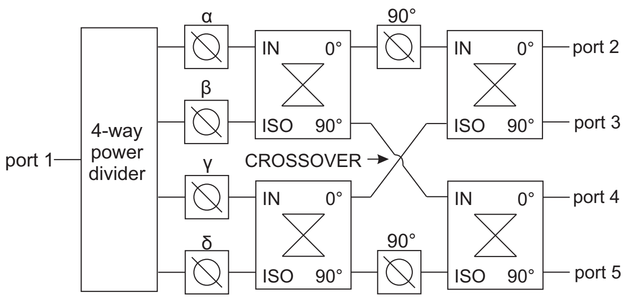

Figure 1. Schematic of the proposed feed network.

A wave incident at port 1 is divided in four equal parts. Each part is then phase shifted by α, β, γ and δ, respectively. The four signals are then further divided in four parts, where each of them is phase shifted depending on its path inside the network, and is routed to a different output port. Therefore, each wave emerging at the ports 2, 3, 4 and 5 of the network is the result of the combination of four complex terms, where each of them depends on α, β, γ and δ, respectively. Under the hypothesis of ideal circuit components, the transmission coefficients of the network can be expressed as follows:

$$S_{21} = \frac{1}{4}\left(-je^{-j\alpha} - e^{-j\beta} - je^{-j\gamma} - e^{-j\delta}\right) \quad (1)$$

$$S_{31} = \frac{1}{4}\left(-e^{-j\alpha} + je^{-j\beta} + e^{-j\gamma} - je^{-j\delta}\right) \quad (2)$$

$$S_{41} = \frac{1}{4}\left(-je^{-j\alpha} + e^{-j\beta} + je^{-j\gamma} - e^{-j\delta}\right) \quad (3)$$

$$S_{51} = \frac{1}{4}\left(-e^{-j\alpha} - je^{-j\beta} - e^{-j\gamma} - je^{-j\delta}\right). \quad (4)$$

We will show that by varying the phase values assumed by the four variable phase shifters, i.e., α, β, γ and δ, the network can activate each couple of adjacent output ports with arbitrary power ratios, without spoiling the matching conditions of the other ports and maintaining in-phase output signals. It is worth mentioning that, since the network is thought for a circular array, port 2 is adjacent to port 5. Therefore, four couples of adjacent output ports can be identified: ports 2-3, ports 3-4, ports 4-5 and port 2-5.

To ease the analysis auxiliary phase variables are defined as follows:

$$x = \alpha - \beta, \quad (5)$$

$$y = \gamma - \delta, \quad (6)$$

$$z = \alpha - \gamma. \quad (7)$$

The squared magnitudes of the transmission coefficients can be expressed as follows:

$$|S_{21}|^2 = \frac{1}{4} + \frac{1}{8}(a+b) \quad (8)$$

$$|S_{31}|^2 = \frac{1}{4} + \frac{1}{8}(a-b) \quad (9)$$

$$|S_{41}|^2 = \frac{1}{4} + \frac{1}{8}(-a+c) \quad (10)$$

$$|S_{51}|^2 = \frac{1}{4} + \frac{1}{8}(-a-c), \quad (11)$$

where

$$a = \sin(x) + \sin(y) \quad (12)$$

$$b = \cos(z) + \sin(z+y) - \sin(z-x) + \cos(z+y-x) \quad (13)$$

$$c = -\cos(z) + \sin(z+y) - \sin(z-x) - \cos(z+y-x). \quad (14)$$

For simplicity, all phase values are reported in the range $[0°, 360°]$.

It can be shown that to activate port 2 and 3, the auxiliary variables must satisfy the following conditions:

$$x = y = 90°, \quad (15)$$

$$0° < z < 180°, \quad (16)$$

where for $z = 0°$ all power is transmitted to port 2, i.e., $|S_{21}|^2 = 1$ and $|S_{31}|^2 = 0$, for $z = 90°$ the power incident at port 1 is equally divided between the two ports, i.e., $|S_{21}|^2 = |S_{31}|^2 = 0.5$, and for $z = 180°$ all power is transmitted to port 3, i.e., $|S_{21}|^2 = 0$ and $|S_{31}|^2 = 1$. The square magnitude of the transmission coefficients of the network versus z under conditions (15) and (16) are shown in Fig. 2(a). It is worth noticing that arbitrary power ratios can be obtained and that the sum of all transmission coefficients is equal to 1 for all z values. Additionally, as long as (16) is valid, the signals at port 2 and 3 are in phase regardless of their power ratio.

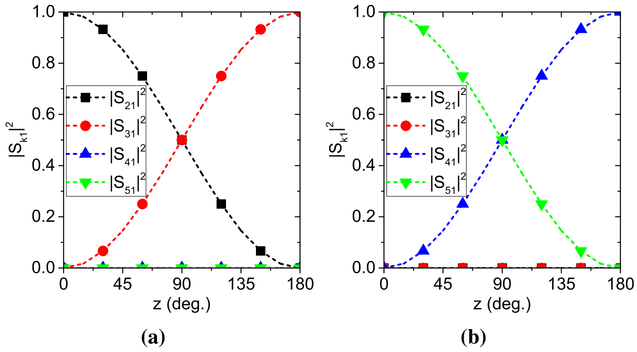

Figure 2. Squared magnitude of the transmission coefficients (a) in case port 2 and 3 are activated, and (b) in case ports 4 and 5 are activated, versus z.

To activate port 4 and 5, the following conditions must be satisfied:

$$x = y = 270°, \quad (17)$$

$$0° < z < 180°. \quad (18)$$

The square magnitude of the transmission coefficients of the network versus z under conditions (17) and (18) are shown in Fig. 2(b). For $z = 0°$ all power is transmitted to port 5, i.e., $|S_{41}|^2 = 0$ and $|S_{51}|^2 = 1$, for $z = 90°$ the power incident at port 1 is equally divided between the two ports, i.e., $|S_{41}|^2 = |S_{51}|^2 = 0.5$, and for $z = 180°$ all power is transmitted to port 4, i.e., $|S_{41}|^2 = 1$ and $|S_{51}|^2 = 0$.

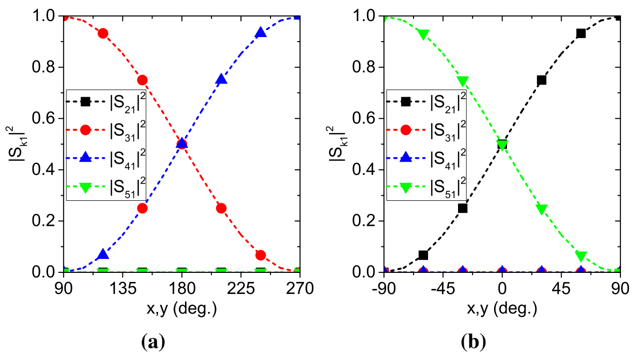

Figure 3. Squared magnitude of the transmission coefficients (a) in case port 3 and 4 are activated, and (b) in case ports 2 and 5 are activated, versus x, y.

In case ports 3 and 4 are activated, the following conditions apply:

$$z = 180° \tag{19}$$
$$90° < x = y < 270°. \tag{20}$$

The transmission coefficients versus x, y are shown in Fig. 3(a). Port 1 and 5 are deactivated, while ports 3 and 4 exhibit arbitrary power ratios. For $x = y = 90°$ all power is transmitted to port 3, i.e., $|S_{31}|^2 = 1$ and $|S_{41}|^2 = 0$, for $x = y = 180°$ the power incident at port 1 is equally divided between the two ports, i.e., $|S_{31}|^2 = |S_{41}|^2 = 0.5$, and for $x = y = 270°$ all power is transmitted to port 4, i.e., $|S_{31}|^2 = 0$ and $|S_{41}|^2 = 1$.

Finally, to activate ports 2 and 5, the following conditions are implemented:

$$z = 0° \tag{21}$$
$$270° < x = y < 90°. \tag{22}$$

The graph in Fig. 3(b) shows how the signals at ports 2 and 5 vary with x, y. To simplify the graph drawing x, y are represented in the interval $[-90°, 90°]$. For $x = y = 270°$ (corresponding to $-90°$) all power is transmitted to port 5, i.e., $|S_{21}|^2 = 0$ and $|S_{51}|^2 = 1$, for $x = y = 0°$ the power incident at port 1 is equally divided between the two ports, i.e., $|S_{21}|^2 = |S_{51}|^2 = 0.5$, and for $x = y = 90°$ all power is transmitted to port 2, i.e., $|S_{21}|^2 = 1$ and $|S_{51}|^2 = 0$.

Therefore, it is demonstrated that all couples of adjacent output ports of the feed network can be activated with arbitrary power ratios only by changing the phase of the variable phase shifters.

3 Proposed Antenna System

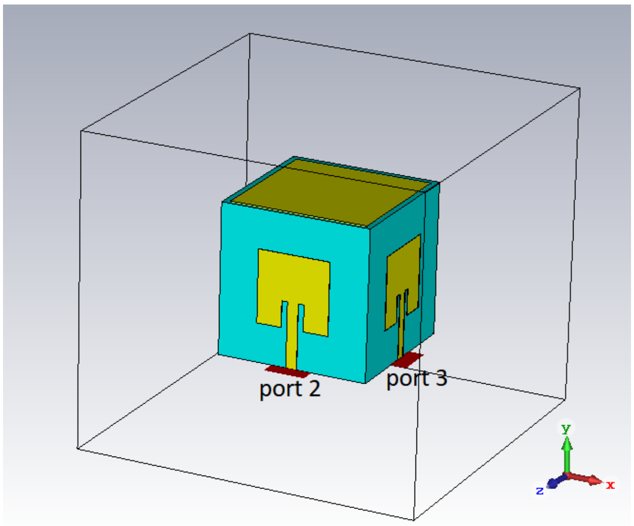

Figure 4. 3D model of the proposed antenna topology.

The feed network described in Sec. 2 can be connected to a four-element conformal array to perform beam-steering. The array considered in this section is composed by four elements arranged on the lateral sides of a cube. The 3D model of the proposed antenna topology is shown in Fig. 4. Without loss of generality, four resonant patch antennas are utilized. The distance between each couple of antennas is lower than one wavelength at the operating frequency.

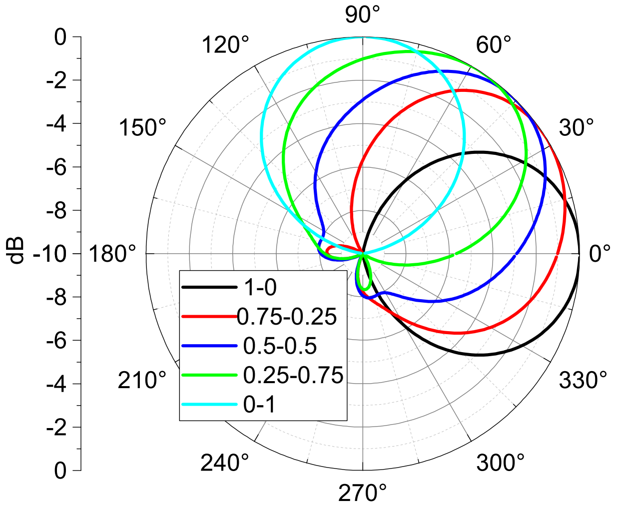

Figure 5. Radiation patterns obtained feeding ports 2 and 3 with signals characterized by equal phase and varying power ratios (in the legend, the first number refers to $|S_{21}|^2$, the second to $|S_{31}|^2$).

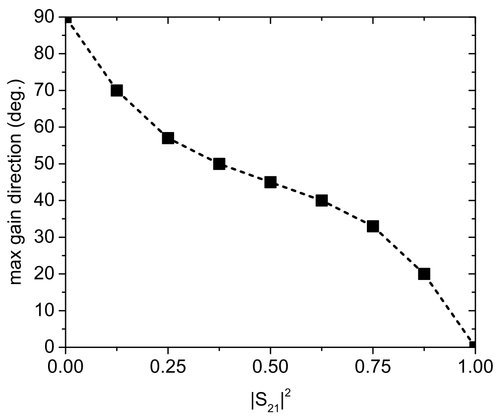

Figure 6. Angular direction of the maximum gain versus $|S_{21}|^2$.

Fig. 5 shows the simulated H-plane radiation patterns obtained feeding two adjacent ports of the antenna topology with signals characterized by equal phase and varying power ratios (as an example, ports 2 and 3 are chosen). To obtain the excitations corresponding to the reported radiation patterns, x and y must satisfy (15), while z must assume the following values: 0°, 60°, 90°, 120°, 180°. The radiation patterns are normalized with respect to the maximum gain obtained with the excitation "$1-0$" (marked in black in Fig. 5). Approximately the same gain is obtained for all excitations. As the power ratio between the signals at the two activated ports changes, the direction of the maximum gain sweeps out a quarter of the azimuthal plane. Therefore, activating all four adjacent couples of radiating elements with different power ratios all azimuthal plane can be covered and the direction of maximum gain can be chosen arbitrarily.

For completeness the angular dependence of the maximum gain on the power ratio between the activated signals at ports 2 and 3 is reported in Fig. 6. In the ideal case, $|S_{21}|^2$ and $|S_{31}|^2$ satisfy the relation:

$$|S_{21}|^2 + |S_{31}|^2 = 1; \tag{23}$$

therefore, the gain direction can be associated with either $|S_{21}|^2$ or $|S_{31}|^2$ indifferently (once one of the two quantities is known, the other can be retrieved from (23) and finally their ratio can be calculated).

4 Conclusions

A reconfigurable 1×4 feed network intended for conformal arrays has been presented. The network proved to be able to activate couples of adjacent output ports with arbitrary power ratios, while keeping in-phase signals. Different power ratios are achieved only by changing the phase shift introduced by four variable phase shifters (i.e., α, β, γ and δ), without needing any line switch. Since the signal distribution only depends on the combination of four terms, all output ports of the circuit remain matched in all cases. The capability of such a network to perform beam-steering with conformal arrays has been investigated as well, and the angular dependence of the maximum gain on the power ratio between the two signals has been shown. This way, a new class of feed networks is shown, which make it possible to modify the power ratios among the output ports without requiring any attenuator/amplifier or tangled switching networks, and are suitable for low-power beam-steering in conformal arrays.

References

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