A Novel Agile Phase-Controlled Beamforming Network Intended for 360° Angular Scanning and Radio Localization

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Abstract
This work presents a novel reconfigurable 1x4 network able to provide beam-forming capabilities to conformal antenna arrays. In particular, the proposed feed network is thought for a four-element antenna cube, and, by selectively feeding either single antennas or couples of adjacent elements, is able to generate eight equally-spaced steerable beams over 360° on the azimuthal plane. The output port selection is achieved by controlling the phase value of 4 variable phase shifters. By properly setting the latter ones also the phase difference among the output signals can be determined, enabling in-phase and out-of-phase signal configurations, which are particularly suitable in radio localization applications. A prototype in microstrip technology, designed to operate in the recently released C band (3.4-3.8 GHz) for 5G applications, has been tested, confirming the adequate behavior of the network.

Index Terms – 5G, beamforming networks, Butler matrix, conformal array, Internet of Things (IoT), MIMO feed network

I. INTRODUCTION
With the advent of the 5G era, an impelling need for multiple-input multiple-output (MIMO) reconfigurable transponders has emerged \cite{1}. Indeed, due to the exploding number of communications insisting on the same crowded area, beam steering techniques are essential to help reduce both interferences and power consumption \cite{2}. Additionally, both the diversity of the applications which are currently being developed and the variability of the operating environments call for next generation transponders to be lightweight, robust and low-cost \cite{3}, \cite{4}. Broadband features are also desirable, so that next generation systems are able to take advantage of the new released bands and thus guarantee higher transmission speed.

So far, several studies have been conducted on beam-steering networks for MIMO systems, and most of them are based on Butler matrix configurations \cite{5}, \cite{6}. The latter circuits, though, are thought for linear arrays (complex multiplayer topologies are required for spatial scanning), and features an angular coverage lower than 180°.

The present effort is devoted to the design and experimental validation of a feed network intended for antenna topologies with radiating
elements placed on the lateral sides of polygons (square in the specific case), able to guarantee beam steering on the azimuthal plane with a spatial coverage of 360°. The circuit design is described in Sec. II, while the performance of the fabricated prototype is discussed in Sec. III.

II. CIRCUIT DESIGN

An azimuthal coverage of 360° can be trivially achieved by arranging four antennas (without lack of generality, planar patches antenna are considered) on the lateral faces of a cube and selecting single antennas by means of a single-pole four-through device. Such radiating elements exhibit a broadside 3-dB beam-width on the H-plane lower than 90°, which means that the gain of the MIMO system in the intermediate directions between adjacent radiating elements is below its maximum value (an angular “ripple” higher than 3 dB is expected).

![Sketch of the proposed antenna system. The four radiating elements are marked with their corresponding cardinal directions “N”, “E”, “S” and “W” [8].](image)

In the present work, a more homogeneous coverage is pursued by conceiving a feed network capable of doubling the number of steerable directions (from four to eight) without increasing the number of antenna elements. Firstly, assuming single radiating elements oriented according to the cardinal directions (N, E, S, W), with inter-element distance lower than their operating wavelength, radiation patterns with maxima in the directions NE, SE, SW and NW and almost similar antenna gain and beam-width to the single radiating element can be obtained by exciting adjacent couples with in-phase signals of equal magnitude (split power). The exemplifying reference antenna system is illustrated in Fig. 1.

Consequently, the goal of the work reported in this paper is to enable
the switching of the feeding signal both among the four single antenna elements and among the four selected couples of antennas. To avoid very tangled RF switching networks (the single element would have to be fed either individually or coupled to different adjacent elements without spoiling the matching conditions of the other elements), a smart concept has been developed starting from the observation of the Butler matrix behavior [7]. Usually, this component is used to provide beam steering by selecting the relevant input port. The input power is equally divided among the output ports with a constant phase difference among adjacent output ports, the latter difference depending on the selected input port.

**FIG. 2** – Schematic of the complete feed network.

Being the matrix reciprocal, its output ports can be logically exchanged with the input. Consequently, it is theoretically possible to combine the power toward a specific output port, by feeding the input ports with signals of equal magnitude, just superimposing a specific relative phase relation among adjacent input ports. Finally, the possibility to analogously select adjacent couples of antennas is introduced by conceiving a modified version of the 4x4 Butler matrix.

<table>
<thead>
<tr>
<th>$\angle \alpha$</th>
<th>$\angle \beta$</th>
<th>$\angle \gamma$</th>
<th>$\angle \delta$</th>
<th>Output</th>
<th>N</th>
</tr>
</thead>
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<tr>
<td>90°</td>
<td>0°</td>
<td>90°</td>
<td>0°</td>
<td>o1</td>
<td>1 (E)</td>
</tr>
<tr>
<td>90°</td>
<td>0°</td>
<td>270°</td>
<td>180°</td>
<td>o2</td>
<td>2 (N)</td>
</tr>
<tr>
<td>180°</td>
<td>270°</td>
<td>0°</td>
<td>90°</td>
<td>o3</td>
<td>3 (W)</td>
</tr>
<tr>
<td></td>
<td>0°</td>
<td>90°</td>
<td>0°</td>
<td>90°</td>
<td>o4</td>
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<tr>
<td>90°</td>
<td>0°</td>
<td>180°</td>
<td>90°</td>
<td>o1-o2</td>
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</tr>
<tr>
<td>0°</td>
<td>180°</td>
<td>180°</td>
<td>0°</td>
<td>o2-o3</td>
<td>6 (NW)</td>
</tr>
<tr>
<td>90°</td>
<td>180°</td>
<td>0°</td>
<td>90°</td>
<td>o3-o4</td>
<td>7 (SW)</td>
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<tr>
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<td>0°</td>
<td>0°</td>
<td>0°</td>
<td>o1-o4</td>
<td>8 (SE)</td>
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<td>0°</td>
<td>270°</td>
<td>270°</td>
<td>180°</td>
<td>o1-o2 (180°)</td>
<td>9 (NE)</td>
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<td>0°</td>
<td>180°</td>
<td>180°</td>
<td>o2-o3 (180°)</td>
<td>10 (NW)</td>
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<td>0°</td>
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<td>90°</td>
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<td>o3-o4 (180°)</td>
<td>11 (SW)</td>
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<td>0°</td>
<td>180°</td>
<td>0°</td>
<td>180°</td>
<td>o1-o4 (180°)</td>
<td>12 (SE)</td>
</tr>
</tbody>
</table>

**Table 1** – Relation between phase shifters and activated output ports.

The scheme of the complete system is shown in Fig. 2. The input signal, marked with “1”, is divided into four equal parts by using a four-way power divider. Each signal is then phase shifted by voltage-controlled 2-bit phase shifters. Finally, the obtained signals enter the matrix, so that the desired output ports are activated. The modified Butler matrix is composed by four 90° hybrid couplers and two 90° phase shifters. The relation between the phases of the matrix input signals and the activated output ports is summarized in Table 1, together with the related beam directions ($\theta$) on the xy-plane. A progressive number N is associated with each phase configuration for future reference. The relative phases of the matrix input signals are required to assume only four different values, i.e., 0°, 90°, 180° and 270°, which can be trivially obtained by utilizing 2-bit phase shifters.

The final system, coherently to the ideal scheme of a beam-steerable antenna, presents one RF input port, four RF output ports and the relevant control pins for the variable phase shifting and consequent beam steering.

The proposed feed network not only make it possible to activate couples
of adjacent output ports with in-phase signals (see rows for N=5, ..., 8 in Table 1), but also with 180° out-of-phase signals (see rows for N=9, ..., 12 in Table 1). Therefore, it provides additional beam-forming capabilities which will further improve the system reconfigurability and its field of applications.

![Prototype of the complete feed network.](image)

**Fig. 3** – Prototype of the complete feed network. From left to right: four-way power divider (red box), 2-bit phase shifters (black box) and 4 × 4 matrix (blue box). Visible cables are for switching control. Active area: 20 × 10 cm² [8].

### III. EXPERIMENTAL RESULTS

Fig. 3 shows a photo of the final feed network prototype. The circuit, intended to operate in the sub-6-GHz 5G band 3.4-3.8 GHz (i.e., 11 % bandwidth around 3.6 GHz), is realized in microstrip technology by adopting the 0.5-mm- thick Roger 4350B substrate (εr = 3.66, tanδ = 0.004). The four-way power divider is implemented by connecting three two-way Wilkinson dividers. The 2-bit phase shifters are based on two switched lines. The desired path is selected by using commercial SPDT switches (AS179-92LF model from Skyworks [9]). Four components are utilized for each 2-bit phase shifter. Each component introduces an insertion loss of 0.5 dB, thereby resulting in a total signal attenuation of 2 dB. Finally, the 90° hybrid couplers and the crossover of the matrix are implemented by using “double-box” 3-dB and 0-dB branch-line couplers, respectively. The “double-box” configuration is chosen to improve the operating bandwidth of the system. The matrix was electromagnetically simulated with CST Microwave Studio, whereas the divider and the phase shifters were designed by using ADS.
The feed network is measured with a FieldFox N9981A VNA and the adequate obtained transmission coefficients for each phase configuration are illustrated in Fig. 5 and compared to simulation results. A very good agreement can be observed. The magnitude of the transmission coefficients of the activated ports in the single-port activation configurations (see Fig. 5(c)) is around -3.7 dB, accounting for both the insertion loss of the switches (around 2 dB) and the line loss (which results in about 1.7 dB of attenuation). The signals are significantly flat in all band of interest, with a very small maximum variation of 0.5 dB. The transmission coefficients of the deactivated ports are below 19 dB. On the other hand, the magnitude of the transmission coefficients of the activated ports in the two-port activation configurations is around 3 dB below the single-port configurations, due to the fact that the input power is split between two ports. A still satisfactory maximum variation of less than 2 dB (i.e., transmission coefficient between -6.1 and -8 dB) is experienced in the band of interest. The transmission coefficients of the deactivated
ports are below −24 dB.

\[ \text{FIG. 5} - (a) \text{ simulated and (b) measured phase difference in the transmission coefficients (cases for } N=5-8) \text{ as a function of the matrix input excitations.} \]

Fig. 5 illustrates the phase difference between the transmission coefficient of adjacent ports for cases \( N=5, \ldots, 8 \). The phase differences between the two activated ports, ideally in phase, are below 6° in all cases, thereby confirming the robustness of the proposed approach.

\[ \text{FIG. 6} - (a) \text{ measured magnitude and (b) measured phase difference of the transmission coefficients for the configurations } N=9-12 \text{ (couple of output signals out of phase).} \]

The magnitudes and phase differences of the transmission coefficients for \( N=9, \ldots, 12 \) are shown in Fig. 6. Magnitudes are on the same level as the in-phase cases, while each couple of activated output ports is fed 180° out of phase with a phase error lower that 8° in the band of interest.
FIG. 7 – Photo of the complete system, including the antenna topology and the beamforming network. The side of the cube is 45 mm, while the side of the square patch is 19.3 mm [8].

FIG. 8 – Comparison between simulated (dashed) and measured (solid) H-plane (xy-plane) radiation patterns versus phase configurations. (a) input phases configured for single-port activation and (b) input phases configured for two-port activation [8].

To demonstrate the steering capabilities of the designed network, a suitable setup has been considered (see Fig. 7). Four square patch antennas, arranged on the later sides of a cube, have been manufactured by using a 1.6 mm-thick low-cost FR4 substrate (εr = 4.7, tanδ = 0.011). The antenna topology is connected to the phase-controlled feed network by means of four identical coaxial cables. The H-plane radiation patterns of the cube for all considered phase configurations have been finally evaluated (see Fig. 8). The measurements are performed in an open-air environment without special anechoic provisions. Despite the impact of the measurement setup, the maximum of each radiation pattern occurs in the correct angular direction, thus confirming the adequate behavior of the system. The absolute level of the received power along the directions of
the maxima is fairly independent from the selected configuration (maximum measured difference below 1.1 dB).

![Measured radiation patterns for N=6 and N=10.](image)

**Fig. 9** – Measured radiation patterns for N=6 and N=10.

In Fig. 9 a comparison between the radiation pattern of the array for cases N=6 and N=10 is reported, corresponding to the cases where the same two output ports are activated (i.e., port o2 and o3) either in phase or out of phase. For N=10 a null is obtained corresponding to the direction of maximum radiation for N=6. This suggest that the feed network provide the antenna with additional beam-forming capabilities, which can be useful in many applications, such as radio localization. In the latter case, the radio detection can be performed with cases for N=1, ...8. These cases allow the system to determine roughly the direction of arrival of the radio. Once this estimation is performed one of the activation configurations for N=9, ...12 corresponding to the quadrant of interest is activated and the antenna is rotated (by at most 90°) for the fine localization.

**IV. CONCLUSION**

A novel phase-controlled 1x4 beamforming network for conformal arrays, able to feed both single antennas and couple of adjacent radiating elements, has been presented. A single-layer feed network prototype has been fabricated, operating in the frequency range 3.4-3.8 GHz and featuring satisfactory performance throughout the band of interest. The feed network has been connected to a 4 element antenna topology, demonstrating its capability to steer beams with a 45° step in the azimuthal plane. Additional beam-forming configurations have been also demonstrated, which are important for applications such as radio localization.

**REFERENCES**


