Ultra-wideband Butler Matrix Fed MIMO Antennas

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Abstract— This work elaborates on the design of an Ultra-Wideband (UWB) Butler matrix fed antenna array, implementing a Multiple Input-Multiple Output (MIMO) configuration. The system aims at applications in future Long Term Evolution (LTE) and multifunctional Radar systems. Specifically, based on the results of our previous works, the research is extended towards the implementation of a MIMO beamforming scheme. Different beamforming scenarios are applied, in order to maximize system performance and minimize noise and interference. A comprehensive analysis and design procedure is presented, along with system simulation results.

1. INTRODUCTION

Wide operational bandwidths have become of critical importance in modern wireless applications. The latest communications systems, such as the Long Term Evolution (LTE), are in the need for wideband operation in order to support high data rate transmission. Wideband LTE, which has recently appeared, is consisted of multiple narrowband signals. These signals must be served by a wideband system, either by simultaneous or by time-shared operation at different frequency channels. Moreover, multifunctional phased array Radars demand for wide operational bandwidths, which they enable different operational modes, such as simultaneous air-space and weather surveillance and target tracking.

Apart from the above, the MIMO concept has been also introduced in modern wireless systems. It is basically referred to the channel, which involves multiple input and multiple output signals (or multiple signal paths). The MIMO approach implements a spatial diversity technique, using multiple transmit and receive antennas, as shown in Fig. 1(a) for the 2×2 case and a single user (SU-MIMO) and can be applied in the same manner for multiple receiver units (MU-MIMO). The technique compensates for the signal fading effects, achieving increased channel capacity, [1, 2].

On the other hand, beamforming techniques are also used, implementing spatial diversity schemes such as the Space Division Multiple Access (SDMA). These techniques are based on spatial multiplexing exploiting directive antenna patterns, as shown in Fig. 1(b). Among others, they increase coverage quality [1, 2].

Despite their differences, the two aforementioned techniques can be combined, implementing a MIMO beamforming scheme [1, 2]. This approach exploits the advantages that both techniques can offer. Thus, different data streams can be transmitted, as in MIMO systems, along with the use of beamforming methods, resulting in both improved transmit/receive and coverage quality.

Considering all the above, we present an UWB antenna system based on a Butler matrix feed [3, 4], suitable for use in MIMO wireless communications and Radar systems. The array is consisted of printed Vivaldi tapered slot antenna (TSA) elements, which can provide a multi-octave bandwidth operation. The Butler matrix network is designed using a wideband multi-layer technology. The system design is presented, along with the simulated radiation patterns of the antenna array, extending previous results [5] and considering different system architectures.

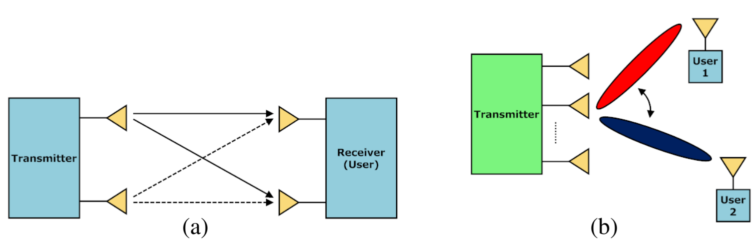


Figure 1: Schematic representation of different wireless access techniques. (a) MIMO approach (2×2), (b) Spatial multiplexing using beamforming.

2. WIDEBAND SYSTEM DESIGN

The system is designed in microstrip technology and it is aimed to cover an operational bandwidth from 3.1 GHz to 10.6 GHz. A simplified schematic diagram is shown in Fig. 2. It is comprised of a circulator (or RF switch) to serve both transmit and receive functions, a switching circuit enabling either single or simultaneous activation of two beams, an N inputs plus N outputs Butler matrix and an N elements Vivaldi TSA array.

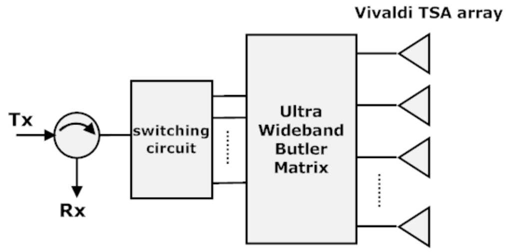


Figure 2: Simplified schematic diagram of the system.

The printed Vivaldi TSA exploited for the design of the array is shown in Fig. 3(a). Board dimensions are 65 mm × 20 mm. The microstrip line-radial stub feed excitation, printed on the back side of the board (Fig. 3(a)), is used for the wideband matching of the antenna. The material employed is a Rogers RO4003C substrate, with $\varepsilon_r = 3.38$, $\tan\delta = 0.0027$ and dielectric thickness $h = 0.508$ mm. Similarly, Figs. 3(b)–(c) depict the 4-element and 8-element linear arrays, respectively, resulting from the periodic repetition of the single element. It must be noted that all successive elements are electrically conducting to each other, in order to attain strong mutual coupling and enhance wideband performance. In turn, this strong coupling should be inevitably accounted for in the array electromagnetic simulation.

Regarding the Butler matrix, its architecture exploits an elliptically or hexagonally shaped multi-layer structure for the directional coupler [6] and the phase shifter [7] design, respectively, which enables not only wideband operation, but also a compact layout. The design starts from an initial geometry based on [6, 7] and [3, 4, 8], which is then utilized within an optimization scheme in order to achieve the best possible performance. The schematic diagrams and the circuit layouts of the 4 × 4 and 8 × 8 configurations are shown in Fig. 4. The top and bottom layer parts of the circuits (as shown in Figs. 4(c)–(d) are designed on two separate RO4003C printed circuit boards, which are conglutinated back to back, with a common ground plane.

SIMULATION RESULTS The finally optimized circuit layouts of Figs. 4(c)–(d) are respectively simulated, in order to attain the excitation signals of the array. The output signals of the matrix

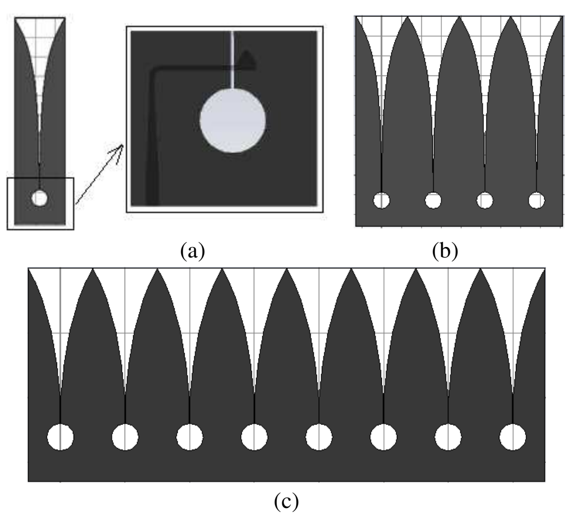


Figure 3: Geometry of the Vivaldi tapered slot antenna element and the corresponding linear arrays. (a) Vivaldi TSA front side showing the microstrip line-stub excitation at the back side, (b) 4-element linear array, (c) 8-element linear array.

circuits are used as excitation coefficients of the Vivaldi TSA array. Fig. 5 depicts the 4-element linear array with one of the produced radiated beams in 3-D space.

Consequently, Fig. 6 shows the produced beam radiation patterns of the 4-element array, when fed by the 4×4 Butler matrix, at different frequencies across the operational bandwidth. As can be seen, the resulted radiation patterns at frequencies other than the center one ($f = 7\,\mathrm{GHz}$), differ mainly in half-power beamwidth and in the strength of the grating lobes. Similar conclusions apply to the results of Fig. 7, showing the radiation patterns of an 8-element TSA array fed by the circuit of Fig. 4(d). However, for the 4-element array case, the total coverage sector is limited to about 80°, while in the 8-element array case the corresponding coverage extends to about 120°.

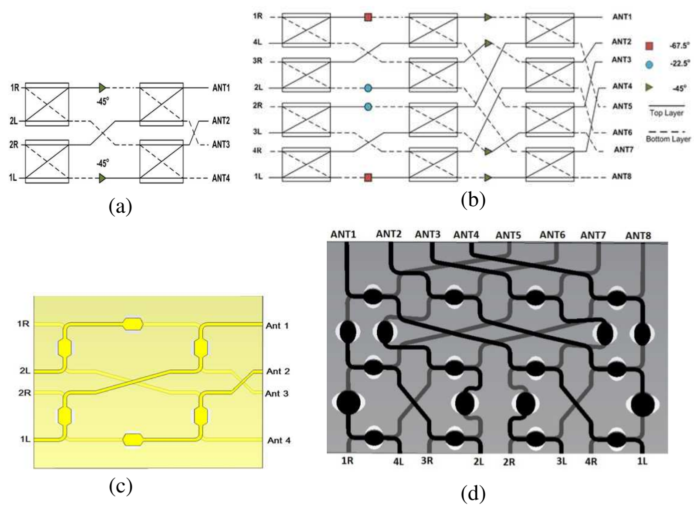


Figure 4: Schematic designs and layouts of the multi-layered wideband Butler matrices (dashed lines and light coloured microstrips are placed at the bottom layer of the boards). (a) 4×4 matrix schematic design, (b) 8×8 matrix schematic design, (c) 4×4 matrix layout and (d) 8×8 matrix layout.

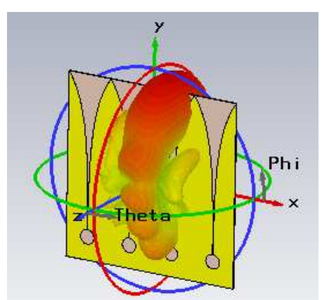


Figure 5: The 4-element vivaldi TSA array radiating a directive beam in 3-D space.

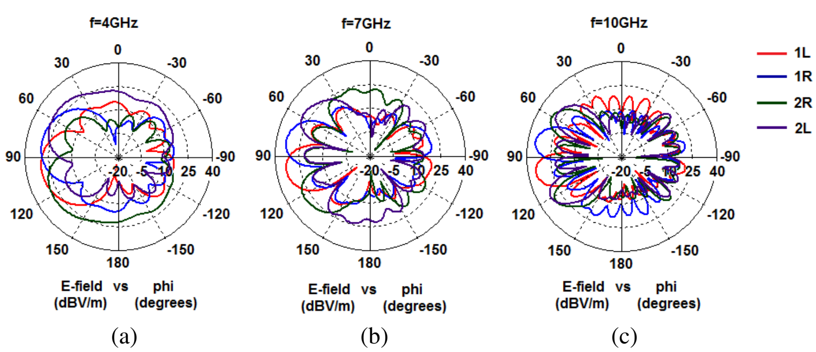
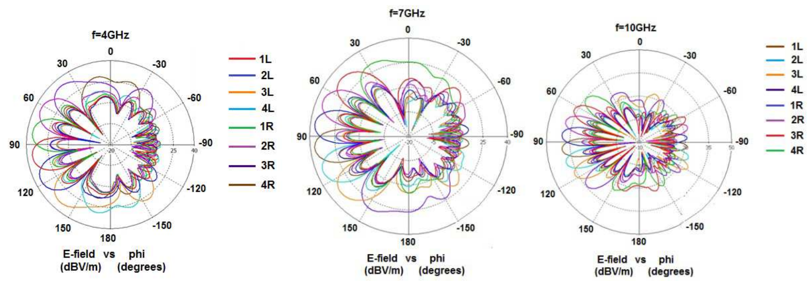


Figure 6: Simulated radiation patterns of the 4-beam Vivaldi TSA Butler matrix fed array. (a) $f = 4\,\mathrm{GHz}$, (b) $f = 7\,\mathrm{GHz}$, (c) $f = 10\,\mathrm{GHz}$.

Moreover, the decreased HPBW and the increased directivity offered in the 8-element array case, makes it more suitable for applications with more stringent specifications. Thus, different circuit topologies may be used under different coverage and channel characteristics scenarios.

Furthermore, aiming at a reduction of the interference, low sidelobe beams could be obtained, by the simultaneous excitation of multiple Butler matrix input ports [4, 9]. An example of simulation results, when this approach is applied to the 4-element 4×4 Butler matrix fed array is shown in Fig. 8, where the four matrix input ports are activated in three appropriate pairs, resulting in a cosine amplitude distribution at the outputs.



(a) (b) (c)

Figure 7: Simulated radiation patterns of the 8-beam Vivaldi TSA Butler matrix fed array. (a) $f = 4\,\text{GHz}$, (b) $f = 7\,\text{GHz}$, (c) $f = 10\,\text{GHz}$.

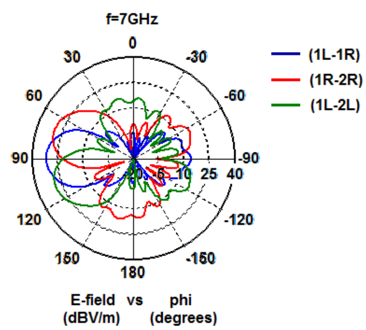


Figure 8: Low sidelobe cosine beams resulting from the simultaneous activation in pairs of the 4×4 Butler matrix input ports.

3. CONCLUSIONS

An ultra-wideband MIMO antenna with Butler matrix feed was designed and simulated. Two different cases were studied, using a 4×4 and an 8×8 Butler matrix network. The technique of the simultaneous activation of Butler matrix input ports was applied, resulting in low sidelobe radiation patterns. In general, the 8×8 circuit case offers advantages in terms of total sector coverage and beam pointing accuracy, improving channel capacity. Future work includes the implementation and testing of the system, emphasizing on its operation at multiple frequency channels.

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