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Digital pattern synthesis with a compact MIMO antenna of half-wavelength diameter

Abel Zandamela\textsuperscript{a,b,c}, Korbinian Schraml\textsuperscript{c}, Suramate Chalermwisutkul\textsuperscript{b}, Dirk Heberling\textsuperscript{c,d}, Adam Narbudowicz\textsuperscript{a,c,*}

\textsuperscript{a} CONNECT Centre, Trinity College Dublin, The University of Dublin, Dublin 4, Ireland
\textsuperscript{b} The Siritdham International Thai-German Graduate School of Engineering, King Mongkut’s University of Technology North Bangkok, 1518 Pracharat 1 Rd. Wongsawang, Bangue, Bangkok 10800, Thailand
\textsuperscript{c} Department of Telecommunications and Teleinformatics, Wroclaw University of Science and Technology, Wroclaw 50-370, Poland
\textsuperscript{d} Institute of High Frequency Technology, RWTH Aachen University, Aachen 52074, Germany
\textsuperscript{e} The Sirindhorn International Thai-German Graduate School of Engineering, King Mongkut’s University of Technology North Bangkok, 1518 Pracharat 1 Rd. Wongsawang, Bangue, Bangkok 10800, Thailand

A R T I C L E   I N F O

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A B S T R A C T

The paper presents a compact multiport antenna, with beamforming capabilities and a realized gain of 4.31 dBi over switch-based analogue beamforming of Electronically Steerable Parasitic Array Radiator (ESPAR) antennas. The reconfiguration properties are achieved by using superposition of three dipole-like radiation patterns, where each radiator generates different spherical mode, i.e. with different angular phase distribution in the horizontal plane. This allows beamsteering with compact size, while the use of different modes ensures low Envelope Correlation Coefficient (ECC) from $10^{-4}$ to $3.2 \times 10^{-5}$ for the operating frequency of 2.4 GHz. The proposed technique allows for significantly greater pattern reconfiguration than any reconfigurable antenna or array of comparable size and is a perfect candidate for Software Defined Radios.

1. Introduction

Reconfigurable radiation pattern is a key requirement for many modern wireless systems, applicable to communication, radar and localization. It enables better spatial coverage, increased spectrum efficiency, improved link budget, and overall adaptability to changing propagation environment [1,2].

Conventional methods for pattern reconfiguration rely on using switching elements such as PIN diodes, MEMS, varactors, and others [1–17]. However, many of such structures have large electric dimensions. Among electrically-small reconfigurable antennas, in [3], a compact reconfigurable Huygens dipole is proposed, which switches between two unidirectional endfire patterns and a bi-directional one. In [4], a two-element array of size 0.62λ is reported to switch between conical and boresight patterns. Electronically Steerable Parasitic Array Radiator (ESPAR) antennas offer pattern reconfiguration by integrating one driven element surrounded by several parasitic ones [5–17]. Applying seven parasitic monopoles in [5] offers a gain of 4 dBi with 0.36λ aperture. Combining beam-switching and polarization reconfiguration with a microstrip antenna in [6] gains up to 3.5 dBi with significantly increased aperture of 1.2λ. Integrating orthogonally crossed dipoles in [7] offers a choice between 4 reconfigurable patterns with a reduced size of 0.42λ, however, the gain is reduced to 3.5 dBi. Using three printed monopoles was reported in [8] to allow increased gain of 6 dBi with aperture of 0.63λ. Other ESPAR compact designs also tend to use switches or tunable components [9–17], offering similar size/gain trade-offs. Even though ESPAR antennas exhibit many advantages, they are challenging for any frequency-division multiple access system, as they do not allow simultaneous use of multiple patterns across various frequency channels.

\textsuperscript{*} Corresponding author.

E-mail addresses: zandamea@tcd.ie (A. Zandamela), schraml@ihf.rwth-aachen.de (K. Schraml), suramate.c.ce@tggs-bangkok.org (S. Chalermwisutkul), heberling@ihf.rwth-aachen.de (D. Heberling), narbudoa@tcd.ie (A. Narbudowicz).

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The above disadvantage does not apply to antenna arrays and MIMO antennas, which can use techniques like digital beamforming to flexibly control the radiation patterns (e.g. adjust each frequency-channel independently or use multiple patterns simultaneously). However, classical antenna arrays are bulky structures, and there are few techniques that allow their miniaturization. A theoretical study presented in [18] shows the possibility to synthesize an extremely narrow beamwidth while using an antenna array of arbitrarily small size. However, such a super-directive radiation pattern is expected to have significantly reduced bandwidth [19].

MIMO antennas have the capability for flexible pattern reconfiguration using digital beamforming, while also supporting size reduction. By digitally adjusting amplitudes and phases of multiport antennas, multiple advantages have been reported. E.g.: two-dimensional beamsteering capabilities are investigated in [20]; null steering and limited beamsteering are proposed in [21]; three-dimensional null steering is discussed in [22,23]; adaptive null steering is demonstrated in [24]. In [25], a beam-reconfiguration around 360° is proposed using a dual-port antenna. However, all those solutions allow adjustment of only one parameter of the radiation pattern, be it either null steering or direction of the main beam.

This paper proposes a compact MIMO antenna for digital beamforming, with sufficient degrees of freedom to independently control three parameters: main beam direction, beamwidth, and null-depth. Unlike previous works, the proposed antenna allows to link parameters of the radiation pattern to specific parameters of antenna’s excitation. This simplifies the calculation of desired radiation pattern and allows additional information about incoming signal, i.e. for angle of arrival applications. It should be also noticed, that in the proposed antenna all ports radiate into the same area, with the only distinction being the spatial phase distribution – a property desired for algorithms such as Multiple Signal Classification (MUSIC). It allows realized gains of up to 4.31 dBi, while its diameter is only 0.5\(\lambda\). The proposed technique offers superior flexibility over switch-based analogue beamsteering of ESPAR antennas, i.e. simultaneous generation of multiple patterns at the same frequency, or for different frequency channels. The design is easy to manufacture and offers low Envelope Correlation Coefficient (ECC) values from 10\(^{-5}\) to 3.2 × 10\(^{-5}\), for the operating frequency of 2.4 GHz.

The remainder of this paper is organized as follows: Section 2 describes the antenna structure and parametric studies. Section 3 presents the measured results. Section 4 discusses how to control antenna’s: main beam direction, beamwidth, and null-depth. Comparisons with ESPAR and antenna arrays are presented in Section 5; Conclusions are provided in Section 6.

2. Antenna design and simulation

2.1. Principle of operation

The principle for miniaturization can be best explained through spherical modes, which allow decomposition of 3D radiation pattern
into a set of spherical modes [26]. Since – by definition – all modes are orthogonal to each other, they will result in a very low ECC [27]. The use of different modes offers an alternative approach to beamforming as demonstrated in [20–24,31,32]. However, unlike these works, we propose to use modes that exhibit same spatial amplitude distribution (omnidirectional), but with a linear progression of phase in the horizontal plane that can be described as:

$$\phi_k(\phi) = 2 \left( k - \text{ceil} \left( \frac{N}{2} \right) \right) \phi$$  \hspace{1cm} (1)

where $\phi$ is an angle in the horizontal plane, $k$ is the index of the port, $N$ is the total number of ports used, and ceil is a ceiling rounding function. In the proposed antenna, $N = 3$. However more advanced designs utilising higher order modes and larger $N$ are also feasible.

### 2.2. Antenna and feed system

The proposed antenna, implementing the above principle, is shown in Fig. 1. The circular disk is a higher-order resonant patch antenna, milled on a Taconic RF-60 substrate (relative permittivity $\varepsilon_r = 6$ and height $h = 6.35$ mm). The circular patch is designed to excite two orthogonal TM$_{21}$ modes, i.e. each mode is excited independently through a pin soldered to the patch and a circular slot in the groundplane which is used to provide isolation between the vias and the groundplane (see Fig. 1b). The pin and the slot have radii of $r_1 = 0.25$ mm and $r_2 = 2$ mm, respectively. Since the patch resonates at higher-order modes, its principle of operation is different than in case of circularly polarized antennas: Two orthogonal TM$_{21}$ modes have nodes oriented at $45^\circ$ with respect to each other, with feeding pins located accordingly at a distance $d_f = 11.5$ mm from the patch centre (see Fig. 1c). These pins are intended to be excited simultaneously, through a hybrid coupler, with equal amplitude but $\pm 90^\circ$ phase shift. Differently from classical patches, applying this principle results in a monopole-like radiation pattern, with the phase varying clockwise or counter-clockwise, depending on the sign of the phase shift. This implements in practice the principle proposed in (1) and will be denoted as port $k = 1$ for $+90^\circ$ and $k = 3$ for $-90^\circ$ phase shift.

The monopole is represented by port $k = 2$ (see Fig. 1a). The structure protrudes above the top metallization of the patch, which serves as its groundplane. The base of the metallic rod of the monopole is located at $g = 2$ mm above the patch to achieve optimum 50 $\Omega$ match. The dimensions of the proposed antenna are (all in mm): $L = 28.5$, $E_1 = 26.16$, $E_2 = 27$, $R_m = 1.5$, $R_l = 26.5$, $R_2 = 32$, $g = 2$, $H_l = 6.35$, $r_1 = 0.25$, $r_2 = 2$, $d = 8.34$, and $d_f = 11.5$.

A miniaturized hybrid coupler is used as a feed circuit for ports $k = 1$ and $k = 3$. The miniaturization strategy is based on [28]. Its implementation is shown in Fig. 2. The coupler is realized on a low-cost FR-4...
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2.3. Parametric studies

Parametric studies were conducted using full-wave electromagnetic simulations in CST Microwave Studio. Investigated parameters include the feeding pins distance \(d_f\), the radius \(R_1\) of the circular patch, the thickness \(H_1\) of the substrate supporting the patch, and the gap \(g\) between the monopole and the patch. No significant difference between the total efficiency of ports \(k = 1\) and \(k = 3\) is observed, which is expected due to antenna’s symmetry. Therefore, only the results of port \(k = 1\) are presented.

Fig. 3a shows the isolation \(S_{31}\) between the ports \(k = 1\) and \(k = 3\), and the total efficiency of port \(k = 1\) while changing parameter \(d_f\). It can be seen that the center frequency shifts from 2.406 GHz to 2.424 GHz as \(d_f\) is increased from 9.5 mm to 12.5 mm. A slight increment in efficiency is observed when \(d_f\) is increased. The maximum isolation is at \(d_f = 11.5\) mm, along with peak efficiency for the center frequency of 2.419 GHz. The simulation results depicted in Fig. 3b show that the radius \(R_1\) impacts the center frequency. The frequency decreases from 2.439 to

(A) Distance \(d_f\). (B) Circular patch diameter.

(C) Thickness of the higher-order substrate. (D) Gap between patch and monopole.

Fig. 3. Isolation and total efficiency of the proposed antenna with different parameters.

Fig. 4. Photograph of the fabricated compact multiport reconfigurable antenna.
2.388 GHz, as the radius is increased from 26.25 mm to 26.75 mm. This is accompanied by an increase on the isolation from 37 to 43.2 dB. The impact on efficiency is negligible. The center frequency of 2.419 GHz is seen at $R_1 = 26.5$ mm.

The impact of the substrate thickness $H_1$ on the isolation and total efficiency is shown in Fig. 3 c. The center frequency increases from 2.409 to 2.4205 GHz, and the efficiency slightly increases as $H_1$ is increased from 6 to 7.05 mm. The maximum isolation is seen at $H_1 = 6.35$ mm. It should be mentioned that the impedance bandwidth increases from 26.4 to 28.1 MHz as $H_1$ is increased. Fig. 3 d shows the S-parameter results for port $k = 2$ when changing the gap $g$. It can be seen that the matching decreases as $g$ is increased, and the center frequency shifts towards lower values. The center frequency of 2.419 GHz is seen at $g = 2$ mm.

The parametric results show that for better isolation characteristics of the proposed antenna, a good tuning of the feed location $d_f$ is required. To control the center frequency, the patch radius $R_1$ should be varied. For bandwidth improvements, the substrate thickness $H_1$ should be increased. The matching of port $k = 2$ can be adjusted by using the gap $g$.

3. Fabrication and measurement

The antenna is prototyped as shown in Fig. 4. The monopole is directly fed using SMA connector. The patch is fed through a hybrid coupler, which is integrated vertically below the antenna’s octagonal groundplane to minimize the impact on radiation properties.

The simulated and measured S-parameters are shown in Fig. 5 a and 5 b. The center operating frequency is 2.419 GHz, with a 34 MHz impedance bandwidth (2.401–2.435 GHz). This compares to the simulated bandwidth of 27 MHz (2.406–2.433 GHz) providing a good agreement. The antenna has a good isolation between all of its ports.

Fig. 6 a shows the measured radiation pattern at 2.4 GHz, in the horizontal plane ($xy$-plane in Fig. 1 a) when each port is individually excited. The monopole ($k = 2$) exhibits slightly increased gain over the remaining ports, which is expected due to the lower efficiency of patch antennas, i.e. losses in the dielectric material.

Sb, respectively. The center operating frequency is 2.419 GHz, with a 34 MHz impedance bandwidth (2.401–2.435 GHz). This compares to the simulated bandwidth of 27 MHz (2.406–2.433 GHz) providing a good agreement. The antenna has a good isolation between all of its ports.

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The phase of the radiation pattern for each port is depicted in Fig. 7. As expected, it follows the relation outlined in (1), albeit with the addition of a constant value that corresponds to different lengths of the feed cables. This property enables pattern synthesis despite the compact size of the antenna.

The ECC was calculated based on radiation patterns of each port [29] and is below $10^{-2}$ within antenna bandwidth. At 2.4 GHz the ECCs and the Multiplexing Efficiencies (ME) [36] are as follows between ports pairs (1, 2): ECC = $10^{-4}$, ME = -1.29 dB; (1, 3): ECC = $5.5 \times 10^{-5}$ and ME = -2.3 dB; (2, 3) ECC = $3.2 \times 10^{-5}$ and ME = -1.29 dB. The simulated diversity gain (DG) [33], mean effective gain (MEG) [34] between all antenna ports are 9.99 dB and 3 dB, respectively. The total active reflection coefficient (TARC) [34] is 51.6 dB. The channel capacity loss (CCL) [35] is 0.38 bits/s/Hz. All above values are given for the center frequency 2.4 GHz.

4. Radiation pattern synthesis

Based on (1), the synthesized radiation pattern in the horizontal plane $P(\phi)$ can be easily predicted using the simplified formula:

$$P(\phi) = \frac{1}{\sqrt{N}} \sum_{k=1}^{N} w_k e^{j(2\pi k\phi + \beta_k)}$$

(2)

where $w_k = a_k e^{j\beta_k}$ is a complex weighting factor applied at the $k^{th}$ port; $a_k$ and $\beta_k$ are respectively the amplitude weighting and phase shift applied at the $k^{th}$ port. Although real antenna will exhibit more nuanced properties, Eq. (2) allows good approximation for pattern synthesis with low computational complexity. This is demonstrated in subsequent sections.

4.1. Beam direction

Differently to antenna arrays, the proposed antenna’s beam changes linearly with the applied phase shift. Without loss of generality, we will use port $k = 2$ as a reference with the constant phase. The phase shift required at two remaining ports to direct the beam into $\Phi_d$ can be calculated as:

$$\beta_1 = 2 \times \Phi_d + \beta_2 + C_2 - C_1$$

$$\beta_3 = -2 \times \Phi_d + \beta_2 + C_2 - C_3$$

(3)

where $C_k$ are constants representing phase addition due to cable length.
Fig. 10. Normalized synthesized radiation pattern (vertical polarization) in xy–plane, for the 45°/225° beam configuration using different phase shift values in port 2.
discussed techniques, allowing flexible shaping of the radiation pattern.

5. Comparison with ESPAR-antennas and antenna arrays

A comparison of the proposed antenna with ESPAR antennas is detailed in Table 4. It is noted that contrary to the ESPAR antennas, where only a single port is used, the proposed antenna requires a total of 3 ports. This implies an increase of the RF modules, and the total energy needed by the system, a known disadvantage of MIMO systems. In terms of size and gain trade-off, the proposed antenna is comparable with ESPAR characteristics, offering 4.31 dBi from 0.5λ aperture. The two closest ESPAR antennas offer a slightly lower gain of 3.5 dBi at 0.42λ diameter [7] and a slightly higher gain of 6.05 dBi gain with a size of 0.63λ [8]. However, the main advantage of the proposed design is the digital beamforming capability, that is not achievable using ESPAR. Overall advantages of the proposed technique include a non-discrete configuration, faster adaptation time compared with a pattern configuration using externally controlled diodes, use of individualized beams for each frequency channel and the use of multiple radiation patterns at the same time.

The proposed multiport antenna is compared with 3-element linear and circular arrays in Table 5. The arrays have typical inter-element spacing of λ/2. The proposed antenna offer miniaturization by 35% to 66%, as compared to circular and linear arrays, respectively. Moreover, 3 ports. This implies an increase of the RF modules, and the total energy needed by the system, a known disadvantage of MIMO systems. In terms of size and gain trade-off, the proposed antenna is comparable with ESPAR characteristics, offering 4.31 dBi from 0.5λ aperture. The two closest ESPAR antennas offer a slightly lower gain of 3.5 dBi at 0.42λ diameter [7] and a slightly higher gain of 6.05 dBi gain with a size of 0.63λ [8]. However, the main advantage of the proposed design is the digital beamforming capability, that is not achievable using ESPAR. Overall advantages of the proposed technique include a non-discrete configuration, faster adaptation time compared with a pattern configuration using externally controlled diodes, use of individualized beams for each frequency channel and the use of multiple radiation patterns at the same time.

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### Table 3

Beam properties obtained from 45°/225° configuration by controlling amplitudes of port 1 (a2 = a1).

<table>
<thead>
<tr>
<th>a1</th>
<th>Beamwidth</th>
<th>Null-depth (dBi)</th>
<th>Gain (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>85.5°</td>
<td>80.0</td>
<td>−13.3</td>
<td>4.31</td>
</tr>
<tr>
<td>1/2 a2</td>
<td>90.4°</td>
<td>−10.9</td>
<td>4.25</td>
</tr>
<tr>
<td>1/4 a2</td>
<td>96.3°</td>
<td>−8.2</td>
<td>3.98</td>
</tr>
<tr>
<td>1/8 a2</td>
<td>101°</td>
<td>−7</td>
<td>3.8</td>
</tr>
</tbody>
</table>

### Table 4

Comparisons of measured performance between the proposed antenna and ESPAR antennas.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Size (λ × λ × λ)</th>
<th>Steering plane</th>
<th>Steering range (°)</th>
<th>Steering type</th>
<th>Multiple patterns</th>
<th>Number of ports</th>
<th>Beam-shaping</th>
<th>Gain (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[5]</td>
<td>0.360 × 0.360 × 0.330 λ</td>
<td>Horizontal</td>
<td>D (0–360)</td>
<td>Discrete (N − 6)</td>
<td>No</td>
<td>1</td>
<td>No</td>
<td>4</td>
</tr>
<tr>
<td>[7]</td>
<td>0.420 × 0.420 λ × 0.006 λ</td>
<td>Horizontal</td>
<td>D (0–360)</td>
<td>Discrete (N − 4)</td>
<td>No</td>
<td>1</td>
<td>No</td>
<td>3.5</td>
</tr>
<tr>
<td>This work</td>
<td>0.530 × 0.530 × 0.330 λ</td>
<td>Horizontal</td>
<td>B (0–360)</td>
<td>Continuous</td>
<td>Yes</td>
<td>3</td>
<td>Adjustable Beamwidth, Null-depth</td>
<td>4.31</td>
</tr>
<tr>
<td>[8]</td>
<td>0.630 × 0.590 × 0.016 λ</td>
<td>Horizontal</td>
<td>O &amp; D</td>
<td>Discrete</td>
<td>No</td>
<td>1</td>
<td>No</td>
<td>6.05</td>
</tr>
<tr>
<td>[9]</td>
<td>0.630 × 1.200 × 0.210 λ</td>
<td>Elevation</td>
<td>D (−26 to 20)</td>
<td>Continuous</td>
<td>No</td>
<td>1</td>
<td>No</td>
<td>5.5–6.1</td>
</tr>
<tr>
<td>[10]</td>
<td>0.810 × 0.330 λ × 0.011 λ</td>
<td>Elevation</td>
<td>D (−15 to 15)</td>
<td>Continuous</td>
<td>No</td>
<td>1</td>
<td>No</td>
<td>6.5–7.4</td>
</tr>
<tr>
<td>[11]</td>
<td>0.590 × 0.900 × 0.080 λ</td>
<td>Elevation, Horizontal</td>
<td>D</td>
<td>Discrete (N − 6)</td>
<td>No</td>
<td>1</td>
<td>No</td>
<td>−5.18</td>
</tr>
<tr>
<td>[6]</td>
<td>1.20 λ × 1.20 λ × 0.200 λ</td>
<td>Discrete (N − 10)</td>
<td>D, 1</td>
<td>3 polarization states</td>
<td>2.5–3.5</td>
<td>7.3–7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[10]</td>
<td>1.440 × 1.440 λ × 0.200 λ</td>
<td>Horizontal</td>
<td>D</td>
<td>Discrete (N − 6)</td>
<td>No</td>
<td>1</td>
<td>No</td>
<td>10</td>
</tr>
<tr>
<td>[14]</td>
<td>1.580 × 1.580 λ × 0.580 λ</td>
<td>Elevation</td>
<td>D (−22 to 22)</td>
<td>Continuous</td>
<td>No</td>
<td>1</td>
<td>No</td>
<td>6.6 ± 0.9</td>
</tr>
<tr>
<td>[17]</td>
<td>2.30 λ × 1.40 λ × 0.060 λ</td>
<td>Elevation</td>
<td>D (−27 to 29)</td>
<td>Continuous</td>
<td>No</td>
<td>1</td>
<td>No</td>
<td>5–5.2</td>
</tr>
</tbody>
</table>

D (Directional), O (Omnidirectional), and B (Bidirectional). * Indicates that the size of the groundplane is not specified, hence the total size of the antenna is larger than the values presented in the Table.
the proposed antenna does not suffer from beam broadening that occurs in linear arrays when the beam is steered away from broadside directions. For the main beam directed at 

\[
\phi = 32^\circ,
\]

the beamwidth deteriorates to 57.5° (an increase of 20.5°), compared to a maximum beamwidth of 85.8° (maximum increase of 12.5°) for the proposed antenna at endfire \( \phi = 0^\circ \). For linear arrays the beamforming is limited to \( 0^\circ - 180^\circ \). The full horizontal plane can be obtained with circular array, however with increased beamwidth and larger overall size.

6. Conclusions

The paper proposes a MIMO antenna, with digital pattern synthesis comparable to switch-controlled ESPAR antennas. However, due to the use of multiport and digital beamforming, the proposed antenna offers functionality which cannot be realized with ESPAR, i.e. simultaneous generation of multiple beams or generation of different patterns for different frequency channels. The antenna offers 4.31 dBi of realized gain and is 0.5 m in diameter. Very low ECC between 10^{-4} to 3.2 \times 10^{-5}, DG around 9.99 dB, TARC < 50 dB, CCL < 0.4 bits/s/Hz, allows its use for classical MIMO applications.

The paper also discusses how different parameters of the pattern can be adjusted including beam direction, beamwidth and null-depth. The structure can be further miniaturized by loading the circular patch substrate with a high-permittivity dielectric [30]. The proposed technique allows many advanced radio applications (e.g. angle of arrival, radar, MIMO) to be operated from a small platform.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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