

# A Wideband Collocated Antennas with Five Reconfigurable Patterns and Low Mutual Coupling

Lila Mouffok<sup>1, \*</sup> and Farid Ghanem<sup>2</sup>

**Abstract**—Wideband collocated antennas for multiple input multiple output (MIMO) systems are proposed. The structure is disposed on two substrate layers. On the first top substrate, a disc monopole is etched. The top of the second substrate contains a tapered slot antenna in a form of a Vivaldi antenna and two reflector elements in the form of half disc. The designed antenna can switch among five radiation patterns which radiate in different directions of space with only two excitation ports. All antennas have a relative bandwidth at least 23%. The antenna elements exhibit a low mutual coupling since they are around  $-17$  dB over the considered bandwidths. This performance is believed because the disc monopole mainly has a broadside radiation while the Vivaldi antenna radiates in end-fire directions. With an overall length of about a half guided wavelength, the proposed structure is believed suitable for applications needing radiation pattern diversity.

## 1. INTRODUCTION

With multiple antennas receiving uncorrelated signals, it is possible to avoid fading effects and obtain a better transmission quality. More recently, reconfigurable antennas have received significant research interest with MIMO systems. Since the channel is not stationary, it is interesting that each antenna of the MIMO system can switch between different radiation pattern configurations in order to optimize the channel capacity. Consequently, a reconfigurable antenna used as one of multiple radiating elements offers an additional degree of freedom for MIMO communications [1].

To achieve pattern diversity, the concept of collocated antennas has been introduced [2]. The idea is to co-localize several antennas and make sure to minimize the mutual coupling between them. This can be achieved by using different polarizations in different elements [3], by inserting neutralization lines [4] or simply by using antennas with different intrinsic radiation properties [5–7]. Until now, co-located antennas providing greater than four different radiation patterns on wideband with high isolation are rare.

The antenna system presented in this communication is composed of a monopole, a Vivaldi antenna and two reflectors elements. This system is able to produce five uncorrelated signals by using radiation pattern diversity. The mutual coupling among all antenna elements is less than  $-17$  dB. The design and mechanism of the proposed wideband pattern reconfigurable antenna are described in Section 2. More details on how the reconfiguration has been done in practice are given in Section 3. Finally, Section 4 compares the simulation and measurement results and provides a table of comparison to other works that appeared in literature.

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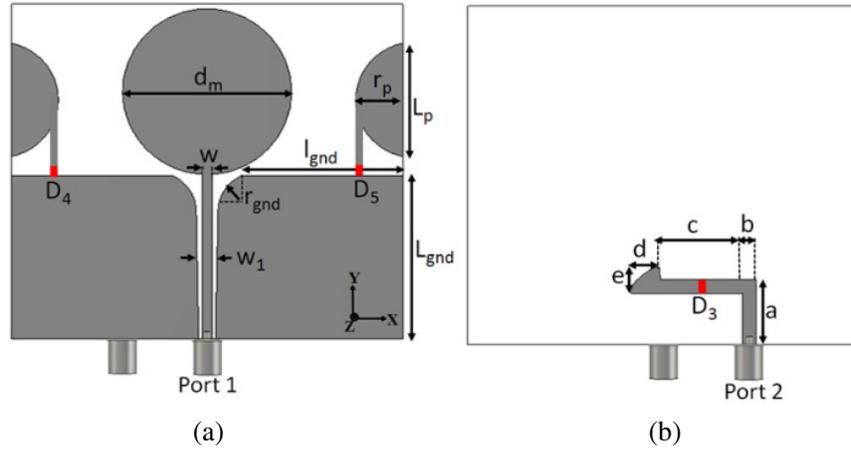
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\* Corresponding author: Lila Mouffok (mouffok.lila@univ-blida.dz).

<sup>1</sup> Institut d'aéronautique et des études spatiales, Saad Dahlad University, Blida, Algeria. <sup>2</sup> Centre de Développement des Technologies Avancées, CDTA, Baba Hassen, Algeria.

## 2. PROPOSED ANTENNA

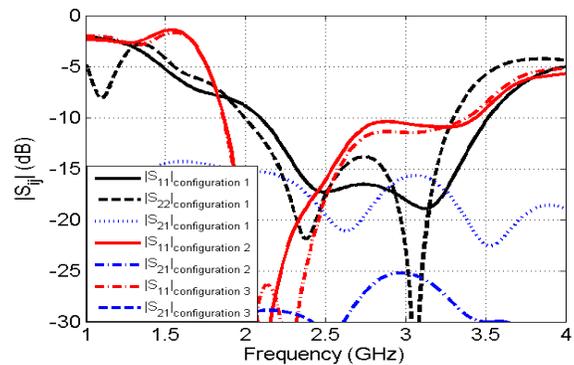
The initial proposed antenna system is a combination of four antenna elements disposed on a single substrate layer. On top of the substrate, a disc monopole fed by a coplanar waveguide is etched, as shown in Fig. 1(a). To form the second element, the tapered ground plane of the monopole is used as the Vivaldi slot that is fed from the bottom of the substrate as shown in Fig. 1(b). Two reflector elements in the form of half disc are etched from either side of the monopole. First, monopole and Vivaldi antennas are studied and realized [8]. Then, the 2 reflectors are added. The impact of these reflectors on the performances of antennas is the deterioration of bandwidth. Thanks to a parametric study on the dimensions of the whole structure, the desired operating band has been improved. The structure is printed on an  $80 \times 70 \text{ mm}^2$  low cost substrate (FR4:  $\epsilon_r = 4.3$ ,  $\tan \delta = 0.0018$ , thickness of 1.6 mm). The dimensions are:  $a = 13.33 \text{ mm}$ ,  $b = 2.86 \text{ mm}$ ,  $c = 16.64 \text{ mm}$ ,  $d = 6.06 \text{ mm}$ ,  $e = 5.33 \text{ mm}$ ,  $w = 2 \text{ mm}$ ,  $w_1 = 4 \text{ mm}$ ,  $d_m = 34.6 \text{ mm}$ ,  $l_{gnd} = 33.1 \text{ mm}$ ,  $L_{gnd} = 34 \text{ mm}$ ,  $r_{gnd} = 5.3 \text{ mm}$ ,  $L_p = 23.6 \text{ mm}$ ,  $r_p = 11.8 \text{ mm}$ . This structure is proposed to exploit the radiation mechanisms in a monopole and Vivaldi antennas. Knowing that a monopole exhibits generally a broadside radiation and that a Vivaldi antenna radiates in end-fire directions, a good decoupling is anticipated. In addition, when the left reflector element is connected to the ground plane, a directive radiation to the positive  $X$  axis is possible. When the right reflector element is connected, a directive radiation towards the negative  $X$  axis is possible. Finally, when the two ports are excited simultaneously, a directive radiation toward  $\varphi = 50^\circ$  is obtained. Therefore, the proposed system can provide five different radiations by integrating three PIN diodes ( $D_3$ ,  $D_4$ ,  $D_5$ ):  $D_3$  has been integrated to Vivaldi feeding line.  $D_4$  is inserted between the left reflector element and ground plane, and  $D_5$  is inserted between the right element and ground plane, as can be seen from Fig. 1. The corresponding antenna configuration is shown in Table 1. Please note that the switches are first used as ideal where the ON/OFF states are modeled by the presence/absence of a metal. Simulations are performed with Transient Solver of CST Microwave Studio<sup>®</sup>. The challenge is



**Figure 1.** (a) Front view, (b) back view of proposed wideband collocated antennas with ideal switch.

**Table 1.** Details of antenna configurations.

Configuration	Operated antenna	Port 1	Port 2	$D_3$	$D_4$	$D_5$
1	Monopole	feed	$50 \Omega$	ON	OFF	OFF
	Vivaldi	$50 \Omega$	feed	ON	OFF	OFF
2	Directive to $X+$	feed	$50 \Omega$	OFF	ON	OFF
3	Directive to $X-$	feed	$50 \Omega$	OFF	OFF	ON
4	Directive to $50^\circ$	feed	feed	ON	OFF	OFF



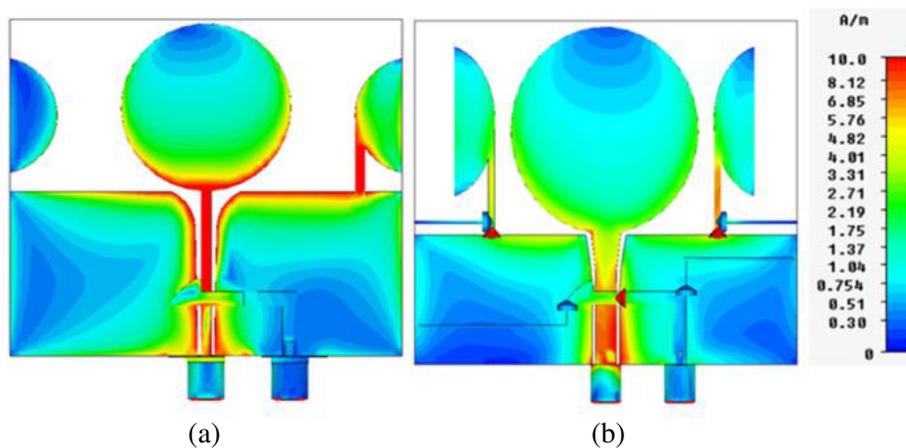
**Figure 2.** Simulated  $S$  parameters of proposed wideband collocated antennas with ideal switches.

to make all antenna elements work on the same band. Fig. 2 shows the obtained  $S$ -parameters of the proposed structure. The matching bandwidth criterion is taken for a return loss less than  $-10$  dB. The bandwidth of monopole is 2.08–3.51 GHz, for Vivaldi antenna is 1.99–3.3 GHz, for directive antenna toward positive  $X$ -axis is 1.86–3.43 GHz and for directive antenna to negative  $X$ -axis is 1.86–3.38 GHz. The isolation between antennas two by two is greater than 15 dB for all configurations.

### 3. IMPLEMENTATION WITH REAL SWITCHES

To implement the proposed structure with real switches, some modification must be made on the dimensions of the antenna to maintain its performances. In addition, to be able to bias the PIN diodes in order to turn them ON/OFF, microstrip lines of 0.6 mm width are introduced. To maintain a DC separation and ensure RF continuity, each diode is connected to 0.1  $\mu$ H surface mount RF inductances. The PIN diodes used are BAR50-02V. To take their effect into account in the simulations, the  $S$  parameters of the component provided by the constructor have been inserted in the antenna. The whole antenna size is now  $90 \times 80$  mm<sup>2</sup>. Insertion of PIN diodes significantly deteriorates matching bandwidth of all antennas especially those of the two directives antennas.

Simulated current distributions for the design with and without real switches for configuration 3 at 1.67 GHz are shown in Fig. 3. For the design with ideal switch, it can be observed that the currents are mainly concentrated on feed line, near the edge of the ground plane (closest to the disc) and distributed along the periphery of the disc edge. On the other hand, for the design with real switches, currents are



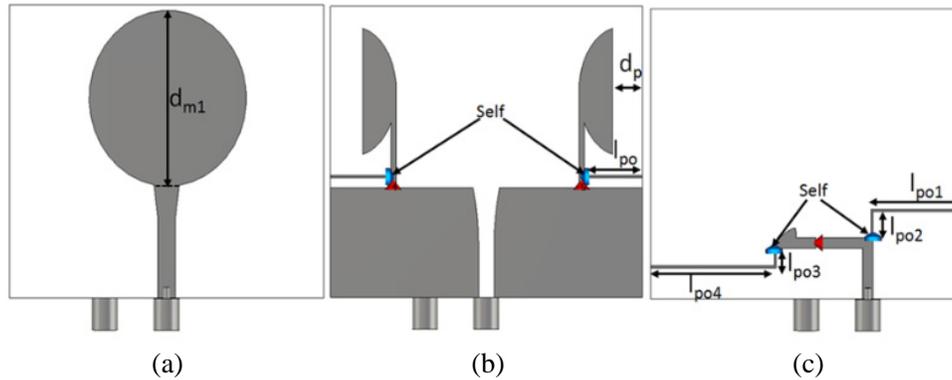
**Figure 3.** Simulated current distribution at 1.67 GHz for configuration 3: (a) With ideal switches, (b) with real switches.

concentrated only on feed line and decrease significantly on the disc edge. Therefore, directive antennas are mismatched. To overcome this problem, a study of monopole feed line width has been done. We observe that the matching of directives antennas can be achieved by increasing the feed line width. However, it is not feasible for this structure because we are restricted by the ground plane edges.

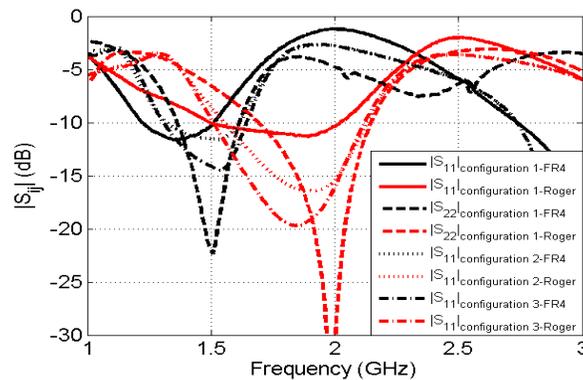
In order to improve impedance matching, we propose to use two substrates. On the first top substrate, the monopole is etched alone. The top of the second substrate contains a tapered slot antenna in a form of a Vivaldi antenna with the two reflector elements etched from either side of the monopole. In the bottom of the second substrate, an  $L$  microstrip line feeding is etched, as shown in Fig. 4. It is seen that the matching bandwidth is enhanced. Indeed, the relative bandwidths of all antennas are now matched with criterion taken for  $|S_{11}| < -10$  dB. The relative bandwidths for the structure with an FR4 substrate are 20.6% (1.22–1.50 GHz), 16.8% (1.36–1.61 GHz), 19.8% (1.32–1.61 GHz) and 23.1% (1.3–1.64 GHz), for monopole, Vivaldi antenna, directive antenna to the positive  $X$  axis and directive antenna towards the negative  $X$  axis, respectively. Since configuration 4 is the feeding of the two ports simultaneously,  $S$  parameters of configuration 4 are not presented in the figure. The isolation between the two ports is better than 20 dB for each configuration in the whole band.

In order to increase operation bandwidths, a Roger RT 5880 substrate with  $\epsilon_r = 2.2$ ,  $\tan \delta = 0.0009$  and thickness of 1.6 mm is used. The different dimensions of the antenna become:  $a = 17.33$  mm,  $b = 3$  mm,  $c = 12$  mm,  $d = 6.2$  mm,  $e = 5.48$  mm,  $e = 7.15$  mm,  $w_1 = 4.42$  mm,  $d_m = 42$  mm,  $l_{gnd} = 40.77$  mm,  $L_{gnd} = 30.8$  mm,  $L_p = 35.36$  mm,  $r_p = 9.53$  mm,  $r_{gnd} = 8.41$ ,  $d_{m1} = 49$  mm,  $d_p = 8.5$ ,  $l_{po} = 16.10$  mm,  $l_{po1} = 26.13$  mm,  $l_{po2} = 7.5$  mm,  $l_{po3} = 5.1$  mm,  $l_{po4} = 36$  mm.

Figure 5 shows the comparison between  $S$ -parameters of the proposed structure with FR4 and



**Figure 4.** Proposed wideband collocated antennas: (a) Front view of substrate 1, (b) front view of substrate 2, (c) back view of substrate 2.



**Figure 5.** Comparison between  $S$ -parameters of proposed structure with FR4 and Roger RT 5880 substrates.

Roger RT 5880 substrates. It is seen that the bandwidth is enhanced. Indeed, the relative bandwidths for the structure with a Roger RT 5880 substrate are: 30.2% (1.49–2.02 GHz), 23.5% (1.69–2.14 GHz), 31.0% (1.55–2.12 GHz) and 33.8% (1.5–2.11 GHz) for monopole, Vivaldi antenna, directive antenna to the positive  $X$  axis and directive antenna towards the negative  $X$  axis, respectively.

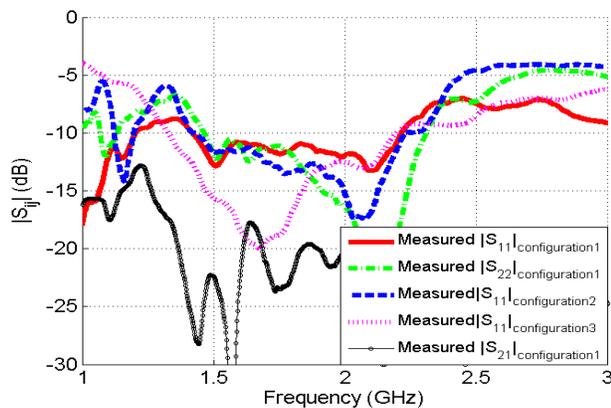
#### 4. RESULTS AND DISCUSSION

A prototype of the proposed antenna has been fabricated and measured. The obtained measured  $|S_{ij}|$  parameters are given in Fig. 6. The measured results show that the relative bandwidths for the structure are: 43.5% (1.42–2.21 GHz), 44.7% (1.46–2.3 GHz), 43.3% (1.43–2.22 GHz) and 50% (1.32–2.2 GHz), for monopole, Vivaldi antenna, directive antenna to the positive  $X$  axis and directive antenna towards the negative  $X$  axis, respectively. The small discrepancies are due to the fabrication process especially to PIN diodes, inductances, SMA connectors which have been manually welded. In addition, the two substrates are not perfectly glued, and a thin nonhomogeneous air layer is created, which can introduce some differences between simulation and measurement. The two antennas are highly uncoupled with a mutual coupling  $|S_{21}|$  below  $-17$  dB within the whole band.

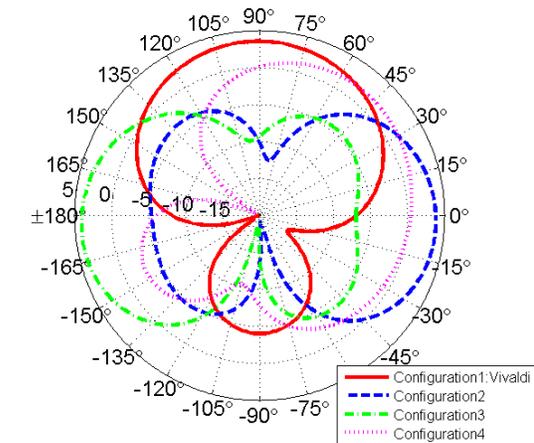
To verify that the decoupling performance is due to the different radiation properties and to validate pattern reconfigurability, the radiation patterns at 1.8 GHz (center frequency) are computed. Each pattern configuration radiates in a different direction in  $XY$  plane as shown in Fig. 7. Indeed, the proposed antenna can radiate to  $\theta = 90^\circ$  (configuration 1),  $\theta = 0^\circ$  (configuration 2),  $\theta = 180^\circ$  (configuration 3) and  $\theta = 50^\circ$  (configuration 4) using two ports and three PIN diodes. Fig. 8 shows the simulated realized gain patterns for the four configurations at 1.8 GHz in the  $XZ$  plane. When the antenna operates at configuration 1, the monopole mainly exhibits a broadside radiation pattern while the Vivaldi antenna radiates parallel to the substrate which is believed to be responsible for the obtained isolation performance.

The maximum simulated realized gain is 2.3 dB for monopole and 1.3 dB for Vivaldi antenna. In Fig. 8(c), when the antenna operates at configuration 2, its main lobe points to direction  $90^\circ$  with a gain of 4 dB.

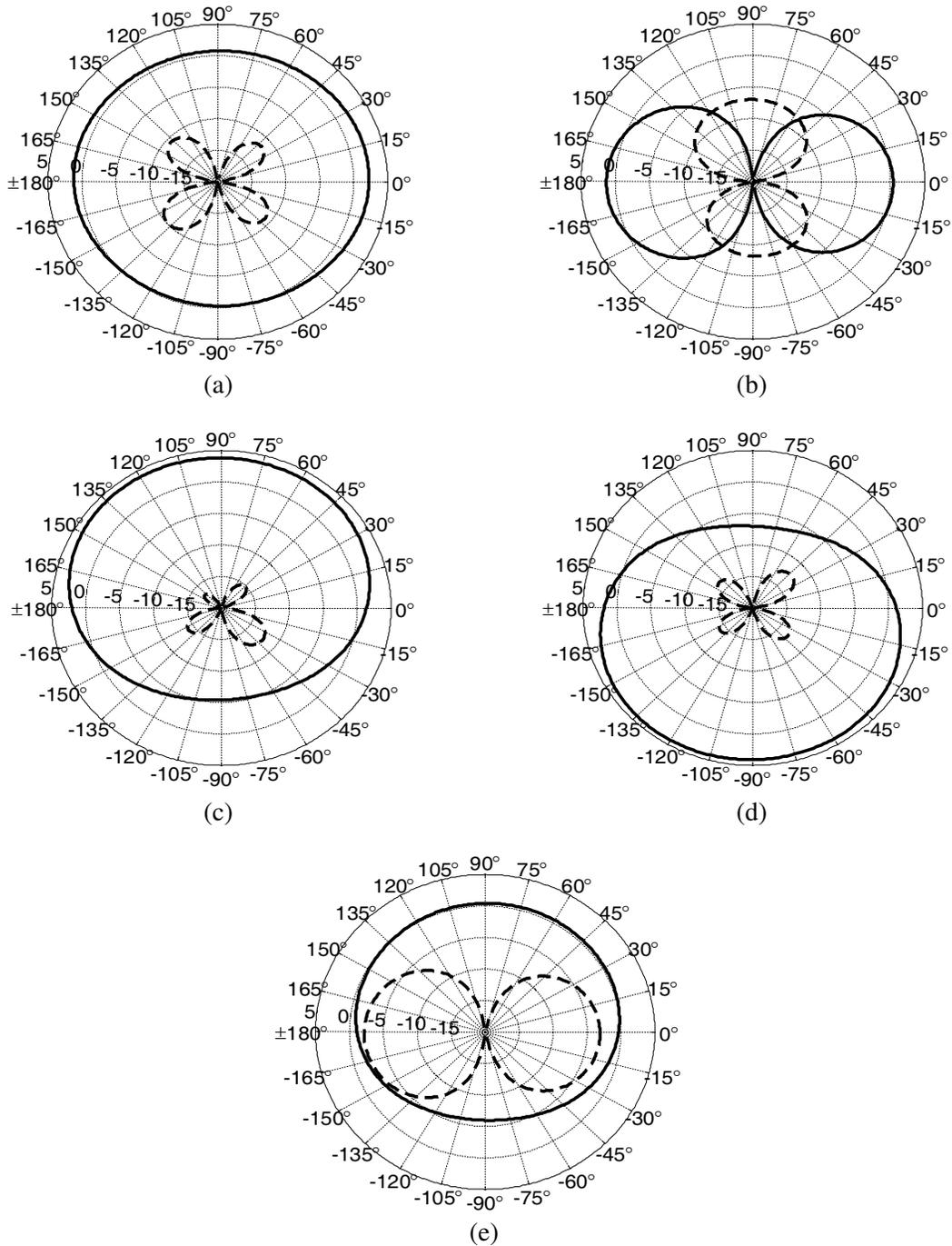
Due to the almost symmetry of the structure, configuration 2 and configuration 3 are opposite. Configuration 3 has a directive radiating pattern pointing to direction  $-90^\circ$  as shown in Fig. 8(d). The maximum simulated realized gain is 1.7 dB for antenna operating at configuration 4 with a cross-polarization level achieving  $-3$  dB, as shown in Fig. 8(e). The radiating gains at configurations 1 and 4 are less than those of configuration 2 and 3 because radiating structures of configurations 1 and 4 operate without reflectors.



**Figure 6.** Measured  $|S_{ij}|$  parameters of the optimized wideband collocated antennas with real switches and with two RT 5880 substrates.



**Figure 7.** Simulated radiation patterns for proposed structure in the  $XY$  plane at 1.8 GHz.



**Figure 8.** Simulated radiation patterns in the  $XZ$  plane at 1.8 GHz: (a) Configuration 1: monopole, (b) configuration 1: Vivaldi, (c) configuration 2, (d) configuration 3, (e) configuration 4.

Table 2 compares the performance of the proposed structure to others with at least  $4 \times 1$  MIMO antenna systems that appeared in literature. The proposed system is a tradeoff among the operating bands, isolation and the configuration radiation pattern number. Only the design of [9] presents a wider band (40%) than the proposed system, but it has a larger size. The system of [10] provides the best isolation (42 dB) but with a narrow band of 2.2%. The proposed system and antenna of [11] are the only systems which propose multiple ports reconfigurable characteristic, with better isolation for

**Table 2.** A comparison table between the proposed antenna system and others allowing at least 4 radiation patterns configurations.

	[9]	[10]	[11]	[12]	[13]	Proposed system
Frequency (GHz)	2–3	2.39–2.45	2.7	2.4–2.5 /5.4–5.7	2.36–2.40	1.69–2.02
Single /Multiple	Single	Single	Single	Multi-band	Single	Single
Relative BW (%) (–10 dB)	40	2.22	4.8	4.0/5.4	1.7	23
Minimum Isolation (dB)		42	7.5	13/16	-	17
Max Gain (dBi) or Efficiency (%)	5 dBi	4 dBi	4 dBi	57%/70%	8.2 dBi	4.4 dBi
Ports number	1	4	4	4	1	2
Reconfigurable	Yes	No	Yes	No	Yes	Yes
Total size (mm <sup>3</sup> )	120 × 120 × 30	119 × 119 × 22	55 × 55 × 1.6	50 × 50 × 0.8	130 × 130 × 5	90 × 80 × 3.2

the proposed system (17 dB against 7.5 dB). This can offer an additional degree of freedom for MIMO communications.

## 5. CONCLUSION

A proposed wideband collocated antenna system has the potential to provide five uncorrelated radiation patterns with only two ports. The antenna elements exhibit a low mutual coupling since they are around –17 dB over the considered bandwidths. This performance is believed because the disc monopole has mainly a broadside radiation while the Vivaldi antenna radiates in end-fire directions. Each pattern configuration radiates in a different direction of space. These properties make such an antenna well-suited to maximize the received power in an urban or indoor environment where signals come from many different angles of arrival. By arranging the antenna elements on two Roger RT 5880 substrates, the frequency bandwidths have been improved compared to the use of only one FR4 substrate. Thus, the 10 dB return loss allows the antenna to be used in wireless applications with at least 23% of relative bandwidth. The use of ON/OFF switches allows a simple control command to change the pattern configuration. Taking effect of PIN diodes into account in simulation allows good agreement between simulated and measurement results when the antenna integrates PIN diodes.

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