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Coupling Measurements of an Antenna System Suitable for Relay-Aided WiMAX Network

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Abstract—In this paper two novel antennas, suitable for access and backhaul links, are designed, fabricated and tested for a Relay Station in a WiMAX wireless network. A single modified E-shaped patch antenna is described, presenting 10 dB gain over 12.4% bandwidth. This antenna element is used for the design of a 4×4 planar array which provides experimental gain of 21.2 dB. The antenna system on the Relay Station operates at 3.4 GHz and includes one single antenna element for access link realization and an antenna array for the backhaul link realization. These antennas are installed in two configuration arrangements and tested in terms of their radiation performances and coupling effects. The simulated and measured results are quite satisfactory and in good agreement at which the maximum coupling between the access and backhaul antennas is found below -25 dB for all tested cases.

1. INTRODUCTION

Nowadays wireless networks should be flexible in a continuously changing environment and ensure high data rates in order to provide for end users with highly demanding applications. Relay Stations are smart transceivers put in certain places within a wireless network to cover regions with poor or no connectivity [1]. Such network devices should be equipped with a suitable antenna system to optimize communication between subscribers and the Base Station. The access antenna is required to provide a wide coverage pattern, with a bandwidth that reaches ideally 500 MHz and gain of 8 dB whilst the backhaul antenna should be directional and provide 18 dB gain. This can be realized by using a single antenna for the access link and an array for the backhaul link.

Microstrip antennas are major candidates for Relay Stations as they provide a set of advantages such as compactness, ease of fabrication and installation and low profile [2]. Many patch shapes can be found in the literature such as U-shaped, E-shaped [3] and C-slot patch antennas providing enhanced bandwidth and increased gain. Moreover composite substrate structures have been investigated [4], including the introduction of high-low permittivity substrates [5].

Another important issue regarding the antennas is their interaction which may distort the radiation pattern and cause cross-polarization increase [6]. In the case where the antennas operate simultaneously and have the same resonant frequency, it is of utmost importance to investigate the coupling between them and to ensure that it is as low as possible in order to prevent degradation of the emitted radiation. Many studies have been published regarding methods for coupling reduction [7]. Defected Ground Structures (DGS) have been reported in literature and widely used for suppressing surface waves and cross polarization levels, reducing the interaction between radiation elements [8]. Also Electromagnetic Band-Gap structures [9] provide antenna coupling reduction, introducing band-stop effects due to the combination of capacitance and inductance. Ground structure slit configurations with removed

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substrates and metal wall introduction have been studied as methods of achieving high isolation between antenna elements [10].

In this paper a novel antenna system is designed, fabricated and tested for the 3.5 GHz frequency band, valid for a relay-based WiMAX network. The antenna system includes a single antenna element for access link realization between the Relay Station and the subscriber terminals and an antenna array for the backhaul link realization between the Relay Station and the governing Base Station. Both antenna features have been specified according to the air-interface specifications of the IEEE802.16j standard [11], where increased bandwidth and gain is required for the proper antenna system operation. Antennas have been designed, simulated and optimized in order to meet the requirements of the standard using the electromagnetic simulator Ansoft HFSS v.12. Moreover the access and backhaul antenna operate at the same frequency and function at the same time. For this reason, two configurations of access and backhaul antenna for coupling reduction are presented and tested. Finally, the measured coupling is compared to previous work where two other antenna models were set in similar configurations and tested in terms of S_{21} parameter.

Figure 1 summarizes the Relay Station operation where the proposed access and backhaul antennas are denoted.

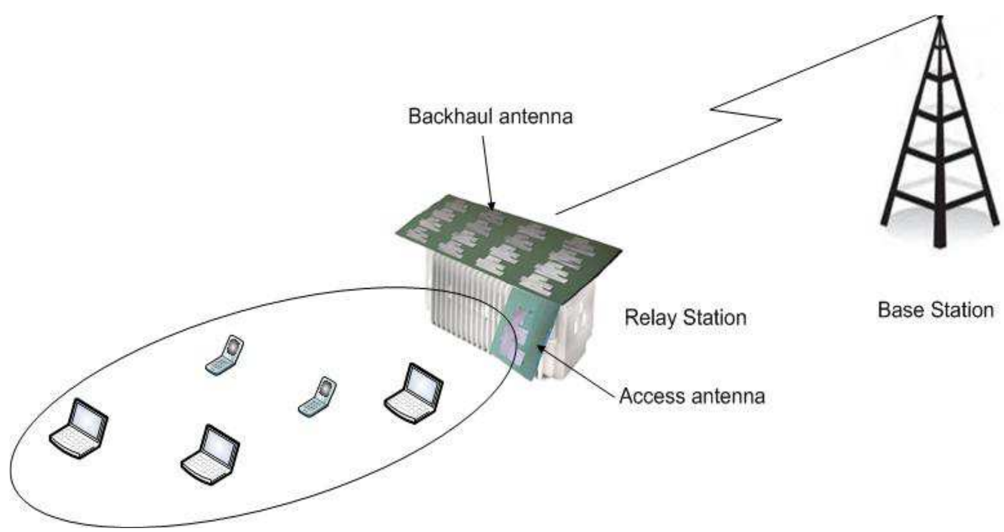


Figure 1. Relay station with antenna system.

The text is organized as follows: In Section 2 the single antenna for the access link and the array for the backhaul link performance are designed and tested in terms of bandwidth and gain. Onwards in Section 3, two new configurations of the proposed antennas are depicted and evaluated in terms of coupling. Results are extracted, shown in relevant graphs and discussed. In Section 4 a summary of the foregoing work is outlined, and conclusions are denoted.

2. ANTENNA SYSTEM

The communication between the Relay Station and the user subscribers is established by a single microstrip antenna element. This element utilizes a modified E-shaped patch radiator in combination with a composite stacked substrate structure for bandwidth enhancement. The initial patch shape had a simple rectangle form which had been updated and optimized in order to meet the features denoted in [11] for the frequency of 3.4 GHz.

The length and width of the initial rectangle patch element has been defined by the formulas [12]:

$$L = \frac{\lambda_0}{2} \tag{1}$$

$$W = \frac{c}{2f_0}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{2}$$

where L is the length, λ_0 the free space wavelength, W the width of the patch, c the free space speed of light, f_0 the free space frequency, and ε_r the relative dielectric constant of the substrate used.

The final modified E-shaped patch antenna, fed by coaxial cable, has the form depicted in Figure 2:

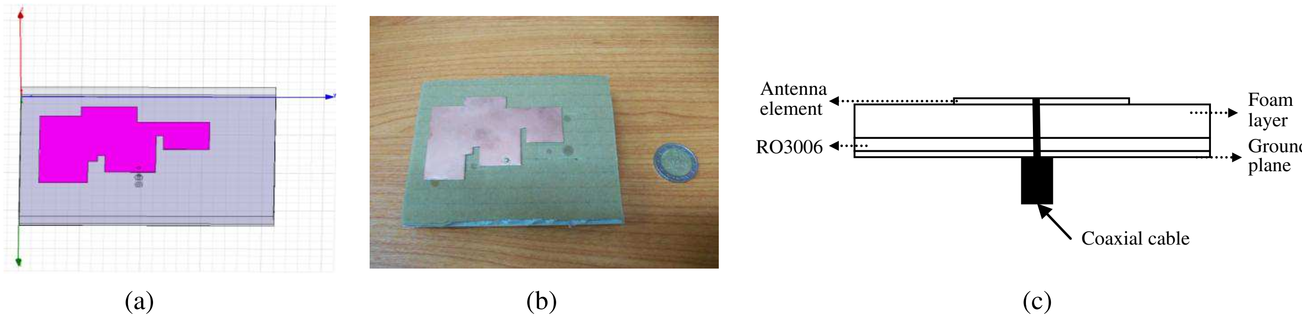


Figure 2. Single modified E-shaped patch element; (a) Simulated design. (b) Constructed antenna. (c) Cross-section of the proposed antenna element.

The patch element has the dimensions denoted in Figure 3(a). The structure of the antenna includes a ground plane of copper. On the top of this, a Rogers RO3006 substrate ($\varepsilon_r = 6.15$, $h = 1.28\,\text{mm}$) is placed and next a foam layer ($\varepsilon_r = 1$, $h = 5\,\text{mm}$). The patch radiator is mounted on the foam layer.

The antenna is a modified E-shaped radiator, providing increased bandwidth and gain as denoted in [13]. Moreover the stacked substrate structure in combination with the coaxial feed leads to broadband antenna behavior [14]. The utilized composite structure of the antenna has an average permittivity equal to [15]:

$$\varepsilon_{r,e} = \frac{\varepsilon_r (H_D + H_A)}{H_D + H_A \varepsilon_r} \tag{3}$$

where $\varepsilon_{r,e}$ is the average permittivity, ε_r the Rogers RO3006 substrate's permittivity, H_D the height of the Rogers RO3006 substrate, and H_A the height of the foam layer.

Based on the utilized stacked geometry, the bandwidth of the antenna can be approximated by the formula [16]:

$$\text{BW} = \frac{16}{3\sqrt{2}} \frac{pc_1}{e_r} \left(\frac{1}{\varepsilon_{r,e}}\right) \left(\frac{h_t}{\lambda_0}\right) \left(\frac{W}{L}\right) \tag{4}$$

where: $p = 1 + \frac{a_2}{20}(k_0 W)^2 + \frac{3a_4}{560}(k_0 W)^4 + \frac{b_2}{10}(k_0 L)^2$, $a_2 = -0.16605$, $a_4 = 0.00761$, $b_2 = -0.09142$, k_0 is the free space wave number, and $c_1 = 1 - \frac{1}{n_1^2} + \frac{2}{5n_1^4}$, n_1 is the refractive index of the substrate, e_r the radiation efficiency, $\varepsilon_{r,e}$ the average permittivity of the composite antenna structure, h_t the total substrate height, λ_0 the free space wavelength, W the width, and L the length of the antenna.

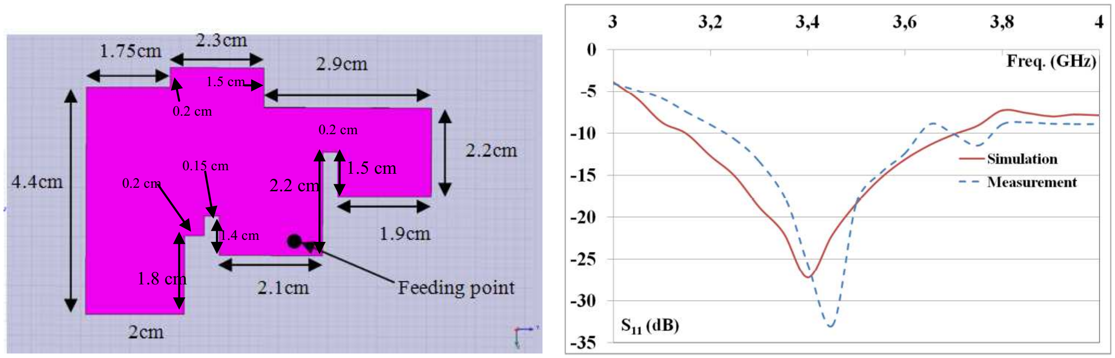
The utilization of a composite substrate consisting of two materials, the Rogers RO3006 and the foam layer, leads to a total permittivity obtained by Equation (3). The total permittivity is much less than that of the Rogers RO3006 substrate, approximating unity and is introduced to Equation (4) resulting in increased bandwidth.

Equation (4) is not suitable for the actual bandwidth evaluation of the proposed antennas but it shows a mathematical dependency of bandwidth in terms of substrate's height h_t and average permittivity. The equation states that increasing substrate's height and decreasing the permittivity, bandwidth is enhanced.

The antenna as can be viewed from Figure 2 is coaxially fed and for the S parameter measurements, Anritsu VNA MS2036A equipment was used. The S_{11} of the proposed antenna element is depicted in Figure 3(b).

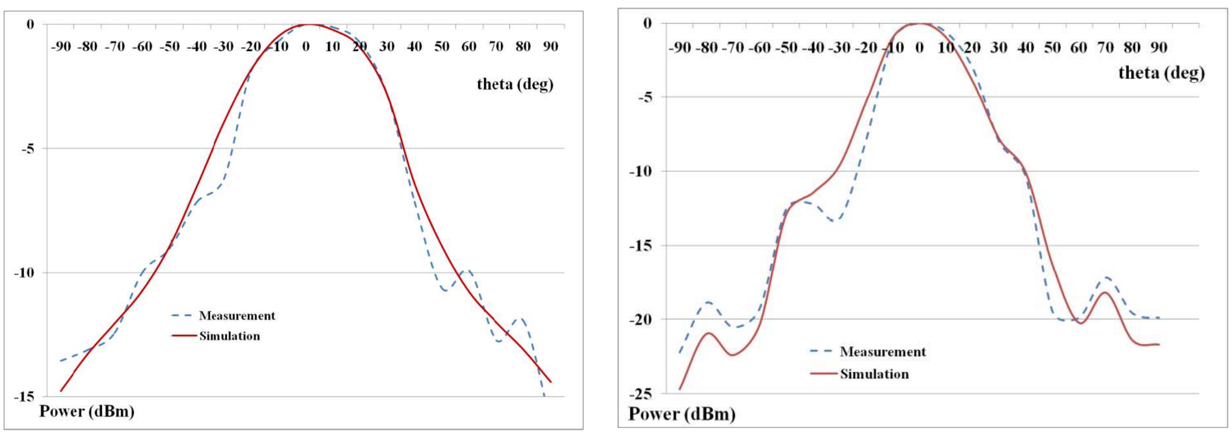
The antenna presents resonance at 3.42 GHz with bandwidth of 424 MHz or 12.4%. The radiation pattern of the proposed patch antenna in terms of normalized power for the frequency of 3.4 GHz is depicted in Figure 4.

The features of the presented antenna are summarized in Table 1.



(a) (b)

Figure 3. Modified E-shaped patch antenna; (a) Dimension description. (b) S_{11} parameter.



(a) (b)

Figure 4. Radiation pattern of the modified E-shaped patch antenna; (a) xz plane. (b) yz plane.

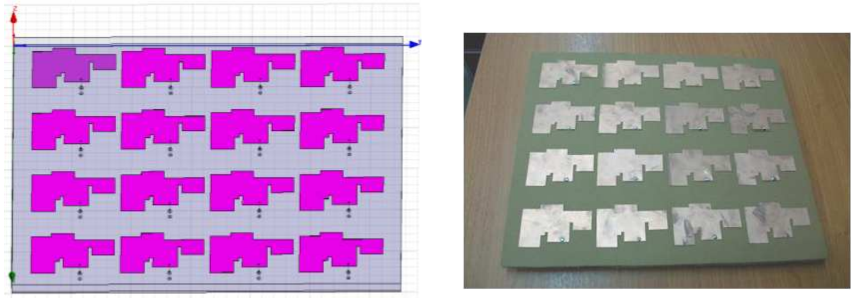
Table 1. Modified E-shaped antenna features.

	Gain (dB) for 3.4 GHz	**HPBW xz plane (deg)**	**HPBW yz plane (deg)**	**Bandwidth (MHz)**
Modified E-shaped patch antenna (experiment)	10	75	42	424
Specifications of IEEE802.16j	9	(sectorial) 60	(sectorial) 50	500

The proposed patch antenna satisfies the specifications of the IEEE802.16j standard in terms of gain, bandwidth. Half Power Beam-width (HPBW) results differ, but we can use the proposed modified E-shaped patch antenna to provide broadband services over a specific region where a limited HPBW is necessary or as part of a sectorial antenna system to provide 360 deg coverage (5 modified E-shaped patch antennas needed).

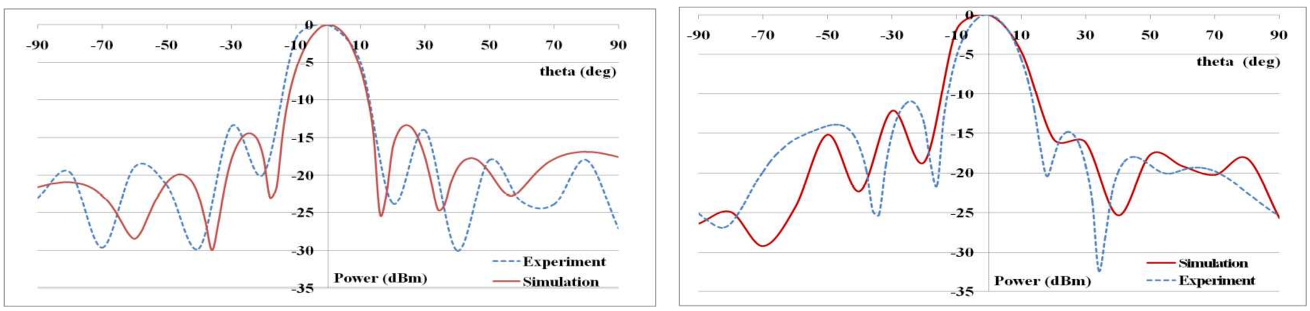
Next, the backhaul antenna is designed and presented. It is a 4×4 planar array based on the structure of the single element. The center to center antenna spacing has been investigated in order to achieve low side-lobe levels and is $0.87\lambda_0$. The proposed array is depicted in Figure 5.

For the excitation of the 16-element array, one 2-way (DMS206) and two 8-way (DMS825)



(a) (b)

Figure 5. 4×4 planar modified E-shaped array; (a) Simulation. (b) Fabrication.



(a) (b)

Figure 6. Radiation pattern of the 4×4 planar modified E-shaped array; (a) yz plane. (b) xz plane.

commercial power dividers based on Wilkinson technology with microstrip construction were used.

The radiation pattern of the presented array is depicted in Figure 6.

The radiation pattern of the array in terms of normalized power provides a main lobe of increased gain, directivity, and low Half Power Beam-width (HPBW) due to the increase in the number of radiation elements. Side lobe level is 12 dB below the main lobe as a result of careful inter-element spacing. The features of the array are included in Table 2.

Table 2. Modified E-shaped array features.

	Size (cm)	Gain (dB) for 3.4 GHz	HPBW xz plane (deg)	HPBW yz plane (deg)
Backhaul antenna (experiment)	32.6×30	21.2	14.4	14.3
Specifications of IEEE802.16j		18	15	15

Gain, HPBW and Bandwidth are at satisfactory level compared to the specification in the standard. By controlling the phase and amplitude of the excitation currents, the resulting radiation pattern can be formed accordingly thus making the presented array suitable for beam-forming applications.

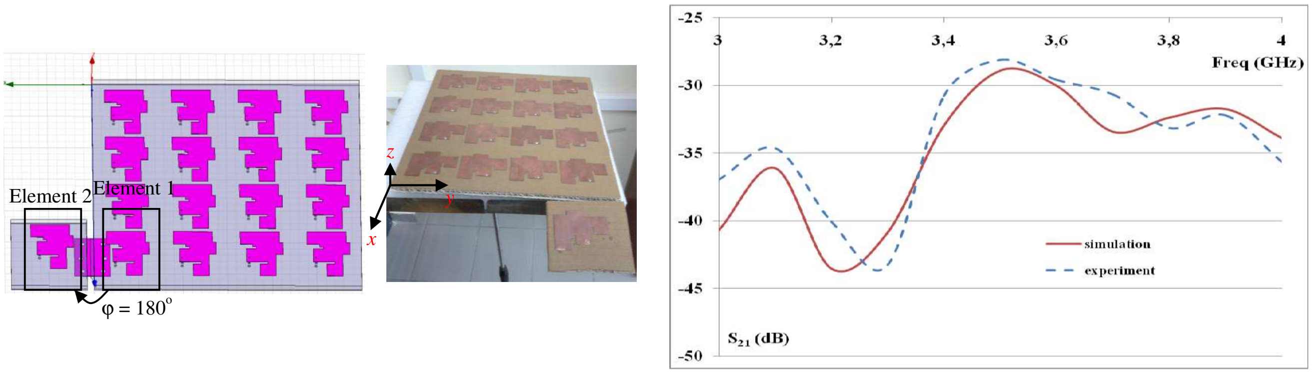
3. COUPLING MEASUREMENTS

The access and backhaul antenna presented in the previous section, are to be incorporated in a Relay Station, operating in the same frequency and at the same time. For this reasons, coupling is an important issue which should be taken into consideration. In this section, two access and backhaul antenna configurations are presented and tested in terms of coupling.

3.1. Configuration 1

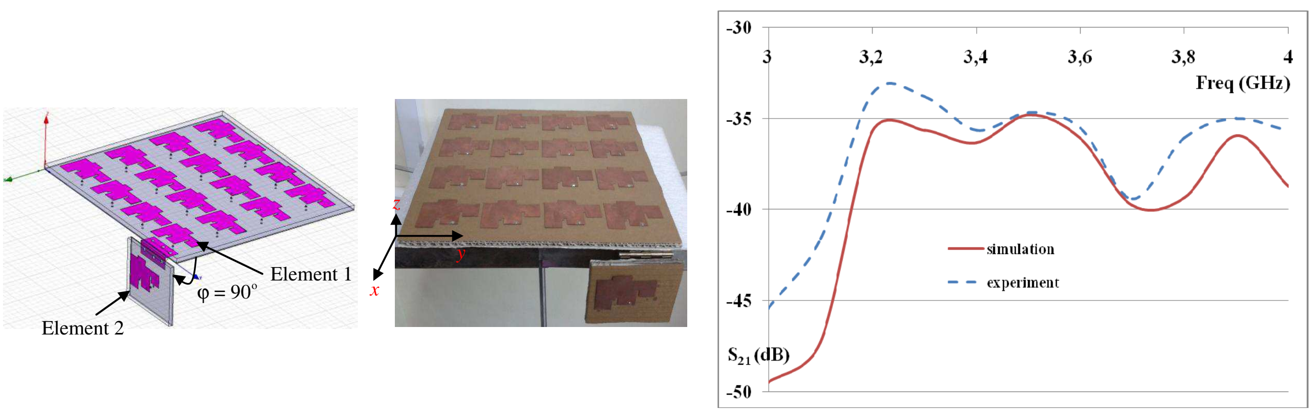
Configuration 1 is depicted in Figures 7(a) and 7(b). The antenna and array are connected with a metallic rotating mechanism. For $\varphi = 180°$, the simulated and experimental coupling in terms of S_{21} between elements 1 and 2 denoted in Figure 7(a) is drawn in Figure 7(c).

Experimental coupling is -30.8 dB for the frequency of 3.4 GHz. For the frequency range of 3.3 GHz to 3.8 GHz, experimental coupling varies from -28.1 dB to -43.5 dB. The configuration described above can be considered as an E-plane arrangement. The edge-to-edge distance between element 1 and 2 shown in Figure 7(a) is $0.3\lambda_0$. Then element 2 is rotated by 90 deg, as shown in Figure 8(a) and simulation and experimental S_{21} is obtained and drawn in Figure 8(c).



(a) (b) (c)

Figure 7. Configuration 1; (a) Simulation for $\varphi = 180°$. (b) Experimental setup for $\varphi = 180°$. (c) S_{21} for configuration 1 when $\varphi = 180°$.



(a) (b) (c)

Figure 8. Configuration 1; (a) Simulation for $\varphi = 90°$. (b) Experimental setup for $\varphi = 90°$. (c) S_{21} for configuration 1 when $\varphi = 90°$.

Experimental S_{21} is -35.7 dB for 3.4 GHz. For the frequency range of 3.3 GHz to 3.8 GHz, S_{21} varies from -33.8 dB to -39.4 dB. A 90 degree rotation leads to a coupling decrease of approximately 5 dB for 3.4 GHz.

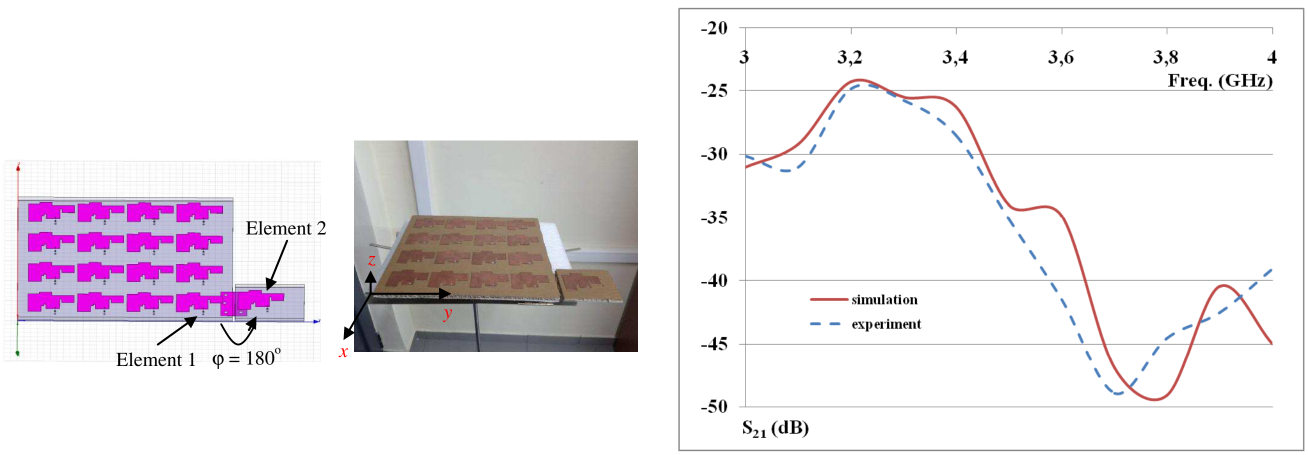
3.2. Configuration 2

Figures 9(a) and 9(b) show the second antenna configuration. The antenna and the array are ground connected through a metallic rotating mechanism. Coupling between elements 1 and 2 denoted in Figure 9(a) can be seen in Figure 9(c).

For the frequency range of 3.3 GHz to 3.8 GHz, experimental S_{21} varies from -25.8 dB to -48.9 dB. For the resonant frequency of 3.4 GHz experimental S_{21} is estimated to be -28.5 dB. This configuration is referred to as an H-plane arrangement. The edge-to-edge distance between element 1 and 2 denoted in Figure 9(a) is $0.3\lambda_0$. Coupling measurements continue with the estimation of S_{21} for configuration 2 with $\varphi = 90°$. The proposed setup is depicted in Figures 10(a) and 10(b). For this case, S_{21} parameter is depicted in Figure 10(c).

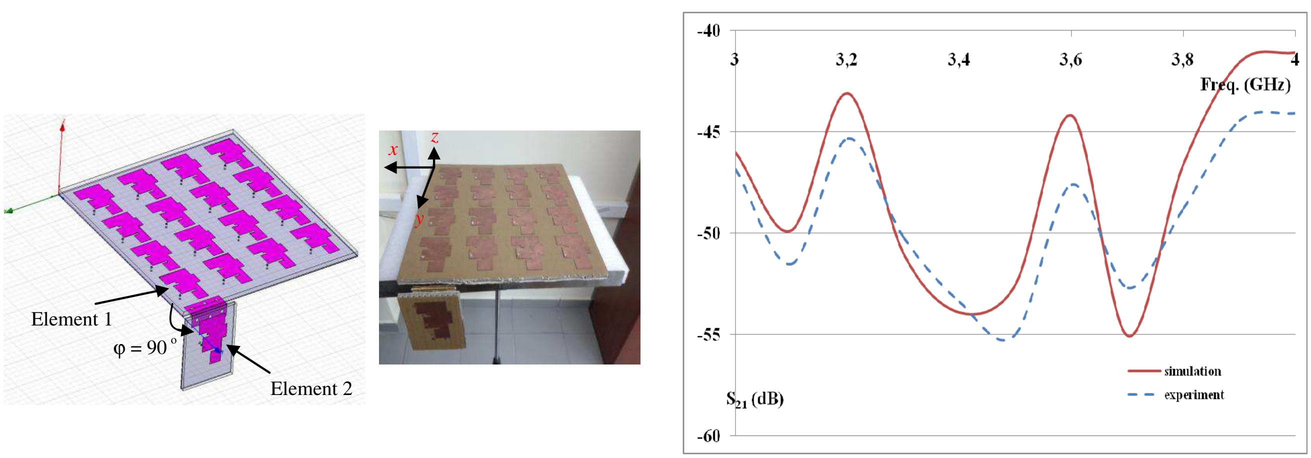
In this case, for the frequency range of 3.3 GHz to 3.8 GHz, S_{21} parameter varies from -47.6 dB to -55 dB. For 3.4 GHz, experimental S_{21} is -53.4 dB. In this case the rotation of element 2 by 90° leads to a coupling decrease of approximately 24 dB for the frequency of 3.4 GHz. The H-plane arrangement is proved to be more efficient and provides better element isolation.

Coupling is in general a phenomenon dependent on two terms: The surface waves that lead from one radiation element to its neighbor through the substrate and the field lines emitted from an antenna and ending on the surrounding radiating elements. In order to minimize the effect of coupling it is necessary to find a way to reduce surface waves and field line influence. A way to succeed in this is to create a substrate discontinuity between the elements maintaining a common ground, in order to



(a) (b) (c)

Figure 9. Configuration 2; (a) Simulation for $\varphi = 180°$. (b) Experimental setup for $\varphi = 180°$. (c) S_{21} for configuration 2 when $\varphi = 180°$.



(a) (b) (c)

Figure 10. Configuration 2; (a) Simulation for $\varphi = 90°$. (b) Experimental setup for $\varphi = 90°$. (c) S_{21} for configuration 2 when $\varphi = 90°$.

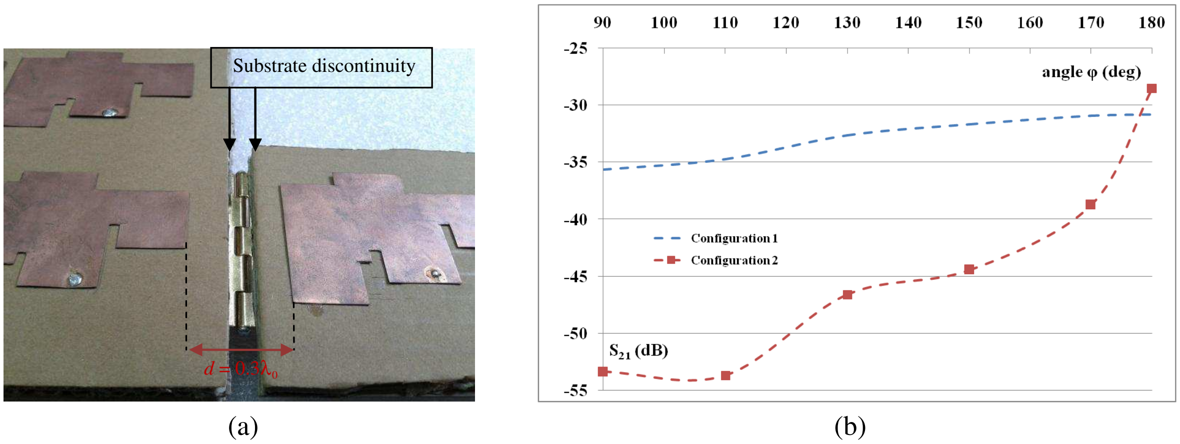


Figure 11. Array/antenna arrangement; (a) Experimental setup. (b) S_{21} for both configurations in terms of the angle φ.

prevent the propagation of surface waves. Such a technique is depicted in Figure 11(a). Field lines that extend from one antenna to the other can be limited by placing the radiating element far enough apart. The common ground not only introduces a gap between the array and the single antenna but is also used for inserting a proper distance (angle φ) between them, increasing the isolation. Next, configuration 1 and 2 were tested in terms of the angle φ, for $\varphi = 90^\circ$ to $\varphi = 180^\circ$. Experimental results of S_{21} as a function of the angle φ, for 3.4 GHz are depicted in Figure 11(b).

Configuration 1 varies from -35.6 dB to -30.8 dB as the angle increases. The curve approximates the behavior of a linear increasing function while in the case of configuration 2, the S_{21} parameter increases non linearly in terms of the angle φ, from -53.5 dB to -28.5 dB. Figure 11(b) shows that the E-plane denoted in configuration 1 is not strongly dependent on the angle φ, providing a 6B coupling increase while the H-plane of configuration 2, results in 25 dB coupling increase. It is assumed that TM mode fields are primarily excited by the modified E-shaped patch antenna, therefore the E-plane arrangement gives higher coupling because of the stronger TM mode field interaction between the radiation elements. On the other hand, in H-plane arrangement, weak TM mode field excitation leads to weaker coupling between the radiation elements [17].

The proposed low coupling mechanic structure has been tested in Ref. [18] for completely different antennas. In reference, the tested antennas utilize one substrate FR-4 and the array includes a power division circuit. In this paper the antenna structure is much more complex comprising two substrates and a modified E-shaped radiation element that fulfill the requirements of the IEEE802.16j air interface standard. For this reason it is useful to examine the coupling between the antennas. Coupling comparison between antennas of [18] and the modified E-shaped ones is denoted in Table 3, were S_{21} in the case of the modified E-shaped antennas is enhanced as a result of the lower distance d. In configuration 1 the coupling presented in this study is enhanced compared to the corresponding measurements of [18] while configuration 2 provides approximately the same value of S_{21} for 90° but coupling of the modified E-shaped antennas for 180° is significantly increased.

Table 3. Coupling comparison.

Antenna arrangement	**Angle (deg)**	S_{21} **(dB) Ref. [18]** $(d = 0.5\lambda_0)$	S_{21} **(dB) Modified E-shaped antenna** $(d = 0.3\lambda_0)$
Configuration 1	90	-47.67	-35.7
	180	-53.94	-30.8
Configuration 2	90	-55.56	-53.4
	180	-60.68	-28.5

Although coupling measurements of the proposed antennas are increased compared to [18], S_{21} is at a sufficiently low level below -28.5 dB and the presented antennas have increased gain and bandwidth therefore their utilization is beneficial and advantageous.

4. CONCLUSIONS

In this paper a single antenna element and an array suitable for a relay-aided WiMAX network has been presented and tested in terms of bandwidth, gain and radiation pattern characteristics. These antennas are based on microstrip technology and have been designed to meet the air-interface specifications of the IEEE802.16j standard. They utilize the same structure, and both operate in the same frequency range from 3.3 GHz to 3.8 GHz, thus making them beneficial for network operators. The single antenna is based on a modified E-shaped patch element, utilizing a composite substrate structure, providing resonance at 3.4 GHz, 10 dB gain and 424 MHz bandwidth. This antenna is intended to be incorporated in a Relay Station, for establishing the access link between the Relay Station and the end users. Moreover, the array presented in this work is a 4×4 planar array that provides 21.2 dB gain. The array is also intended to be incorporated in a Relay Station for establishing the backhaul link, connecting the Relay Station with its governing Base Station. Both the antenna and the array operate at the same frequency and the same time, so coupling issues arise. In order to maintain the antenna coupling at low levels, two novel configurations were presented and tested in terms of S_{21} parameter. Configuration 1 resulted in S_{21} equal to -30.8 dB for $\varphi = 180°$ and -35.7 dB for $\varphi = 90°$, while configuration 2 gave S_{21} equal to -28.5 dB for $\varphi = 180°$ and -53.4 dB for $\varphi = 90°$ at 3.4 GHz. Configuration 1 gives efficiently low coupling ($S_{21} < -30$ dB) for all values of φ angle while in configuration 2, S_{21} becomes ideally small for $\varphi < 165°$ where $S_{21} < -40$ dB. In conclusion both antenna arrangements provide low coupling and are valid for efficient performance.

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