

Compact Dual-Printed Inverted-F Antenna Diversity Systems for Portable Wireless Devices

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Abstract—Dual-printed inverted-F antenna diversity systems for terminal devices operating at 5.2 GHz under both switched and combining schemes are presented. Diversity performance is evaluated by means of the calculated envelope correlation coefficient, the mean effective gain and the effective diversity gain of the two antennas. An investigation for the antennas' placement and the corrugated ground plane effect on the performance of the system has also been conducted. It is shown that many configurations can provide uncorrelated signals of the same power level, but with significantly different radiation pattern complementarity, antenna efficiency, and effective diversity gain.

Index Terms—Correlation, diversity gain, multiple-input multiple-output (MIMO) systems, mutual coupling, printed circuit antennas.

I. INTRODUCTION

ANTENNA diversity is a well-known technique to enhance the performance of wireless communication systems by reducing the distortions of the channel [1]. In order to create an antenna diversity system on a wireless device [2], two or more antenna elements could be placed in positions that provide uncorrelated signals of the same power level [3]. These signals are then combined according to a diversity technique such as switched diversity, selection diversity, equal gain, or maximal ratio combining, in order to create an improved signal. Among the different diversity techniques, switched diversity is commonly used due to its simplicity and implementation cost. In switched diversity, the receiver monitors one antenna branch at a time leaving the others open. If the signal level falls below a preset threshold, the receiver switches to another branch searching for a better signal level. In combining diversity schemes, on the other hand, the transceiver receive the signals from all the antenna branches at any instant in time and then weight, cophase, and sum them. The summed signals are then used as the received signal and connected to the demodulator providing an improved performance. A typical multi-element antenna (MEA) diversity system would require multiple radio receivers and a/d converters, which are difficult to be implemented on a handheld device given the restricted available space. Alternately, an RF combining circuit could be used in order to combine the received signals directly behind the antennas, e.g., [4], thus requiring a single receiver.

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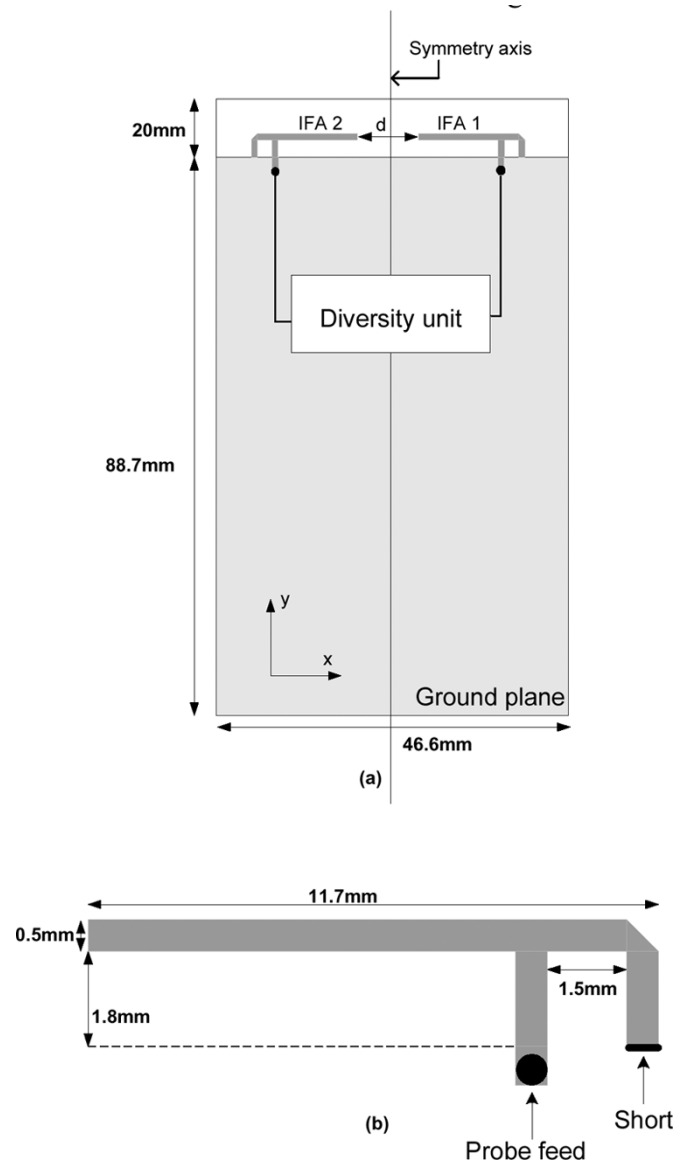


Fig. 1. Geometry and dimensions of the dual-element diversity system. (a) PC card layout. (b) Dimensions of the printed inverted-F antenna element.

Compact MEA systems will also be needed on the user equipment side of a multiple-input multiple-output (MIMO) system. In this kind of terminal, two to four antenna elements are envisaged and the restricted space available for the antennas is an open issue [5]. MIMO systems use space-time processing techniques that improve the reliability and increase the capacity of wireless communication systems [6]. High data rates in the

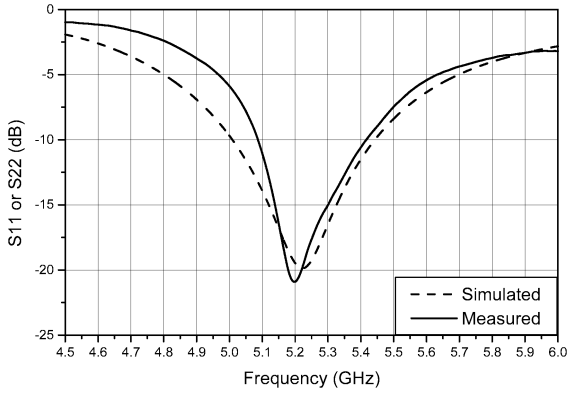


Fig. 2. The return loss (S11 or S22) of the printed IFA under switched diversity scheme.

order of 170 Mbits/s in a 2×2 setup on a HiperLAN/2 channel with 99% probability have been reported [7]. The capacity of these channels has recently been proven that is affected by the mutual coupling between the antenna elements [8].

In this work, a two-branch diversity system for PC cards operating in the 5.2-GHz industrial scientific and medical (ISM) band is addressed. The antenna element employed is the printed inverted-F antenna (IFA) [9], [10] due to its compact size, flexible tuning, large bandwidth, and ease in manufacturing at no additional cost. The proposed dual antenna system is examined under both a switched and a combining diversity scheme. The impact of different antenna placements and ground plane corrugation on the mutual coupling between the two elements and their diversity performance is investigated. It is shown that many configurations are capable to provide uncorrelated signals of the same power level, exhibiting though significant differences in their radiation patterns, efficiency, and effective diversity gain.

II. DIVERSITY PERFORMANCE EVALUATION

Diversity gain is the amount of improvement obtained from a multiple element antenna system relative to a single element one. It depends on the cross-correlation and the relative mean power levels between the signals delivered from each antenna branch. In general, diversity gain increases when the cross-correlation and the power imbalance between the diverted signals decrease.

The cross-correlation of the diverted signals can be characterized by the complex correlation coefficient ρ_{cij} ($i, j = 1, 2$) and the envelope correlation coefficient ρ_{eij} , which are related by [1]

$$\rho_{eij} \cong |\rho_{cij}|^2 \quad (1)$$

ρ_{cij} can be evaluated either from the mutual coupling (mc) between antenna ports (ρ_{cij}^{mc}) or from the radiation patterns (rp) of the antenna elements and the statistics of the channel (ρ_{cij}^{rp}). The former is estimated by using the normalized mutual resistance $r_{ij} = \text{Re}(Z_{ij})/\text{Re}(Z_{ii})$ according to [1]

$$\rho_c^{mc} \cong r_{ij} \quad (2)$$

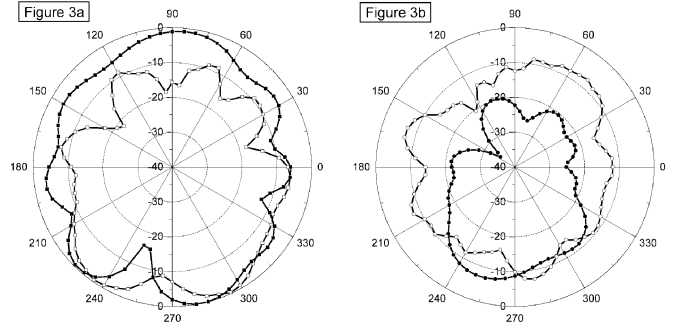


Fig. 3. The radiation patterns of the printed inverted-F antenna. (a) E_ϕ component at the azimuth plane: $\blacksquare$ E_ϕ simulated, $\square$ E_ϕ measured. (b) E_θ component at the azimuth plane: $\bullet$ E_θ simulated, $\circ$ E_θ measured.

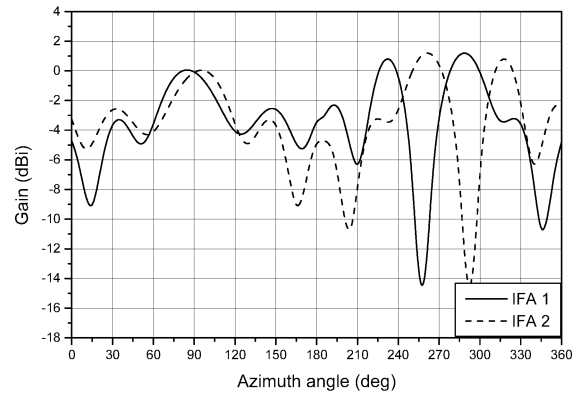


Fig. 4. Antenna gain patterns at the azimuth plane under switched diversity scheme.

where Z_{ij} are the port impedances and $\text{Re}(\cdot)$ denotes the real part. On the other hand, ρ_{cij}^{rp} can be calculated from (3) and (4) [11]

$$\rho_{cij}^{rp} = \frac{\int_0^{2\pi} A_{ij}(\varphi) d\varphi}{\left[\int_0^{2\pi} A_{ii}(\varphi) d\varphi \int_0^{2\pi} A_{jj}(\varphi) d\varphi \right]^{1/2}} \quad (3)$$

$$A_{ij}(\varphi) = \Gamma E_{\theta i} \left(\frac{\pi}{2}, \varphi \right) E_{\theta j}^* \left(\frac{\pi}{2}, \varphi \right) + E_{\varphi i} \left(\frac{\pi}{2}, \varphi \right) E_{\varphi j}^* \left(\frac{\pi}{2}, \varphi \right) \quad (4)$$

where E_θ and E_φ are the θ and φ polarized electric field patterns of the antennas at the azimuth plane and Γ the cross polarization discrimination (XPD) of the incident field. The asterisk denotes the complex conjugate.

The mean power P_i received from each antenna branch, can also be obtained from the radiation patterns and the statistics of the channel using the concept of the mean effective gain (MEG). The MEG of an antenna, which is defined as the ratio of the mean received to the mean incident power at that antenna, can be calculated from [12]

$$\text{MEG} = \oint \left[\frac{\Gamma}{1+\Gamma} P_\theta(\Omega) G_\theta(\Omega) + \frac{1}{1+\Gamma} P_\varphi(\Omega) G_\varphi(\Omega) \right] d\Omega \quad (5)$$

where G_θ and G_φ are the θ and φ polarized components of the antenna power gain pattern, Ω is the solid angle (θ, φ), and P_θ, P_φ are the θ and φ polarized components of the incident power density.

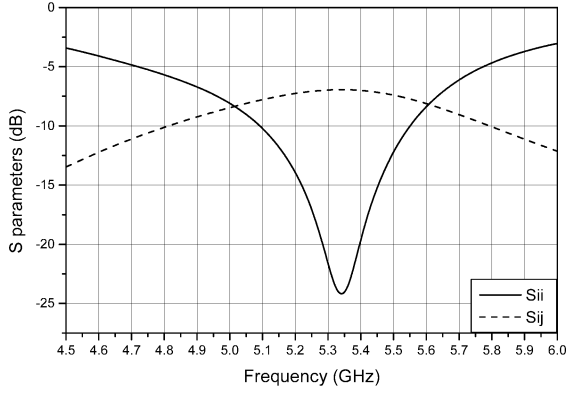


Fig. 5. The return loss S_{11} and the mutual coupling (S_{12}) parameters of the dual IFA system under combining diversity/MIMO schemes ($i, j = 1, 2$).

P_φ are the θ and φ components of the angular density functions of incoming plane waves. In this letter, a uniform propagation environment is assumed, i.e., $\Gamma = 1$ and $P_\theta = P_\varphi = 1/4\pi$.

Diversity gain can be achieved when the signals received from two antennas satisfy the following criteria [1]:

$$\rho_{eij} < 0.5 \text{ and } P_i \cong P_j. \quad (6)$$

Assuming that the mean incident power on each antenna is the same, the equality criterion between P_i and P_j reduces to equality between MEG_i and MEG_j .

Apart from the traditional definition of diversity gain, Kildal *et al.* [13] defined the effective diversity gain, which is an absolute measure of the diversity performance between different antenna systems. According to this definition, the effective diversity gain is expressed mathematically from

$$G_{\text{effdiv}} = \frac{P_{\text{div}}}{P_{\text{ideal}}} \quad (7)$$

where P_{div} is the received power level of the combined signal and P_{ideal} is the received power level of a single antenna with unit radiation efficiency operating in the same environment. P_{div} and P_{ideal} are read at the same probability level in a cumulative probability density versus power level plot. In this letter, the cumulative density function of P_{div} is computed as a function of the envelope correlation coefficient and mean effective gain for the maximum ratio combining case [14, pp. 366], [15] and P_{ideal} follows the Rayleigh distribution [13].

III. A DUAL INVERTED-F ANTENNA DIVERSITY SYSTEM

The geometry and dimensions of the investigated configuration are depicted in Fig. 1. It has the dimensions of a PC card while the dimensions of the ground plane are 46.6×88.7 mm. The prototype consists of two $35\text{-}\mu\text{m}$ -thick copper layers with the two antennas placed at the upper one and the ground plane at the bottom. The antennas are printed on an 8-mils-thick Rogers RO4003 substrate, with $\epsilon_r = 3.38$ and $\tan \delta = 0.0027$ [16]. Both antennas are probe fed, as shown in Fig. 1. The configuration was simulated using IE3D, a commercial method of moments based electromagnetic field solver [17].

The switched diversity scheme was simulated feeding one antenna and leaving the other one open-circuited. Owing to the identical shape of the antennas and the symmetry of the whole

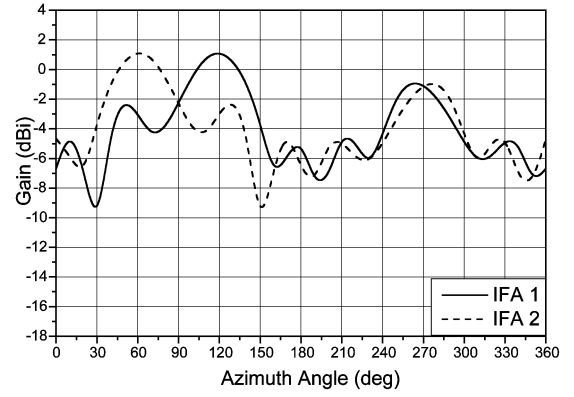


Fig. 6. Antenna gain patterns at the azimuth plane under combining diversity/MIMO schemes.

TABLE I
ENVELOPE CORRELATION COEFFICIENT AND MEG RATIO OF THE ANTENNAS OF FIG. 1

Diversity Scheme	ρ_e		MEG ₁ /MEG ₂
	mutual coupling	radiation pattern	
Switched	n/a	0.329	0.999
Combining/MIMO	0.178	0.069	1.005

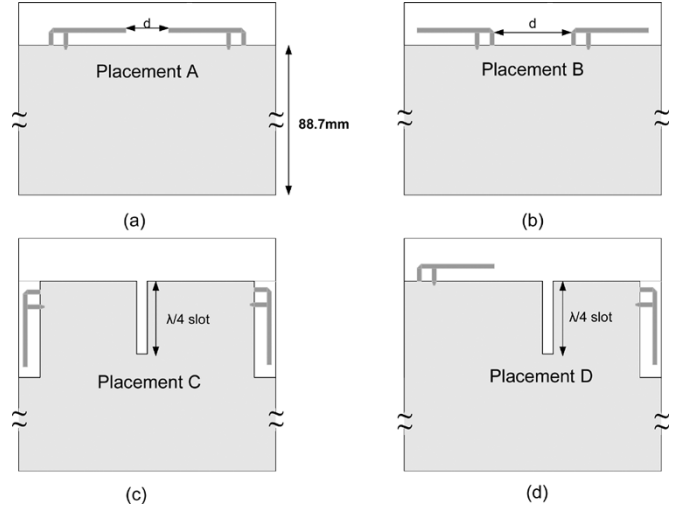


Fig. 7. The geometry of the four different antenna placements.

configuration, the measured and simulated return losses for both ports (S_{11} and S_{22}) are exactly the same as depicted in Fig. 2. The IFA elements are well tuned in the 5.15–5.35 GHz ISM band and have over 300 MHz (6%) bandwidth, which allows proper tuning and operation in a real environment, where other metallic elements of the terminal may exist in the near field of the antennas.

The simulated and measured radiation patterns of the antenna elements on the azimuth (x - y) plane are shown in Fig. 3 and are in good agreement with some deviations being noticeable due to the interference of the feeding cable during the measurement procedure [18]. In Fig. 4, the complementary performance of the two antennas is depicted, proving that it is a hybrid space-pattern diversity system with omnidirectional antennas.

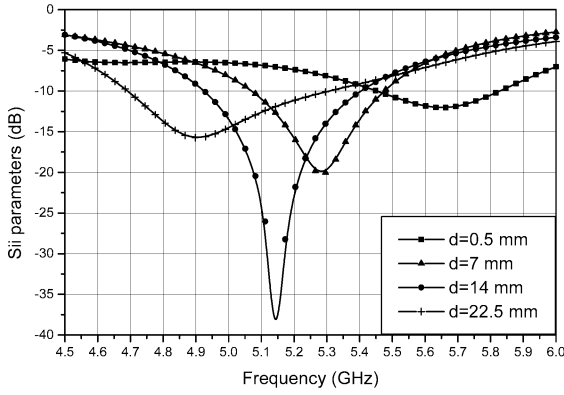


Fig. 8. The S_{ii} parameters of placement A for different separation distances (d) under a combining/MIMO scheme.

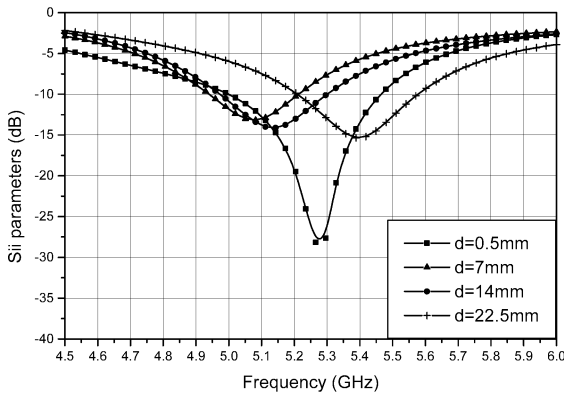


Fig. 9. The S_{ii} parameters of placement B for different separation distances (d) under a combining/MIMO scheme.

The same configuration was also examined under a combining/MIMO scheme, that is to say, when the first element radiates, the second one is terminated to a $50\text{-}\Omega$ impedance. The S_{ii} parameters are depicted in Fig. 5, where a bandwidth of over 8% and a frequency shift of approximately 150 MHz relative to the switched diversity case can be observed, due to the different termination impedance of the nonradiating element. In Fig. 6, the gain patterns of the two IFAs are displayed showing, as previously, their complementary performance that mainly occurs in the opposite direction compared to the switched diversity case.

The performance of the antenna system of Fig. 1(a) under the two diversity schemes was examined using the criteria stated in the second section and expressed in (1)–(6). The envelope correlation coefficient by means of mutual coupling and radiation patterns, as well as the mean effective gain ratio of the antennas are shown in Table I. The effective diversity gain of the system under maximum ratio combining is discussed in Section IV.

The MEG ratio in both cases is almost unity, indicating that the mean power delivered from each antenna branch is the same. The values for ρ_e obtained under the combining scheme differ, but this can be attributed to the fact that the mutual coupling approach is just a quick method to calculate ρ_e from the antenna terminal characteristics during the design process without taking into account the radiation patterns and the statistics of the channel. The comparison of the two diversity schemes exhibits the superior performance of the combining case, showing that the mutual coupling between the antennas when they are termi-

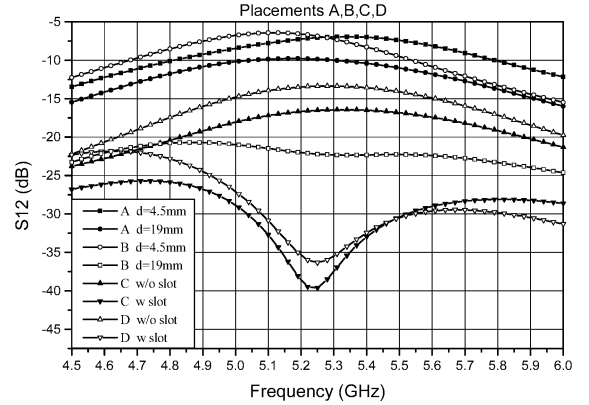


Fig. 10. The S_{12} parameters for various antenna placements under a combining/MIMO scheme.

nated in $50\text{-}\Omega$ impedances decreases the correlation of the received signals. This phenomenon was first reported in [19] and, recently, in [8].

IV. ANTENNAS' PLACEMENT EFFECT ON SYSTEM'S PERFORMANCE

The impact of the antennas' orientation, their separation distance and the slotted ground plane on the performance of the system, is investigated for the four placements at the edge of the ground plane depicted in Fig. 7, where the antenna elements are matched for each placement separately. The antennas illustrated in Fig. 7(a) and (b) are matched for $d = 4.5$ mm and the S_{ii} parameters of these placements for different values of the separation distance d under a combining/MIMO scheme are illustrated in Figs. 8 and 9.

From these figures it can be observed that deeper resonances are achievable with placement A than with B. It is, also, apparent that an increase in distance d in placement A, results in a frequency shift to the left of the ISM band, which corresponds to an increase of the electrical length of the elements, while on the contrary, increasing d in placement B results in a decrease of their electrical length.

The increased mutual coupling under a combining/MIMO scheme, besides its beneficial decorrelation effect stated in the former section, results on the contrary, in a reduction of the efficiency and the MEG of the antennas [1]. In order to reduce mutual coupling, a slow wave structure can be introduced between the two elements in order to effectively decrease the wavelength of the signal in the antenna's vicinity and thus increase the number of wavelength separation between the elements. In this letter, a corrugated ground plane [20] with four fingers was found to exhibit a comparable isolating performance with a single $\lambda/4$ slot [Fig. 7(c), (d)], thus forming a preferable option due to the restricted available space. The S_{12} parameters of the antenna elements for the various configurations depicted in Fig. 10 indicate that the antenna placement is a very critical issue for the mutual coupling reduction and that the use of the $\lambda/4$ slot can reduce the S_{12} below -35 dB, allowing the dual antenna system to be used as a duplexer as well.

Antenna placement plays also an important role on the radiation pattern's performance. Fig. 11 depicts this performance for

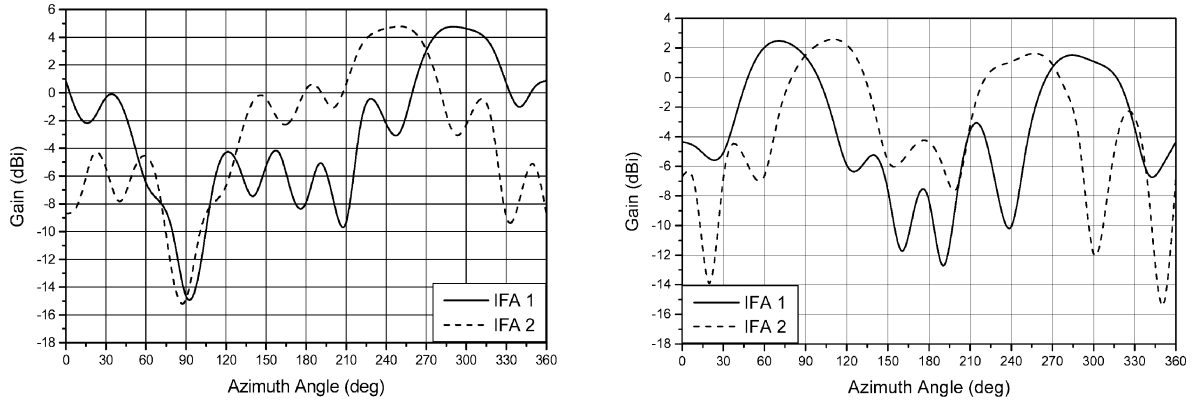


Fig. 11. Antenna gain patterns at the azimuth plane for placement B ($d = 19$ mm) and C with slot.

TABLE II
MEAN EFFECTIVE GAIN, EFFICIENCY, ENVELOPE CORRELATION COEFFICIENT
AND EFFECTIVE DIVERSITY GAIN AT 1% OUTAGE PROBABILITY UNDER
MAXIMUM RATIO COMBINING FOR VARIOUS ANTENNA PLACEMENTS

Placement	MEG ₁ (dBi)	Antenna efficiency %	ρ_e	MEG ₁ /MEG ₂	Effective Diversity Gain (dB)
A $d=4.5$ mm	-5.72	72	0.069	1.005	6.0
A $d=19$ mm	-4.84	81	0.025	1.000	6.9
B $d=4.5$ mm	-4.78	61	0.030	1.002	7.1
B $d=19$ mm	-3.29	85	0.016	1.004	8.4
C without slot	-4.28	89	0.085	0.999	7.2
C with $\lambda/4$ slot	-4.45	91	0.057	0.999	7.2
D without slot	-4.67	87	0.084	0.933	7.1
D with $\lambda/4$ slot	-4.17	89	0.032	0.981	7.6

placements B ($d = 19$ mm) and C with slot. In the first case, a deep null can be observed for both antennas in a 30° azimuth window, which can be avoided with the second placement.

Table II presents a comprehensive description of the diversity performance for each placement of Fig. 10. It can be observed that all systems easily fulfill the diversity criteria (6), demonstrating though different values for antenna efficiency and effective diversity gain. Regarding the efficiency, the highest value (91%) is observed in placement C with $\lambda/4$ slot, while the third system (B $d = 4.5$ mm) exhibits the lowest one (61%). This is attributed to the small distance between the antenna ports and not to losses due to mismatch. Regarding the effective diversity gain, the fourth system (B $d = 19$ mm) exhibits the best performance with 8.4 dB of effective diversity gain, whereas the “worst” case is the first one (A $d = 4.5$ mm) with 6 dB gain. The 2.4 dB difference in effective diversity gain as well as the 30% variation in antenna efficiency are considerable values that impel us to consider the antenna placement effect in the design of a highly efficient antenna diversity system.

V. CONCLUSION

Dual branch antenna diversity systems for wireless terminals operating in the 5.2-GHz ISM band under switched and combining schemes have been presented. The proposed diversity systems consist of two printed inverted-F antennas, which have compact size, large bandwidth, omnidirectional radiation patterns, no additional cost, are easily tuned, and exhibit a hybrid space-pattern diversity. The use of a corrugated ground plane can greatly reduce mutual coupling between antenna ports, allowing the system to be used as duplexer as well. The diversity performance was evaluated by means of the calculated envelope

correlation coefficient, mean effective gain ratio, and effective diversity gain under maximum ratio combining at the 1% outage probability level. Although all the investigated configurations provide uncorrelated signals of the same power level, they exhibit different radiation pattern complementarity, antenna efficiency (61%–91%) and effective diversity gain (6–8.4 dB). This shows that antennas’ placement has a critical impact on the performance of the system and that the selection of the optimum configuration cannot be based on a single figure of merit.

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