Design and Performance Investigation of a Dual-Element PIFA Array at 2.5 GHz for MIMO Terminal

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Abstract—A study is described of a modified planar inverted-F antenna (PIFA) operating in 2.5 GHz band on a printed circuit board (PCB) of a mobile phone handset. The antenna dimension is reduced substantially with a miniature ground plane and capacitive loading. While inheriting the attractive features of PIFAs, such as low profile, easy fabrication and low cost, the proposed antenna exhibits low coupling to the PCB. A dual-element PIFA array is implemented on a mobile handset PCB and the diversity performance of the dual-element PIFA array is evaluated in both simulation and measurement.

Index Terms—Diversity gain, multiple input multiple output (MIMO), mutual coupling, planar inverted-F antenna (PIFA).

I. INTRODUCTION

MULTIPLE INPUT multiple output (MIMO) systems have attracted a considerable research interest as a practical approach to achieving significant increases of wireless channel capacity. Theoretical and experimental investigations have revealed substantial improvements in data throughput and reliability in rich scattering environments when multiple transmitter and receiver antennas are deployed [1], [2]. However, several practical aspects pose challenges for achieving the predicted high data rates and coverage [3], [4]. One of the most important aspects is that the antennas need to be small enough to be accommodated on a mobile terminal, while having low coupling between them in order to have good diversity performance and high channel capacity. A number of parameters, such as mean effective gain (MEG), correlation coefficient, mutual coupling and diversity gain have been defined to describe the performance of a multielement antenna array in a mobile terminal [5].

Separation between multiple antenna elements is the most critical parameter affecting mutual coupling. Analytical studies have shown that for minimal or no mutual coupling, the distance between typical antenna elements needs to be at least half wavelength [6]. A dual-element planar inverted-F antenna (PIFA) array operating in 5.2 GHz band with a separation of less than half wavelength (20 mm = 0.35 wavelength) was designed to obtain an isolation better than 28 dB and correlation less than 0.01, as presented in our previous studies [7], [8]. It is noticed that mutual coupling depends on the frequency of received/transmitted signals since the distance is expressed in terms of the wavelength. Therefore, a dual-element PIFA array operating at the lower frequency (2.5 GHz band) with an even closer separation (0.17 wavelength) has been studied in this paper. The configuration is the same as that operating in the 5.2 GHz band, while the length of each element has been increased in order to obtain the resonant frequency of 2.5 GHz. Its characteristics and diversity performance are evaluated in simulation and measurement.

II. ANTENNA DESIGN

The modified PIFA with a small ground plane constitutes a stand alone structure, as shown in Fig. 1(a). It was made by bending a strip of copper to a rectangle with a slit which acts as capacitive loading. The antenna is fed by a coaxial cable from the bottom of the rectangle. Fig. 1(b) shows that two modified PIFAs are mounted on a FR-4 PCB substrate with gap. The coaxial feed of the PIFAs was drilled through the bottom of the rectangle. The modified PIFA and the PCB so that the coaxial cable does not contact the PEC. The ground plane, as small as the antenna, is located between the PIFA and the PCB and so the PCB is no longer a ground plane for the PIFA. The mechanical support of the modified PIFA can be further enhanced if a low dielectric or air equivalent solid former is used.

Computer-aided design (CAD) was carried out by using the Computer Simulation Technology (CST) Microwave Studio package, which utilizes the Finite Integral Technique (FIT) for electromagnetic computation [9]. The performance of the modified PIFA is dependent on a number of design parameters, such as antenna height, length, width, shorting plate, and slit. The optimized dimensions of the modified PIFA operating in 2.5 GHz band are: L = 23 mm, W = 5 mm, H = 4 mm, and S = 0.5 mm. The optimal gap between the small ground plane and the PCB is 1 mm (gap = 1 mm). The thickness of the copper sheet is 0.35 mm. A 50Ω RG405 coaxial cable (d = 0.51 mm, D = 1.7 mm, εr = 2.1) is used as the feed of the proposed PIFA. The two PIFAs are placed 20 mm (0.17 wavelength) apart on the PCB.

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III. CHARACTERISTICS OF A MODIFIED PIFA

A prototype of the modified single PIFA, as shown in Fig. 2, was fabricated and mounted on the PCB in the Antenna Measurement Laboratory at Queen Mary, University of London (QMUL). A HP8720ES vector network analyzer was used to measure the return loss in an anechoic chamber. Fig. 3 shows the simulated (dotted curve) and measured (solid curve) return losses. The measured centre resonant frequency of the single PIFA is at 2.49 GHz, which is 0.02 GHz higher than the simulated one (2.47 GHz). This is due to the imperfection during the fabrication process of small antennas. The measured 10 dB bandwidth (52 MHz) is slightly narrower than the simulated one (61 MHz).

The radiation patterns of the prototype PIFA were measured inside an anechoic chamber with the transmitting field provided by a quad ridge horn with dual-polarization capability. Fig. 4 and Fig. 5 show the simulated and measured radiation patterns of the modified PIFA at the resonant frequency of 2.5 GHz. Generally speaking, the measured patterns are in good agreement with the simulated patterns, and are like the typical ones of the conventional PIFAs. The ripples in the measured radiation patterns are due to the effect of the long and bent feeding cable used in the measurement.

The radiation patterns in Fig. 4 are plotted along the XZ-plane. They are asymmetrical in the positive and negative X-directions. There are stronger cross-polarized radiations between 210 and 270 degrees in comparison with the angles from 90 to 150 degrees which is the region below the PCB. However, in the region above the PCB, the radiation on the left-hand side (i.e., between 270 to 360 degrees) is slightly stronger than that on the right-hand side (i.e., between 0 to 90 degrees). This is due to modified PIFA being placed in the right corner of the PCB and more room for the coupled current flow on the left of the modified PIFA.

Fig. 5 shows the radiation patterns plotted along YZ-plane, which are close to an omni-directional pattern in both simulation and measurement. Like radiation patterns of a conventional PIFA, there are less radiation gains on the back of the PCB (the radiation patterns from 90 to 270 degrees). The discrepancies between the measurement and simulation are mainly due to the long and bent coaxial feed cable as mentioned earlier. These results verify the computer model of the antenna and have given us confidence to carry out a further simulation study.

The effect of the slit (S) on the modified PIFA was studied. The simulation shows that the slit strongly affects the resonant frequency. As shown in Fig. 6, the narrower slit the lower resonant frequency. The slit is a capacitive load for the modified
PIFA and by reducing the slit to 0.1 mm, the dimension is reduced to 5 mm × 17 mm × 4 mm for operating in 2.5 GHz. However, the capacitive load reduces the resonant frequency at the expense of bandwidth and impedance matching, as analysed in [10].

The characteristics of the conventional PIFA, such as return loss, bandwidth and gain at the frequency of interest, strongly depend on the ground plane size [11], [12]. When the size of the PCB in a handset is changed the PIFA has to be redesigned. So, further simulations were conducted to check the dependence of the modified PIFA on the main PCB (which for this antenna is no longer the ground plane). It has found that the fluctuation of the resonant frequency is less than 3 MHz, and therefore the changes of the PCB’s size do not affect the modified PIFA performance due to its self-contained structure.

The RF current induced by the modified PIFA on the PCB is observed in simulations, as shown in Fig. 7. It is found that the RF current is localized underneath the antenna on the PCB, and the coupling between the PCB and the modified PIFA is dramatically reduced. The flexibility and current reduction on the PCB of the proposed PIFA operating in 2.5 GHz band corresponds to those operating at 5.2 GHz [7]. This gave us an increased confidence to implement more PIFAs on the PCB operating in 2.5 GHz band.
Fig. 6. Return losses for different slit sizes of the modified single PIFA.

IV. CHARACTERISTICS OF THE DUAL-ELEMENT PIFA ARRAY

The modified dual-element PIFA array was fabricated in the Antenna Measurement Laboratory at QMUL. Both PIFAs are placed 2 mm from top and 5 mm from side on the PCB with a separation of 20 mm, as shown in Fig. 8. The S-parameters were measured and compared to the simulation results in Fig. 9. The simulated return losses of both PIFAs are identical due to the symmetric configuration. The measured return loss of Antenna 1 is slight difference from that of Antenna 2. This is caused by the imperfection in the fabrication of two PIFAs. It is also shown in Fig. 9 that an isolation (S12) better than 20 dB can be achieved in both simulation and measurement. Overall, there are less than 5 dB difference between the simulation and measurement within the frequency band from 2.4 to 2.6 GHz.

A conventional dual-element PIFA array with the same length (L), width (W), the same location, and the same size of the PCB as those of the modified dual-element PIFA array was modelled for comparison. The height is 1.5 mm higher than that of the modified PIFAs in order to achieve 2.5 GHz operating frequency and the PCB was acting as the ground plane, i.e., the small ground plane and the slit being removed from the modified PIFA model. The S-parameters of the dual-element conventional PIFA array are shown in Fig. 10. The isolation between the two elements is now less than 8 dB, which is 12 dB worse compared to that of the modified dual-element PIFA array. This is primarily due to more RF current coupled to the PCB in the conventional PIFA. In contrast, the small ground plane in the modified PIFA acts as part of the radiator and so reflects most of the radiation back towards the PIFA. Consequently, there is only a little current coupled to the PCB, and, hence, better isolation is obtained.

The 3-D radiation patterns (total E-field) of Antennas 1 and 2 at the resonant frequency of 2.5 GHz were measured in a Satimo chamber at Sony Ericsson Mobile Communications AB, as shown in Fig. 11. It is noticed that the radiation patterns of Antennas 1 and 2 are complementary to each other when both antennas were mounted on the PCB. Hence, the dual-element PIFA array has shown a good pattern diversity characteristic.

V. DIVERSITY PERFORMANCE EVALUATION OF THE DUAL-ELEMENT PIFA ARRAY

Diversity performance is one of most important measures of multiple antennas for mobile terminals. In this section, the antenna diversity technique and statistical propagation models are briefly addressed, and the diversity performance of the dual-element PIFA array is evaluated in terms of correlation, MEG and selection combiner diversity gain.

A. Antenna Diversity Analysis

For a selection combiner with N independent antennas, assuming that the N antennas have independent signals (correlation equal to zero) and equal mean SNRs, the probability of all antennas having a SNR below the given threshold is defined as

\[ P(\gamma < \gamma_s / \Gamma)_N = \left( 1 - e^{\frac{-\Delta}{\Gamma}} \right)^N \]  

where \( \Gamma \) is the mean SNR, \( \gamma \) is the instantaneous SNR, \( P(\gamma < \gamma_s / \Gamma) \) is the probability that the SNR will fall below the given threshold, \( \gamma_s / \Gamma \). In this ideal case, the diversity gain for two antennas with 100% efficiency using a selection combiner is 10 dB with \( P(\gamma < \gamma_s / \Gamma) = 1\% \), where the radio link reliability is 99%. In order to achieve the diversity gain as high as the
ideal case, the received signals from two antennas must have low correlations and the power levels of the signals received by the two antennas must not be too different in the diversity system in a multipath environment [13].

The correlation coefficient of the received signals can be characterized by the envelope correlation coefficient in a Rayleigh fading environment, \( \rho_c \), which approximately equals to \( |\rho_c|^2 \) (\( \rho_c \) is the complex correlation coefficient). The complex correlation is computed as follows [14]:

\[
\rho_c = \frac{\int_0^{2\pi} \int_0^{\pi} A_{12}(\theta, \phi) \sin \theta d\theta d\phi}{\sqrt{\int_0^{2\pi} \int_0^{\pi} A_{11}(\theta, \phi) \sin \theta d\theta d\phi \int_0^{2\pi} \int_0^{\pi} A_{22}(\theta, \phi) \sin \theta d\theta d\phi}} \tag{2}
\]

where \( A_{mn} = XPR \cdot E_{\delta,m}(\theta, \phi)E_{\phi,m}^*(\theta, \phi)P_{\theta}(\theta, \phi) + E_{\phi,m}(\theta, \phi)E_{\delta,m}^*(\theta, \phi)P_{\phi}(\theta, \phi) \), in which \( E \) denotes the electric far field of the antenna and \( XPR \) is the ratio of averaged vertical power to time average horizontal power in the fading environment in linear form [15], [16].

The previous discussion of diversity gain in (1) assumed that independent signals are received on the diversity antennas, i.e., there is no correlation between the signals received where \( \rho_c = 0 \). However, it is clear that in the majority of cases for a portable receiver this cannot be achieved because of insufficient antenna spacing. If the correlation coefficient is bigger than zero (\( \rho_c > 0 \)), then the diversity gain will be reduced.

Hence, the correlation coefficient must be kept low enough so that the diversity is still effective. The effects of envelope correlation on diversity gain can be found in [17]. The analysis shows that where the correlation is not too close to unity or \( \rho_c \leq 0.7 \), the degradation of the diversity gain due to envelope correlation is given by a factor defined as [17]

\[
DF = \sqrt{1 - \rho_c}. \tag{3}
\]

The other essential condition for high diversity gain is that the power levels of the signals delivered by the antennas in the diversity system must not be too different. One way of illustrating this is by using the ratio of two antenna power levels, \( k = \frac{P_{\min}}{P_{\max}} \) where \( P_{\min} \) is the power from the antenna with the lower power and \( P_{\max} \) is the power from the antenna with the higher power in each pair of antennas. An alternative method to obtain the antenna branch power ratio is derived from the MEG of the antennas as follows (assuming only two branches) [18]:

\[
k = \min\left(\frac{\text{MEG}_1}{\text{MEG}_2}, \frac{\text{MEG}_2}{\text{MEG}_1}\right). \tag{4}
\]
The following equation can be used to evaluate the MEG [13], [19]:

$$\text{MEG} = \frac{2\pi}{\text{XPR}} \int_0^\infty \int_0^\pi P_\theta(\theta, \phi)G_\theta(\theta, \phi)$$

$$\times \left[ \frac{1}{1 + \text{XPR}} P_\phi(\theta, \phi)G_\phi(\theta, \phi) \right] \sin \theta \, d\theta \, d\phi$$  \hspace{1cm} (5)

where $G_\theta$ and $G_\phi$ are the spherical power gain $(\theta, \phi)$ of the antenna, and $P_\theta(\theta, \phi)$ and $P_\phi(\theta, \phi)$ are the angular density functions of the incoming plane waves as used in (2). The ratio of the MEG between the two antennas must be close to unity to ensure high diversity gain.

Equation (1) is for the ideal case when $k$ is equal to unity. For a selection combiner the ratio of the powers delivered by the two antennas, $k$, is multiplied by the diversity gain to obtain a more realistic diversity gain [17]. Hence when $N = 2$, (1) becomes:

$$P(\gamma < \gamma_0 / T) = \frac{1}{k} \left( -\frac{\gamma_0}{T} \right)^2.$$  \hspace{1cm} (6)

### B. Statistical Propagation Models

In the multipath environment, the incident radio waves arriving at the mobile terminal antennas have various angles of arrival (AOA) and cross polar ratio (XPR). The AOA distributions (also defined as angular density functions) at both $\theta$ and $\phi$ polarizations and the cross polar ratio have an affect on the diversity performance of the antennas. As evident by the correlation (2) and MEG (5) aforementioned, the correlation coefficient and MEG is dependent on the multipath environment via the angular density functions $P_\theta(\theta, \phi)$ and $P_\phi(\theta, \phi)$. For simplicity, the angular density function are modelled in elevation and azimuth separately and combined according to

$$P_\theta(\theta, \phi) = P_\theta(\theta)P_\phi(\phi)$$

$$P_\phi(\theta, \phi) = P_\phi(\phi)P_\phi(\theta)$$  \hspace{1cm} (7)

where $P_\theta(\phi)$, $P_\phi(\phi)$ are the angular density functions in azimuth, and $P_\theta(\theta)$, $P_\phi(\theta)$ are the angular density functions in elevation for the $\theta$ and $\phi$ polarizations, respectively. For reference purposes, $\theta$ is the angle relative to the vertical axis $z$ and $\phi$ is the angle in the horizontal plane as shown in Fig. 12.

Generally speaking, the value of the cross polar ratio is reported between 4 and 9 dB at frequencies around 900 MHz in urban macrocell environment [20]–[22] from the mobile terminals to the base stations. A few different environments have been studied at 2.15 GHz and the cross polar ratio varied between 6.6 and 11.4 dB, being lowest for indoor environments and highest for urban microcell environments [23]. All these reported results have shown that the cross polar ratio is not constant due to varying frequencies and environments.

When a user of a mobile terminal moves along a random route, a uniform distribution is a reasonable assumption for the angular density functions in azimuth direction as was assumed in [19]. However, the angular density functions in the elevation direction are not uniformly distributed and the two most common distributions, i.e., Gaussian and Laplacian distributions are typically used [24].

In this paper, uniform distribution is assumed in the azimuth direction whilst Gaussian and Laplacian distributions are assumed in the elevation direction. Also, an isotropic environment is used for the purpose of comparison between the numerical model and the measurement. The values of AOA and XPR for each environment are same as those used in [5].

### C. Diversity Performance of the Dual-Element PIFA

The correlations for dual-element PIFA array are evaluated using (2) by means of the measured 3-D radiation patterns and statistical propagation models used in [5]. The results are summarized in Table I. The impact of the outdoor and indoor environments on the envelope correlation has been evaluated using two different statistical models as discussed early (i.e., Gaussian and Laplacian distribution). Table I shows that the envelope correlation of less than 0.3 (as evaluated by two different statistical models) has been achieved in both indoor and outdoor environments. These low correlation values will result in high diversity gains, as evident by (3) the degradation factors are small.

The MEG of each antenna within the different environments is evaluated using (5) and the results are also tabulated in Table I. It is noticed that the MEG values of each antenna within the different environments can vary up to 1.5 dB. The difference of the MEG values between Antenna 1 and 2 is less than 1 dB and these very similar MEG values are ideal to achieve a high diversity gain.

After assessing the correlation and MEG results, the diversity gain in an isotropic environment and more realistic environments such as indoor and outdoor environments are used to statistically assess the diversity performance of the dual-element PIFA array using a selection combiner. The diversity gain results have included the degradation factor (DF) from (3) due to the correlation and the branch power ratio (k) from (4). In
Fig. 13, it has been shown that selection combiner diversity gain of the dual-element PIFA array in Gaussian/Uniform and Laplacian/Uniform statistical models for both indoor and outdoor environments compared with those of two ideal antennas and a dual-element PIFA array in an isotropic environment, and a single antenna.

As predicted, the selection combiner diversity gain of the dual-element PIFA array in an isotropic environment are higher than that in indoor or outdoor environments using the Gaussian/Uniform or Laplacian/Uniform statistical models as shown in Fig. 13. However, the differences are very small. The selection combiner diversity gains in different environments using different statistical models have less than 1 dB variation. Therefore, the dual-element PIFA array can work well in different situations.

The dual-element PIFA array was also tested in a scattering field chamber at Sony Ericsson Mobile Communications AB to examine its diversity performance [25]. The scattering field chamber is a method to reproduce a 3-D isotropic random field environment by using three rotating stirrers and a phantom torso. The 4000 samples were measured in the chamber for the evaluation of the diversity gain. The measured results at 99% and 50% reliability compared to those calculated in an isotropic environment are tabulated in Table II. There is only 0.1 dB difference of selection combiner diversity gain between the measurement and calculations. This verified the previous numerical modeling and analysis.

### Table II

<table>
<thead>
<tr>
<th>Combining Methods</th>
<th>Diversity Gain at 99% Reliability (dB)</th>
<th>Diversity Gain at 50% Reliability (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection Combining (SC)</td>
<td>9.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Equal Gain Combining (EGC)</td>
<td>10.8</td>
<td>3.5</td>
</tr>
<tr>
<td>Maximum Ratio Combining (MRC)</td>
<td>11.0</td>
<td>3.6</td>
</tr>
</tbody>
</table>

As predicted, the selection combiner diversity gain of the dual-element PIFA array in an isotropic environment are higher than that in indoor or outdoor environments using the Gaussian/Uniform or Laplacian/Uniform statistical models as shown in Fig. 13. However, the differences are very small. The selection combiner diversity gains in different environments using different statistical models have less than 1 dB variation. Therefore, the dual-element PIFA array can work well in different situations.

### VI. Conclusion

A compact dual-element PIFA array on a PCB operating in 2.5 GHz band for the MIMO application has been studied in this paper. The PIFA elements used were modified by introducing a small ground plane between the PIFA and the PCB and a load slit to reduce the antenna size and influence of the PCB. The dual-element PIFA array has achieved low mutual coupling with more than 20 dB of isolation over the operating bandwidth. It has obtained a selection combiner diversity gain of around 9.5 dB at the 99% reliability in both numerical model and measurement. It also has been shown that the dual-element PIFA array can work well in different fading environments. Therefore, the proposed dual-element PIFA array on a handset PCB can be considered as a strong contender for MIMO applications.

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### REFERENCES


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