Polarization Diversity in UMTS Mobile Phones analyzed with Characteristic Modes

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***Abstract*—In this paper, we propose a novel approach to achieve polarization diversity in a realistic UMTS mobile phone. A modal analysis of a two-element Planar Inverted-F Antenna (PIFA) array over a realistic PCB of a mobile phone is performed to obtain the radiation behavior of the structure. According to the Theory of Characteristic Modes, the total surface current over the structure is the superposition of modal currents. The relative phase in which the elements are fed defines the modes to be excited. Five characteristic modes are computed in the 0.7-2.5 GHz frequency band and the radiation characteristics of these modes are studied. With in-phase feeding of PIFAs, only the modes with dominant surface current in the Y-direction are excited: radiated far field has vertical polarization. In the case of out-of-phase feeding of PIFAs, the X-oriented currents dominate and horizontally polarized electric field is radiated which has never been achieved yet in a realistic UMTS mobile phone at 2 GHz. For both feeding cases, the superposition of relevant modes is compared with the results obtained by the CST Microwave Studio.**

***Index Terms*—MIMO Systems, Mobile Antennas, Diversity methods, Characteristic Modes, Planar Inverted-F Antenna.**

I. Introduction

One of the major issues to be solved in mobile communications is the signal fading caused by a multi-path propagating environment. Using polarization or pattern diversity technique at the terminal side of the wireless link is a possible solution [1-6]. Although these techniques can be theoretically described, easily implemented and controlled for a regular-sized antenna positioned over a large ground plane, the situation is somewhat different if we deal with several small antennas integrated within a small communicating device. The small space devoted for the antennas in a smart phone or a PDA, the strong coupling between these radiating elements and the unintended coupling with nearby metallic components may drastically degrade the array capability. For example, pointing the main radiated beam in any specific direction might be difficult or quite impossible to achieve.

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Therefore, several attempts have been made to design electrically small antenna-systems for mobile phones with reconfigurable radiation pattern suitable for diversity and MIMO applications around 2 GHz [7-17] but so far, from the best knowledge of the authors, no attempt has been made yet to design antenna-systems for such realistic mobile phones with polarization diversity capabilities.

In this paper, we propose to address this issue. The starting point comes from the fact that at cellular frequency bands, the Printed Circuit Board (PCB) of a mobile phone is also an important radiating element of the system [18]. So, modifying the phase difference between two electrically small antennas over this PCB could have a strong influence on the flowing currents over the PCB and therefore on the associated radiation patterns of the whole structure. This effect could be helpful in trying to achieve different shapes and polarized radiation patterns.

In the past, we designed a two-antenna system operating in the UMTS band (1.92-2.17 GHz). The two Planar Inverted-F Antennas (PIFAs) were located at the top edge of a PCB whose size is representative of a typical bar mobile phone [19]. The measured results have been presented as well in our previous paper [20]. Here, the extended modal analysis (up to five significant modes) of this dual PIFA structure is performed using the Theory of Characteristic Modes (TCM) [21-25] to explain its radiation behavior. According to this theory, the overall surface current on the antenna-system may be decomposed into a set of orthogonal modal currents [26]. The radiation characteristics of the relevant modes are studied and combined to explain the polarization properties of the structure. Indeed, we theoretically analyze and demonstrate that changing the relative phase shift of the PIFAs can modify the polarization of the radiated far fields. Full wave simulations of one particular feeding configuration intended to achieve polarization diversity are presented to validate the TCM analysis. The method and concept might be extended to operate in different frequency bands and therefore could easily find applications in future cognitive and software defined radio systems.

II. MODAL ANALYSIS OF THE DUAL-PIFA STRUCTURE

The structure of interest is composed of a 100x40 mm^2 metallic ground plane acting as the PCB of the mobile phone. Two UMTS PIFAs are located at the top edge of this PCB (see Fig. 1) and are designed to operate in the UMTS band (1.92-2.17 GHz).

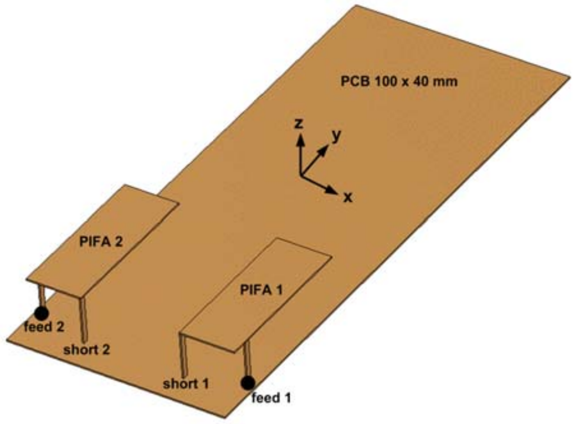


Fig. 1 3D View of the dual PIFA structure

Using the in-house Characteristic Mode analyzer [27-28], the proposed structure has been analyzed within the following frequency range: 0.75-2.5 GHz. Five modes have been found to be significant around the center frequency of interest (2 GHz). Their modal amplitudes $1/|1+j\lambda_n|$ are presented in Fig. 2 [25]. Those factors, which stay between 0 and 1, reflect the amount of contribution of a given mode to the overall current distribution. The higher order modes (higher than order 5) have much smaller amplitudes (<0.2) and thus are not taken into account in our analysis. Therefore, we will only use these five first modes to explain how different polarization states are achievable by the structure. The characteristic current distributions of the first five modes are shown through Figures 3 to 5 with the main directions of current schematically depicted by bold black arrows. The orientation of the current on the feeding strips is very essential as it determines the coupling coefficient (the reaction of the impressed electric field with modal current). Simply, the phase of the impressed excitation intensities should match the phase (orientation) of the modal currents in order to properly excite them.

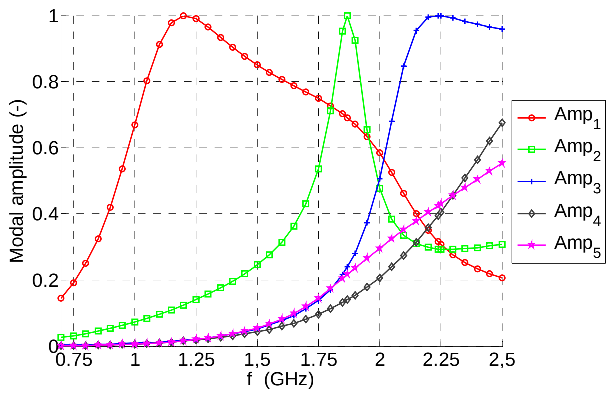


Fig. 2 Modal amplitudes $1/|1+j\lambda n|$ of the dual-PIFA structure. The frequency of interest is 2 GHz.

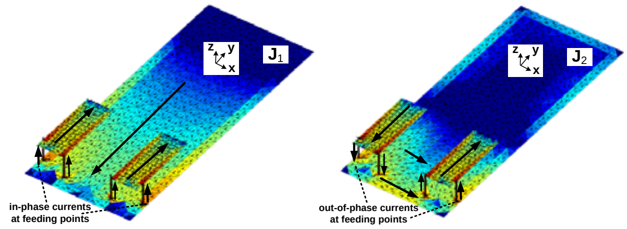


Fig. 3 Distribution of the characteristic currents $\mathbf{J}_1$ (left) and $\mathbf{J}_2$ (right) at 2 GHz

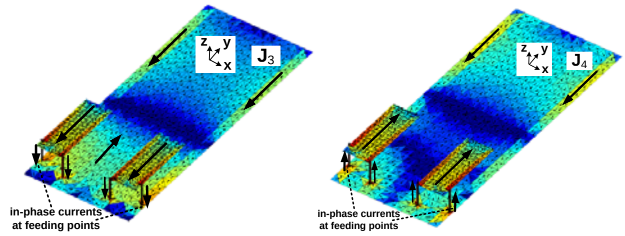


Fig. 4 Distribution of the characteristic currents $\mathbf{J}_3$ (left) and $\mathbf{J}_4$ (right) at 2 GHz

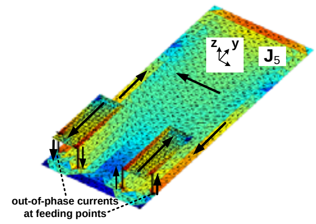


Fig. 5. Distribution of the characteristic current $\mathbf{J}_5$ at 2 GHz

Looking at the direction of the currents at the feeding points, it is easily observed that modal currents may be divided into two separate groups: $\mathbf{J}_1$, $\mathbf{J}_3$ and $\mathbf{J}_4$ excitable with in-phase signals and $\mathbf{J}_2$ and $\mathbf{J}_5$ excitable with out-of-phase signals. Modal decomposition gives us vivid physical insight into the two different polarization states attainable by different excitation scenarios. This is the key result illustrating the polarization diversity ability of this dual PIFA structure. To confirm this observation, modal far field patterns of both polarizations (vertical/horizontal according to the Ludwig-3 definition [29]) have been calculated. They are shown in Figure 6.

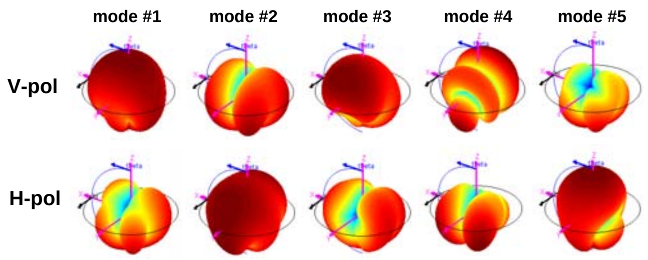


Fig. 6. Vertical (top) and horizontal (bottom) far field components of all the five modes at 2 GHz

III. COMPARISON OF MODAL APPROACH WITH CST

Both, the in-phase and out-of-phase excitation scenarios have been modeled in the full-wave simulator CST MWS [30] in order to confirm the TCM results of the realistic structure presented in Fig. 1.

A. In-phase excitation

In the case of in-phase excitation, $\mathbf{J}_1$, $\mathbf{J}_3$ and $\mathbf{J}_4$ are dominant and excites vertical component of the far-field (D_{max} = 4.3 dBi), see Fig. 7.

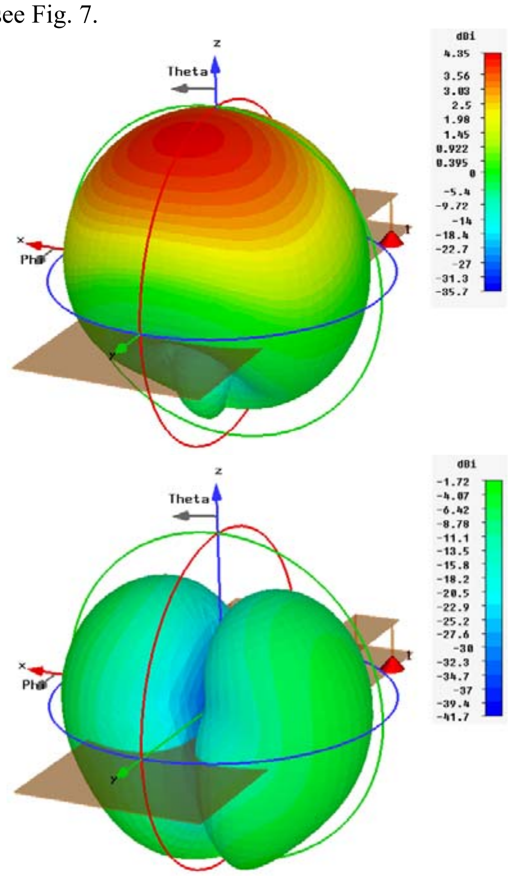


Fig. 7. Vertical (top) and horizontal (bottom) far field components at 2 GHz for in-phase excitation

B. Out-of-phase excitation

Here, $\mathbf{J}_2$ and $\mathbf{J}_5$ are dominant and excite horizontal component of the far-field (D_{max} = 2.9 dBi), see Fig. 8.

The radiation patterns obtained in Figures 7 and 8 fully support the modal analysis results. $\mathbf{J}_1$, $\mathbf{J}_3$ and $\mathbf{J}_4$ currents are mostly Y-directed and so the far-field polarization purity is quite good (Fig. 7). On the opposite, $\mathbf{J}_2$ and $\mathbf{J}_5$ distributions are a little bit more complicated, with J_x sources located mainly between the PIFAs. There is also considerable presence of J_y currents on the PCB. This explains the reason of worse polarization purity and gain loss for the horizontal component (Fig. 8). Fortunately, J_y components of $\mathbf{J}_2$ and $\mathbf{J}_5$ flowing on both PIFA's plates have opposite directions, canceling each other (as seen from figures 3 right and 5). Finally, modal superposition for both polarization states has been performed using voltage-gap excitation placed at the feed positions. For in- and out-of-phase excitations, the total currents may be expressed as Eq. 1 where coefficient a_4 is negligible and Eq. 2.

$$\boldsymbol{J}_{in} \cong a_1\boldsymbol{J}_1 + a_3\boldsymbol{J}_3 = 9.8\mathrm{e}^{-j56^\circ}\boldsymbol{J}_1 + 13.5\mathrm{e}^{j56^\circ}\boldsymbol{J}_3 \quad (1)$$

$$\boldsymbol{J}_{out} \cong a_1\boldsymbol{J}_2 + a_5\boldsymbol{J}_5 = 12.5\mathrm{e}^{-j64^\circ}\boldsymbol{J}_2 + 2.9\mathrm{e}^{-j93^\circ}\boldsymbol{J}_5 \quad (2)$$

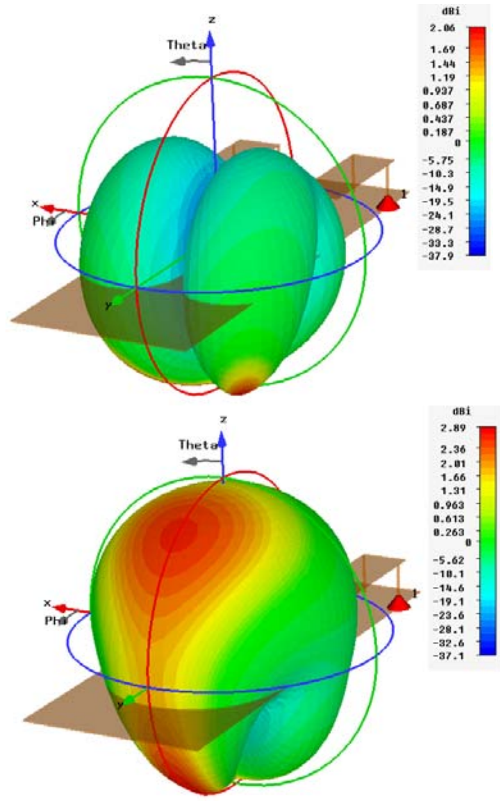
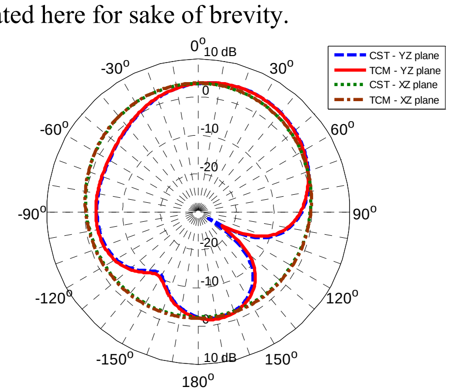


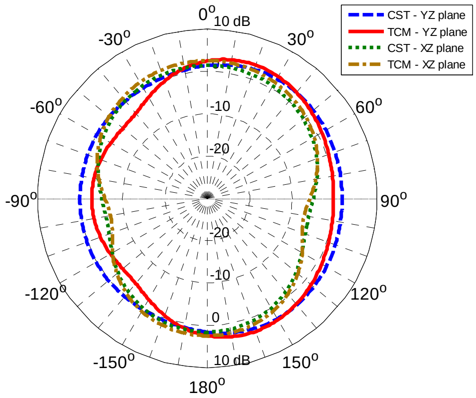
Fig. 8. Vertical (top) and horizontal (bottom) far field components at 2 GHz for out-of-phase excitation

Using the superposed currents $\mathbf{J}_{in}$ and $\mathbf{J}_{out}$, we are now able to calculate the corresponding radiation patterns of both feeding states and compare them to the CST results (Fig. 9). Very good agreement is achieved even for quite low number of modes used for expansion.

A prototype which partially validates the theoretical approach developed here was fabricated and measured for two polarization states only: in-phase and out-of-phase PIFAs on a UMTS mobile phone radiating respectively vertically and horizontally polarized far field patterns. This limited case to two states only was already published in [20] without the general approached developed in this paper and therefore, it is not repeated here for sake of brevity.



(a)



(b)

Fig. 9. Comparison of CST and TCM farfields cuts at 2 GHz (superposition of two modes for each polarization) – (a) vertical and (b) horizontal

IV. Conclusion

In this paper, the radiation characteristics of a dual PIFA structure for practical UMTS mobile phone was theoretically studied using modal decomposition. Such antenna-system is able to radiate vertically or horizontally polarized fields depending on the relative phase between the feeding points of each radiator. Observed polarization diversity was analyzed and fully explained by the theory of characteristic modes. Two groups of modes were identified, one for vertical polarization and the other for horizontal polarization. The decomposition into orthogonal modes provided very useful insights into antenna behavior and was used to tune the properties of each polarization separately. The theory was verified in a previous publication. This new kind of structure truly opens the field of polarization diversity and MIMO at 2 GHz for realistic smartphones. The method and concept might be extended to operate in different frequency bands.

Acknowledgements

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