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Design of MIMO Terminal Antennas with User Proximity Using Characteristic Modes

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***Abstract*— Although the classical Theory of Characteristic Modes allows an arbitrary structure to be analyzed prior to the implementation of physical feeds, structures containing dielectrics have so far received very little attention. Recently, a mesh perturbation method is proposed to remove internal resonances from the characteristic mode (CM) solution for lossy dielectrics obtained using the computationally efficient surface integral equation. Herein this method was applied to extract the CMs of a lossy structure consisting of a terminal chassis held in a user hand. These modes were then individually analyzed and a subset was chosen to design a MIMO antenna with not only very low correlation, but also low hand-induced losses.**

Index Terms—Terminal antennas, characteristic modes, user interaction, MIMO system.

I. Introduction

Today's smartphones are primarily used for high data rate communications. A recent study found that more than 94% of data access on smartphones involves close proximity to human tissue (e.g., a hand) [1]. However, conventionally terminal antennas are first constructed using standard free space design methodologies, and then tuned to work well for a set of predefined user interactions. This approach presents a significant loss in performance of what could be achieved in mobile terminal antennas, since the user consideration is an afterthought in the design process.

Proximity of human tissue has several adverse effects on a terminal antenna, including decreased efficiency from detuning and absorption, as well as a possible increase in envelope correlation coefficient (ECC) for multi-antennas. Some previous studies have aimed to mitigate these effects through parametric optimization [2], ground plane current reduction [3], and adaptive matching [4]. However, there is no method to design antennas in the presence of lossy dielectrics that shows where, and how, to place antenna feeding elements to obtain low correlation and high efficiencies.

In this paper, a recent extension of the Theory of Characteristic Modes (TCM) [5] is used to design MIMO terminal antennas in the presence of lossy dielectrics. Using this extension, it is possible to analyze a terminal chassis for optimal feed design and feed placement in the presence of lossy dielectrics prior to designing and implementing the excitation structures. This design technique presents optimal locations to excite specific chassis modes, which are chosen based on the total amount of current that is excited within a lossy dielectric. This technique minimizes the effect of human body tissue when placed in close proximity to terminal antenna structures, allowing for decreased ECC while maintaining high efficiencies.

II. Extended Characteristic Mode Analysis

The current method of designing antennas using TCM does not allow a chassis to be simulated in the presence of dielectrics. All previous work to develop mobile terminal antennas using TCM techniques is based on the theory described in [6]. Due to limitations in the original work, the basic theory on characteristic modes was expanded upon in [7] to produce a more general eigenvalue problem to handle dielectrics as well as losses

$$(X_v + X_m)\,(J_n) = \lambda_n\,(R_v + R_m)\,(J_n), \qquad (1)$$

where J_n is the characteristic current, X_v and R_v are the real and imaginary components of the complex impedance operator based only on the shape of the structure; X_m and R_m are similar but based on the relationships between all physical quantities.

However, the characteristic modes (CMs) obtained using (1) provide characteristic far-fields that are not fully orthogonal [7]. Secondly, although (1) may be solved using the volume integral equation (VIE) method to provide real and excitable modes, the use of VIE is not computationally practical. Conversely it is possible to solve (1) using the surface integral equation (SIE), which greatly reduces the number of unknowns. However, solving for the CMs using SIE produces an extensive number of internal resonances, which are non-excitable and non-radiating modes [8].

In this work, the non-orthogonal, non-excitable modes are eliminated in three steps. First, we apply the mesh perturbation technique in [5] to remove non-excitable modes from the solution set. Second, all remaining far-fields are cross-correlated using the standard far-field ECC equation to identify excitable modes which are highly correlated to one another. Only one of any of these correlated modes should be retained, and this mode can be determined by means of calculating the total radiated power of each mode, i.e., the correlated mode with the highest radiated power should be kept. The remaining uncorrelated modes can then be excited using CM feed analysis. Finally, the selected modes with highest far-field efficiency, will pertain to the most efficient modes when perfectly excited. However, the most efficient mode of the system may not be excitable, as the excitation currents must be isolated to the terminal chassis, and not the surrounding dielectric medium. Therefore, once the final set of usable modes has been obtained, the modes with the highest current contribution on the chassis can be excited, with greater efficiency than modes with high current distribution within the lossy medium. If the selected modes can be properly fed, user influence can be mitigated and high efficiency, low correlation antennas can be implemented.

III. Chassis and CTIA Hand Analysis

To demonstrate the benefits of the described technique, a typical terminal antenna chassis in the presence of a CTIA standard hand model was analyzed. The chassis measured 136 mm × 66 mm and it was placed in the hand model as shown in Fig. 1. Using the SIE method in FEKO 7.0 as well as an in-house Matlab code, 76 different modes with eigenvalues between -20 and 20 were obtained for a mesh size of 0.01 wavelengths at 850 MHz. Using the three-step procedure above, the number of CMs was reduced to 14 modes, six of which are related to at least one other mode with an ECC greater than 0.25.

The remaining 8 modes were analyzed and sorted by the percentage of current in the CTIA hand (relative to the entire structure of terminal chassis and hand). The mode with the lowest percentage of current in the CTIA hand is referred to as mode 1, whereas the mode with the highest current is referred to as mode 8. The most efficient mode (mode 1), as shown in Fig. 1(a), yields less than 20% of the total current in the hand, whereas mode 6, as shown in Fig. 1(b), yields more than 60% of the total current in the hand.

Through isolating the near-fields around the metallic chassis, a nominal feeding position can be found for each mode using the method described in [9]. The near-fields were analyzed at 4 mm below the chassis and 4 mm above the chassis in the X axis. This resulted in locating appropriate electric and magnetic field feeding positions. The analysis shows high coupling occurs between feeds if both modes 1 and 2 were excited using coupling elements. However, modes 1 and 3 could be excited without significant cross coupling. Near-fields of mode 1 show high Z-directed electric fields in position 1 of Fig. 1(a) and low Z-directed fields in position 1 of Fig. 1(a), demonstrating that a Z-directed capacitive coupling element (CCE) could be placed along the top of the chassis. Near-fields of mode 3 showed high Y-directed electric fields in position 2 of Fig. 1(a) and low Y-directed fields in position 2 of Fig. 1(a), demonstrating that a Y-directed CCE could be placed along the side of the chassis. Exciting the chassis at the stated locations allows for two antennas with high efficiency and uncorrelated far-field patterns to be created in close proximity to a human hand.

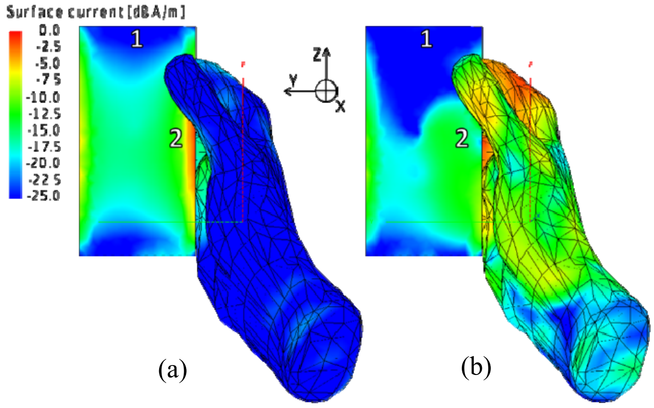

Fig. 1. Surface currents of (a) mode 1 and (b) mode 6 for the terminal chassis in the presence of a CTIA hand model.

IV. Verification of CM Analysis

The described two-port terminal antenna was simulated and matched in CST 2016 (see Fig. 2 for the simulation model). Mode 1 was fed using a 66 mm × 8 mm CCE spaced 1 mm from the top of the chassis (port 1). Mode 3 was fed using a 56 mm × 8 mm CCE centered at position 2 in Fig. 1(a), with an offset of 1 mm from the side of the chassis (port 2). The feed position was optimized and a parallel lumped element was used to match both feeds. Mode 1 was matched with a feed offset (from the center of the CCE) of 31 mm and a parallel 4.3 nH Murata inductor. Mode 3 was matched using a 27 mm feed offset and a parallel 6.5 nH Murata inductor. Both elements maintained a reflection coefficient (S_{11}/S_{22}) in the CTIA hand and in free space of below -10 dB and -7 dB respectively from 824 to 896 MHz (covering LTE Band 5) in CST simulations. The maximum simulated ECC within the band was 0.12. The average efficiencies for modes 1 and 3 were found to be 52% and 29% from 824 to 896 MHz.

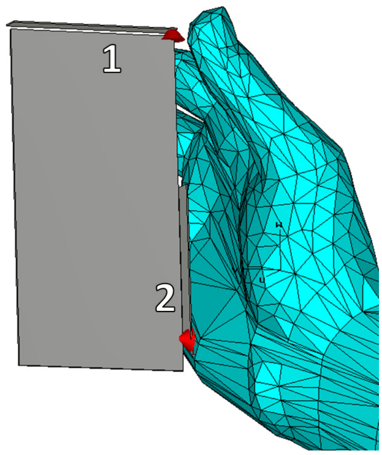

Fig. 2. Terminal chassis with the two feeding elements (ports 1 and 2) and the presence of the CTIA hand model.

V. CONCLUSION

This work proposes a method to design MIMO terminal antennas that explicitly account for the presence of a user hand based on a recent extension to the classical TCM. Future work includes measurement verification as well as the study of practical issues such as variations in hand grip style.

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