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Systematic Design of MIMO Terminal Antennas Using Theory of Characteristic Modes

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Abstract—The Theory of Characteristic Modes (TCM) offers a natural and systematic way to design Multiple-Input Multiple-Output (MIMO) antennas with high total efficiency and uncorrelated antenna patterns. In this paper, recent advances in the growing field of TCM-aided MIMO antenna design are reviewed. In particular, the focus is on the challenging problem of designing MIMO antennas for compact mobile terminals below 1 GHz. It was found that low correlation can be achieved by allowing only one antenna to excite the single-mode terminal chassis. However, this led to small bandwidths for other antennas. To improve the bandwidth performance, the chassis could be slightly modified to support multiple excitable modes, which can give larger bandwidths for the multi-antennas designed to couple into these modes.

Keywords—MIMO systems; mobile antennas; mutual coupling; correlation; capacity; Theory of Characteristic Modes

I. INTRODUCTION

Multi-antennas are mandatory in Long Term Evolution (LTE) terminals to provide Multiple-Input Multiple-Output (MIMO) operation [1]. However, in order for MIMO technology to deliver the ideal performance benefit of linear capacity (“data rate”) increase with the number of antennas used, the physical multi-antenna channels must be of sufficient channel gain and mutually uncorrelated. In a rich multipath environment, this translates to the multi-antenna requirements of high total antenna efficiency and low pattern correlation.

Designing highly efficient and uncorrelated MIMO antennas is very challenging for today’s mobile terminals, since their compactness as well as constraints in antenna size and location can lead to high mutual coupling and correlation among the multi-antenna elements. This problem is especially severe for antennas operating at frequencies below 1 GHz, since the entire terminal is electrically compact and the antenna elements are electrically close to one another [1]. Moreover, the chassis has only one resonant mode, i.e., fundamental (or flat dipole) mode. The small antenna elements can easily excite the fundamental mode of the chassis, since they are often placed at the shorter ends of the chassis for practical reasons, corresponding to regions of high electric fields of this mode [2]. The excitation of the same chassis mode by multiple antenna elements results in very severe coupling and correlation, which degrades MIMO performance.

To counteract the chassis-induced coupling problem, the

Theory of Characteristic Modes (TCM) [3], [4] was utilized to allow only one antenna (i.e., main antenna) to couple into the fundamental chassis mode [2], [5], [6]. This strategy was successfully implemented in three different ways, i.e., by: (1) optimizing the multi-antenna positions on the chassis [2], (2) localizing the current to the antenna elements [5], and (3) utilizing a magnetic antenna at a shorter chassis edge [6]. Even though this strategy is effective in reducing the chassis-induced coupling, the resulting bandwidth of the antennas that do not excite the chassis is relatively small, e.g. 20 MHz at the 6 dB impedance bandwidth. Even though frequency tuning can be applied to cover larger bandwidths [6], additional tuning circuits are required and higher losses can be expected.

Apart from only allowing only one antenna to excite the single chassis mode, chassis-induced coupling can also be avoided if different resonant modes can be excited by the antennas. This is because these modes are mutually orthogonal. Indeed, this approach was demonstrated to be effective for designing uncorrelated MIMO antennas at the higher frequency of 2.4 GHz [7], [8]. The main obstacle in applying this approach to frequencies below 1 GHz is that there is only one resonant mode for typical chassis sizes at these frequencies.

Fortunately, recent results show the feasibility of generating and feeding more than one characteristic mode below 1 GHz [9]–[13]. In particular, one can either take advantage of existing design features (e.g. metal bezel) [9], [10] or incorporate minor modifications into the chassis [12], [13] to synthesize additional modes. One added benefit of using multi-modes to design MIMO antennas is that these modes represent the inherent ability of the *entire* chassis to radiate, which may allow significantly larger bandwidths to be obtained for the secondary antennas than could be achieved by avoiding chassis excitation. Moreover, even wider bandwidths and multiband resonances can be achieved by correlating the currents and the near field of modes with high modal significance across different frequencies [13].

In the remaining parts of this paper, the aforementioned TCM-based approaches in designing efficient MIMO antennas below 1 GHz will be further elaborated. Section II focuses on the strategy of allowing chassis excitation for only one antenna and the three ways to practically implement this strategy. The relaxation of single-mode excitation is discussed in Section III, where additional modes are created using structures that can be included in compact mobile terminals. Section IV summarizes an effective approach to enlarge bandwidth and synthesis

multi-resonances in a single feed. Conclusions and future work are provided in Section V.

II. MITIGATING CHASSIS EXCITATION BELOW 1 GHz

The first strategy that was conceived to obtain efficient MIMO terminal antennas below 1 GHz relied on the inherent property of the basic rectangular chassis in offering only one resonant characteristic mode in this frequency range [2]. Three different ways to implement this strategy has been successfully attempted, as will be described in this section.

The main drawback of this strategy is that only the (main) antenna that is designed to excite the chassis can provide a relatively large bandwidth for cellular band coverage below 1 GHz. This is because by avoiding chassis excitation, the other (or secondary) antennas can only excite the much smaller physical sizes of the antenna elements for radiation. According to Chu's limit [15], a smaller radiating structure will lead to a smaller impedance bandwidth, a result which was confirmed in the studies performed [2], [5], [6]. Nevertheless, the achieved bandwidth for the secondary antenna in the two-antenna case is sufficient to cover one 20 MHz LTE channel and frequency tuning can be used to ensure coverage of the entire band of interest (e.g., see [6]).

A. Positioning of Antennas

For a 100 mm \times 40 mm chassis (e.g., for a candybar phone), it was shown that there is only one resonant mode (i.e., fundamental mode) below 1 GHz [2]. The magnitude of the characteristic electric field of this mode is largest at the two shorter edges of the chassis, as shown in Fig. 1(a). Therefore, an electric antenna (i.e., an antenna with dominant electric near-field e.g., a folded monopole) can be placed at one shorter edge to excite the chassis. For a two-antenna configuration, the secondary electric antenna, e.g., a planar inverted-F antenna (PIFA), can be placed in the middle of the chassis length where the characteristic electric field is weakest. This approach minimizes the excitation of the chassis, which reduces chassis-induced coupling. Detailed parametric studies revealed that when compared to a PIFA-monopole configuration with the two antennas placed at the two shorter ends, a new configuration with the PIFA located in the chassis center gives a significant MIMO capacity gain, due to a reduction in chassis-induced mutual coupling and correlation [2]. Furthermore, it was found that the bandwidth of the secondary antenna can be improved by positioning the PIFA in the middle along the side of the chassis length [2]. Nevertheless, whereas this chassis coupling mitigation approach is conceptually interesting, in practice it is often more convenient for the antennas elements to be placed at one or both shorter edges of the chassis.

B. Localizing Antenna Currents

In order to keep the antenna elements at the two shorter edges of the chassis while simultaneously mitigating chassis-induced coupling, a current localization approach was proposed in [5]. The main idea is to localize the current of the secondary antenna element(s) such that it does not effectively excite the fundamental mode of the chassis, even when it is still located

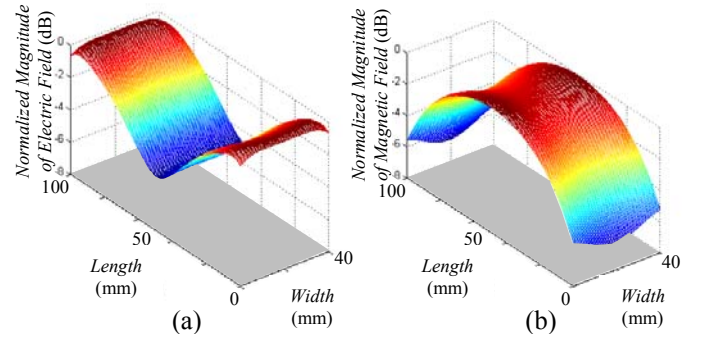


Fig. 1. Normalized magnitude of (a) total electric field and (b) total magnetic field for the fundamental mode 5 mm above a 100 mm \times 40 mm chassis. The gray rectangular surfaces illustrate the chassis dimensions.

in the region of high characteristic electric field for that mode, i.e., at a shorter edge in Fig. 1(a). In [5], the increased localization of the excitation current is achieved by using dielectric loading of higher permittivity for the PIFA, which requires a corresponding reduction of the size of the PIFA to retain the same resonant frequency. Therefore, this method also has the added benefit that physically smaller PIFA can be used, which is attractive for real implementations.

C. Utilizing Magnetic Antenna

Another method to mitigate the chassis excitation of secondary antennas without having to move them from the shorter edges is to use magnetic antennas [6]. This is because the characteristic magnetic field of the chassis is minimum at the shorter edges, as illustrated in Fig. 1(b). This means that a magnetic antenna placed in these locations does not effectively excite the chassis. This method was attempted using a dual-antenna configuration with an electric antenna (monopole) and a magnetic antenna (coupled loop), which were placed at either the same or different shorter edges. Results show that the concept works very well and very low coupling and correlation were achieved [6]. However, for the case of co-located electric and magnetic antennas at one shorter edge, it was important to ensure that the adjacent feed lines of the two antennas were designed to circumvent high mutual coupling [6].

III. GENERATING AND FEEDING MULTIPLE CHARACTERISTIC MODES BELOW 1 GHz

In Section II, the strategy to achieve uncorrelated antennas was to ensure that the single-mode of the chassis was utilized by only one antenna. As explained, this method has the drawback of relatively small bandwidth of the secondary antennas. To overcome the bandwidth limitation, it was proposed that existing design features of the terminals as well as minor modifications to the chassis can be exploited to create additional resonant modes below 1 GHz. Two such examples had been proposed in [9]–[13], as will be elaborated below.

A. Chassis with T-strip Structure

To enable the chassis to radiate along its width, in addition to its length, one possible solution is to capacitively load each of the longer sides with a grounded metallic strip (i.e., T-

strip). This measure effectively creates a resonant mode that represents a flat dipole oriented along the chassis width [12]. In order to feed this new mode, a capacitively coupled feed was placed near one of the T-strips, effectively exciting the mode by generating high electric field in the region of high characteristic electric field of this mode.

B. Chassis with Bezel Structure

Apart from implementing the T-strips, it is also possible to take advantage of the metal bezel designs of some current smartphone models to create additional modes. However, instead of a dipole mode along the width of the chassis, the bezel introduces a loop mode as well as a mode equivalent to two dipoles separated by the chassis width [10]. Based on the characteristic electric near-fields, the fundamental mode and the loop mode were excited by capacitive coupling feeds that are placed on the top and the middle of the longer side, respectively.

IV. BANDWIDTH ENHANCEMENT AND MULTIBAND OPERATION OF MULTIMODE MIMO ANTENNAS

For practical applications, it is important for MIMO terminal antennas to achieve large bandwidths and provide multiband resonances [13]. Both features can be accomplished using TCM by correlating the currents and the near-fields of different modes in a given feed region across frequency [13]. The idea is that an antenna feed that provides a low-band resonance can potentially be reused to excite additional resonances. If the additional resonances are close by, then the bandwidth can be enhanced, whereas if the additional resonances are far away, multiband resonances are obtained. The concept has been successfully demonstrated for both the chassis with the T-strips [13] as well as the chassis with the bezel [10]. It was found that fine tuning of the higher band can be performed via some minor changes in the chassis, for example, through changing the strip length for the multiband version of the T-strip MIMO antenna [13].

V. CONCLUSIONS AND FUTURE WORK

As highlighted in this review, TCM is a promising and powerful tool for designing efficient MIMO terminal antennas with high total efficiency and low correlation. Moreover, slight modifications of the plain rectangular chassis have been shown to enable multimode operation below 1 GHz, which leads to significantly larger bandwidths of the uncorrelated MIMO antennas relative to previous approaches.

Although a lot of useful results have been achieved in recent studies, there remain many interesting aspects for future studies. For example, mobile operators are now more interested in the performance of mobile terminals in usage scenarios than in free space. An initial user effect study on the MIMO antenna with the T-strip structure in [12] shows that the TCM-aided design outperforms a state-of-the-art MIMO antenna design. However, only two hand grip styles were considered (i.e., one-hand and two-hand scenarios). A more comprehensive user effect study could involve more MIMO terminals (of both conventional and TCM aided designs) and user scenarios, in

order to achieve better insight into their relative performances. Another interesting topic is the use of TCM to design pattern reconfigurable MIMO antennas. In [14], TCM was employed to design a single reconfigurable terminal antenna at 900 MHz by modifying the feed structure with PIN diodes to switch between the excitation of two characteristic modes. A MIMO version of the antenna in [14] can be obtained by adding another feed to excite a further mode of the chassis.

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