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On User Effects in MIMO Handset Antennas Designed Using Characteristic Modes

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***Abstract*—The Theory of Characteristic Modes (TCM) has been applied to design high-performance MIMO antennas for mobile terminals. However, existing studies focus on free-space (FS) performance, which is mostly irrelevant in real usage. This paper investigates the performances of two TCM-based MIMO terminal antenna designs in 7 realistic user scenarios for frequencies below 1 GHz. Full-wave simulation results indicate that the TCM designs can significantly outperform conventional designs in user scenarios that require good MIMO performance. Higher multiplexing efficiency (ME), by up to 3 dB, was recorded for a TCM design relative to a conventional terminal in a two-hand scenario. Performance advantages of the TCM designs were mainly due to lower correlation as well as higher impedance matching and coupling efficiency. Moreover, a combined usage study based on weighted ME over different user cases established that on average TCM designs outperform conventional designs by up to 1.6 dB. This suggests that the TCM designs not only give superior performance in FS, but also in realistic user scenarios.**

***Index Terms*— MIMO systems, mobile antennas, impedance matching and mutual coupling.**

I. Introduction

User interaction can significantly degrade terminal antenna performance via absorption of electromagnetic waves in body tissues and impedance mismatch due to resonance frequency offset [1]. To counteract the degradation, several design approaches were proposed in recent years, e.g., [2]-[3]. A metamaterial-inspired Z antenna was used in [2] as a parasitic element to improve impedance matching with user proximity, reducing total loss by 2.3 dB. In [3], an antenna shielding approach was shown to improve total efficiency by up to 5 dB in a user scenario. However, the existing contributions in the field largely focus on single-antenna designs and consider only a limited number of user scenarios.

Today, multi-antenna terminals are widely available, due to the growing use of multiple-input multiple-output (MIMO) systems for providing high data rates [1]. To achieve the high performance, the terminal antennas are required to be robust in real usage, which includes user interaction. However, the emphasis on multi-antenna design has been on decoupling the antennas in free space (FS), which is especially challenging for frequencies below 1 GHz [1]. In particular, the Theory of Characteristic Modes (TCM) has been found to provide an effective design framework for achieving MIMO terminal antennas with low correlation and high total efficiency [4]-[6].

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The work in [4] focused on employing TCM to design a MIMO terminal antenna at frequencies below 1 GHz, by slightly modifying the terminal chassis to yield two resonant characteristic modes. The MIMO antenna in [4] was later developed into a dual-band design [5]. In [6], a metal bezel structure was used as an alternative design to [5] that also enables dual-band excitation of two modes. Despite the promising performance achieved by the TCM designs, the evaluations were mostly carried out in FS, except for a one-hand (OH) and a two-hand (TH) scenario in [4]. Relative to a state-of-the-art terminal antenna design, a single-band TCM design offered superior capacity in the FS and OH cases [4].

In this context, a comprehensive study on the robustness of TCM designs in realistic scenarios is provided in this letter by comparing the performance of five MIMO terminals with fundamentally different antenna designs (two TCM designs) in 7 representative user scenarios. Specific Absorption Rate (SAR) and usage-weighted performances are also compared. Selected user-terminal setups are verified experimentally.

II. Simulation Setup

Full-wave simulations of the terminal prototypes and user models were performed using the time domain solver of CST Microwave Studio. MIMO performance was evaluated using multiplexing efficiency $\eta_{\text{mux}} = \sqrt{\eta_1\eta_2\left(1-\rho_e\right)}$ [7], where η_i is the total efficiency of port i and ρ_e the envelope correlation coefficient (ECC). Multiplexing efficiency (ME) is a simple and intuitive metric allowing insight into the impact of antenna efficiency, efficiency imbalance and correlation on the multiplexing performance of MIMO antennas [7]. The contributions of efficiency and correlation can be isolated as $\eta_{\text{e}} = \sqrt{\eta_1\eta_2}$ and $\eta_{\text{c}} = \sqrt{\left(1-\rho_e\right)}$, respectively. Moreover, η_i= $\eta_{i,\text{rad}}\eta_{i,\text{mc}}$, where $\eta_{i,\text{rad}}$ and $\eta_{i,\text{mc}}$ are the radiation and matching/coupling (MC) efficiencies, with $\eta_{1,\text{mc}}= 1-\left|S_{11}\right|^2 -\left|S_{21}\right|^2$ and $\eta_{2,\text{mc}}= 1-\left|S_{22}\right|^2-\left|S_{12}\right|^2$. η_{e}, η_{rad} and η_{mc} are the geometric averages of total, radiation and MC efficiencies over two ports (arithmetic averages in dB). In this study, any change in radiation efficiency, in cases with user hand/head, relative to FS is approximated as absorption loss. Peak specific absorption rate (SAR) values were obtained with an averaging mass of 10g (ICNIRP standard [8]) and a reference accepted power of 23 dBm (0.2 W) [9].

A. MIMO Terminals

The five MIMO terminal prototypes investigated in this study cover LTE Band 5 (824-894 MHz) and Band 2 (1850-1990 MHz). The prototypes P1-P5 and the feeding locations are shown in Fig. 1. Depending on the design approach, they are classified into two groups: 1) TCM-based

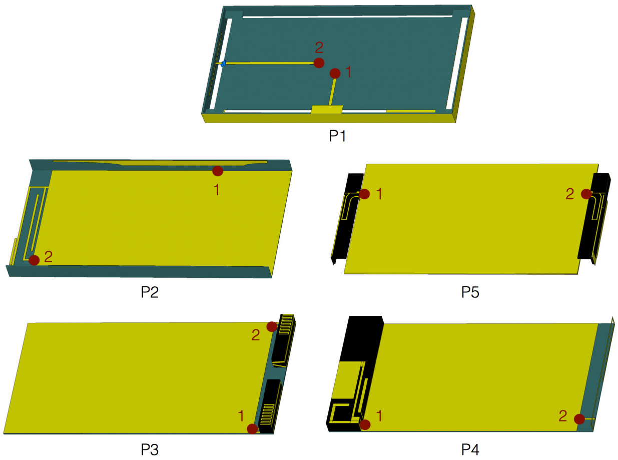

Fig. 1. MIMO terminals with feeding locations and port numbers indicated. P1 and P2 are TCM designs, whereas P3-P5 are conventional designs.

TABLE I
FS BANDWIDTH, COUPLING COEFFICIENT (S_{21}) AND ENVELOPE CORRELATION COEFFICIENT (ECC) FOR ALL FIVE PROTOTYPES AT 860 MHZ

Prototype	*P1*	*P2*	*P3*	*P4*	*P5*
Bandwidth [MHz]	51	79	182	31	68
S_{21} [dB]	-10	-19	-7	-8	-4
ECC or ρ_e	0.003	0.01	0.5	0.5	0.4

designs (P1 and P2) and 2) conventional designs (P3, P4 and P5). Prototypes P1 [6] and P2 [5] employ TCM to excite orthogonal radiation patterns. P3 consists of two coupled-fed monopoles co-located on one shorter edge of the chassis [10], whereas P4 consists of a planar inverted-F antenna (PIFA) and a monopole [11]. P5 is based on two inverted-F (IFA) antennas placed at two shorter edges of the terminal [12]. All prototypes were designed for the same length (130 mm) and width (66 mm), with the height within 8.5 mm. The FS performances of P1-P5 in Table I reveals that the TCM designs (P1 and P2) offer superior correlation and coupling performances. However, P1 does not cover the full LTE Band 5, due to the use of lossless matching elements in simulations, which decreased the bandwidth achieved in [6]. Likewise, P4 also suffers from bandwidth limitation due to the inherently small PIFA bandwidth. Nonetheless, the narrower bandwidths in P1 and P4 are sufficient to cover the downlink of Band 5, fulfilling the LTE requirement of MIMO operation in the downlink. This study focuses on Band 5 (i.e., below 1 GHz), due to it being more challenging for MIMO antenna design.

B. *User Scenarios*

In any given user scenario setup, each of the five prototypes was confined to a bounding box of dimensions 131 mm × 67 mm × 9.5 mm, to account for a 0.5 mm thick casing. To ensure fair comparison and facilitate worst case interaction, the prototypes were positioned within the box so that a minimal separation of 0.5 mm to the user was achieved. Apart from a FS and a talk mode three TH data modes were also simulated: TH-Browse, TH-Video and TH-Portrait (see Fig. 2). Furthermore, two OH data modes were evaluated: OH-Browse and OH-Video. CTIA standard specific anthropomorphic mannequin (SAM) head phantom (ε_r = 42 for the SAM liquid and ε_r = 5 for the SAM shell at 859 MHz) was used in the talk mode, whereas the hands were designed in the open source MakeHuman software according to the size and composition of the CTIA phantom hand [13] (ε_r = 30 at 859 MHz). However, the positions of the fingers and palms were altered to fit the larger prototypes used here. The non-standard user cases such as the TH-Portrait were inspired by the study in [14], where user grips were identified based on 1333 observations of people using their devices.

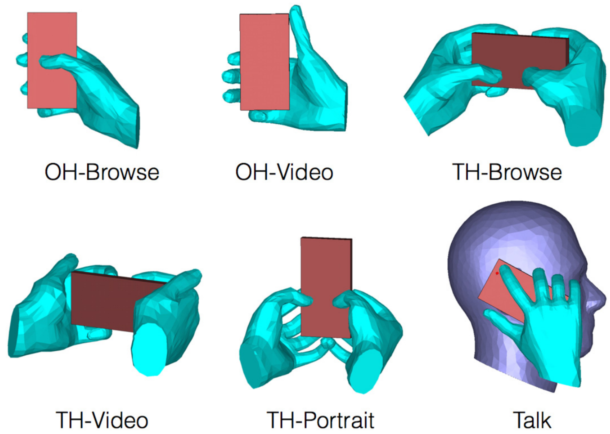

Fig. 2. The 6 user scenarios illustrated: Talk, OH-data (OH-Browse, OH-Video), and TH data (TH-Browse, TH-Video, TH-Portrait).

III. RESULTS AND DISCUSSIONS

The average multiplexing efficiency over Band 5 for all user scenarios are presented in Fig. 3. The TCM designs are seen to outperform the conventional ones in all data mode cases, except for P1 in OH-Browse and P2 in OH-Video. However, they function less favorably in the talk mode. To gain insight into the results, detailed analysis was performed for the different groups of user cases.

A. *Free Space and One-Hand (OH) User Scenarios*

Figure 4 presents the separate contributions of correlation and efficiency [7] to the multiplexing efficiency in the FS, OH and talk cases. Due to efficient chassis excitation, P1 and P2 featured orthogonal antenna patterns in FS, outperforming all conventional designs both in correlation (up to 1.6 dB in terms of η_c) and total efficiency (up to 2.2 dB in η_e). Moreover, both TCM designs retained low correlation (high η_c) and high matching and coupling efficiency in the OH scenarios, except for P1 in OH-Browse and P2 in OH-Video. However, significant degradations compared to FS can be seen in Fig. 3 (3.6 dB lower multiplexing efficiency for P2 in OH-Browse).

In OH-Browse, P1 was outperformed by all other designs mainly due to the position of the hand relative to the regions of high near-field radiation on the terminal. It was verified that port 1 of P1 excites strong near-fields around the longer edges of the bezel structure. Since in OH-Browse the palm and the fingers wrapped around the terminal along the longer edges, the efficiency of port 1 suffered from high absorption loss and impedance mismatch (see Fig. 4), leading to the lower multiplexing efficiency of P1. Moreover, the position of the thumb also contributed to the efficiency drop as it was placed on top of the feeding structure for port 1, which had strong near-fields emphasizing the negative impact of P1's side port location on its performance in the OH-Browse scenario. To quantify this effect in simulation, the top 4 cm of the thumb were cut off to remove the tissue around the feed structure. This resulted in an efficiency increase of 2 dB at port 1 and a multiplexing efficiency gain of 1.1 dB relative to the original OH-Browse case, highlighting the significant impact of body tissue in regions of strong near-fields. In addition, even though the OH-Browse and OH-Video grips share some similarities, P1 has higher multiplexing efficiency in OH-Video than OH-Browse (see Fig. 3) due to the larger separation between the hand and the regions of strong near-fields in OH-Video.

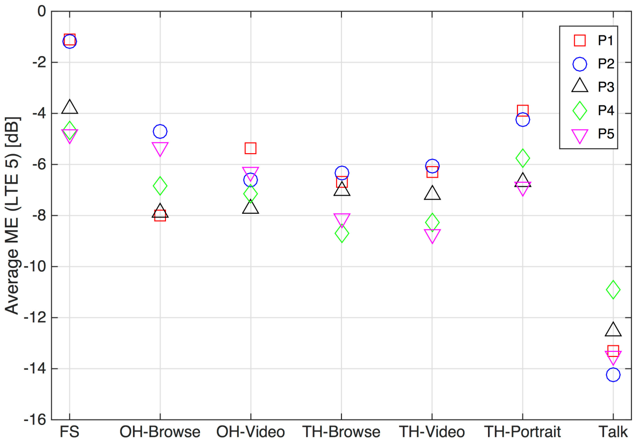

Fig. 3. Multiplexing efficiency (ME) over LTE Band 5 in 7 user scenarios.

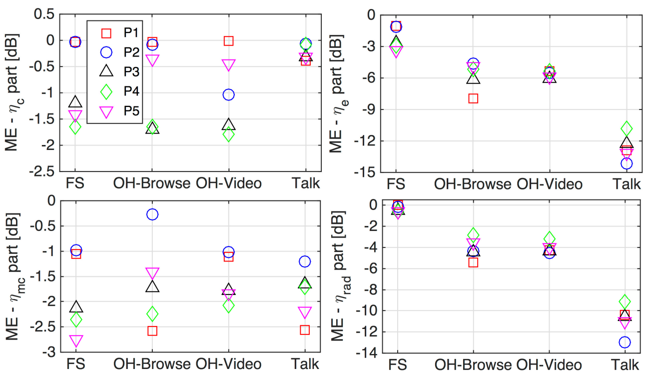

Fig. 4. FS, OH and Talk multiplexing efficiency (ME) contributions.

For P2, the strong near-fields from port 1 were at the top part of one of the longer edges and the bottom part of the other longer edge. This diagonal distribution of the near-fields was favorable for OH-Browse, since the palm and the fingers were located at the center of the chassis. However, in OH-Video, the thumb and the other fingers were within the strong near-field region, leading to higher mismatch than OH-Browse. Moreover, the relatively high correlation in OH-Video (i.e., low η_c in Fig. 4) can be explained by the hand impairing efficient excitation of the diagonal mode on port 1 and increasing coupling into port 2.

B. Two-Hand (TH) User Scenarios

It can be seen in Fig. 5 that the TCM designs (P1, P2) show superior multiplexing efficiency in all TH scenarios. The key trends observed for the OH cases are even more apparent here. As in FS, both P1 and P2 provide considerably lower correlation in the TH scenarios compared to P3-P5. Another key observation is the opposing trend in the efficiency part (η_e): P1 and P2 had higher absorption losses (lower η_{rad}) in general, especially in comparison to P3 and P4. However, they were more robust in MC efficiency η_{mc} than P3-P5 (see Fig. 5). The higher η_{mc}, especially of P2, is mainly attributed to lower impedance mismatch (lower S_{11}, S_{22}) rather than lower coupling (lower S_{21}, S_{12}). This is because the hands helped to decouple the antennas in all prototypes, resulting in mismatch losses dominating over coupling losses. On the other hand, the higher absorption losses of P1 and P2 can be explained by the observations that the conventional designs (especially P3 and P4) tended to excite more localized near-fields around the antennas, whereas the TCM designs (and P5) provided more distributed near-fields around the entire chassis. Since the localized near-field regions of P3 and P4 were further away from the user hands than P1 and P2, more energy was absorbed in P1 and P2. Therefore, as in the OH cases, lower correlation and higher MC efficiency result in the higher multiplexing efficiency performance of the TCM designs.

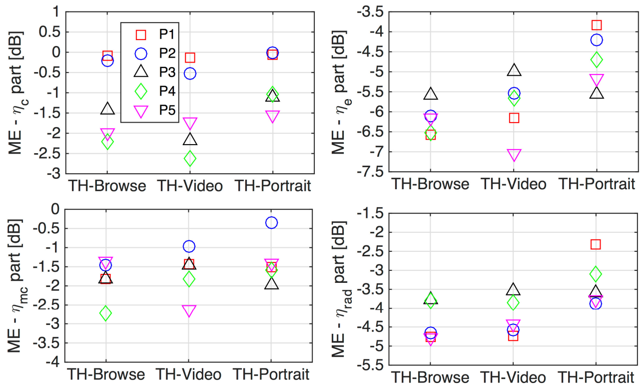

Fig. 5. TH multiplexing efficiency (ME) contributions.

C. Talk Mode Scenario

Overall, the presence of the head led to a notable decrease in correlation for P3-P5 (see Fig. 4). This is because the head acted as an asymmetric scatterer for P3 and P4, resulting in decorrelated far-field patterns. Therefore, unlike previous cases, the TCM designs no longer have a correlation advantage over conventional designs. Furthermore, the TCM designs also had high absorption losses (up to 13 dB for P2 in Fig. 4) as a result of fingers being present in the regions of strong near-fields. Therefore, the decorrelation in the conventional designs, coupled with high absorption losses in the TCM designs, substantially degrade the capability of the TCM against the conventional designs, with respect to the data mode cases. However, from a system perspective, talk modes do not require as high data rates as web-browsing or video streaming modes [15]. Hence, P1 and P2 are not expected to be inferior to P3-P5 in terms of user experience.

D. SAR Performance

The peak SAR results for all setups are presented in Fig. 6. It can be seen that the SAR specifications (2 W/kg for talk mode and 4 W/kg for hand-only modes [8]) are marginally exceeded in three cases (4.3 W/kg on port 2 for P4 in OH-Video, 2.4 W/kg on port 1 for P1 in the talk mode, and 2.2 W/kg on port 1 for P2 in the talk mode). However, the purpose of this study is to compare the user effects for different antenna designs rather than ensuring SAR compliance. The results on Fig. 6 confirm previous observations in Section III-A that in the OH-Browse and OH-Video modes, the port location and near-field distribution lead to higher absorption losses (and higher SAR values) in P1 port 1 and P2 port 1. Similar observations apply to the TH data modes. Overall, P1 and P2 are outperformed by the remaining prototypes on port 1, whereas the results for port 2 suggest marginal differences in favor of P1 and P2 relative to P3-P5. Nevertheless, as mentioned previously the higher absorption losses of P1 and P2 (seen in the higher SAR values) are compensated by the low envelope correlation and higher mismatch and coupling efficiency leading to the better MIMO performance of the TCM-based designs compared to P3-P5 (see Fig. 3).

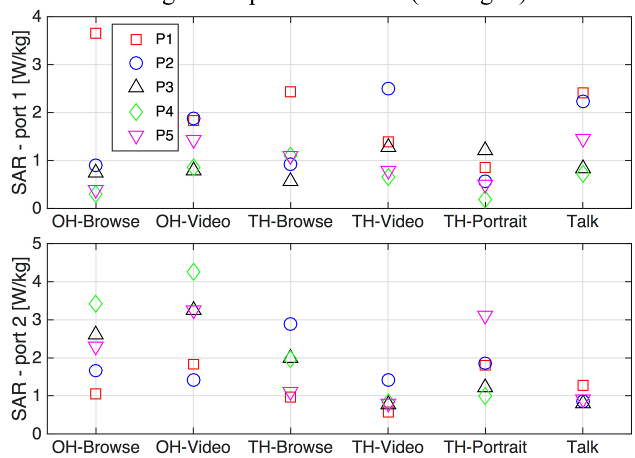

Fig. 6. Peak SAR in 6 user scenarios at 859 MHz.

E. Overall Performance over Usage Scenarios

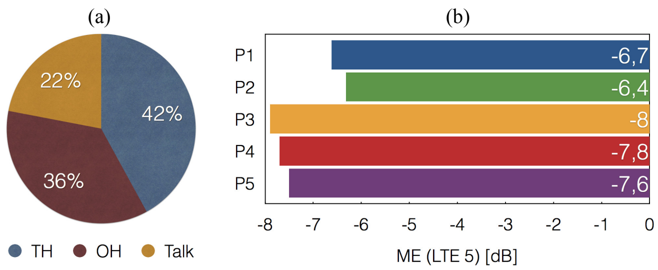

Fig. 7. (a) Relative usage in TH, OH and Talk modes, (b) usage-weighted ME.

To account for usage trends in real life, the study in [14] was used as a guideline to classify the 6 user scenarios (excluding FS) into three groups of user interactions: two-hand (TH), one-hand (OH) and talk (Talk) modes. The relative smartphone usage for these three groups as obtained from [14] is given in Fig. 7(a). An overall performance metric can then be formulated by giving equal weighting to each user scenario of each group (e.g., 42%/3 = 14% for each of three two-hand scenarios) and weighting the multiplexing efficiency of all scenarios. The usage-weighted multiplexing efficiency for the five prototypes are provided in Fig. 7(b). It can be seen that both TCM designs offer similar performance (-6.7 dB vs. -6.4 dB) and they outperform conventional designs by 0.9-1.6 dB.

F. Experimental Verification

To verify the simulation results for selective cases, P3 and P5 were fabricated and measured in a OH scenario similar to OH-Browse, using an IndexSAR hand phantom. The measured and simulated results have been found to be in good agreement (within 1 dB for η and within 0.1 for ρ_e).

IV. Conclusions

This work studied user effects on five terminal prototypes, comparing TCM designs with conventional designs. Due to the more distributed near-fields and side port placement, the TCM designs were more susceptible to finger proximity and hence in general suffered higher absorption losses and SAR than conventional designs. However, low correlation and high MC efficiency enable overall performance benefits of the TCM designs in all TH cases. Moreover, a weighted usage study revealed that the TCM designs outperformed the conventional ones in multiplexing efficiency by up to 1.6 dB, indicating the TCM design approach as promising for improving user robustness.

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