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Adaptive Impedance Matching Performance of MIMO Terminals with Different Bandwidth and Isolation Properties in Realistic User Scenarios

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Abstract—Using the metric of channel capacity, three dual-antenna multiple-input multiple-output (MIMO) terminals with adaptive impedance matching were evaluated at LTE Band 13 in four different user scenarios using simulation. Each of the three terminals is equipped with a slot-monopole antenna and a planar inverted-F antenna (PIFA). The slot monopole is fixed at one edge of the chassis, whereas the location of the PIFA differs among the terminals to provide different bandwidth and isolation characteristics in free space (FS). The results show that adaptive matching leads to an average capacity gain of up to 24% at the center frequency, favoring the terminal with the smallest antenna bandwidth and the largest isolation. However, the maximum capacity gain from adaptive matching decreases to 15.7% when averaged over the entire system bandwidth. Moreover, the terminal with moderate antenna bandwidth and isolation offers the best overall absolute capacity performance under different user scenarios, indicating a design tradeoff. These results highlight important design considerations for MIMO terminals with adaptive impedance matching.

Index Terms—*adaptive impedance matching; channel capacity; terminal antennas; user effects*

I. INTRODUCTION

Multiple-input multiple-output (MIMO) communication systems have been gaining increasing attention, both in academia and industry, over the past twenty years. In fact, the technology has been adopted in recently introduced wireless communications standards such as High Speed Packet Access (HSPA), IEEE802.11n and Long Term Evolution (LTE). Notably, LTE requires multi-antennas to be deployed at both the transmitter and receiver [1]. This requirement provides significant benefits in terms of higher data rates and better link reliability, but it also imposes significant challenges on antenna designers [1]. Such challenges include strong mutual coupling among antennas due to terminal size limitations, as well as increased sensitivity of performance to real user scenarios and propagation channel characteristics.

The use of adaptive impedance matching networks for MIMO performance enhancement has been investigated in [2]–[5]. These studies mainly focus on simple dipole antennas with no user interaction [2]–[4]. In [5], adaptive matching is found to provide up to 44% capacity improvement for one dual-band, dual-antenna terminal prototype in a two-hand scenario. However, the study in [5] is limited in scope and it makes no attempt to compare the impact of different user scenarios on

the antenna parameters and overall performances of different terminal antenna designs over an entire system bandwidth, when adaptive matching is applied. Therefore, the existing knowledge on the benefits of adaptive matching for realistic MIMO terminals under user influence is limited. In this context, we investigate the performance of three dual-antenna terminals with adaptive matching under four different user scenarios – free space, two one-hand grips (talk mode and data mode) and a two-hand grip (gaming mode). The goal is to determine both the achievable capacity gains as well as the mechanisms underlying the gains, in order to provide useful insights for practical implementations.

II. ANTENNA PROTOTYPES AND USER SCENARIOS

All three antenna prototypes were re-designed from [6] for LTE Band 7 (2.5–2.69 GHz) and Band 13 (0.746–0.787 GHz), in a volume of $126 \times 66 \times 9$ mm. However, in this work, we only focus on LTE Band 13 since the lower band is more challenging for multi-antenna implementation. Each of the dual-antenna prototypes is equipped with a slot monopole (Slot-M) at one short edge of the chassis as well as a PIFA at the center (“Prototype 1” or P1), center but rotated (“Prototype 2” or P2) or other short edge (“Prototype 3” or P3) of the chassis (see Fig. 1). For LTE Band 13, the 6 dB impedance bandwidth of P3 covers the 40 MHz system bandwidth, whereas the impedance bandwidths of P1 and P2 are limited by the PIFA bandwidth, which is 6 MHz for P1 and 17 MHz for P2. As explained in [6], this is because the PIFA at the center locations does not use the chassis for radiation, as opposed to the Slot-M and PIFA at the short edges. As a result, P1 has a significantly better isolation of 16.6 dB, as compared to 13.2 dB and 6.3 dB for P2 and P3, respectively.

We investigated four user scenarios – free space (FS), one-hand grip in talk mode (OH-TM), one-hand grip in data mode (OH-DM) and two-hand grip (TH). Figure 2 illustrates the position of the hands with respect to the terminal for the two-hand grip case. This specific TH scenario is chosen here, since it is representative of a common user case, where users either play games or browse their devices with each hand holding one short edge of the chassis. Moreover, the exact position of the hands relative to the terminal follows the study in [5]. Figure 3 illustrates the one-hand grip user scenarios for P3. The exact positions of the hand and fingers in these cases closely follow [7], where a detailed grip study emphasizes the significance of the one-hand talk and data modes in real world scenarios.

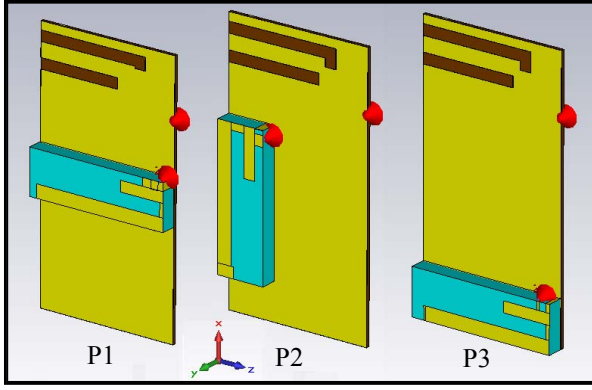


Fig. 1. Antenna prototypes in free space – P1 to P3 (left to right)

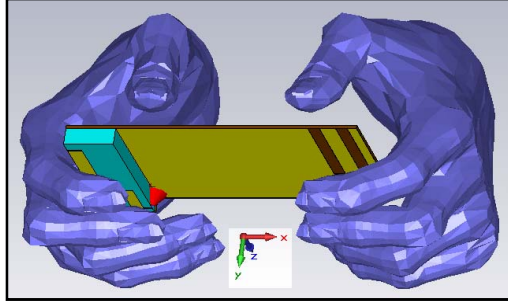


Fig. 2. P3 in the two-hand grip (TH).

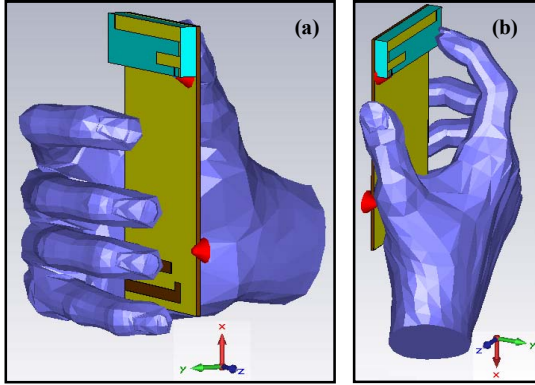


Fig. 3. P3 in one-hand (OH) grips: (a) data mode (DM), (b) talk mode (TM)

CST Microwave Studio was used for both the antenna design and full-wave antenna simulations involving the user.

III. EVALUATION MODEL

Figure 4 shows the block diagram of the evaluation model. It is divided in two main parts: impedance matching networks and voltage sources (i.e., parts 1_B and 1_A) and mobile terminal antennas in different user scenarios (i.e., part 2). In this study, each of the matching networks consists of an open-circuit stub and a transmission line. By varying the length of the stub and the transmission line, the matching network can cover the entire Smith chart with a user defined resolution. A total of 96 matching states were investigated and are presented in Fig. 5. Part 2 represents the antenna elements subjected to different user cases.

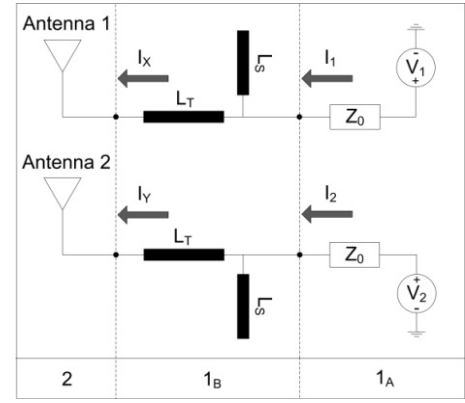


Fig. 4. Evaluation model block diagram

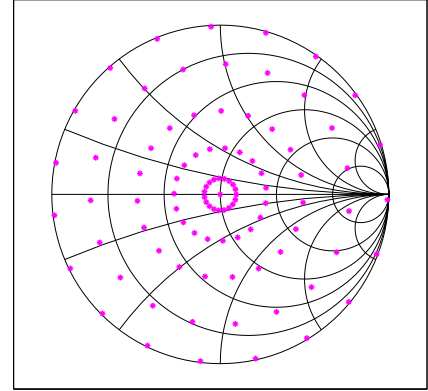


Fig. 5. Impedance matching states investigated

Using CST Microwave Studio, 3D far-field radiation patterns for all different user scenarios were simulated, recorded and used in a Matlab post-processing program for further evaluation. The antenna pattern (or “embedded pattern”) for each port was obtained with the port excited and the other port terminated in 50 ohm.

The effects of each of the impedance matching states on the antenna patterns, antenna total efficiencies and correlations were calculated based on the discussions in [8]. Essentially, the embedded patterns, current matching state and antenna scattering parameters (S parameters) were used to calculate the new antenna pattern for the given matching state. Next, correlation and total efficiencies were computed based on the updated antenna patterns. The correlation calculation assumed a reference environment with uniform 3D angular power spectrum (APS), which reflects a rich-scattering environment.

The final step in the evaluation process was the 2×2 MIMO downlink capacity calculation, which is the main performance metric used throughout this paper. The calculation was based on the Kronecker model and closely follows the discussions in [9], where the correlation matrix at the terminal antennas was obtained from the total antenna efficiencies and the correlation of the radiation patterns (i.e., assuming uniform 3D APS). No correlation was assumed at the base station (BS) antennas and there was no channel

knowledge at the BS. Average capacity was obtained from Monte Carlo simulations over 1000 channel realizations. The state that provided maximum capacity performance was chosen as the optimal state. For cases that considered the entire system bandwidth of 40 MHz, the open-circuit stub and transmission line matching network that realized the optimal state was used to calculate the capacity performance over frequency. Since there were two possible realizations of the matching network for a given optimal state, the realization that offers the larger impedance bandwidth was chosen. For the 40 MHz bandwidth case, the capacity was averaged over both channel realization and bandwidth.

IV. SIMULATION RESULTS

In this section, the focus is on total antenna efficiency (i.e., mismatch and absorption losses, with conductor and dielectric losses in terminals almost unchanged with user proximity) and its impact on capacity performance. This is because the envelope correlations of the dual-antennas terminals (with and without adaptive matching) under different user scenarios are below 0.24, except for P3, indicating overall a smaller impact from correlation on the capacity results.

A. Average Capacity at the Center Frequency

Table I presents the average capacity results at the LTE Band 13 center frequency (0.767 GHz) for all three prototypes P1-P3 and all user scenarios evaluated at an SNR of 20 dB. The capacity performance at the center frequency corresponds to the narrowband case, which ignores the frequency responses of the antennas and the matching networks. The results for FS with no adaptive matching network indicate that P1 outperforms P2 and P3, mainly due to the higher isolation (and lower correlation) between the antennas in P1. Since both terminals are well-matched at the center frequency in FS, no major improvement is observed when adaptive matching is used (i.e., the maximum capacity gain is 2.7%).

However, the results in Table I on the user effects of the TH grip indicate that, in the presence of a user, the average capacity performances at the center frequency of operation for P1 and P3 are comparable (7.67 bits/s/Hz for P1 and 7.41 bits/s/Hz for P3). This can be justified by the significant difference in antenna bandwidth between the two prototypes (6 MHz for P1 and 40 MHz for P3), which results in different degrees of mismatch (or detuning) for P1 and P3. The detuning is caused by the user decreasing the resonant frequencies of the antennas [10]. Due to its larger bandwidth, P3 experienced less severe detuning as compared to P1, which allowed for the performance gap observed in FS to be reduced in the presence of a user. At the same time, P2 shows a significantly better performance than both P1 and P3 for the same user scenario (TH). Due to the similar locations of the PIFAs in P1 and P2, except that one is rotated by 90° relative to the other, one would expect that the degrees of detuning of P1 and P2 are similar. Nevertheless, there is a significant difference in antenna bandwidth for P1 and P2 (6 MHz for P1 and 17 MHz for P2). Therefore, the TH user case does not detune P2 as severely as it detunes P1. Hence, the average capacity of P2 at the center frequency is higher (8.86 bits/s/Hz for P2 and 7.67 bits/s/Hz for P1).

TABLE I. AVERAGE CAPACITY AT THE CENTER FREQUENCY

Case	No Adaptive Matching [bits/s/Hz]			Adaptive Matching [bits/s/Hz]		
	P1	P2	P3	P1	P2	P3
FS	10.29	10.20	9.16	10.57	10.43	9.36
OH-TM	5.79	7.89	7.02	7.16	8.41	7.25
OH-DM	6.34	6.20	7.84	7.80	7.53	8.28
TH	7.67	8.86	7.41	9.19	9.34	8.02

Comparing the FS and TH scenarios for P1 in Table I, it can be seen that the introduction of the user hands leads to a capacity degradation of 2.62 bits/s/Hz. On the other hand, employing an adaptive impedance matching network will result in a performance enhancement of 19.8% and the absolute capacity loss due to user influence will drop by 47% from 2.62 bits/s/Hz to 1.38 bits/s/Hz. This significant improvement is due to the retuning of the PIFA to the center frequency. The results in Table I further suggest that by employing adaptive matching, the advantage of P1 over P3 at the center frequency is restored in the TH scenario (i.e., 9.2 bits/s/Hz for P1 and 8 bits/s/Hz for P3, after adaptive matching). Since the matching networks effectively retune the antennas (especially the PIFAs) to the center frequency in both P1 and P3, the discrepancy is attributed to higher user absorption loss (2.6 dB vs. 1.8 dB) and higher envelope correlation (0.43 vs. 0.03) in P3 than in P1. It is noted that the absorption loss was obtained relative to the FS case, with values averaged over the two antennas. The antenna bandwidths of P1 and P3 after retuning do not influence the performance at the center frequency.

In some of the cases investigated, the detuning effect of the user on the prototype is relatively small, such as the one hand cases (OH-TM and OH-DM) for P3. This is due to the location of the PIFA element and the relatively large bandwidth of both antenna elements. The PIFA is located at the top edge of the chassis and thus it is further away from the hand, avoiding severe detuning. Moreover, the bandwidths of the PIFA and the Slot-M in P3 are larger than those in other prototypes, which further limits detuning. Therefore, the gain from using adaptive matching is minimal (i.e., the capacity gain is up to 5.6%). Hence, in the OH-TM and OH-DM cases for P3, the loss of capacity performance as compared to the FS scenario is mainly attributed to the absorption of power by the user.

Nevertheless, user effects and adaptive matching gains are more pronounced in other cases. For example, in the OH-TM and OH-DM user scenarios for P1, the location and bandwidth of the PIFA are again the main reasons for its severe detuning and thus high adaptive matching gain. In this case, the PIFA is at the center of the chassis and is much closer to the hand in the one-hand scenarios than the TH scenario. This leads to high absorption and mismatch losses due to the presence of the user. Furthermore, this prototype offers only a small bandwidth around the center frequency and is therefore much more susceptible to user influence. As can be seen from Table I, the average capacity drops by 44% (from 10.29 bits/s/Hz to 5.79 bits/s/Hz) in OH-TM as compared to FS. Employing adaptive matching improves the performance by 24% (from 5.79

bits/s/Hz to 7.16 bits/s/Hz) due to re-matching the antennas (especially the PIFA) to the center frequency.

It can be concluded from the discussions so far that the performance of the terminals at the center frequency with no adaptive matching is strongly dependent on the bandwidths of the terminal antennas and the proximity of the antenna elements to the user hand(s). When adaptive matching is introduced, the antennas are retuned and the effect of the bandwidth is mitigated. However, user terminals do not only operate at the center frequency. It is therefore crucial to discuss the performance of the prototypes for the entire system bandwidth. In this paper, we consider LTE Band 13, which covers a 40 MHz bandwidth (0.747 GHz to 0.787 GHz).

B. Average Capacity over the System Bandwidth

In this subsection, we consider the average capacity over the full system bandwidth of 40 MHz. In all cases, we assumed a reference SNR of 20 dB. From the results in Table II, P3 has a marginally better performance than P1 for all user cases except the TH scenario. This is due to the larger antenna bandwidth of P3 in FS. In the TH scenario, the location of the hands with respect to the antenna elements leads to significant (though not severe) mismatch and absorption losses, since the antennas in P3 are located at the short edges of the chassis and both hands hold the terminal at these edges. Although adaptive matching can compensate for detuning loss, it is less effective against absorption loss. Furthermore, as noted in Section IV-A, envelope correlations in P3 are significantly higher than those in P1 and P2. For the TH scenario, the envelope correlations are up to 0.04, 0.20 and 0.47 for P1, P2 and P3, respectively. Therefore, the capacity performance of P3 for TH is worse than those of P1 and P2.

TABLE II. AVERAGE CAPACITY OVER 40 MHz SYSTEM BANDWIDTH

Case	No Adaptive Matching [bits/s/Hz]			Adaptive Matching [bits/s/Hz]		
	P1	P2	P3	P1	P2	P3
FS	8.59	9.45	8.85	8.44	9.29	8.78
OH-TM	5.91	7.44	6.75	6.84	7.73	7.05
OH-DM	6.50	6.01	7.55	7.48	6.69	7.82
TH	7.76	8.27	7.16	8.12	8.34	7.65

Moreover, the results in Table II show that P2 outperforms the other two prototypes in all user scenarios, except for the OH-DM case, where the PIFA element is partly covered by the hand and is thus more detuned than in all other cases. We attribute the strong performance of P2 to a combination of relatively wider antenna bandwidth than P1 (6 MHz for P1 and 17 MHz for P2 in FS) and a higher isolation than P3 (13.2 dB for P2 and 6.3 dB for P3 in FS). The larger antenna bandwidth makes the prototype less susceptible to detuning and inherently increases the performance over the 40 MHz system bandwidth, whereas the higher isolation is often associated with lower envelope correlation, which together support high capacity performance.

From Table II, after employing adaptive matching, we observe a maximum capacity gain of 15.7% in P1 for the OH-

TM case over the entire system bandwidth. Nevertheless, the performance trends observed for the different prototypes in Table I are preserved. Comparing the results in Tables I and II, it is observed that the average capacity over 40 MHz can be significantly lower than that at the center frequency. This is partly due to the simple matching networks used in this study, which are optimized only for the center frequency. In cases where the differences are large, more sophisticated wideband matching can be investigated to achieve better performance.

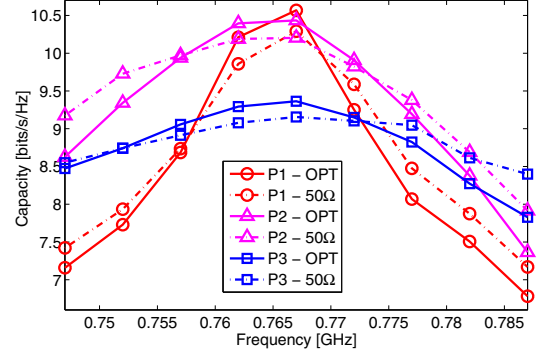


Fig. 6. Average capacity over LTE Band 13 – FS scenario

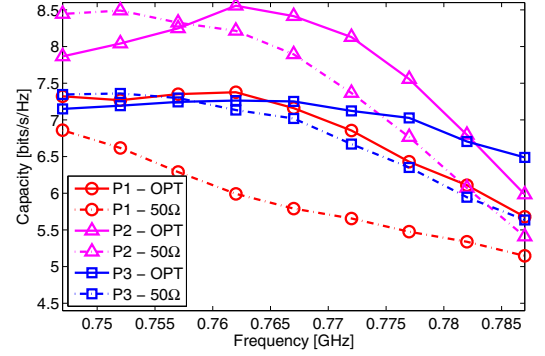


Fig. 7. Average capacity over LTE Band 13 – OH-TM scenario

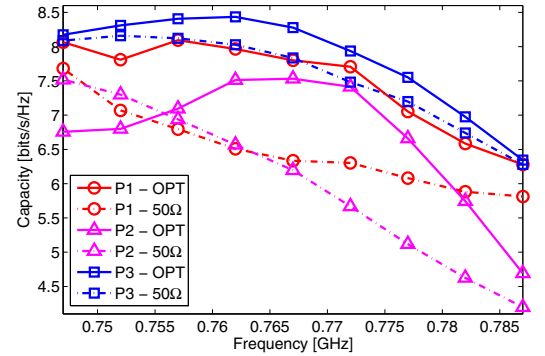


Fig. 8. Average capacity over LTE Band 13 – OH-DM scenario

Figures 6 to 9 present a comparison between the MIMO capacity results for all prototypes in all user scenarios over the entire system bandwidth. It can be seen in Fig. 6 that the gain from adaptive matching (“OPT”) in FS is low due to the well-matched antennas. Moreover, we note that there are certain frequency points where no matching (“50 ohm”) offers better

capacity than adaptive matching. This is because the matching networks were only optimized for the center frequency.

In the one-hand scenarios (see Figs. 7 and 8), we confirm the observations from Tables I and II on P3. When the PIFA is located at one short edge of the chassis (P3) and is relatively far away from the user hand, no significant performance improvement is observed (up to 0.85 bits/s/Hz in the OH-TM scenario at the upper band edge of 787 MHz). On the other hand, it is evident that both P1 and P2 show significant performance enhancements (up to 1.39 bits/s/Hz for P1 in OH-TM at 762 MHz and up to 1.75 bits/s/Hz for P2 in OH-DM at 772 MHz). As was concluded earlier from the tabulated results, these higher capacity gains with adaptive matching are due to the locations of the PIFAs with respect to the hands as well as the bandwidth and isolation characteristics of the prototypes.

In the TH scenario (see Fig. 9), both P1 and P2 display large capacity improvements over certain frequency ranges, but the average capacity performance with matching over the entire band shows only marginal improvements over no matching (see Table II). Moreover, for both P1 and P2, the effect of user-induced detuning can be seen in that the capacity peaks with no adaptive matching have shifted towards the lower band edge (0.746 GHz), though by a lesser degree compared to the one-hand cases.

V. CONCLUSIONS

In this work, three dual-antenna terminal prototypes with adaptive matching are evaluated in four user scenarios. The dual-antenna terminals are designed with similar antenna elements but placed at different locations on the terminal chassis for different bandwidth and isolation characteristics. The study focused on the effectiveness of adaptive matching in compensating for user effects on the antenna bandwidth and impedance matching of these terminals. For the narrowband case, it was found that the prototype with the smallest antenna bandwidth and largest isolation (P1) can benefit the most from adaptive matching in the presence of a user (i.e., 24% capacity gain). This is because the adaptive matching networks used can effectively compensate for user-induced severe detuning at the center frequency. Nevertheless, the maximum average capacity gain decreased to 15.7% for the wideband (40 MHz) case, mainly due to the narrowband behavior of the PIFA in P1.

Moreover, this study shows that the best overall capacity performance over the full system bandwidth was achieved by the prototype with moderate antenna bandwidth and isolation (P2). This is because the advantage of high isolation (and low correlation) in P1 is offset by the small antenna bandwidth giving lower average capacity over the system bandwidth, as the adaptive matching networks can only provide good matching over a small bandwidth. On the other hand, the prototype with the largest bandwidth and lowest isolation (P3) suffers from high correlation in different user scenarios, except for the OH-DM case, which inherently limits its capacity performance.

For OH-DM, P3 provides a better performance than P2, due to the hand grip affecting the PIFA in P2 more than that in P3. Therefore, the results show that even though the capacity performance of a MIMO terminal may reflect the antenna

bandwidth and isolation characteristics in free space, the interaction between the user and the antenna elements plays a dominant role in determining the overall performance.

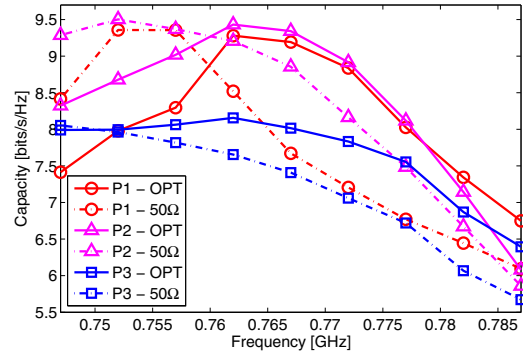


Fig. 9. Average capacity over LTE Band 13 – TH scenario

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