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Experimental Study of Adaptive Impedance Matching in an Indoor Environment

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***Abstract*—In recent years, adaptive impedance matching (AIM) has been used to compensate for severe performance degradation in terminal antennas due to user proximity. In particular, user effect compensation is critical for multiple-input multiple-output (MIMO) terminals, to achieve high data rates. In this study, the AIM performance of a MIMO terminal is measured for three user scenarios at two locations in an indoor office environment, using real impedance tuners. It was established that AIM leads to MIMO capacity gains of up to 25%, corresponding to 2.2 dB of power gain. On the other hand, the insertion loss of the tuners was found to be about 0.3 dB for free-space conditions. These results suggest that AIM can offer significant net performance gains in practice. Moreover, we provide physical insight into the similar AIM results for the two measured locations, representing geometrical line-of-sight (LOS) and non-LOS links, respectively.**

I. INTRODUCTION

User proximity is known to cause performance degradation in terminal antennas [1]. However, the increasing number of mobile terminal applications (e.g., gaming, navigation) and form factors creates new usage scenarios and handgrip styles, which further complicate user effects on terminal antennas.

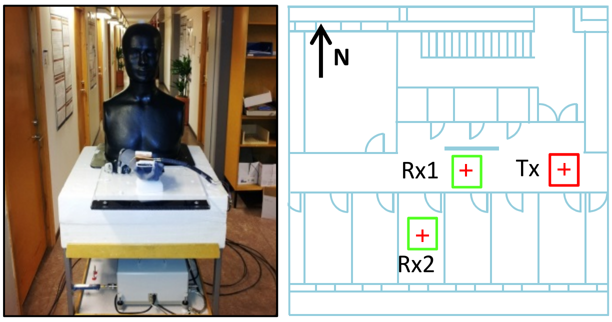
Adaptive impedance matching (AIM) has been suggested as a promising solution for user effect compensation [2]. The study in [3] proposed a complete closed-loop AIM solution for mitigating the degradations due to power amplifier (PA) and terminal antenna mismatches. Severe performance drops were recorded in three commercial phones, which further motivated the need for an AIM module in the RF front-end. However, the work focused on the mismatch between the PAs and the antennas, and it did not provide channel measurements in different usage conditions. In [4] a realistic mobile terminal subject to a two-hand grip was measured in an indoor environment. The results indicated MIMO channel capacity gains of up to 44%. Nevertheless, AIM was simulated in post-processing and no actual tuners were used. Therefore, tuner insertion losses were not taken into account.

The latest study in [5] reports on the measured AIM performance of a MIMO terminal in both indoor and outdoor environments and it involved real impedance tuners. It was shown that AIM results in MIMO capacity gains of up to 25% indoors and up to 18% outdoors. The tuner insertion losses were estimated to vary between 0.1 dB and 0.7 dB, depending on the user and propagation scenario. Furthermore, it was established that the directional characteristics of the propagation channel can severely affect AIM performance.

In this paper, we focus on the indoor environment of the measurement campaign reported in [5]. In particular, the AIM results are presented for two receiver locations, which involved a geometrical line-of-sight (LOS) setup (not treated in [5]) and a non-LOS setup. A comparison of the LOS and non-LOS results provides interesting physical insight into the role of the antennas used in the study. Moreover, we present additional experimental data to verify the operation of the impedance tuners and to determine corresponding insertion losses.

II. METHODS AND RESULTS

The wireless channel measurements performed for this study are detailed in [5]. In summary, a MIMO terminal with two dual-band inverted-F antennas (IFAs) was connected to the receiver (Rx), whereas two wideband monopole (base station) antennas were connected to the transmitter (Tx). Only measurements in the low frequency band (LB) (0.8-0.85 GHz) are reported in this paper. The terminal prototype was subjected to three user scenarios, each including a half-body human phantom: free space (FS), one-hand (OH), and two-hand (TH). Moreover, two Maury MT982EU30 mechanical tuners were used to experimentally verify the results obtained from simulation-based AIM, for predefined regions on the Smith chart. A comparison between the measured and simulated results also provides an estimate of the insertion losses of the tuners. Figure 1 shows the Rx antenna configuration in the OH mode (Fig. 1(a)) and the indoor channel measurement floor map (Fig. 1(b)) [5]. Two Rx locations were measured, with location Rx1 designed to give a geometrical LOS link (along a corridor) and location Rx2 giving a non-LOS (NLOS) link.

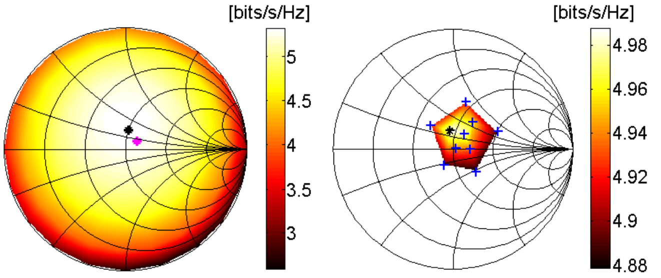


(a) (b)

Fig. 1. (a) Terminal antenna and user setup in OH mode with Maury MT982EU30 tuners at location Rx1 and (b) Channel measurement floor map.

Table I. Capacity Gain, Power Gain and Eigenvalue Dispersion (ED) for Rx Locations Rx1 and Rx2

Case	**Average Capacity – no AIM [bits/s/Hz]**	**Capacity Gain with ideal AIM**		**ED Gain [dB]**	**Power Gain [dB]**
		[bits/s/Hz]	**[%]**		
FS-Rx1	5.3	0.1	1	-0.6	0.4
OH-Rx1	2.6	0.3	10	-0.2	0.8
TH-Rx1	3.5	0.9	25	0.2	2.2
FS-Rx2	5.3	0.1	1	-0.6	0.3
OH-Rx2	1.8	0.2	13	-0.2	1.0
TH-Rx2	3.4	0.8	25	0.7	2.1



(a) (b)

Fig. 2. Average capacity – (a) FS-Rx1 with ideal tuners; (b) FS-Rx1 with Maury MT982EU30 tuners. Markers indicate conjugate of antenna input impedance Z_{IN}^* (magenta star), optimal state (black star) and 10 Maury tuner states (blue crosses).

Table I shows MIMO capacity (evaluated at 10 dB signal-to-noise ratio, with channels normalized to the FS case), eigenvalue dispersion (ED) and power gain for both indoor positions in all user cases. These results were obtained using the same procedure as in [5] and ideal AIM was added to the measured channel data in post-processing. We note that user influence significantly degrades capacity (e.g., from 5.3 bits/s/Hz in FS-Rx2 to 1.8 bits/s/Hz in OH-Rx2). However, AIM improves the terminal performance and leads to capacity gains of up to 25%, corresponding to 0.9 bits/s/Hz or 2.2 dB in power gain. Table I also suggests that the power gain is more pronounced than the ED gain and is therefore the main source of performance enhancement. Consequently, we can conclude that radiation pattern variations resulting from AIM (indicated by the ED gain) are minimal, and in the cases studied here re-matching the antennas is more critical and beneficial.

Comparing the results for Rx1 and Rx2 in Table I, we note that the performances of the terminal at both locations are very similar. In both the FS and TH user scenarios, the capacity differences are within 0.1 bits/s/Hz for both the absolute capacity gain and the average capacity without AIM. In the OH scenario, the difference in capacity without AIM is more pronounced (1.8 bits/s/Hz at Rx2 vs. 2.6 bits/s/Hz at Rx1), whereas the capacity gains are similar (13% at Rx2 vs. 10% at Rx1). The similarities between the two locations are due to the propagation characteristics of the environment, as well as the radiation patterns and orientations of the Tx and Rx antennas. Specifically, even though Rx1 is designed to give a geometrical LOS link, the maxima of the Tx antennas' radiation patterns were not aligned to the geometrical LOS direction. In fact, the Tx antenna gain in the geometrical LOS direction is 8 dB lower than the maximum antenna gain. Given the strong multipath propagation expected in the corridor environment, the reduced gain in LOS direction effectively changed Rx2 into a NLOS link. Moreover, the Rician K-factor for both locations was calculated to be between 1.7 and 5, which at best indicates weak LOS propagation.

In [5], channel measurement results were shown for an indoor (In-FS-LB at Rx2) and an outdoor (Out-OH-HB at Rx2) case, both with the Maury impedance tuners. The tuner insertion losses for the indoor and outdoor cases were estimated to be 0.1 dB and 0.7 dB, respectively. Figure 2 presents additional experimental verification results for the indoor, LB FS-Rx1 case (In-FS-LB at Rx1). Figure 2(a) shows the average capacity contour over the Smith chart, assuming ideal AIM, whereas Fig. 2(b) plots the average capacity contour obtained with the Maury tuners for a limited region on the Smith chart. As in [5], very good agreement between the ideal and real tuner cases is observed both in terms of the absolute capacity as well as the location of the optimal capacity states. Naturally, the capacity with the Maury tuners is lower as a result of the insertion losses. By comparing the average channel gains at the optimal state for both the ideal and real AIMs, the tuner loss was estimated at 0.3 dB. This result is within the range of insertion losses specified for the Maury tuners [5]. Given the power gains in Table I of up to 2.2 dB, the real tuners are then able to offer significant net performance gains of up to 1.9 dB. Moreover, the higher gains are obtained when the user is present (i.e., OH and TH cases), which corresponds to real usage scenarios.

III. CONCLUSIONS

In this work we studied and experimentally verified the potential of AIM to compensate for user effects on terminals. It was found that for an indoor scenario and a TH grip, average capacity gain of 25%, corresponding to 2.2 dB power gain, was achieved. Moreover, two different terminal locations (i.e., LOS and NLOS) yielded similar AIM results due to the orientation of the antenna radiation patterns relative to the LOS direction. Moreover, experimental results showed an insertion loss of 0.3 dB for the Maury impedance tuners in the In-FS-LB-Rx1 case. Therefore, we conclude that in cases with user effects (OH and TH), AIM can give significant performance gains even when tuner losses are accounted for.

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