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Multiplexing Efficiency of MIMO Antennas with User Effects

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***Abstract*—Recently, the multiplexing efficiency metric is proposed for characterizing the MIMO performance of terminal antennas. Here, we show that it can also provide useful insights into the impact of user on MIMO terminal performance. In particular, the impact of user hand and head on the efficiency and correlation of a MIMO antenna can be conveniently quantified using the multiplexing efficiency metric. For example, we find that the hand introduces a $4\,\mathrm{dB}$ loss in total efficiency relative to the free space case, for a penta-band two-element MIMO terminal antenna operating at $750\,\mathrm{MHz}$. However, the multiplexing efficiency drops by only $2.4\,\mathrm{dB}$, due to the de-correlation effect of the hand partly compensating the loss in total efficiency.**

I. Introduction

Recently, a simple and intuitive metric "multiplexing efficiency" has been proposed to characterize the absolute efficiency of MIMO antennas [1]. The multiplexing efficiency metric η_{mux} defines the loss of power efficiency when using a multi-antenna prototype to achieve the same channel capacity as that of an ideal array in the same propagation channel. For the reference propagation channel with uniform 3D angular power spectrum (APS), a closed form expression of η_{mux} has been derived. For the two-antenna case,

$$\eta_{\mathrm{mux}} = \sqrt{\eta_1 \eta_2 (1 - |r|^2)}, \tag{1}$$

where η_i is the total efficiency of antenna i, and $|r|$ is the magnitude of the complex correlation between the two antennas. Because of the unique features of the expression, multiplexing efficiency is ideal for evaluating the effectiveness of MIMO terminal antennas. Moreover, the multiplexing efficiency metric is also found to yield results that are consistent to those from link-level performance evaluations of MIMO antennas [2].

However, it is known that the user can significantly influence the performance of multi-antenna terminals [3]. In this contribution, we illustrate that the multiplexing efficiency metric can be used to effectively quantify and hence address critical design parameters of MIMO antennas in typical user scenarios. In order to focus on the impact of user on multiplexing efficiency, we use the reference uniform 3D APS to describe the incident field of the antennas with the user, *i.e.*, the expression in (1) can be used directly. On the other hand, if other statistical descriptions of the APS are considered, such as those given in [4], the mean effective gain (MEG) and the complex correlation of the antennas can be employed to generalize this metric for arbitrary propagation scenarios [5]. More details on the evaluation procedure using the multiplexing efficiency metric can be found in [1], [5].

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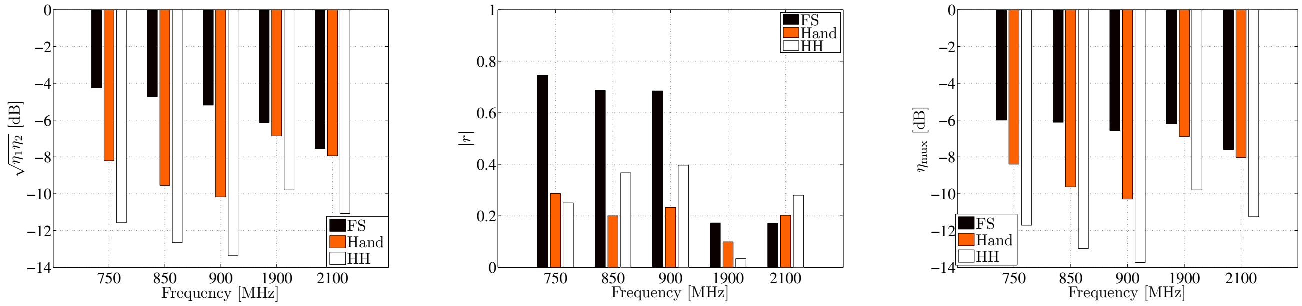
II. Impact of User on Performance Characteristics of a MIMO Terminal

To highlight the effectiveness of multiplexing efficiency for evaluating MIMO antennas in the presence of a user, we study the performance of a penta-band two-element MIMO terminal antenna. The total efficiency of the antenna is measured at the five nominal frequencies in each of three scenarios. In addition to the no-user or "free space" (FS) reference scenario, we also evaluate typical user scenarios with a "hand" scenario and a "head & hand" (HH) scenario. In Fig. 1(a), the average total antenna efficiency (in dB) of the two-element MIMO antenna is shown, *i.e.*, the term $\sqrt{\eta_1\eta_2}$ in (1). It is noted that this term quantifies not only the mean value of the antenna efficiencies, but also the efficiency imbalance, since the geometric mean (in linear scale) describes the "flatness" of the branch power. For the FS scenario, it is observed that the average efficiency decreases monotonically as the frequency increases. However, this is not the case in the presence of the user, since the user absorbs power and de-tunes the antennas to different extents at different frequencies. In comparison to the FS scenario, the hand introduces a $4 \sim 5\,\mathrm{dB}$ loss in efficiency for the three low-band cases, whereas the loss is less than $1\,\mathrm{dB}$ for the two remaining (high-band) cases. In the HH scenario, an additional loss of $3\,\mathrm{dB}$ is introduced due to the head for all the five bands.

The presence of the user is also known to have significant impact on the correlation between the two antenna elements. In Fig. 1(b), the magnitude of the complex correlation is calculated using the measured radiation patterns of the antennas in the different scenarios. It is noted that the correlation coefficient is about 0.7 for the three low-band cases in the FS scenario, whereas it is below 0.2 for the two high-band cases. However, when the hand or both the hand and head are introduced, the correlation in the three low-band cases is reduced to below 0.4 for the hand case and below 0.3 for the HH case. For the two high-band cases, the presence of the user reduces the correlation at 1900 MHz but slightly increases it at 2100 MHz, although in practice the overall



(a) Averaged antenna total efficiency (b) Correlation coefficient (c) Multiplexing efficiency

Fig. 1. Performance characteristics of a two-element MIMO terminal antenna in free space and typical user scenarios.

TABLE I
MULTIPLEXING EFFICIENCY OF TWO-ELEMENT MIMO TERMINAL ANTENNA IN FS, HAND AND HH SCENARIOS.

Frequency [MHz]		750	850	900	1900	2100
$\sqrt{\eta_1\eta_2}$ [dB]	FS	-4.2	-4.7	-5.2	-6.1	-7.5
	Hand	-8.2	-9.5	-10.2	-6.9	-7.9
	HH	-11.6	-12.7	-13.4	-9.8	-11.1
$\sqrt{1-\lvert r\rvert^2}$ [dB]	FS	-1.8	-1.4	-1.4	-0.1	-0.1
	Hand	-0.2	-0.1	-0.1	-0.0	-0.1
	HH	-0.1	-0.3	-0.4	-0.0	-0.2
$\eta_{\rm mux}$ [dB]	FS	-6.0	-6.1	-6.6	-6.2	-7.6
	Hand	-8.4	-9.6	-10.3	-6.9	-8.0
	HH	-11.7	-13.0	-13.7	-9.8	-11.3

performance impact is insignificant, due to the low correlation values involved.

The multiplexing efficiency $\eta_{\rm mux}$ of the MIMO terminal antenna in the three scenarios is given in Fig. 1(c). In comparison to Fig. 1(a), it can be seen that $\eta_{\rm mux}$ is largely determined by the average efficiency $\sqrt{\eta_1\eta_2}$ (both with and without user), except for the three low-band cases in the FS scenario. In the context of multiplexing efficiency, the impact of the antenna total efficiency is intuitive. This is because antennas with lower total efficiencies will reduce the signal-to-noise ratios (SNRs) of the received signals, which will in turn degrade the capacity performance. However, the impact of correlation on $\eta_{\rm mux}$ is given by the term $\sqrt{(1-|r|^2)}$ in (1), where only a very high correlation value will cause a significant impact. As can be observed in Table I, the correlation of about 0.7 in the three low-band cases for the FS scenario causes a drop in the multiplexing efficiency of about $1.6\,\rm dB$.

In Fig. 2, the loss of multiplexing efficiency $\Delta\eta_{\rm mux}$ is defined as the difference between the $\eta_{\rm mux}$ of the FS scenario and that of the hand or HH scenario. In particular, it has been discussed previously that the hand introduces a $4 \sim 5\,\rm dB$ loss in efficiency for the three low-band cases. However, as observed in Fig. 2, $\Delta\eta_{\rm mux}$ is only about $2.5 \sim 4\,\rm dB$ in the hand scenario. This is because the loss due to the high correlation of the three low-band cases in the FS scenario is significantly reduced in the presence of the user. Thus, $\eta_{\rm mux}$ allows the impact of the user to be understood both in terms

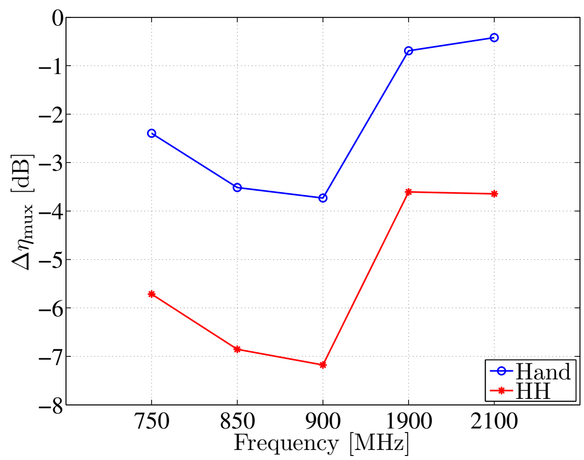


Fig. 2. Loss of multiplexing efficiency $\Delta\eta_{\rm mux}$ in the presence of the user comparing to the free space scenario.

of the loss in antenna efficiency and the effect on correlation.

III. CONCLUSIONS

In this work, we show that the impact of the user on the performance of MIMO terminals can be clearly explained using the multiplexing efficiency metric, based on the separate contributions from the antenna efficiency and the correlation. This insight allows antenna designers to effectively quantify and address key parameters in designing MIMO terminal antennas for typical usage scenarios.

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