

Effect of User Presence on Receive Diversity and MIMO Capacity for Rayleigh-Fading Channels

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Abstract—The effects of the presence of the user on multiple-input–multiple-output (MIMO) performance for wireless communications systems is investigated through measurements in a reverberation chamber. Measured results have demonstrated that despite a decrement on the envelope correlation coefficient, a degradation of both diversity gain and MIMO capacity are expected when the user is present. While the validity of the correlation coefficients for predicting MIMO performance is limited in the presence of the user, the effects have also been found to be strongly dependent upon frequency, antenna topology, and user characteristics.

Index Terms—Correlation coefficient, multiple-input–multiple-output (MIMO) systems, power absorbed.

I. INTRODUCTION

DESPITE the potential of multiple-input–multiple-output (MIMO) systems, recent studies have shown that there are severe limits to the theoretical ergodic MIMO capacities when more realistic scenarios are accounted for [1]. Factors influencing performance in real MIMO fading scenarios include mutual coupling, radiation efficiencies, or the presence of the user, among others. While the electromagnetic field-human body interaction has been thoroughly investigated in the literature, the effect of the presence of the user on MIMO performance has not received as much attention [2]–[8]. The presence of the user has demonstrated to have immediate influence on radiation patterns, input impedances, and therefore, on the correlation matrix, yet the effects are not fully understood and contradictory findings are commonplace. In [3], the envelope correlation coefficients were significantly increased and the mean effective gain (MEG) was decreased when the user was present. These changes showed a more important dependence to antenna orientation in [2]. In contrast, constant correlation coefficients have been found regardless of the distance from the receiving antenna to the user [5], and a simultaneous increment of both the correlation coefficients and the MEG is also available in the literature [8]. Furthermore, these contradictory results have also been found between simulated and measured results [7]. Contradictory findings can also be found for the effects on diversity gain and MIMO capacity

[6], [7]. While most studies do not find significant changes in diversity performance when the user is present, measured diversity gain effects were found to be user- and antenna-dependent in [7]. Two different adult males and antennas were employed, and for one scenario, the diversity gain was increased with one user and decreased with the other [7]. This effect was inverted when a different antenna type was employed [7]. Regarding the effects on MIMO capacity, a reduction in the MEG and a significant change in MIMO capacity was attributed to a power imbalance created by the presence of the user in [6], somehow contradicting what was previously neglected in [7] but later evaluated in ~ 2 dB in [9]. Thus, the complex dynamic role of the presence of the user on diversity gain and MIMO capacity has been identified as one of the issues for further study [10].

In this letter, we have investigated the effects of the presence of the user on the envelope correlation coefficient, power absorbed, diversity gain, and MIMO capacity. These parameters have been evaluated for different frequencies and antenna orientations under Rayleigh-fading scenarios measured in a reverberation chamber.

II. MEASUREMENT SETUPS AND RESULTS

Reverberation chambers provide a statistically repeatable laboratory-produced multipath environment for characterizing mobile terminals and antennas, and their validity is well described in the literature for both Rayleigh- and Ricean-fading environments [11], [12]. The processed S -parameters in the chamber represent estimates of the matrix H of multipath communication channels set up between the transmitting wall antennas and the MIMO receive array. Diversity gain and MIMO capacity estimates are obtained from the processed S -parameters by evaluating the cumulative probability distributions of the measured channel samples received at each MIMO array antenna

$$h_{mn} = \frac{S_{mn} \sqrt{e_{\text{ref}} (1 - |\bar{S}_{nm}|^2)}}{T_{\text{ref}}} \quad (1)$$

where m is the index for the transmitting antenna, n is the index for the receiving antenna, T_{ref} is the net chamber transfer function for a reference antenna, and e_{ref} is its radiation efficiency [13]. All measurements presented in this letter have been performed with the RC800 reverberation chamber by Bluetest AB (Gothenburg, Germany). The chamber has dimensions of 0.8 m \times 1 m \times 1.6 m, and three wall-mounted antennas, 25 platform stirring positions, two mechanical stirrer positions for each platform position, and 20-MHz frequency stirring were employed in the measurements. The 30 150 independent power samples were provided for each measured

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Fig. 1. Measurement setup inside the reverberation chamber.

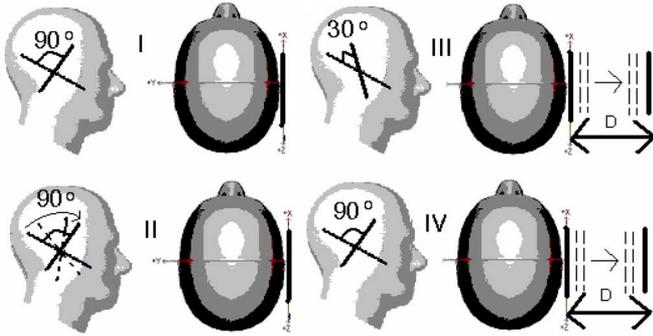


Fig. 2. Measured scenarios.

receive antenna so that a rich Rayleigh-fading environment was ensured. Measurements were performed with commercial $\lambda/2$ Bluetest 001-B-019 dipoles with operating ranges from 890 to 3000 MHz. The systems under test were formed by three transmit antennas, two receive antennas, and the standard anthropomorphic model (SAM) head phantom by MCL (U.K.), filled with CENELEC A2400 (2400 MHz) or A900 (900 MHz) head simulating liquids (HSL). Measurements were carried out at 900 and 2400 MHz and were performed with and without the phantom. The three transmit antennas were orthogonal to each other and fixed to the chamber walls. The commercial $\lambda/2$ dipoles were used as the receive antennas. The measurement setup within the reverberation chamber is illustrated in Fig. 1. In order to evaluate the solo influence of the presence of the user on diversity gain and MIMO capacity we have measured each isolated antenna in a different position within the chamber loaded with the head phantom, that is, using uncorrelated branches. This avoids merging the effects due to the presence of the user to other effects such as mutual coupling, and it is similar to the switched-array technique for outdoor measurements [14].

Four different measurement scenarios, illustrated in Fig. 2, were prepared using the setup depicted in Fig. 1. In all scenarios dipole 1 was tilted according to the European Committee for Electrotechnical Standardization (CENELEC, Brussels, Belgium) measuring procedure [15]. In scenario I, dipole 2 was placed in a position orthogonal to dipole 1. Scenario II was prepared to distinguish the effect of the user presence due to differences on the correlation coefficients from that due to the power absorbed. In scenario II, dipole 2 was rotated 90°

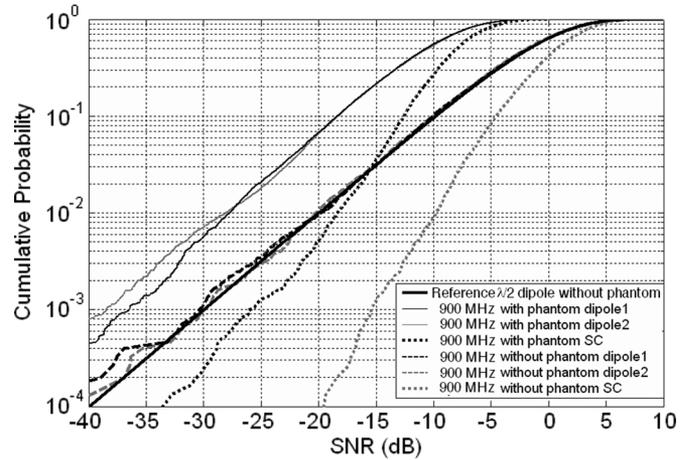


Fig. 3. Measured cumulative probability density functions for single branch and SC diversity with and without the phantom at 900 MHz.

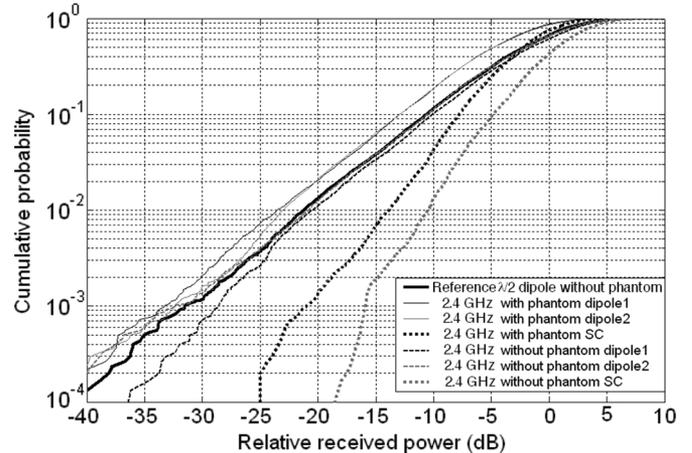


Fig. 4. Measured cumulative probability density functions for single branch and SC diversity with and without the phantom at 2400 MHz.

relative to the position of dipole 1 with 10° steps. In this way, different correlation coefficients were obtained for the same user-antenna and dipole 1–dipole 2 separating distances. Since a combination of both spatial and true polarization diversity has proven as an effective way to improve diversity in reduced volumes such as the handset [16], two more measurement scenarios were prepared. In scenario III (IV), the distance from a 30° -rotated (90° -rotated) dipole 2 to the phantom was varied in 0.1λ steps. In scenarios III and IV, dipole 2 was always collocated to dipole 1, therefore, a minimum variation if the correlation coefficients was expected. Selection combining (SC) diversity gain measured results at 900 and 2400 MHz in scenario I can be observed from Figs. 3 and 4, respectively. From these figures, it can be observed that the presence of the user causes a displacement to the left of the cumulative distribution function (CDF) curves in all cases, which is proportional to the absorbed power. A lower loss in SC diversity gain can be seen at 900 MHz respectively to that at 2400 MHz. This difference demonstrates a frequency dependence of the effect of the user's presence, as also outlined in [6]. Since at 2400 MHz more power is absorbed in the head than at 900 MHz, diversity gain loss is larger.

TABLE I
COMPARISON OF DIVERSITY GAIN MEASURED RESULTS

Frequency (MHz)	Presence of user	Diversity gain (dB)	Envelope correlation coefficient	Power absorbed (mW)
900	NO	9.51	0.139	-
900	YES	1.02	0.117	7.80
2400	NO	9.68	0.145	-
2400	YES	6.08	0.101	4.42

Table I summarizes measured SC diversity gain at 1% probability level, the envelope correlation coefficients between the two receive antennas and the power absorbed by the phantom. An interesting effect is observed from this Table I. While the envelope correlation coefficients are slightly reduced when the user is present, a relatively large diversity gain loss is accounted for. This indicates that the diversity gain loss has a stronger dependence on power absorbed than on the envelope correlation coefficient.

Since power absorbed has demonstrated to be strongly dependent on both antenna and human body topologies [17], one can conclude that the effect of the user presence on diversity gain cannot be generalized, requiring specific and detailed studies.

A. Effects on MIMO Capacity

Channel capacity is calculated using the measured channel estimates h_{mn} in (1) between each of the n MIMO receiving antennas and each one of the m wall-mounted transmitting antennas. With only one wall-mounted transmitting antenna, the normalized channel estimates from the channel vector becomes

$$H_{1 \times n} = [h_{11} \quad h_{12} \quad \dots \quad h_{1n}]. \quad (2)$$

For each channel matrix estimates $H_{1 \times n}$, the channel capacity is calculated for a specific signal-to-noise ratio (SNR) range. All channel capacity estimates are averaged to produce a maximum average channel capacity as a function of the SNR, identified as mean capacity. Since correlation, except for that associated for mutual coupling, is inherently accounted for in the measurements, mean capacity for selection combining is then derived by

$$C_{m \times n} = \log_2 \left(\det \left(I_R + \frac{\text{SNR}}{m} H_{m \times n} H_{m \times n}^* \right) \right). \quad (3)$$

MIMO capacity measured results with and without the phantom in scenario I can be observed from Fig. 5. The presence of the user causes a loss in MIMO capacity, which is again proportional to absorbed power. A larger MIMO capacity loss can be seen at 2400 MHz respectively to that at 900 MHz. This difference demonstrates again the frequency dependence of the effect of the user's presence, this time also for MIMO capacity. In a similar way to what happened to SC diversity gain, the slope of MIMO capacity curves is not altered by the presence of the user, except for low SNRs. A parallelism can be established between the rationale for the relationship between correlation, SNR and MIMO capacity of [18], and that of power absorbed in the user, SNR and MIMO capacity. From [18], it seems clear that an increase in correlation implies a decrease in received SNR and, consequently, on MIMO capacity. Similarly, we can conclude

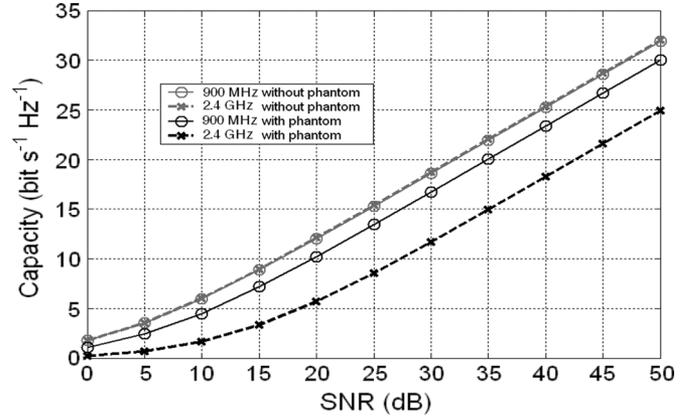


Fig. 5. Measured MIMO capacity versus SNR.

TABLE II
MEASURED RESULTS FOR SCENARIOS II AND III AT 900 MHz

II	Angular separation (°)	20	50	80
	Correlation coefficient with user	0.846	0.301	0.048
	Correlation coefficient without user	0.859	0.352	0.019
	Power absorbed (mW)	7.76	7.43	7.27
III	Distance to phantom	0 λ	0.1 λ	0.2 λ
	Correlation coefficient with user	0.640	0.670	0.563
	Correlation coefficient without user	0.687	0.687	0.687
	Power absorbed (mW)	7.80	4.50	0.90

that an increase in power absorbed by the user implies a decrease in received SNR and, consequently, on MIMO capacity. This rationale is also valid for SC diversity gain. The power absorbed in the user, however, is largely dependent on the antenna and user characteristics. Consequently, the effect of the presence of the user on MIMO capacity cannot be generalized, requiring specific and detailed studies. In fact, despite a decrease in the envelope correlation coefficients when the user is present (Table I), both SC diversity gain and MIMO capacity are decreased. This calls for a study on the effect on MEG to be able to determine the validity of the correlation coefficient for predicting MIMO performance in the presence of the user.

B. Effect on MEG

Table II summarizes measured results in scenarios II and III. The results do not show an important role of the presence of the user on the envelope correlation coefficient with a maximum change around 11%.

The combined effect of correlation and power absorbed due to the presence of the user on the CDF at 900 MHz in scenario III is depicted in Fig. 6. The displacements in the CDF curve due to power absorbed and due to the envelope correlation coefficient are clearly distinguished. A larger CDF displacement effect due to power absorbed is observed respectively to the displacement due to the alteration in the envelope correlation coefficient when the user is present.

This can also be observed by studying the effect of the presence of the user on MEG, depicted in Fig. 7 for scenario IV. In this figure, the reference antenna for the best branch MEG is

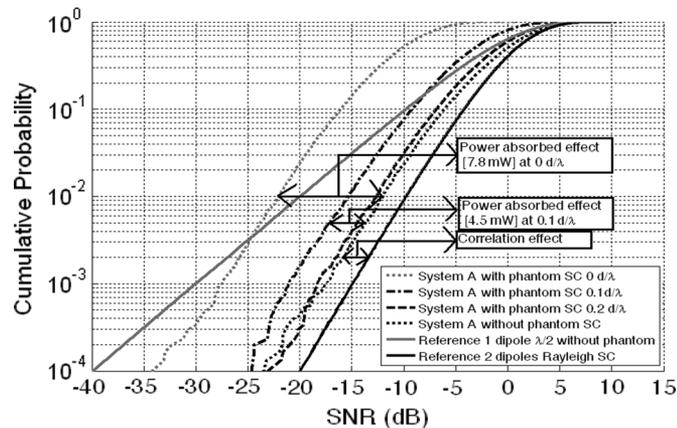


Fig. 6. Measured cumulative probability density functions for system A.

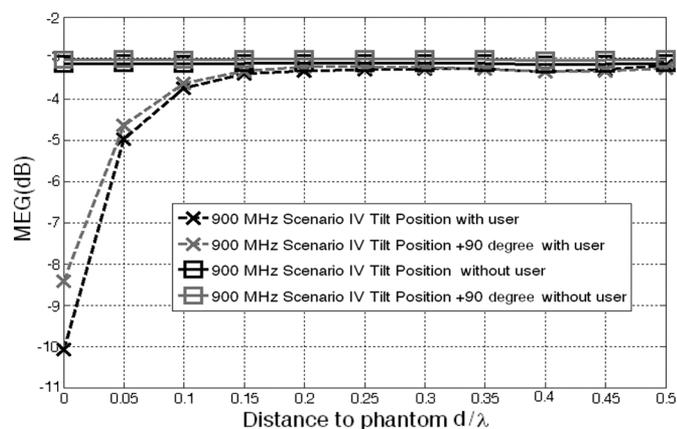


Fig. 7. Measured MEG in scenario IV.

always a dipole antenna without user [9]. From this figure, it is observed that the presence of the user clearly reduces MEG and unbalances branch power (~ 1.7 dB). When the antenna is displaced away from the user, its MEG tends to approach that of the best branch MEG, and branch power tends to be balanced. These results confirm that use of correlation coefficients is not appropriate for predicting MIMO capacity when in the presence of the user.

III. CONCLUSION

In this letter, we have evaluated the effects of the presence of the user on the envelope correlation coefficient, selection combining diversity gain and MIMO capacity through measurements in a reverberation chamber. It has been demonstrated that the power absorbed in the user plays a more important role for MIMO capacity than the change on the correlation coefficients due to the user's presence. Despite a reduction in the correlation coefficients when the user is present and in spite of the effects being frequency dependent, a reduction in MEG, diversity gain, and MIMO capacity is expected when the user is present. It has also been demonstrated not only that the correlation coefficients are not enough for properly predicting MIMO performance in the presence of the user, but also that the expected degradation in MIMO performance due to the presence of the user is strongly dependent on both antenna topology and user characteristics. This calls for detailed studies including different users

and antennas. Future research includes the extension to other more complicated effects at the handset scenario, such as radiation efficiency or mutual coupling between receive antennas in the presence of the user. Likewise, more research is envisaged to evaluate the presence of the user on other non-Rayleigh fading scenarios, which may not be straightforwardly extracted from the conclusions derived using Rayleigh-fading environments.

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