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Empirical comparison of MIMO antenna configurations

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Abstract—**By now, it is well known that Multiple–Input Multiple–Output (MIMO) communications systems are able to bring considerable performance gains for wireless communications. It is also evident that both the propagation channel and the antenna characteristics influence the MIMO capacity. In this paper, we consider the problem of comparing MIMO antenna configurations using measured radio channels. We introduce a new figure of merit called mean effective link gain (MELG), which characterizes the signal power transfer properties of a MIMO antenna system. We emphasize the importance of proper normalization of the results when comparing different MIMO antenna candidates. Evaluation examples with synthetic and measured channels illustrate the usability of the proposed methods.**

Keywords - MEG, MIMO, antenna evaluation, outage capacity, mean capacity, spatial diversity, spatial multiplexing

I. INTRODUCTION

In Single-Input Single-Output (SISO) systems mean effective gain (MEG) is a well known figure of merit that characterizes the receiving antenna's ability to capture impinging signal energy [1]. However, with MIMO arrays, both transmitting and receiving ends have multiple antenna elements. Thus, optimality criterion is more complex, as it depends not only on system's capability to transfer power from the transmitter to the receiver, but also on the signal's correlation properties, which affects the system's capability to transfer information over parallel spatial subchannels. The purpose of this paper is to present a framework on how to empirically compare Multiple-Input Multiple-Output (MIMO) antenna configurations. A generalized MEG measure provides a good yardstick for the antenna comparison. We have a realization of the propagation channel, and we plug in different MIMO antenna configurations ("spatial filters") to see their effect on the performance of MIMO system. We use measurement based antenna test bed (MEBAT), which is based on the convolution of the estimated channel data and the measured or the simulated radiation patterns of the antennas [2].

Capacity of MIMO systems has been considered e.g. in [3], [4], [5], and [6]. However, we address MIMO systems in a more systematic way – our results subsume SIMO/MISO systems as a special case. We highlight the SNR dependence of antenna configuration and importance of proper normalization of the results. We use outage capacity, which is better approach in mobile communications applications than the use of mean capacity.

II. EVALUATION METHODS OF MIMO ANTENNA SYSTEMS

A. Normalization

Normalization of the measured channel matrices is a key issue to retain the SNR properties of the antenna configurations. By considering identical and independently Rayleigh fading channels with "isotropic" antennas each branch receives equal mean power. The radiation pattern of the "isotropic" antenna can be defined as $E_{a,iso}(\theta,\phi)=\sqrt{E_\theta^2+E_\phi^2}=1$, where E_θ and E_ϕ are theta and phi polarized signal components, respectively. In such a case the channel matrices are usually normalized according to $E\left[\|\mathbf{H}\|_F^2\right]=n_t n_r$, where $\|\bullet\|_F$ is Frobenius norm, and $\mathbf{H}$ is the channel matrix. E is expectation operator, and n_t and n_r are the numbers of transmitter and receiver antennas, respectively. However, "isotropic" antenna is physically impossible in practice. Any real antenna cannot radiate constant power to each direction, or in other words, radiation pattern cannot be constant as a function of incidence angle. Further, efficiency varies between the antennas, and also polarization properties of the antennas are different. For those reasons antennas in some specific environment probably not receive the same mean power. Thus, in the context of antenna comparison such normalization distorts the effect of the antennas. Therefore we propose to use a common reference $\mathbf{H}_{ref}$ in normalization as was proposed for SISO systems in [1].

In case of real channels slow fading occurs due to obstacles in the propagation route. In real mobile communications systems slow fading is usually mitigated by slow power control. We removed slow fading from the signal using following procedure: First of all, using MEBAT, we can utilize isotropic reference in normalization. We remove fast fading form the reference system by taking a sliding mean over $\mathbf{H}_{ref}^{(i)}$ by $\left\|\mathbf{H}_{ref,sli}^{(i)}\right\|_F^2=\frac{1}{2N+1}\sum_{i-N}^{i+N}\left\|\mathbf{H}_{ref}^{(i)}\right\|_F^2$, where $2N+1$ is the number of

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samples in the sliding window. Normalization by $\mathbf{H}_{ref,sli}^{(i)}$ mitigates slow fading from the channel matrix $\mathbf{H}_{aut}^{(i)}$, which includes the effect of the test antennas. Thus, we can compare antenna systems to the common reference, which is not corrupted by the radiation pattern of any real antenna.

B. Definition of mean effective link gain (MELG)

The mean effective gain (MEG) is a useful antenna performance measure in mobile communications systems since it takes into account both the antenna and the channel characteristics [1]. Suppose that we have obtained two sequences of channel matrices from the measurements, say $\mathbf{H}_{ref}^{(i)}$ and [illegible], where $i = 1 \ldots N_s$. N_s is the number of samples in the channel. $\mathbf{H}_{aut}^{(i)}$ and $\mathbf{H}_{ref}^{(i)}$ are the channel matrices of the antenna-system-under-test and the reference antenna system, respectively. The mean received power of the channel can be defined by $P = \frac{1}{N_s}\sum_{i=1}^{N_s} P^{(i)} = \frac{1}{N_s}\sum_{i=1}^{N_s}\left\|\mathbf{H}^{(i)}\right\|_F^2$. Now, the definition of MEG in [1] generalizes to MIMO systems in a straightforward way. The mean effective link gain (MELG) is simply a sample mean power over antenna-system-under-test divided by a sample mean power over reference antenna system by

$$G_{e,MIMO} = \frac{P_{aut}}{P_{ref}} = \frac{\frac{1}{N_s}\sum_{i=1}^{N_s} P_{aut}^{(i)}}{\frac{1}{N_s}\sum_{i=1}^{N_s} P_{ref}^{(i)}} = \frac{\frac{1}{N_s}\sum_{i=1}^{N_s}\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}{\frac{1}{N_s}\sum_{i=1}^{N_s}\left\|\mathbf{H}_{ref}^{(i)}\right\|_F^2}. \qquad (1)$$

We also assume that the number of reference "isotropic antennas" equals with the number of antennas under test. Array gain is later introduced by additional parameter G_{arr}. MELG does not pose any restrictions on antenna array geometry nor it does require equal-power antenna branches. Further, absorption and matching losses are generally included in the MELG.

C. Comparison metrics of MIMO antenna configurations

First we define the instantaneous link gain by

$$G_{\mathbf{H}}^{(i)} = \frac{\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}{\frac{1}{n_t n_r}\left\|\mathbf{H}_{ref,sli}^{(i)}\right\|}, \qquad (2)$$

which is further divided into two constant terms (G_{arr}, G_{eMIMO}) and a variable term ($G_{div}^{(i)}$) by

$$G_{\mathbf{H}}^{(i)} = n_t n_r \cdot \frac{P_{aut}}{P_{ref}} \cdot \frac{\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}{P_{aut}} \frac{P_{ref}}{\left\|\mathbf{H}_{ref,sli}^{(i)}\right\|_F^2} = G_{arr} \cdot G_{e,MIMO} \cdot G_{div}^{(i)}, \quad (3)$$

where $G_{arr} = n_t n_r$ can be considered as array gain, $G_{e,MIMO} = P_{aut} / P_{ref}$ is MELG (1), and $G_{div}^{(i)} = \frac{\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}{P_{aut}} \frac{P_{ref}}{\left\|\mathbf{H}_{ref,sli}^{(i)}\right\|_F^2}$ can be considered as SNR fading. The statistics of $G_{div}^{(i)}$ gives insight into diversity properties of the system.

Mutual information can be defined[1] by

$$C_{\mathbf{H}}^{(i)} = \log_2\left|\mathbf{I} + \frac{\rho}{n_t}\mathbf{H}_N^{(i)}\mathbf{H}_N^{(i)H}\right|, \quad (4)$$

where

$$\mathbf{H}_N^{(i)}\mathbf{H}_N^{(i)H} = \frac{\mathbf{H}_{aut}^{(i)}\mathbf{H}_{aut}^{(i)H}}{\frac{1}{n_t n_r}\left\|\mathbf{H}_{ref,sli}^{(i)}\right\|_F^2}, \quad (5)$$

where $|\bullet|$ denotes determinant. By multiplying (4) by the dummy factor $\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2 / \left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2$, reordering the terms, and using the result (3), we can rewrite (4) as

$$\begin{aligned} C_{\mathbf{H}}^{(i)} &= \log_2\left|\mathbf{I} + \frac{\rho}{n_t}\frac{\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}{\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}\frac{\mathbf{H}_{aut}^{(i)}\mathbf{H}_{aut}^{(i)H}}{\frac{1}{n_r n_t}\left\|\mathbf{H}_{ref,sli}^{(i)}\right\|_F^2}\right| = \\ &\log_2\left|\mathbf{I} + \frac{\rho}{n_t}G_{\mathbf{H}}^{(i)}\frac{\mathbf{H}_{aut}^{(i)}\mathbf{H}_{aut}^{(i)H}}{\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}\right| = \qquad (6) \\ &\log_2\left|\mathbf{I} + \frac{\rho}{n_t}G_{arr}G_{e,MIMO}G_{div}^{(i)}\frac{\mathbf{H}_{aut}^{(i)}\mathbf{H}_{aut}^{(i)H}}{\left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2}\right|, \end{aligned}$$

where a knowledge about the parallel channels is enclosed in $\mathbf{H}_{aut}^{(i)}\mathbf{H}_{aut}^{(i)H} / \left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2$. Cumulative distribution functions (Cdf) of $C_{\mathbf{H}}^{(i)}$, $G_{div}^{(i)}$, and $\mathbf{H}_{aut}^{(i)}\mathbf{H}_{aut}^{(i)H} / \left\|\mathbf{H}_{aut}^{(i)}\right\|_F^2$ define the properties of the system at all probability levels. The factorization (6) gives better understanding of the mechanisms, which affect the capacity of the system. The definition is general and makes sense with arbitrary MIMO antenna configurations, e.g. ones where the antennas have different look directions − a common situation e.g. for mobile terminals. The MELG of the test antenna system directly modifies the SNR at which the mutual information is computed.

In order to compare MIMO antenna configurations, we compare the difference in capacities evaluated at a certain

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[1] Channel is unknown at the transmitter

capacity outage level. Shannon capacity is the ultimate upper bound for the maximum achievable rate of information transmission [7] without any channel knowledge at the transmitter. If channel matrix **H** is random, mutual information $C_{\mathbf{H}}$ is random as well. For the random channels typically either mean (ergodic) capacity $E[C_{\mathbf{H}}]$ or outage capacity $\{t_p : \mathrm{Prob}(C_{\mathbf{H}} < t_p) = p\}$ is considered. Mean capacity indicates channel's capability to transfer information over a large number of independent channel realizations. Outage capacity, on the other hand, is the information rate that a channel realization supports with probability of $1 - p$, where p is capacity outage probability. It assumes signal encoding over a single fading block only; this is a more realistic assumption in contemporary mobile communications systems than mean capacity. In empirical comparison outage capacity does not presume ergodicity. Hence, outage capacity is a more suitable measure for MIMO antenna comparison than mean capacity.

III. ANTENNA EVALUATION

We used ideal half wavelength dipoles at 2×2 MIMO antenna systems (*ver_synt*, *cro_synt*, *ver_real*, *cro_real*). The directivity of the dipole is 2.15 dB and antenna losses are neglected. Two different dipole antenna systems were compared: 1) two vertical dipole antennas at both ends (*ver*), 2) vertical and horizontal dipole antenna at both ends (*cro*). Inter–element spacing between the antennas at both ends of the link was λ/2. Rx array was rotated in azimuth using 30 degree steps in order to perform statistically significant and extensive analysis. We used both synthetic and measured data in the analysis.

A simple geometric based channel model modified for MIMO systems was adopted (see Fig. 1) in the synthetic analysis. In this scattering model of 10 scatterers, which are uniformly distributed within a 2D single scattering disc, the scatterers are updated randomly for every sample of the signal. The considered Rx antenna arrays are located in the middle of the scattering disc. The distance (l) between the Tx and the Rx is 1000 m, and the radius of the scattering disc (r) is 100 *m*. The model produces independent signals for two orthogonal polarizations (θ,ϕ). We stress that a more realistic channels should be used in order to compare MIMO antenna configurations. However, this simple channel model is sufficient for demonstrating how antenna properties affect the MIMO system performance.

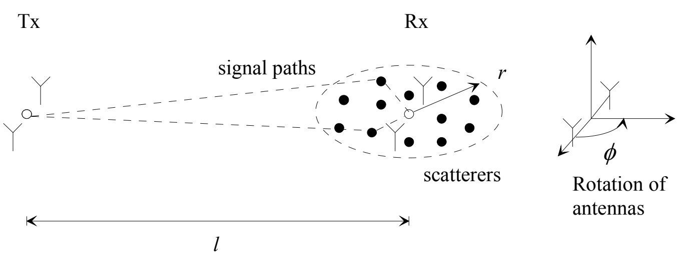

Figure 1. A geometric based channel model

Investigations using measured channel data were carried out for the support of the theoretical study. A wideband channel sounder [8], [9] was adopted in the microcell (line of sight) measurement campaign in Helsinki downtown. The measurement antenna arrays – zigzag at the Tx and spherical at the Rx – were equipped with dual–polarized patch antennas [9]. Two adjacent antenna elements were selected from the Tx measurement array. The measurement based antenna test bed (MEBAT) was utilized at the Rx end of the link [2]. Complex impulse responses – the outcomes of the measurement process – were first estimated using a beam-forming algorithm at the Rx [9]. The estimated signal distribution was weighted (convolved) with the ideal dipole antennas. Channel estimation at the Rx enables to exploit the definition of "isotropic sensor" in normalization. Thus, the normalization matrix was generated using two vertically polarized patch antennas and two "isotropic sensors" at the Tx and the Rx, respectively. Slow fading was removed using the sliding window of 20 λ.

The characteristics of the antennas were analyzed using four criteria. The analysis of outage capacity (6) is presented in Figs. 2 and 3, and the analysis of eigenvalue dispersion in Fig. 4. Eigenvalue dispersion is defined by the ratio of geometric and arithmetic means of the eigenvalues of $\mathbf{H}_{aut}^{(i)}\mathbf{H}_{aut}^{(i)H}$ [10]. The outage capacity using "isotropic sensors" was also presented for comparison purposes. This basically models the performance of "pure" radio channel, since the "antenna" response is the same for each direction. The analysis of $G_{e,MIMO}$ and $G_{div}^{(i)}$ are presented in Fig. 5. Outage capacity, diversity gain, as well as eigenvalue dispersion are given at 10% probability level.

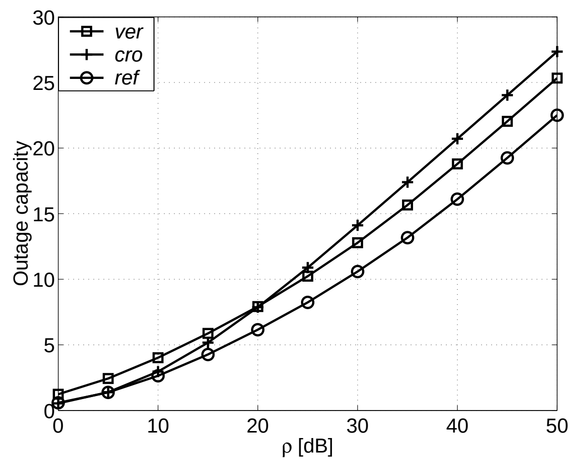

Figure 2. The results of outage capacity using sythetic channel presented at 10% probability level

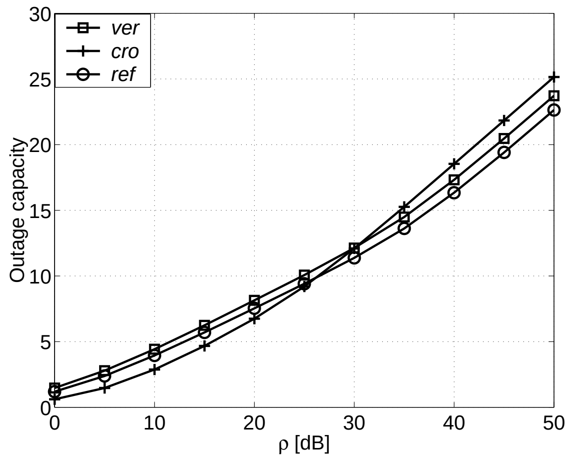

Figure 3. The results of outage capacity using real channel presented at 10% probability level

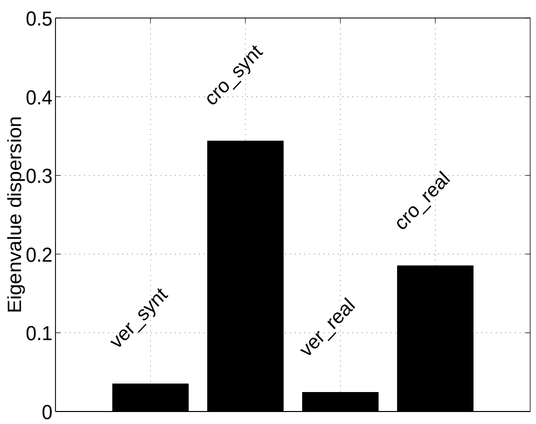

Figure 4. The results of eigenvalue dispersion presented at 10% probability level. Both synthetic and real channel is considered.

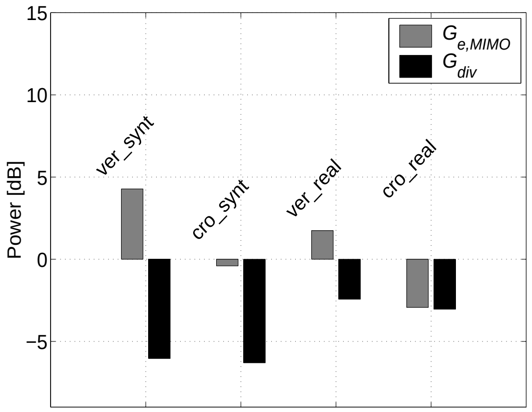

Figure 5. The results of $G_{e,MIMO}$ and $G_{div}^{(i)}$. $G_{div}^{(i)}$ presented at 10% probability level. Both synthetic and real channel is considered.

The results of eigenvalue dispersion, and MELG ($G_{e,MIMO}$) show a significant difference between the cross polarized antennas (*cro*) and the vertically polarized antennas (*ver*) (see Figs. 4 and 5). *ver* produces higher $G_{e,MIMO}$, whereas *cro* deliver lower eigenvalue dispersion. Thus, *ver* and *cro* would perform better and worse in low and high ρ range, respectively. Thus, the antenna system performance is related to the signal to noise ratio, meaning that the system with lower eigenvalue dispersion does not necessarily guarantee higher outage capacity if its MELG is low. The results of $G_{div}^{(i)}$ and eigenvalue dispersion show no correlation meaning that the antenna, which perform well in diversity applications, does not necessarily perform well in MIMO applications. The theoretical and synthetic results agree fairly well in the comparison; only the power levels are somewhat different which can be seen from the results of $G_{e,MIMO}$ and $G_{div}^{(i)}$.

IV. CONCLUSIONS

Both multiplexing and signal power transferring properties have to be considered in MIMO system evaluation. The antenna element orientations and the radiation properties of the antenna elements can influence remarkably on the capacity. In this paper, a new criterion is proposed for the MIMO antenna system performance study. A figure of merit called a mean effective link gain (MELG) defines the ability of a MIMO antenna system to transfer power from the transmitter to the receiver.

The proper normalization of the results in the evaluation of different MIMO antenna prototypes plays a significant role. Normalization to the used antennas themselves (antennas under test) removes the effect of MELG and makes the comparison of different MIMO antenna systems difficult. Normalizing the received power of test antennas to a common reference enables evaluating signal transferring properties between antenna candidates.

Generally, the capacity of a MIMO system is a trade-off between $G_{e,MIMO}$, G_{div}, and the distribution of eigenvalues. Low eigenvalue dispersion of one MIMO system does not necessarily guarantee higher capacity as compared to the other system with higher MELG – the performance of antenna system in MIMO systems is related to the signal to noise ratio.

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