Evaluation of the Relative MIMO Gain

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Abstract — This paper shows some results for the relative MIMO capacity (compared with a SISO system) with respect to the number of antennas, antenna orientation and distance. The MIMO capacity is extracted from the Geometrically Based Single Bounce Channel Model, where the channel is modelled by propagation in an environment composed of clusters of scatterers. The results are shown for the pico-, micro- and macro-cell environments. For pico- and micro-cells, an increase in the number of antennas has a larger impact on capacity gain than the one for macro-cells. For micro-cell scenarios, a 20% variation in performance is obtained, depending on the orientation of the antennas of both transmitter and receiver. For the macro-cell, a similar variation is seen, but only for the orientation of base station antennas. For pico- and micro-cells, the relative MIMO gain is very similar for both up- and downlinks. The gain increases from macro- to pico-cell scenarios, ranging from 1 to 8.

I. INTRODUCTION

Radio propagation is an important aspect of any radio design or radio network planning. Channel models try to give a realistic representation of the radio propagation between two or more points, and can roughly be divided into two groups [1]: deterministic and stochastic models.

Deterministic models aim at predicting channel characteristics for a specific location, by using information from the environment and the locations of the transmitter (Tx) and receiver (Rx). This means that a deterministic model is only valid for the specific location, where it was modelled after. On the other hand, stochastic models aim at modelling the statistical properties of the channel, therefore, being more general. The same model can often be used unchanged for many similar environments, e.g., rural, suburban and urban [2], [3], [4].

The model used in this work is a semi-stochastic one, as it uses some information from the environment to give more realistic results. For instance, for micro-cells, when modelling a scenario where Tx and Rx are located in a street, its width is used as a parameter. In contrast with deterministic models, the model shown here does not require detailed building information or street-layouts.

By implementing multiple antennas at transmitters and receivers, i.e., Multiple Input-Multiple Output (MIMO) with \( n_t \) and \( n_r \) antennas, one can increase the throughput of the system. With a simulator, the effects of MIMO [5] can be studied for different cell types, but also for multi-user scenarios [6]. In this work, MIMO has been applied in single user scenarios, in order to isolate the effects from MIMO and from multiple users.

This paper describes the work related to MIMO that has been carried out in the IST-AROMA project [7]. In Section II, the channel model that was used to extract the capacity information is described. Section III defines the upper and lower bounds for the MIMO capacity and the relative MIMO gain. The results obtained from simulating the three different cell types are shown and analysed in Section IV. The conclusions of this work are drawn in Section V.

II. GEOMETRICALLY BASED SINGLE BOUNCE CHANNEL MODEL

In the Geometrically Based Single Bounce Channel Model (GBSBCM) developed by IST/TUL [8], the propagation environment is composed of scatterers, which are grouped into clusters. Clusters are distributed inside the environment by means of the uniform distribution, while the scatterers inside the clusters follow a 2D Gaussian distribution. Among others, the number of clusters and the average number of scatterers within a cluster is set as a parameter. The reflection coefficient of each scatterer is described by its complex value, where the magnitude of the reflection coefficient is the attenuation, due to reflection losses, uniformly distributed in \([0, 1]\); the phase of the reflection coefficient is an extra phase change, which is uniformly distributed in \([0, 2\pi]\). Pico- and micro-cell environments consider a Line-of-Sight (LoS) signal, while the macro-cell does not, Figure 1. The micro-cell environment is modelled by an ellipse, whereas the pico- and macro-cell ones are modelled by circles. For both pico- and micro-cells, Base Station (BS) and Mobile Terminal (MT) are located inside the area, whereas for the macro-cell only MTs are located inside the circle, the BS being outside.

The previously described model was implemented [5], [6] so that a Channel Impulse Response (CIR) is calculated for each channel between MT-MT and MT-BS pairs. For each pair, a scatter region is defined, common clusters of scatterers for two or more regions having the same reflection coefficient. In the case of MIMO, the CIR is also calculated between all Tx and Rx antenna pairs of each region. In this case, the exact location of the antennas is used to calculate the Directions of Departure (DoD) and Arrival (DoA), and the distances between Tx and scatterer, and scatterer and Rx. However, time differences between the paths from a reflector to the Rx antennas are neglected. The mutual coupling between antennas is not considered, which holds true in some cases [9].
The capacity of a Single Input-Single Output (SISO) system in a band-limited case is obtained by using the well-known Shannon’s formulation

\[ C_{\text{SISO}} = \log_2 (1 + \rho) \]  

(1)

where \( \rho \) is the Signal-to-Noise-Ratio (SNR).

Based on this initial formulation, the general capacity for a MIMO system, as well as its upper and lower bounds can be calculated [10].

The upper bound for the MIMO capacity is obtained when all the CIRs of the antenna pairs are completely uncorrelated, being given by

\[ C_{\text{upper}} = \min(n_r, n_t) \log_2 (1 + \rho) \]  

(3)

In a similar way, the lower bound for the MIMO capacity can be obtained when the CIRs between the different antenna pairs are completely correlated, resulting in

\[ C_{\text{lower}} = \log_2 [1 + \rho \cdot \min(n_r, n_t)] \]  

(4)

The gain one can achieve by using a MIMO system over a SISO one can be defined by

\[ G_{\text{M/S}} = \frac{C_{\text{MIMO}}}{C_{\text{SISO}}} \]  

(5)

IV. RESULTS

A. Simulation Conditions

The scenarios described in the previous section were analysed with the parameters given in Table 1. This section looks into the influence on the relative MIMO gain of the angle between the antenna array of the Tx and the Rx, the number of Tx and Rx antennas, and the distance. The distribution of the relative MIMO gain is also addressed, which has been proposed as a simple statistical model for MIMO in system-level simulators [11].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency [GHz]</td>
<td>2</td>
</tr>
<tr>
<td>Bandwidth [MHz]</td>
<td>5</td>
</tr>
<tr>
<td>Time resolution (receive filter) [ns]</td>
<td>200</td>
</tr>
<tr>
<td>Antenna spacing</td>
<td>( \lambda )</td>
</tr>
<tr>
<td>Noise floor [dBm]</td>
<td>-150</td>
</tr>
<tr>
<td>SNR [dB]</td>
<td>10</td>
</tr>
<tr>
<td>Number of runs</td>
<td>500</td>
</tr>
</tbody>
</table>
B. Rotation of the Antenna Array

In previous work [11], [13], the rotation of the antenna array was investigated for the three cell types. Figure 2 shows the normalised relative MIMO gain for the micro-cell, which shows a maximum of 20% variation, depending on the angle between Tx and Rx antenna arrays, the smallest value being obtained when Tx and Rx antenna arrays are perpendicular. The macro-cell has a very similar shape as the micro-cell, whereas the relative MIMO gain for the pico-cell does not show these effects, as the angle of the antenna arrays does not influence the relative MIMO gain.

In the simulations, the angle of both BS and MT antenna arrays was set randomly between [0, 2π] for each run, in order to average out these effects.

![Fig. 2. Normalised relative MIMO gain for different angles between Rx and Tx antenna arrays for the micro-cell.](image)

C. Number of Antennas

Equations (6) and (7), defining the upper and lower bound of the relative MIMO gain respectively, indicate that the relative MIMO gain depends on the number of Tx and Rx antennas. The relative MIMO gain for the micro-cell is given in Figure 3.

As expected, the relative MIMO gain is the highest for the 16 × 16 antenna system in all three the scenarios. Both pico- and micro-cells show a very symmetrical pattern for up- and downlinks (UL and DL), which is not the case for the macro-cell. Taking the model of the macro-cell into account, Figure 1.c, this effect can be explained by the fact that only the MT is surrounded by scatterers, creating different angle of arrival patterns for the MT and the BS.

D. Distance between BS and MT

Another important factor of influence on the relative MIMO gain is the distance between Tx and Rx, although this is not very noticeable for the case of a 2 × 2 antenna system. Figure 4 shows the average relative MIMO gain vs. distance for symmetric antenna systems, i.e., n_r = n_t. The case of asymmetric antenna systems shows very similar results. In both systems, the relative MIMO gain is the highest curve, which corresponds to the antenna system with the highest number of antennas (16 × 16). The relative MIMO gain in the pico-cell reaches its maximum at 30 m, staying more or less constant after that. In micro-cell scenarios, the relative MIMO gain decreases rapidly with distance; distance does not seem to influence the relative MIMO gain in the macro-cell environment. Note that the MIMO capacity in the macro-cell does decrease with the distance, but the gain of MIMO over SISO does not change, as the SISO capacity has the same decline with respect to the distance.

E. Distribution of the Relative MIMO Gain

A statistical model for the relative MIMO gain was developed based on the distribution of this gain. The cumulative distribution function (CDF) of the relative MIMO gain is shown in Figure 5, where the vertical lines indicate the minimum and maximum relative MIMO gains according to (6) and (7); a micro-cell is taken, where the curve of the CDF shifts to the left, reducing the relative MIMO gain, when distance increases (the arrow indicates the pattern of increasing distance).

![Fig. 3. Normalised relative MIMO gain for different number of Rx and Tx antennas for the micro-cell.](image)

![Fig. 5. Distribution of the relative MIMO gain for the micro-cell for increasing distance [100, 600]m (direction of the arrow).](image)
The distributions of the relative MIMO gains for the pico-cell are quite close, with the exception of the CDF for the relative MIMO gain at a distance of 10 m, and shows $G_{MS} > 3$ for 50% of the cases. As expected from earlier results for the macro-cell, the distribution of the relative MIMO gain for these cells does not depend on the distance between the BS and MT.

V. CONCLUSIONS

This paper defines the relative MIMO gain, $G_{MS}$, as the ratio of the MIMO capacity over the SISO capacity. Results are shown, based on simulations with a Geometrically Based Single Bounce Channel Model, for the relative MIMO gain related to the number of antennas, their orientation and the distance. A statistical model for the relative MIMO gain, based on the distribution of the relative MIMO gain, extracted from the simulation results, is presented. It is observed that the relative MIMO gain depends on these parameters, as well as on the cell type (pico-, micro- or macro-cells), ranging form 1 up to 8.

REFERENCES


Fig. 4. Relative MIMO Gains versus distance for symmetrical antenna systems.