Realistic Ray-Tracing Based Assessment of MIMO Performance in Indoor Environments

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Abstract—Realistic evaluation of a multiple-input multiple-output (MIMO) system in an indoor rectangular corridor is carried out using an image based 3-D ray-tracer. The simulated patterns of the antennas used are incorporated in the simulations. Results show that the channel statistics such as correlation depend strongly on the receiver locations sampled. Using a set of randomly distributed points it is shown that the capacity of a 2x2 system using antennas with low mutual coupling closely follows the performance of an ideal MIMO channel.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) systems using receiving and transmitting antenna arrays can be used to increase channel capacity relative to a single-input single-output (SISO) system [1]. The performance of a MIMO system mainly depends on the channel matrix of the propagation environment which in turn depends on the type of antenna elements being used among other things. The capacity of a MIMO system has been studied using measurement campaigns [2], however these results apply only for the given propagation environment. Modeling efforts based on deterministic methods such as ray-tracing and vector parabolic equations have also been used which can require much fewer resources and time than measurements. In this paper, a 3-D ray-tracing tool is used to study the effect of using closely spaced antennas with low mutual coupling on the correlation coefficient at the receiving antenna elements, the channel matrix and hence the channel capacity of 2x2 MIMO system.

II. SIMULATION SETUP

A. 3-D Ray-Tracer

The channel impulse response, $h_{ij}$, from the $j$th transmitter (TX) to the $i$th receiver (RX) is computed using an image based 3-D ray-tracer presented in [3]. The maximum number of reflections allowed between the TX and RX is 8 which is chosen based on preliminary simulations which show that paths with more reflections do not have significant contribution to the overall solution. The ray-tracer makes use of the simulated antenna pattern of each element of the antenna array in the transmit mode and therefore provides realistic results incorporating the effects of mutual coupling between the antenna elements.

B. Metamaterial Antenna Array

A two-element metamaterial antenna array designed in [4] is used both as the transmit and receive array. The simulations are carried out near the resonant frequency of 2.53 GHz. The center-to-center separation distance between the array elements is $\lambda/13$ or 0.009 mm. The slots of the antennas of the transmitter and the receiver are aligned and placed vertically in the channel.

C. Channel Geometry

Simulations were carried out for a 2.83 m wide and 3.3 m high corridor with a uniform rectangular cross section. The electrical properties of the walls were approximated as those commonly used in literature for walls in indoor office environments, a relative permittivity, $\epsilon_r$, of 5 and conductivity, $\sigma$, of 0.001 S/m. The transmit array was placed in the middle of the corridor at a height of 1.3 m above the ground. In order to obtain the channel statistics, multiple channel realizations in the form of varying the location of the receive array were used. Several types of receive array distributions were considered. Ray-tracing simulations showed that channel statistics such as correlation are highly sensitive to the receiver location, therefore the most realistic and practical choice was a set of uniformly randomly distributed receiver locations over a volume of space spanning the cross section of the corridor 20 m on either side of transmit array. A top view of the channel is shown in Fig. 1, where the transmit array is marked with the red cross, the receive array locations are shown in blue dots and the walls are represented with thick black lines.

The minimum number of receiver locations required to compute the channel statistics is dependent on the volume of space over which the receiver can be varied. Through simulations, it is observed that for the given geometry 5000 uniformly distributed points are sufficient for obtaining converged results.
III. RESULTS

A. Correlation

To evaluate the impact of using the metamaterial arrays with low mutual coupling on correlation, equivalent simulations using a two-element array of ideal half-wave dipole antennas is used at the transmit and receive locations. A comparison between the magnitude of the received signal at the first element \((h_{11} \text{ from } TX_1 \text{ and } h_{12} \text{ from } TX_2)\) indicates a low correlation for the metamaterial array. Similar result for the dipole array shows the two received signals to be very similar indicating a much higher correlation. The phase difference between the received signal at the first element for both the metamaterial and dipole arrays is shown in Fig. 2.

![Fig. 2. Phase difference of the voltage setup at the first receiver element due to the transmitters.](image)

For the metamaterial array, the correlation coefficient at the first RX element, \(\rho(h_{11}, h_{12})\) is 0.079 and the second, \(\rho(h_{21}, h_{22})\) is 0.526 compared to 0.968 and 0.972 respectively for the dipole array. The correlation is lower with the metamaterial array as is expected. The correlation coefficients for the metamaterial array are asymmetric because the pattern of the 2 elements is designed to be orthogonal to each other to reduce mutual coupling and additionally due to the narrow corridor where the majority of the radiation comes from the broadside directions. If a grid of points with uniform spacing is used, the correlation changes significantly as the grid is shifted even by a few millimeters, where as the random distribution yields stable results regardless of the receive locations as long as a sufficiently large number of points, here 5000, is chosen as shown in Fig. 3. The solid lines show the mean correlation value of the 20 iterations and the dashed lines mark one standard deviation from the mean.

B. Channel Capacity

The channel capacity calculated using the channel matrix obtained from simulations, where the variance of each \(h_{ij}\) is normalized to unity is shown in Fig. 4. The capacity curve of the MIMO system using the metamaterial array has almost the same slope for SNR beyond 15 dB as that of an i.i.d. MIMO channel and is a significant improvement over the correlated MIMO channel. The system using the dipole array, however, produces capacity results similar to that of a fully correlated MIMO channel, which is expected since the two closely spaced dipole antennas receive virtually the same signal.

![Fig. 3. Correlation coefficient for samples of 5000 randomly distributed receiver locations.](image)

![Fig. 4. Channel capacity calculated using the metamaterial array compared with i.i.d. MIMO channel and correlated MIMO channel.](image)

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REFERENCES