Simulation and measurement of a MIMO antenna system

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In this paper we present simulation and measurement results of the channel capacity of a 3?3 MIMO antenna system. The aim of this research is maximization of a MIMO channel capacity for indoor environment. The dependence of the channel capacity on the antenna position was analyzed by simulations. We have also examined the effect of the frequency dependence of the antenna system (in case of conjugate-matching and non-conjugate-matching) for the channel capacity. Based on the simulation results in the created and measured antenna system the antennas were at a right angle to each other. At the two chosen different structures we measured the antenna parameters and the channel capacity. In this paper we present the results of the measurements which clearly confirm our simulations. We will point out to the differences between the two antenna structures.

1. Introduction

Wideband indoor wireless systems are gaining increasing importance nowadays. This is why the analysis of MIMO systems which eliminate the problems of indoor propagation is of primary significance. In case of indoor propagation a frequent problem is that there are disturbing objects between the transmitter and the receiver antennas, consequently there are no direct line of sight in the wireless channel. The objects in the channel adversely affect the transmission because they scatter and reflect the signals, resulting in attenuation and phase errors. MIMO systems can be a solution to these problems.

MIMO system can eliminate the phase, distance and polarization diversity. Thus in an indoor environment the theoretically highest channel capacity can be nearly achieved. It is known that the channel capacity scales linearly with the number of antennas at both the receiver and transmitter for complex Gaussian fading channels. When designing a complete multiple antenna system we have to try to approach a maximal mean capacity with a minimal number of antennas in the system.

For multiple antenna systems an important problem is the reduction of the number of antennas for practicability and usability reasons. We will assume that the multiple antenna system with three elements on both the receiver and transmitter issues is the simplest structure for the highest mean capacity.

In this paper we present simulation and measurement results for the channel capacity of a 3x3 MIMO antenna system. The aim of this research is the maximization of a MIMO channel capacity for indoor environment. Three-dimensional (3-D) double-bouncing (DB) stochastic scattering model was used for the channel simulations. The dependence of the channel capacity on the antenna position was analyzed by simulations [1,2].

We have also examined the effect of the frequency dependence of the antenna system (in case of conjugate-matching and non-conjugate-matching) for the channel capacity. Based on the results of the simulation we have created the antenna system and measured the antenna parameters and the channel capacity. In this paper we present the results of the measurements which clearly confirm our simulations. We will point out to the difference between the two antenna structures.

2. Simulation model and calculation methods

The investigated MIMO system contains tree wire dipole antennas both on the transmitter and the receiver device.

2.1. Wire antenna analysis

Let us consider an antenna consisting of many arbitrary oriented wire elements. Starting with Maxwell equations and by enforcing the boundary condition for the total tangential electrical field on the antenna wire, it is possible to obtain the simplified general integral equation for arbitrary oriented wires. The tangential component of the electrical field generated by the current which flows on the conductor's surface is E^s_{tan} while the incident field generated by the excitation is E^i_{tan}. Then the boundary condition is

$$E^i_{\tan} + E^s_{\tan} = 0 \quad (1)$$

on the conductor's surface. The E^s electrical field can be derived from the A magnetic vector potential due to the current I:

$$\mathbf{E}^s = \frac{1}{j\omega\varepsilon}\left(\text{grad div} + k^2\right)\mathbf{A} \quad (2)$$

where

$$\mathbf{A} = \frac{\mu}{4\pi}\int_L \mathbf{I}\frac{e^{-jkR}}{R}ds \qquad R = |\mathbf{r} - \mathbf{r}'|$$

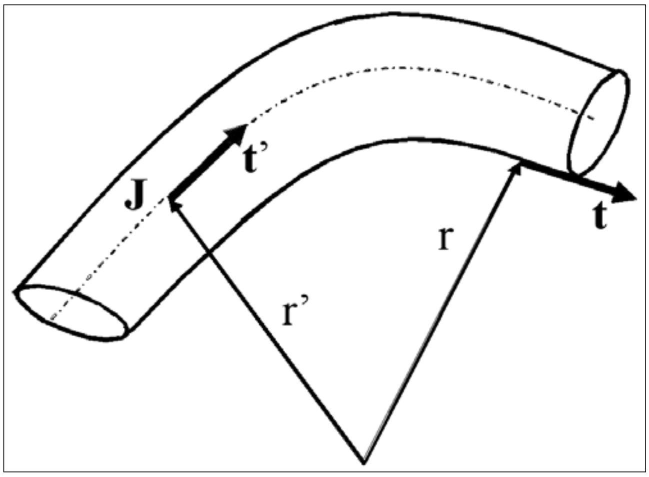


Fig. 1. Thin wire geometry

The Pocklington's procedure, applied to wire antennas, supposes the current to be located over a thin filament over the conductor *(Fig. 1)*.

The Pocklington's integral equation can be obtained finally by substituting (2) into (1).

$$E^{i}_{\tan} = -\frac{1}{4\pi j\omega\varepsilon}\int_{L}\left(\mathbf{t}\cdot\mathbf{t'}k^{2}I\frac{e^{-jkR}}{R}+\frac{\partial}{\partial l'}I\frac{\partial}{\partial l}\frac{e^{-jkR}}{R}\right)dl' \quad (3)$$

The Method of Moments (MM)

Operator equation (3) has the form

$$Lf = g \quad (4)$$

where

L represents the linear integro-differential operator,

f is the unknown current and

g is the known excitation.

The f should be determined and MM expands by a set of N known expansion functions (f_1, f_2, f_3, ...), as a linear combination

$$f = \sum_{n}\alpha_{n}f_{n} \quad (5)$$

The α_n expansion coefficients are to be determined for the selected set of expansion functions. Substituting (5) into (4) and considering the linearity of L, we have the equation for N unknowns:

$$\sum_{n}\alpha_{n}Lf_{n} = g \quad (6)$$

Taking the inner product of (6) with other set of functions, the weighting functions, the system of linear equations can be derived:

$$\sum_{n}\alpha_{n}\langle w_{m}, Lf_{n}\rangle = \langle w_{m}, g\rangle \quad (7)$$

Comparing (7) and (3), the system of equations to be solved can be written in the form

$$[Z_{mn}][I_{n}] = [V_{m}] \quad (8)$$

where

$[Z_{mn}]$ is the impedance matrix,

$[V_m]$ is the voltage vector.

The inner product is defined as a line integral over L and using the Galerkin method to simplify the equation (8), the impedance matrix and voltage vector elements are as follows:

$$Z_{mn} = \frac{j\omega\mu}{4\pi}\int_{s_n}\int_{s_m}\mathbf{t}_{n}\mathbf{t}_{m}f_{n}f_{m}\frac{e^{-jkR_{mn}}}{R_{mn}}ds_{m}ds_{n} + \\ + \frac{1}{4\pi j\omega\varepsilon}\int_{s_n}\int_{s_m}\frac{df_{n}}{ds_{n}}\frac{df_{m}}{ds_{m}}\frac{e^{-jkR_{mn}}}{R_{mn}}ds_{m}ds_{n}$$

$$V_{m} = \int_{s_m}f_{m}E^{i}_{\tan}ds_{m}$$

To solve (8) we used piecewise sinusoidal expansion and weighting functions.

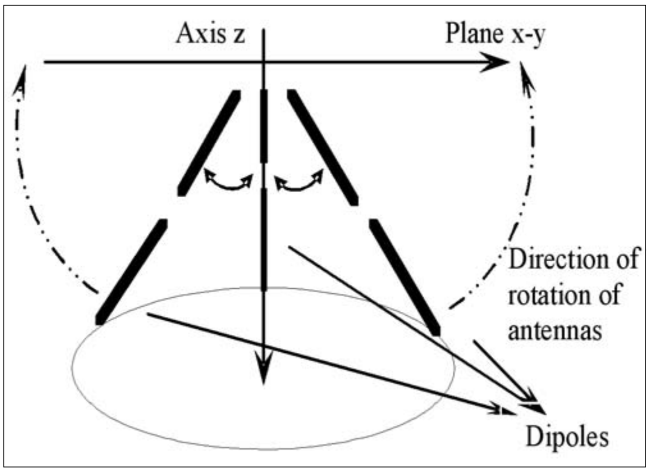
The resulting mutual impedance between MIMO antenna elements can be obtained using the N port analysis to the whole system of antennas.

2.2. 3D – environment simulation model

The antenna system is situated in a 3-D scattering environment indoor channel. Waves of arbitrary polarizations are incident on the antenna structure from all possible directions. The waves launch from the transmitter antennas and first they reach the elements of the primary reflection surface and from here they re-scatter to the second group of scatterers and finally they are reflected to the receiving antennas. The transmission matrix (**H**) which connects the receiver and transmitter antennas is filled by assuming DB scattering [1,2].

Our multiple antenna system is composed of M_t=3 and N_r=3 electric dipoles at both the transmitter and the receiver units. In this way, the transmission channel matrix H consists of nine transmission links (3x3). At the start of the simulation the antennas were oriented in the Z axis and later they were rotated toward the X-Y axes (the structure was opened like an umbrella). The radiated electric field of each dipole is applied for the calculation of the transmitter matrix. The current distribution for each electric dipole is sinusoidal, which is often assumed for finite length dipoles. *Fig. 2* shows the method of rotating of antennas in the simulation structure [3].

Fig. 2.
3x3 MIMO antenna structure for maximizing the mean capacity by rotation of the antennas, parallel at the transmitter and the receiver units, from the axis Z toward X-Y plane (it's opened like an umbrella)



This simulation model statistically describes the material, surface and motion of these objects which results in phase and amplitude error in the course of propagation. By this method we could describe the continuously varying indoor environment.

For a MIMO radio channel with channel matrix H, the SVD is given as $H=SVD^T$, where S and D^H (complex conjugate transpose of D) are complex unitary matrices, $V=diag(\sqrt{\lambda_1},....,\sqrt{\lambda_r})$ diagonal square-matrix with λ_1, λ_2,...., λ_r are the positive eigenvalues of HH^H and $r \leq \min\{Mt,Nr\}$ denotes the rank of HH^H. With the assumption of known channel at the transmitter, the theoretical capacity from water filling [4] is given as

$$C = \sum_{i=1}^{r'} \log_2(1+\lambda_i SNR_i) \tag{9}$$

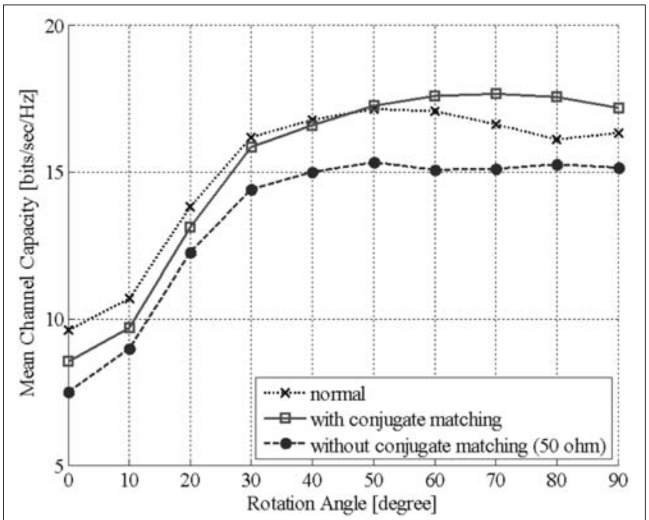
where $SNR_i=P_t/\sigma^2$ is the individual SNR of the eigenmodes after water filling and r' denotes the number of useful eigenmodes with positive power allocation [4,5].

3. Results of simulations

3.1. Effect of mutual coupling for the channel capacity

We simulated the motion of the antennas by the rotation method described above. At the beginning of this simulation the antennas are parallel with the axis Z. In the midst of the simulation the antennas opened in the space like an umbrella. At the end of the simulation the antennas reached the X-Y plane. In this case the antennas are on the farthest position, where the phase between antenna and axis Z was changing from 0° to 90°. The result of the simulation shows perfect symmetry for the X-Y plane. We look for the perfect position for the maximal mean channel capacity in consideration of the effect of mutual coupling in case of conjugate matching and non-conjugate matching. *Fig. 3* shows the mean capacity versus the angle of rotation.

Fig. 3.
Channel capacity of a 3x3 MIMO antenna system, in the normal case, in the case of mutual coupling with and without conjugate matching



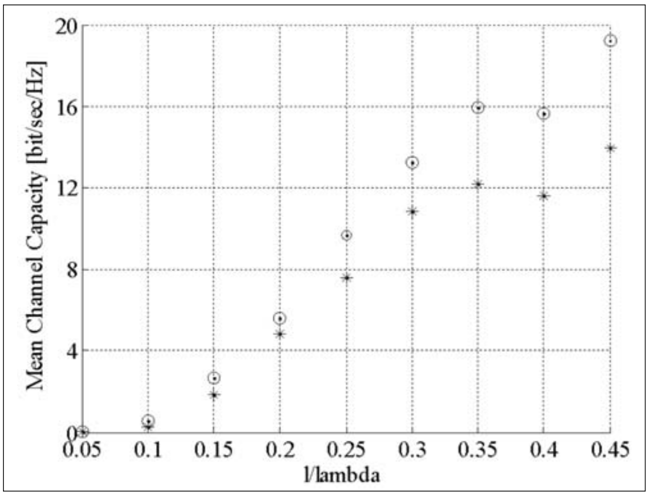
In Fig.3 when the rotation angle is zero the antenna elements of structure are close to the Z axis, and when the phase is ninety degrees the antennas are on the X-Y plane.

In normal case the maximal channel capacity is about 45°. In case of conjugate matching the maximal channel capacity is at 70° and without conjugate matching the capacity is maximal and approximately constant from 50°. We chose the 45° – structure, because the realization was the easiest in this case, since the antennas were on three different edges from one corner of a cube in this adjustment.

3.2. Alternation of frequency

In the next phase of simulation we investigated the mean channel capacity for various frequencies. It was easy to realize by changing the length of antenna at a constant wavelength. *Fig. 4* shows the result of the simulation.

Fig. 4.
Mean capacity of a 3x3 MIMO dipole antenna system versus of l/λ, with (o) and without (∗) effect of mutual coupling



We investigated the effect of the mutual coupling for 0.05 to 0.45 antenna length to wavelength ratios. The optimal is when the dipole length is $l/\lambda > 0.35$). Evidently we found that in case of conjugate matching the mean channel capacity is higher than for non conjugate matching case. According to our expectation the effect of the mutual coupling is stronger if the antenna-length is reduced.

4. Measurements

Based on the results of the simulation, the realized antenna system both on the transmitter and receiver side were built on three different edges from one corner of a virtual cube. We made two different structures: the first was like the simulated unit, the other was a modified variation of the preceeding constellation *(Fig. 8)*. The antennas are shifted from the edges to the center of faces which are touched at edges *Fig. 5*.

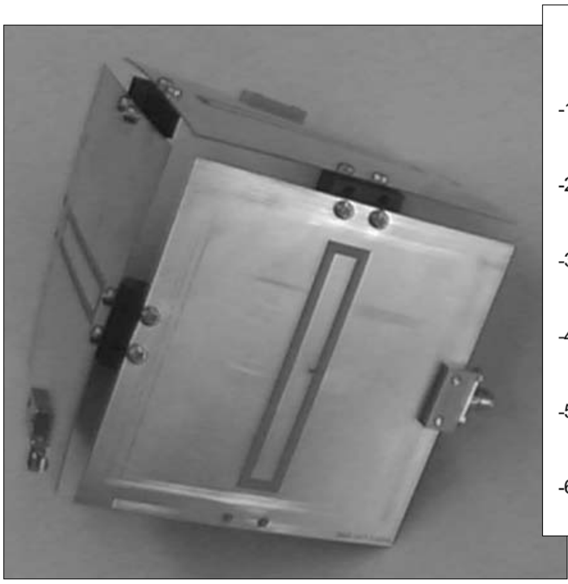


Fig. 5. Three antennas in the middle of the faces

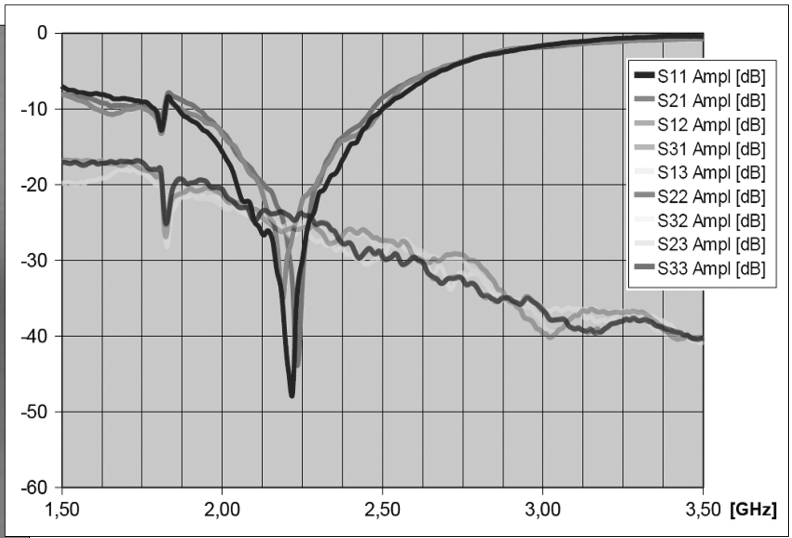


Fig. 6. Measured S-parameters versus frequency

Fig. 7.
Calculated channel capacity versus frequency

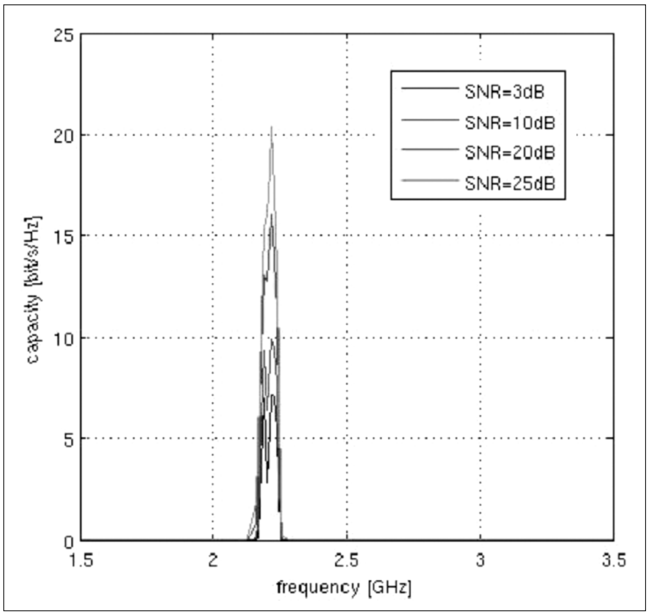


Fig. 5 and 6 show the realized antenna structures. The result of the measurement are the Sij (mutual coupling) and Sii (reflection) parameters of the antennas. Fig. 6 (antennas on faces) *and 9* (antennas on edges) show these results. From the S parameters we calculated the mutual coupling values and the mean channel capacity *(Fig. 7 and 9)*.

The results show that the second structure (antennas on the faces) is better than the first one, because it realizes the highest channel capacity. Note that the antennas in the second case (antennas on the faces) do not disturb each other, because they are placed far apart.

The next challenge will be the direct measurement of the channel capacity. So far we have carried out a test measurement.

5. Conclusions

In this paper we investigated a 3x3 MIMO antennas system. Simulations were made for analysing the effects of antenna positions on the mean channel capacity. We found that the maximum mean channel capacity is achieved by the structure in which the antennas are perpendicular to each other. We examined the frequency dependence of the antenna structure also by simulation in case of conjugate and non-conjugate matching. The simulation gave the expected results, thus the maximal channel capacity is at $l/\lambda = 0.35$ in case of conjugate matching.

Based on the simulation results in the realized and measured structure the antennas were perpendicular to each other. The measurements confirmed our results of simulations.

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Fig. 8. Three antennas on the edges

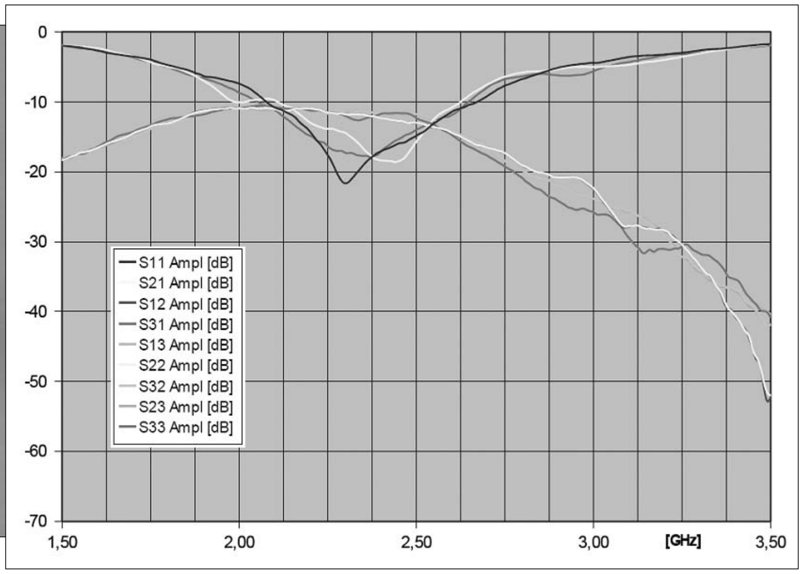
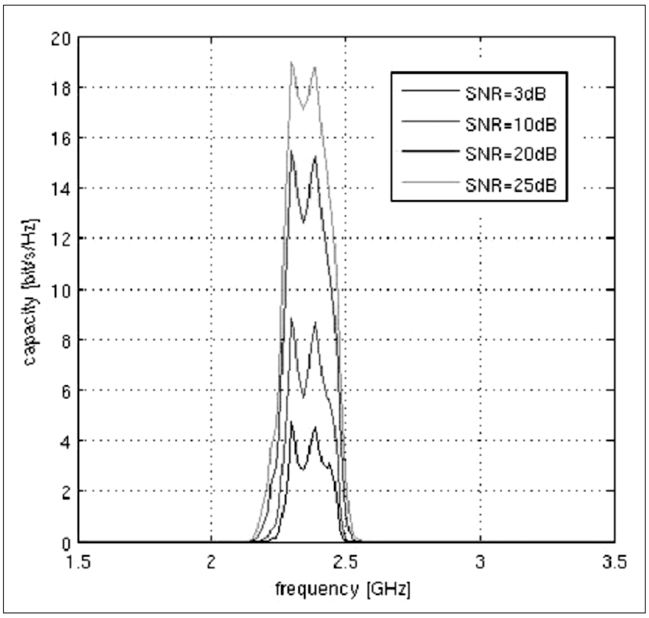


Fig. 9. Measured S parameters versus frequency

Fig. 10.
Calculated channel capacity versus frequency



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