Numerical Investigation of Effects of Wall Reflection on Indoor MIMO Channel Capacity

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Abstract

The channel capacity of the indoor multiple input multiple output (MIMO) system is investigated with consideration of the effects of the wall by using a hybrid method of the finite difference time domain (FDTD) method and the method of moments (MoM). Firstly, the effects of wall material on indoor MIMO channel capacity are investigated according to the physical parameters of the wall, i.e. the relative permittivity, the conductivity and the thickness. Secondly, the channel capacity, the average received power on each receiving branch and the effective degrees of freedom (EDOF) of multiple paths of the indoor MIMO system are statistically analyzed with the wall reflectivity instead of the physical parameters of the wall. Finally, the effects of wall reflection on the eigenvalues of the MIMO channel transfer matrix and the spatial correlation between the antenna elements are statistically investigated. It is found that the wall reflectivity is a suitable parameter to investigate the wall effects on the indoor MIMO system.

1. INTRODUCTION

Recently, the indoor multiple input multiple output (MIMO) communication system has attracted considerable research attentions [1]-[5]. Because the wall is an important scatterer in the indoor communication environment, the effects of the wall on the MIMO system are worth investigating. Some research works on the effects of the wall have been done by using FDTD method [1]-[2], but those analyses were limited only in two dimensions (2-D). The three dimensional (3-D) indoor model has been analyzed by using the array decomposition fast multipole method (AD-FMM) [3], and the experimental measurements have been carried out [4]-[5]. However, the effects of the wall material and reflection have not been investigated enough in the previous research works. In this paper, firstly, the effects of the wall material on indoor MIMO channel capacity are investigated according to the physical parameters of the wall, i.e. the relative permittivity, the conductivity and the thickness. Secondly, the channel capacity, the average received power on each receiving branch and the effective degrees of freedom (EDOF) of multiple paths of the indoor MIMO system are statistically analyzed with the wall reflectivity instead of the physical parameters of the wall. Finally, the effects of wall reflection on the eigenvalues of channel transfer matrix and the spatial correlation between the antenna elements are investigated and statistically analyzed.

2. NUMERICAL METHOD AND SIMULATION MODEL

The channel transfer matrix of the indoor MIMO system is investigated accurately by using the hybrid method of FDTD and MoM [6]. In the hybrid method, the FDTD method is used to analyze the transmitting array antennas and the propagation channel, and the MoM is applied to analyze the receiving array antennas which move randomly in the local receiving area in order to obtain the spatial statistical characteristics of the received signals. If only the FDTD method is used to analyze the same spatial statistical characteristics, the calculation of the FDTD has to be repeated many times so that the CPU time is usually unacceptable. In the hybrid method, the electric field of the whole region is calculated by the FDTD method except for the receiving array antennas. The electric field in the local receiving area is stored according to the Yee Cell and then used as the incident electric field on the receiving array elements which are analyzed by the MoM. Both the FDTD analysis and the inverse calculation of the mutual impedance matrix of the receiving array antennas in MoM analysis are executed only one time, so the CPU time can be saved significantly. The hybrid method can be applied to investigate the complex indoor MIMO system by using the advantage of FDTD method which is powerful in analyzing almost arbitrary structure and material scatterers.

In the simulation, a single user to single user narrow band 2×2 MIMO system with uniform power strategy is considered. In order to investigate the effects of the wall mainly, only the wall is considered and the other scatterers are not included in the analysis model. The vertical half wavelength dipole antennas are used as the transmitting and receiving antennas. The array spacing of transmitting and receiving antenna arrays are an half of wavelength. The length, width and height of the analysis region are 8.6 m, 7.1 m and 3.4 m, respectively. The geometry of the indoor MIMO analysis model is illustrated in Fig. 1. The thickness of the wall can be changed from 0.05 m to 0.4 m, but the inner size of the room is fixed. The receiving antenna array moves randomly in the local receiving area (0.4 m × 0.4 m × 0.4 m). The distance between the transmitting array antennas and the center of local receiving area is 6.8 m. The whole analysis region is divided by the FDTD Yee cells (678×558×258) with the 8-layer perfectly matched absorbing boundary (PML). The total transmitted power is constrained to -20 dBm. Only the additive white noise with a power of -93.98 dBm is considered on each output of the receiving antennas. The operation frequency is 800MHz.

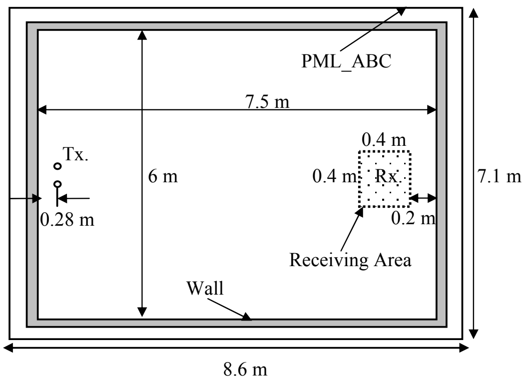

Fig. 1: Plan of indoor MIMO analysis model.

3. NUMERICAL RESULTS

Based on the channel transfer matrix obtained by using the hybrid method, the effects of the wall material on indoor MIMO channel capacity are investigated according to the physical parameters of the wall, i.e. the relative permittivity, the conductivity and the thickness. The relative permittivity (ε_r) is from 1.5 to 8.5, the conductivity (σ) is from 0.001 S/m to 1.0 S/m and the thickness (D) is from 0.05 m to 0.3 m. These numerical results are shown in Fig. 2, Fig. 3 and Fig. 4, respectively. The channel capacity is the average values in the local receiving area. It is found that there is no direct relationship between the physical parameters of the wall and the channel capacity. According to the electromagnetic theory [7], the physical parameters of the wall have effects on the indoor electric field distribution which can be analyzed by using the wall reflectivity. Therefore, it is worth investigating that the effects of the wall reflectivity on the indoor MIMO channel capacity.

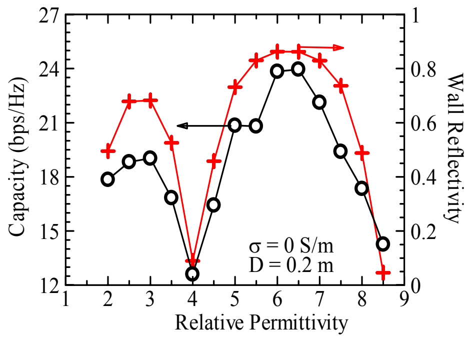

Fig. 2: MIMO channel capacity and the wall reflectivity with the relative permittivity of the wall when the conductivity and the thickness are 0 S/m, and 0.2 m, respectively

In the simulation, the wall reflectivity is calculated according to the infinite width and finite thickness lossy slab with the oblique incidence [7]. The average incident angle is 48.5º which is decided according to the relative position of the side wall and the transmitting and receiving arrays. The electric field is the perpendicular polarization which is normal to the plane of incidence. The results of the reflectivity with the physical parameters of the wall are also shown in Fig. 2, Fig. 3 and Fig. 4, respectively. It is found that the change of the MIMO channel capacity with the physical parameters of the wall has the similar tendency with that of the wall reflectivity.

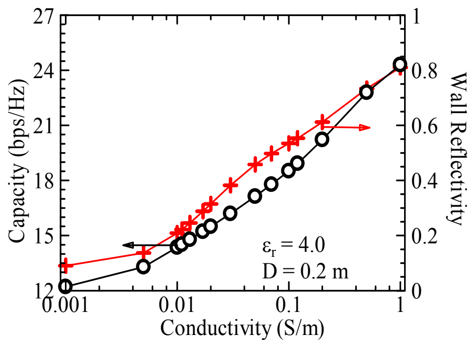

Fig. 3: MIMO channel capacity and the wall reflectivity with the conductivity of the wall when the relative permittivity and the thickness are 4.0, and 0.2 m, respectively

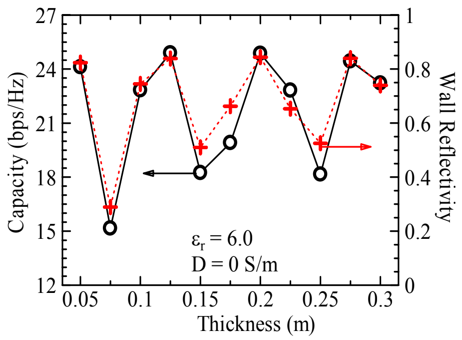

Fig. 4: MIMO channel capacity and the wall reflectivity with the thickness of the wall when the conductivity and the relative permittivity are 0 S/m, and 6.0, respectively

The MIMO channel capacity is statistically analyzed with the wall reflectivity instead of the physical parameters of the wall, and the results are shown in Fig. 5. It is found that the indoor MIMO channel capacity is improved with the increasing of wall reflectivity. According to the general MIMO channel capacity formula [8], it is found that the MIMO channel capacity is determined by the received power and the multiple paths essentially. In order to investigate the effects of wall reflectivity on the indoor MIMO channel capacity sufficiently, the average received power and the multiple paths are also statistically analyzed with the wall reflectivity.

The average received power on each receiving antenna branch is calculated by

$$P_{avg} = E\left[\frac{1}{Nr}\sum_{i=1}^{Nr}\left(\frac{P_T}{Nt}\sum_{j=1}^{Nt}\left|h_{ij}\right|^2\right)\right], \quad (1)$$

with the total transmitted power (P_T) and the entries of the channel transfer matrix (h_{ij}). $E[\cdot]$ is the expectation. Nt and Nr are the number of transmitting and receiving array elements, respectively.

The multiple paths of MIMO system is analyzed by the effective degree of freedom (EDOF) [2]. EDOF denotes the number of the effective parallel sub-channels can be formed by the MIMO wireless channel and is calculated by

$$EDOF = \sum_{i=1}^{n}\lambda_i^2 / \max\left[\lambda_i^2\right], \quad (2)$$

where λ_i is the i^{th} eigenvalue of the MIMO channel transfer matrix. EDOF is a real number between one and the minimum value of transmitting and receiving array antennas, and the effect of path loss is not included.

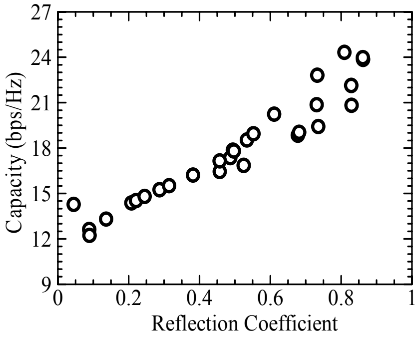

Fig. 5: Indoor MIMO channel capacity versus the wall reflectivity

In the simulation, the average received power and the EDOF of the indoor MIMO system are also statistically analyzed with the wall reflectivity and the results are shown in Fig. 6 and Fig. 7, respectively. It is found that the EDOF of multiple paths is improved with the increasing of wall reflectivity. When the wall reflectivity is lower, the EDOF is close to 1. The average received power is also improved with the increasing of wall reflectivity. However, the change of received power is not large when the wall reflectivity is increased from 0.2 to 0.4. But the MIMO channel capacity is improved with the wall reflectivity. Therefore, in order to estimate the MIMO channel capacity reasonably, the average received power and EDOF should be considered together.

The eigenvalues of channel transfer matrix are very important to analyze the channel capacity and the Bit Error Rate (BER) of the MIMO system. Therefore, the relation between the eigenvalues (λ) of $\boldsymbol{HH}^{\dagger}$ and the wall reflectivity are also investigated ($\boldsymbol{H}$ and † denote the MIMO channel transfer matrix and the complex conjugate transpose operation, respectively). The results are shown in Fig. 8. It is found that the effects of wall reflectivity on the first eigenvalue of $\boldsymbol{HH}^{\dagger}$ is not significant. However, the second eigenvalue of $\boldsymbol{HH}^{\dagger}$ is improved with the increasing of wall reflectivity. This is because there is no other scatterers except the wall in our simulation model, namely it is a line of sight (LOS) propagation environment. The wall reflectivity has lower effects on the dominant signal path, but the multipath components are improved when the wall reflectivity becomes higher. The improvement of the second eigenvalue can reduce the BER of MIMO system. Therefore, the higher wall reflectivity can bring benefit to both of the channel capacity and BER of indoor MIMO system.

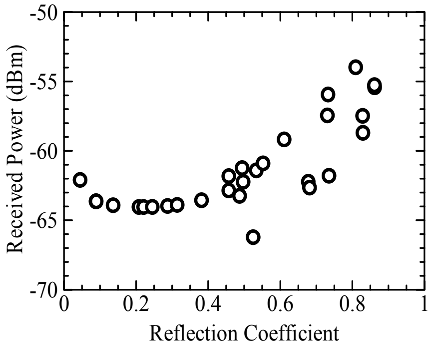

Fig. 6: Average received power on each receiving branch of indoor MIMO system versus the wall reflectivity

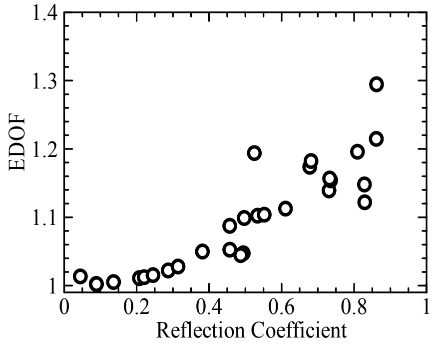

Fig. 7: EDOF of indoor MIMO wireless channel versus the wall reflectivity

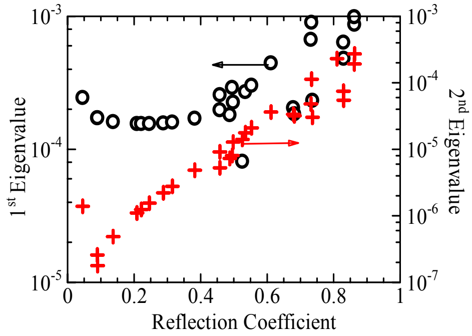

Fig. 8: Eigenvalues of $\boldsymbol{HH}^{\dagger}$ of indoor MIMO system versus the wall reflectivity.

The MIMO channel capacity is also affected by the spatial correlation of antenna elements. In our research, the spatial correlation coefficients between the transmitting and the receiving antenna elements are also investigated with the wall reflectivity. The results are shown in Fig. 9. In that figure, the "ρ(T1,T2)" denotes the spatial correlation coefficient between the first and the second transmitting antenna elements, and the "ρ(R1,R2)" denotes the spatial correlation coefficient between the first and the second receiving antenna elements. It is found that the higher wall reflectivity can reduce the spatial correlation of antenna elements which will improve the MIMO channel capacity.

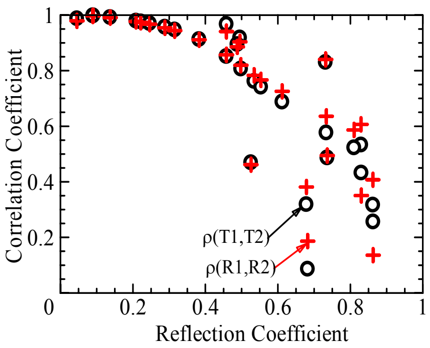

Fig. 9: Correlation coefficient between the transmitting and the receiving antenna elements of indoor MIMO system versus the wall reflectivity.

4. Conclusions

The effects of the wall material and reflectivity on the indoor MIMO channel capacity have been investigated by using the hybrid techniques of FDTD method and MoM. It has been found that there is no direct relationship between the physical parameters of the wall and the MIMO channel capacity. By statistically analyzing the channel capacity with the wall reflectivity, it has been found that the higher wall reflectivity can cause the higher MIMO channel capacity. The effects of the wall reflectivity on the average received power, the EDOF, the eigenvalues and the spatial correlation between the antenna elements have also been investigated, it has been proved that the wall reflectivity is a suitable parameter instead of the physical parameters of the wall to investigate the wall effects on the indoor MIMO system.

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