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Numerical Investigation of Channel Capacity of Indoor MIMO System

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SUMMARY The effect of wall and indoor scatterers on the indoor multiple input multiple output (MIMO) communication system is investigated by using the hybrid technique of finite difference time domain (FDTD) method and method of moments (MoM). MIMO channel capacity with the wall reflection is investigated with consideration of the eigenvalue of channel covariance matrix, the received power and the effective multipaths of MIMO system. It is found that the stronger side wall reflection can lead to the higher MIMO channel capacity. MIMO system with indoor scatterers is also analyzed and compared with the line of sight (LOS) indoor MIMO system. It is found that the scatterer material has different effect on the received power and the effective multipaths of MIMO system.

key words: *MIMO, channel capacity, indoor channel, hybrid methods, reflection coefficient, effective multipaths*

1. Introduction

Recently, the multiple input multiple output (MIMO) communication system which uses multiple antennas at both the transmitter and the receiver has attracted considerable research attention, especially the indoor MIMO system [1]–[4]. It has been well established that the performance of MIMO system is strongly reliant on the wireless propagation environment [3]–[6]. In the indoor MIMO system, the effect of wall and indoor scatterers is worth investigating. The effect of wall geometry has been analyzed in [4] and [7], but they were limited only in two dimensional models because of the limitation of the conventional analysis methods. Therefore, a hybrid technique of finite difference time domain (FDTD) method and method of moments (MoM) has been proposed in our previous research [8], which can be used to analyze a more realistic MIMO wireless channel model. By using the hybrid technique, the effect of wall material in three dimensional indoor models has been investigated [9], where the investigation was based on a certain thickness of wall. Because the effect of geometry, material and thickness of the wall can be synthetically analyzed by the wall reflection, the effect of wall reflection on MIMO system has been analyzed [10], [11]. It has been found that the wall reflection coefficient is a suitable parameter instead of the individual physical parameters of wall to analyze the wall effect on indoor MIMO system, but in those researches only the effect of side wall reflection was considered.

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In this paper, the channel capacity of indoor MIMO system is calculated with the electrical parameters and the thickness of indoor walls by using the hybrid technique of FDTD method and MoM [8]. Based on the obtained numerical results, MIMO channel capacity is further statistically analyzed respectively with the reflection coefficients of side wall, ceiling wall and behind wall which are calculated based on the geometry and the material of the wall and the relative position between antenna elements and the wall, where the eigenvalue of MIMO channel covariance matrix, the received power and the effective multipaths of MIMO system are also statistically analyzed with these reflection coefficients. In order to validate the effect of side wall reflection further, the effect of antenna array spacing on MIMO channel capacity with the side wall reflection coefficient is also investigated.

In pervious researches, the non-line of sight (NLOS) MIMO wireless channel was usually obtained by placing a metal partition to artificially obstruct the LOS path between the transmitting and receiving antenna arrays [3], [12]. However, the effect of partition geometry and material has not yet been investigated. In this paper, 28 cubic scatterers are placed uniformly in the middle of indoor environment to form the NLOS indoor wireless channel. The effect of indoor scatterers on MIMO channel capacity is investigated and compared with the line of sight (LOS) indoor MIMO system (i.e. only the wall is included in the indoor environment) with consideration of the eigenvalue of MIMO channel covariance matrix, the received power and the effective multipaths of MIMO system. Furthermore, the effect of indoor scatterer material is also analyzed.

2. Effect of Wall Reflection

In the simulation, a single user to single user narrow band 2×2 indoor MIMO system with uniform power allocation is considered. The vertical half wavelength dipole antennas are used as the transmitting and receiving antenna elements. In order to focus on the investigation of the wall effect, only the indoor walls are considered and the other scatterers are not included in the analysis model in this section. The geometry of indoor MIMO analysis model is illustrated in Fig. 1. The length, the width and the height of the analysis region are 8.6 m, 7.1 m and 3.4 m, respectively. The wall thickness is changed from 0.05 m to 0.4 m, but the interior size of the room is fixed as 7.5 m×6 m×2.25 m. The receiving antenna array moves randomly in the local receiv-

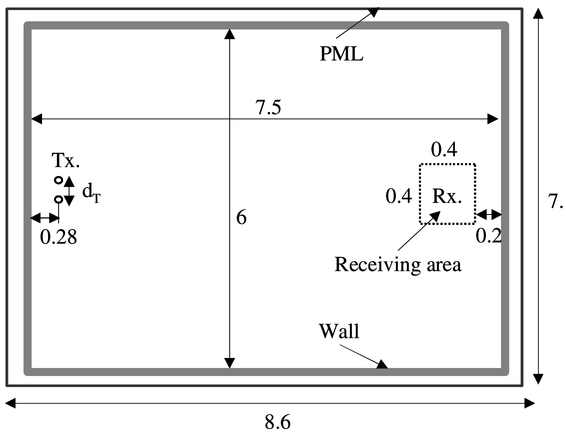


Fig. 1 Plan view of indoor MIMO analysis model (Unit: m).

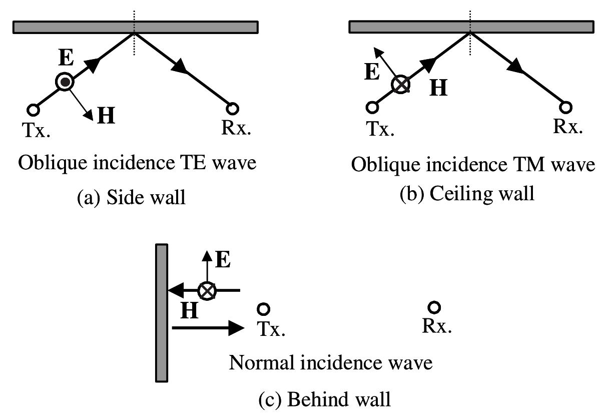


Fig. 2 Calculation model of wall reflection coefficient.

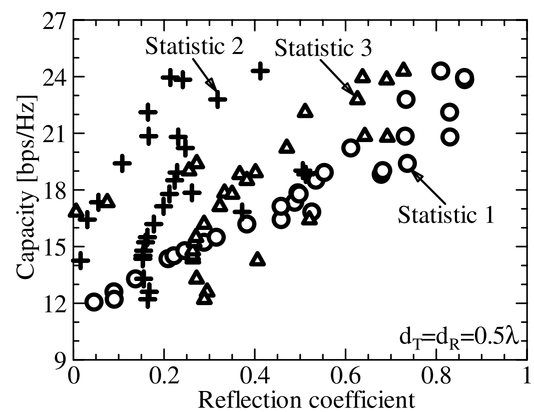


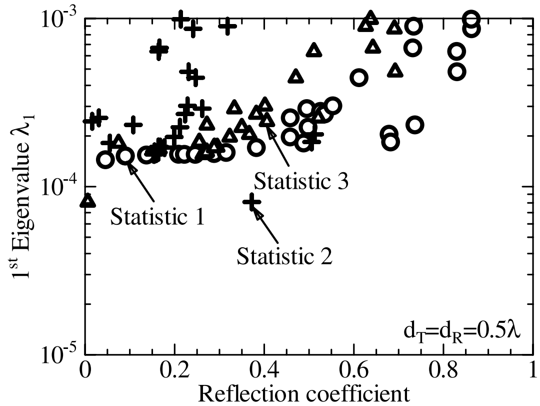
Fig. 3 MIMO channel capacity versus the reflection coefficients of the side wall (Statistic 1), the ceiling wall (Statistic 2) and the behind wall (Statistic 3).

ing area (0.4 m×0.4 m×0.4 m) to obtain the spatial statistical characteristic of received signals, in which there are approximately 3×10^4 receiving points, and the distance between the receiving area and the wall is 0.2 m. The distance between the transmitting antenna array and the center of local receiving area is 6.8 m. The whole analysis region is divided into 688×568×272 Yee cells with 8-layer perfectly matched absorbing boundary (PML), and each Yee cell has a size of 1.25 cm×1.25 cm×1.25 cm. The number of time steps is 16384. In MoM analysis, each receiving dipole antenna is divided into 15 segments, and the operating frequency is 800 MHz. The total transmitted power is fixed as −20 dBm, and only the additive white Gaussian noise with a power of −94 dBm is considered on each receiving branch.

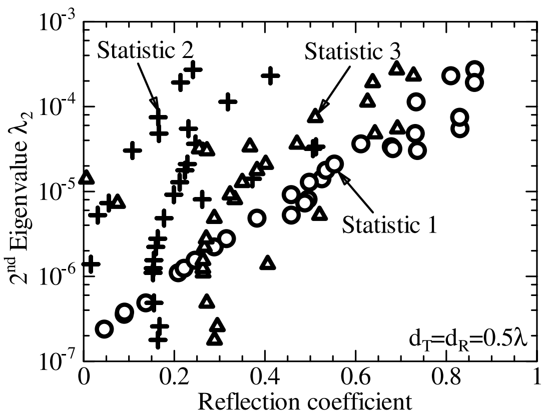
In the simulation, MIMO channel capacity is calculated according to the electrical parameters (the relative permittivity and the conductivity) and the thickness of the indoor walls, where the relative permittivity is from 1.5 to 8.5, the conductivity is from 0.001 S/m to 1 S/m, the thickness is from 0.05 m to 0.3 m and MIMO channel capacity is the average value for all the receiving points in the local receiving area. Based on the obtained numerical results, MIMO channel capacity is further statistically analyzed with the wall reflection coefficient which is calculated by using a lossy infinite width and finite thickness slab model with oblique incident wave. The electrical parameters and the thickness of the slab are same with those of the indoor walls, and the incident angle is determined by the relative position between the antenna elements and the reflection point on the wall. The reflection coefficients of the side wall, the ceiling wall and the behind wall are calculated, which are named according to the relative location to the transmitting antenna array (Tx.). The calculation models of wall reflection coefficient are illustrated in Fig. 2. In our analysis model, the side wall reflection coefficient is estimated based on TE wave with 49° oblique incidence, where the incident angle is the average value of all incident angles. The ceiling wall reflection coefficient is estimated based on TM wave with 72° oblique incidence, and the behind wall reflection coefficient is estimated with normal incidence wave.

MIMO channel capacity is statistically analyzed with these wall reflection coefficients, and the results are shown in Fig. 3, where the array spacing of transmitting and receiving antenna array is a half wavelength. It is found that there is no simple correlation between MIMO channel capacity and the reflection coefficients of the ceiling wall and the behind wall (Statistic 2 and Statistic 3). However, MIMO channel capacity increases almost linearly with the increase of the side wall reflection coefficient (Statistic 1), namely the stronger side wall reflection can lead to the higher MIMO channel capacity. In order to investigate the effect of wall reflection sufficiently, the eigenvalue of channel covariance matrix, the received power and the effective multipaths of MIMO system are also statistically analyzed in the following.

According to the general Shannon channel capacity formula of MIMO system [1] and the singular value decomposition (SVD) of channel matrix, MIMO channel capacity is determined by the transmitted power and the eigenvalue of MIMO channel covariance matrix. Because the total transmitted power is fixed and the uniform power allocation is applied in our simulation, the effect of wall reflection on the eigenvalue of MIMO channel covariance matrix is statisti-

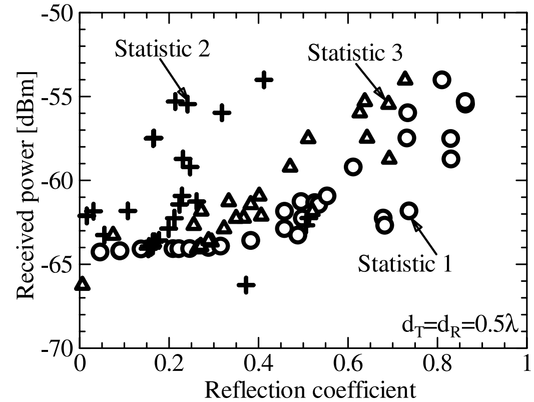


(a) The first eigenvalue

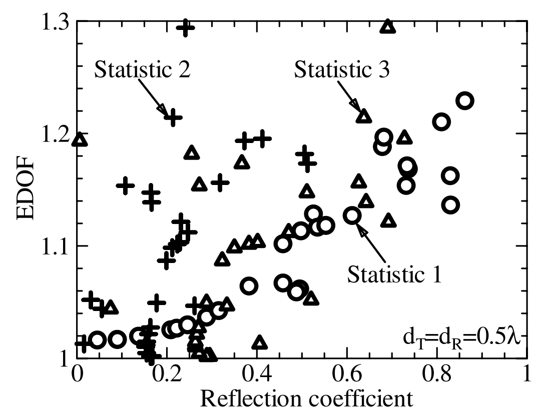


(b) The second eigenvalue

Fig. 4 Eigenvalues of channel covariance matrix of MIMO system versus wall reflection coefficients.



(a) Received power



(b) EDOF of multipaths

Fig. 5 Received power and EDOF of multipaths of MIMO system versus wall reflection coefficients.

cally analyzed with these wall reflection coefficients, and the results are shown in Fig. 4, where the eigenvalue is the average value for all MIMO channel covariance matrices obtained in the local receiving area. It is found that both the eigenvalues λ_1 and λ_2 with the ceiling wall reflection coefficient (Statistic 2) are distributed in a small range, and the correlation between the eigenvalues and the behind wall reflection coefficient (Statistic 3) is also not distinct. Therefore, there is no simple correlation between MIMO channel capacity and the reflection coefficients of the ceiling wall and the behind wall. However, both the eigenvalues λ_1 and λ_2 are improved with the increase of the side wall reflection coefficient (Statistic 1), and the improved relatively magnitude of the second eigenvalue λ_2 is much more than that of the first eigenvalue λ_1. These results indicate that the stronger side wall reflection can lead to the higher MIMO channel capacity.

The eigenvalue of MIMO channel covariance matrix has included the effects of the path loss and the effective multipaths of wireless transfer channel together. Therefore, the received power and the effective multipaths of MIMO system are also statistically analyzed with the wall reflection coefficients, and the results are shown in Fig. 5. In the simulation, the received power is the average power on each output branch of receiving antenna array. The relative effective degree of freedom (EDOF) of the propagation channel is used to analyze the channel multipaths. In our research, this EDOF is calculated by the ratio of the summation of all eigenvalues of MIMO channel transfer covariance matrix to the maximum eigenvalue [9], which denotes the number of effective parallel sub-channels can be formed by MIMO wireless channel. This EDOF is a real number larger than one and less than the minimum number of transmitting and receiving array antennas and the effect of path loss has been removed, which is different from the conventional concept of EDOF defined in [13]. By analyzing the numerical results, it is found that the received power and the EDOF of MIMO channel multipaths are improved with the increase of side wall reflection coefficient (Statistic 1). Therefore, when the side wall reflection becomes stronger, MIMO channel capacity is improved.

In order to validate the effect of side wall reflection further, the effect of antenna array spacing on MIMO channel capacity with the side wall reflection is statistically analyzed, and the results are shown in Fig. 6. In the simulation, the array spacing of transmitting antenna array is changed as a quarter, a half and one wavelength (0.25λ, 0.5λ and λ), respectively, and the array spacing of receiving antenna array is fixed as a half wavelength (0.5λ). It is found that MIMO channel capacity is improved with the increase of antenna

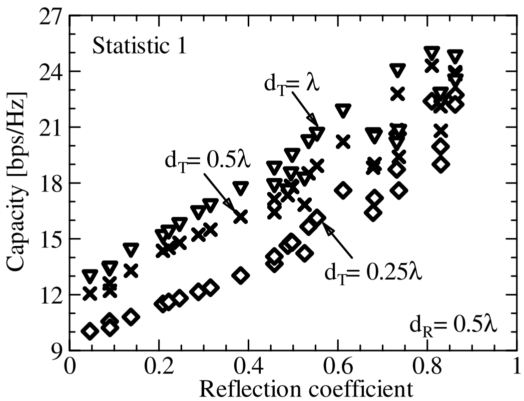


Fig. 6 MIMO channel capacity versus side wall reflection coefficient when the array spacing of transmitting antenna array (d_T) is 0.25λ, 0.5λ and λ, and the array spacing of receiving antenna array (d_R) is 0.5λ.

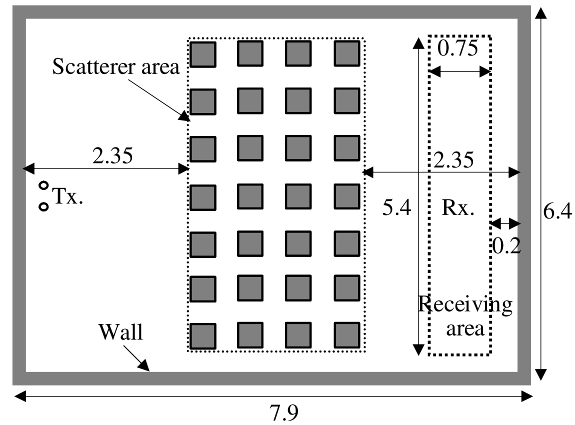


Fig. 7 Plan view of indoor MIMO analysis model with 28 cubic scatterers (Unit: m).

array spacing, and when the array spacing increases from a quarter wavelength to a half wavelength, MIMO channel capacity is improved much more. The linear relationship between MIMO channel capacity and the side wall reflection coefficient has become more distinct with the increase of array spacing. These results agree with the analysis of the antenna correlation effect on MIMO system. Therefore, the stronger side wall reflection can bring the benefit to indoor MIMO system.

3. Effect of Indoor Scatterer

The effect of indoor scatterers is analyzed in this section. There are 28 cubic scatterers uniformly placed with 4 columns and 7 rows in the middle of indoor environment to form NLOS wireless channel. The geometry of MIMO analysis model with the indoor scatterers is illustrated in Fig. 7. The scatterer size is 0.4 m×0.4 m×2.25 m, and the height of which is same with that of the room. The spacing between the adjacent scatterers and the distance between the scatterer area and the side wall are 0.4 m. The size of local receiving area is 0.75 m×5.4 m×1.7 m, in which there are approximately 9×10^5 receiving points. The relative permittivity, the conductivity and the thickness of the wall is 3, 1.95×10^{-3} S/m and 0.2 m, respectively. The whole analysis region is divided into 458×378×178 Yee cells, and each Yee cell has a size of 1.875 cm×1.875 cm×1.875 cm. In MoM analysis, each receiving dipole antenna is divided into 9 segments. The array spacing of transmitting antenna array and receiving antenna array is a half wavelength (0.5λ). The other simulation conditions are same with those in Sect. 2.

When the scatterer material is perfect conductor, the indoor environment is named as Case 1. When the scatterer material is dielectric, where the relative permittivity and the conductivity is 3 and 0, the indoor environment is named as Case 2. In order to compare, when there is no scatterer in the indoor environment which is named as Case 0, i.e. only the wall is included in the analysis model, the indoor MIMO system is also investigated. The complementary cumulative distribution function (CCDF) of MIMO channel

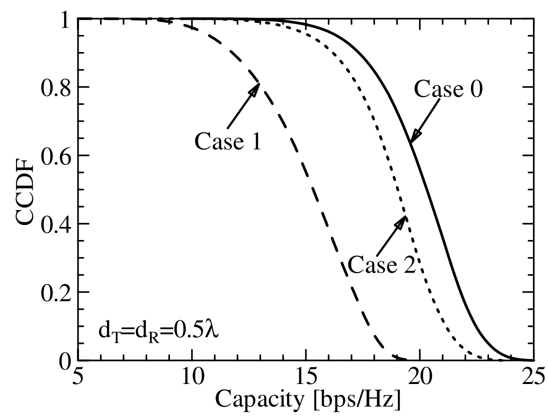


Fig. 8 CCDF of MIMO channel capacity with indoor scatterers. Case 0: No scatterer. Case 1: Metallic scatterers. Case 2: Dielectric scatterers.

capacity with the indoor scatterers is investigated and the results are shown in Fig. 8. It is found that MIMO channel capacity is highest in LOS indoor channel (Case 0) and smallest in NLOS metallic scatterer indoor channel (Case 1). MIMO channel capacity in NLOS dielectric scatterer indoor channel (Case 2) is between that in Case 0 and Case 1. The presence of indoor scatterers between the transmitting and receiving antenna arrays will degrade MIMO channel capacity, and the effect of scatterer material is obvious.

In order to investigate the effect of indoor scatterers sufficiently, the eigenvalue of MIMO channel covariance matrix, the received power and the EDOF of channel multipaths of MIMO system are also statistically analyzed in the different cases, and the results are shown in Fig. 9, Fig. 10 and Fig. 11, respectively. From Fig. 9, it is found that both the eigenvalues λ_1 and λ_2 are largest in Case 0 and are smallest in Case 1. The first eigenvalue λ_1 in Case 2 is between that in Case 0 and Case 1, and the second eigenvalue λ_2 in Case 2 is almost the same with that in Case 0. The scatterer material has effect on the eigenvalue of MIMO channel covariance matrix, and then has effect on MIMO channel capacity. From Fig. 10 and Fig. 11, it is found that the presence of indoor scatterers will degrade the received power

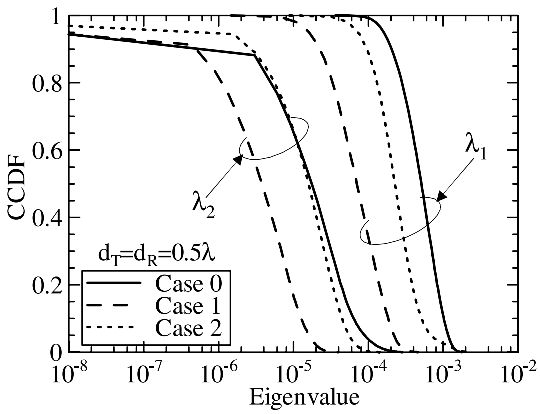


Fig. 9 CCDF of eigenvalues of MIMO channel covariance matrix with indoor scatterers (in different cases).

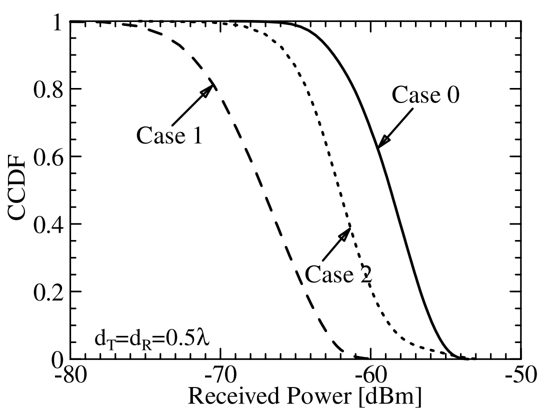


Fig. 10 CCDF of received power of MIMO system with indoor scatterers (in different cases).

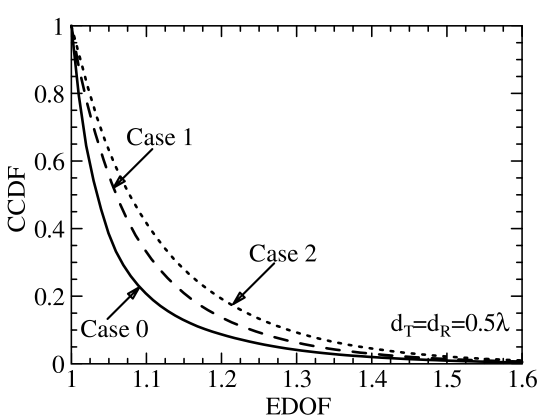


Fig. 11 CCDF of EDOF (Effective multipaths) of MIMO system with indoor scatterers (in different cases).

of MIMO system. Especially when the scatterer material is perfect conductor (Case 1), the received power is smallest. However, the effective multipaths of MIMO system (EDOF) are improved when the indoor scatterers are presented, and EDOF is highest in NLOS dielectric scatterer indoor channel (Case 2). Although the effective multipaths are improved in NLOS indoor channel, however the loss of received power is much more, so that MIMO channel capacity is degraded ultimately. The numerical results also indicate that the indoor scatterer material has the different effect on the received power and the effective multipaths of MIMO system.

4. Conclusions

The effect of wall reflection on indoor MIMO system has been statistically investigated with the reflection coefficients of the side wall, the ceiling wall and the behind wall. It has been found that the stronger side wall reflection can lead to the higher MIMO channel capacity, because the eigenvalue of MIMO channel covariance matrix, the received power and the effective multipaths of MIMO system are improved with the increase of side wall reflection. The effect of indoor scatterers has also been investigated. It has been found that MIMO channel capacity in NLOS indoor channel is smaller than that in LOS indoor channel because of the obstruction effect of scatterers. Although the effective multipaths of MIMO system are improved in NLOS indoor channel by the presence of indoor scatterers, however the loss of received power is much more, so that MIMO channel capacity is degraded ultimately. Furthermore,the effect of indoor scatterer material has also been analyzed. It has been found that the indoor scatterer material has the different effect on the received power and the effective multipaths of MIMO system.

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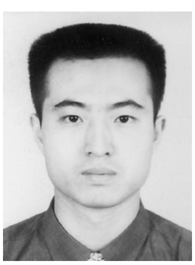

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