PAPER

Investigation of Wall Effect on Indoor MIMO Channel Capacity by Using MoM-FDTD Hybrid Technique

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SUMMARY A numerical hybrid method for analyzing the wireless channel of Multiple-Input Multiple-Output (MIMO) communication system is proposed by combining of the method of moments (MoM) and the finite difference time domain (FDTD) method. The proposed method is capable of investigating a more practical MIMO wireless channel than the conventional methods, and CPU time is much less than that of the FDTD method in analysis of spatial statistical characteristics of received signals. Based on the channel transfer matrix obtained by the proposed method, the wall effect on indoor MIMO channel capacity are investigated with consideration of received power, Ricean K-factor and effective degrees of freedom (EDOF) of multipaths by changing the wall locations and material.

key words: *MIMO, channel capacity, hybrid method, MoM, FDTD, Ricean K factor, effective degrees of freedom (EDOF)*

1. Introduction

Multiple-Input Multiple-Output (MIMO) communication system which uses multiple antennas at both the transmitter and the receiver could achieve much higher spectral efficiency and transfer reliability than the conventional wireless communication techniques with the same transmitted power and frequency bandwidth [1]–[3]. Because the performance of MIMO system is significantly affected by the wireless propagation channel [3]–[5], it is very important to investigate MIMO wireless channel accurately. At present, several analysis methods have been used to analyze MIMO wireless channel, such as the empirical formulae [6]–[9], the Monte-Carlo method [1]–[4], [10]–[12], the ray tracing method [13]–[15] and the experimental measurement [21]–[23], etc. The empirical formulae are simple and easy, but they are only applicable to some limited communication environments. The Monte-Carlo method, a mathematical statistical method to solve uncertain problems, is mainly applied to the one-ring, two-ring and scattering disc MIMO wireless channel models [3], [4]. On the other hand, the ray tracing method with the combination of geometrical optics (GO) and uniform theory of diffraction (UTD) methods is currently a widely used technique for the site specific large scale path propagation channel, but the CPU time increases greatly when the number of scatterers becomes larger, and the accuracy is degraded when the electrically small scatterers are included in the propagation channel. The experimental measurement can provide the accurate and reliable information to characterize the indoor and outdoor MIMO wireless channel, but the cost and complexity of conducting the measurement is significant.

Recently, indoor MIMO system has attracted considerable research attention [17]–[24]. In indoor propagation environment, the wall is an important scatterer and its effect on MIMO system is worth investigating. Although some researches have been done [17]–[19], they were limited only in two dimensional (2-D) models and the effect of wall locations and material has not been investigated.

In this paper, a hybrid technique of the method of moments (MoM) and the finite difference time domain (FDTD) method is proposed, which can be used to investigate a more realistic MIMO wireless channel model with the spatial statistical characteristics of received signals in an acceptable CPU time. Further more, based on the channel transfer matrix obtained by the proposed hybrid technique, the effect of wall locations and material on the indoor MIMO channel capacity are investigated with consideration of received power, Ricean K-factor and effective degrees of freedom (EDOF) of multipaths.

2. Hybrid Technique of MoM and FDTD Method

The MoM is a powerful method in analyzing various antennas, especially the thin wire antennas [25]. It is also capable of analyzing MIMO wireless channel, but the computation time becomes tremendous when a number of electrically large scatterers exist in the wireless channel because the MoM costs $O(N^3)$ order of CPU time due to the inverse of impedance matrix, where N is the number of unknowns. On the other hand, because the FDTD method which is based on the direct solution of Maxwell's equation can solve the problem including both the conducting scatterers and dielectric objects with arbitrary structures [26], it is suitable to investigate MIMO multiple paths channel with almost arbitrary scatterers. However, it is difficult to analyze the spatial statistic characteristics of received signals for MIMO system. In this paper, a hybrid technique of the MoM and the FDTD method is proposed to solve this problem. The MoM-FDTD hybrid technique for MIMO wireless channel is illustrated in Fig. 1.

In the hybrid technique, the FDTD method is used to analyze the transmitting array antennas and the propagation channel, and the MoM is applied to analyze only the receiving array elements which are moved randomly in a proper

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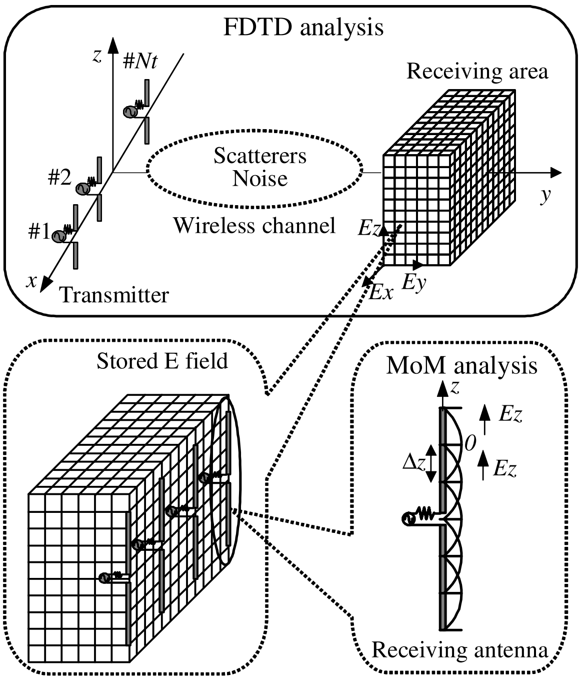

Fig. 1 Analysis model of MoM-FDTD hybrid technique for MIMO wireless channel.

area in order to obtain the spatial statistical characteristics of received signals. The electromagnetic field of the whole region is calculated by the FDTD method without consideration of the receiving array antennas and the electric field at the Yee Cell in the receiving area is stored. The stored electric field is then used as the incident field on the receiving array elements. In the MoM analysis, the piecewise sinusoidal function is used as the basis function and weighing functions, which is denoted by

$$f_m(z) = w_m(z) = \frac{\sin\left[k_0\left(\Delta z - |z|\right)\right]}{\sin\left(k_0 \Delta z\right)} \tag{1}$$

where k_0 is the wave number in free space, m denotes the mth segment of receiving antenna elements, and Δz is a half length of receiving antenna segments which is the same with the size of Yee cell. The voltage of mth segment of receiving antenna element is calculated by

$$V_m = \int w_m(z) \cdot E_m(z)\, dz \tag{2}$$

where $E_m(z)$ is the incident electric field on the mth segment of receiving antenna calculated by the FDTD method. The current on receiving antenna array is calculated by

$$[I] = [Z]^{-1}[V] \tag{3}$$

where the voltage vector $[V]$ is changed with the movement of receiving antenna array. However, because the mutual impedance matrix calculated by the Richmond's method [28] is independent of the movement, the matrix inverse is performed only once.

The hybrid technique is suitable to analyze the complex indoor wireless channel with consideration of the spatial statistical characteristics of received signals. If only the FDTD method is used to analyze the spatial statistical characteristics, the FDTD analysis has to be repeated as many times as the sampling number so that CPU time is tremendous. For example, if it is required to calculate the bit error rate (BER) of MIMO system less than 10^{-4}, the FDTD analysis has to be repeated more than 10^4 times for statistical analysis. On the other hand, the complementary cumulative distribution functions (CCDF) of spatial statistics are usually required in multipath environment, and the receiving area is at least larger than a half of wavelength (0.5λ). If the size of receiving area is $\lambda \times \lambda \times \lambda$ with 0.1λ sampling interval in three dimensional (3-D) models, the FDTD analysis has to be repeated 10^3 times. These problems can be solved in the proposed hybrid technique of the MoM and the FDTD method. In the proposed hybrid technique, the spatial statistical characteristics of received signals can be evaluated by only once execution of the FDTD calculation, so that CPU time is saved significantly. The reliability and effectiveness of the proposed hybrid technique will be validated in Sect. 4.1.

The calculation processing of MIMO channel transfer matrix $\boldsymbol{H}$ is illustrated briefly in Fig. 2. When the transmitted signals are fed at the jth transmitting antenna, and the other of transmitting antennas are terminated with 50 Ω resistance, h_{ij} (i=1, ···, N_r) can be evaluated according to the ratio of received voltage of the ith receiving antenna to the input voltage of the jth transmitting antenna. The same processing is repeated for different transmitting antennas (j=1 ··· N_t) till all the elements of matrix $\boldsymbol{H}$ is obtained. Here, N_r and N_t denote the number of receiving and transmitting antenna elements, respectively.

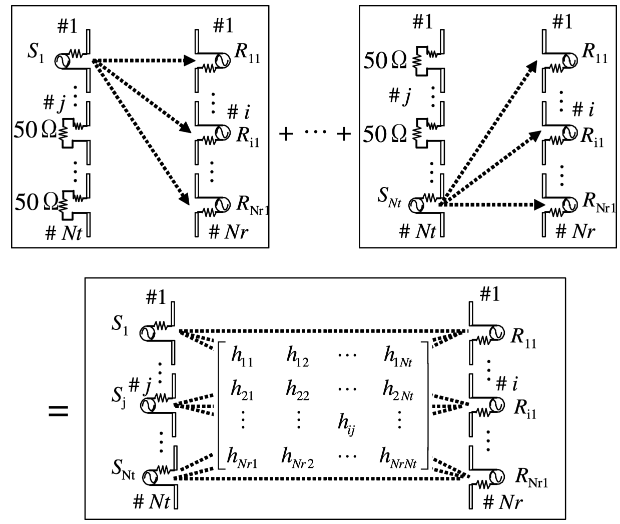

Fig. 2 Calculation processing of the channel transfer matrix of MIMO system.

3. Definition of Received Power, Ricean K Factor and EDOF

Based on the analysis of general MIMO channel capacity formula [1], it is found that MIMO channel capacity is determined by the received power and the effective multipaths. The average received power on each receiving branch is calculated by

$$P_{avg} = E\left[\frac{1}{Nr}\sum_{i=1}^{Nr}\left(\frac{P_T}{Nt}\sum_{j=1}^{Nt}\left|h_{ij}\right|^2\right)\right] \tag{4}$$

where P_T is the total transmitted power and $E[\cdot]$ is the expectation.

Ricean K factor and the effective degrees of freedom (EDOF) of multipaths are useful parameters to analyze the multipath richness for MIMO system. When the statistical values of electric field distribution are known, Ricean K factor can be calculated by [31]

$$K = \frac{\sqrt{1-\gamma}}{1-\sqrt{1-\gamma}} \tag{5}$$

where γ is the ratio of the variance of the electric field power to its mean. While EDOF is a number to approximately indicate the effective parallel sub-channels which are formed by MIMO wireless channel and is calculated by

$$EDOF = \sum_{i=1}^{n}\lambda_i / \max\left[\lambda_i\right] \tag{6}$$

where λ_i is the ith eigenvalue of MIMO channel covariance matrix. The EDOF, a real number between one and the minimum number of transmitting and receiving array antennas, is independent of the path loss [20], [30].

4. Wall Effect on Indoor MIMO Channel Capacity

4.1 Simulation Conditions

A single user to single user narrowband 2×2 MIMO system with uniform power allocation is considered. The vertical half wavelength dipole antennas are used as the transmitting and receiving antennas, and the array spacing of transmitting and receiving antenna arrays is a half of wavelength. The whole analysis region is divided into $346 \times 211 \times 211$ Yee cells with the 8-layer perfectly matched (PML) absorbing boundary [32], and each cell has a size of 1.25 cm × 1.25 cm × 1.25 cm. The number of time step is 8192. The total transmitted power is constrained to −30 dBm. Only the additive white noise with a power of −94 dBm is considered on each output of the receiving antenna elements. In the MoM analysis, each receiving dipole antenna is divided into 15 segments. The operation frequency is 800 MHz. The receiving array antennas are moved randomly in the receiving area $(0.5\lambda \times \lambda \times \lambda)$, in which there are 16384 receiving points. The distance between the transmitting array and the center of local receiving area is 2.6 m.

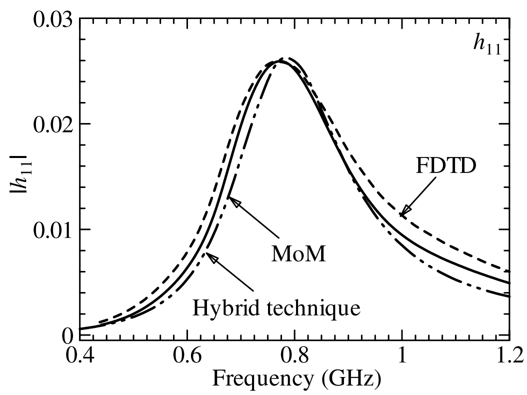

Fig. 3 Magnitude of h_{11} in MIMO channel transfer matrix calculated by MoM, FDTD and hybrid technique.

In order to validate the proposed technique, the channel transfer matrix of MIMO system in free space is calculated by the proposed hybrid technique and the results are compared with those of the MoM and the FDTD method, respectively. The magnitude of (h_{11}) in frequency domain is calculated and shown in Fig. 3. It is found that the results of hybrid technique agree with those of the MoM and the FDTD method. The CPU time of the hybrid technique to give the spatial statistical values is 2.7×10^3 s by using the supercomputing system SX-7 at Information Synergy Center, Tohoku University. However, if only the FDTD method is used, the CPU time of 4.5×10^7 s is required for repeating the FDTD analysis 16384 times to get the same spatial statistical results. It is found that CPU time of the proposed technique is much less than that of the FDTD method in analysis of spatial statistical characteristic of received signals.

4.2 Effect of Wall Location

The wall location is defined according to the relative position between the transmitting antenna array and the wall, which is illustrated intuitively in Fig. 4. When the wall is located behind, top and side to the transmitting antenna array, it is named as Case 1, Case 2 and Case 3, respectively. Case 4 denotes that the wall is located between the transmitter and the receiver. The wall geometry in the different Cases is shown in Table 1. The wall thickness is 0.2 m.

The CCDF of MIMO channel capacity with wall location is calculated and shown in Fig. 5. The average values of EDOF, Ricean K factor and received power are listed in Table 2. The results of MIMO system in free space are also calculated and named as Case 0. It is found that the highest and the lowest channel capacity are obtained in Case 3 and Case 4, respectively. In Cases 1, the same as Case 2 and Case 3, the average received power is near that of free space, but MIMO channel capacity is improved, because the effective multipaths are increased. Although the highest EDOF and the smallest Ricean K factor are obtained in Case 4, the

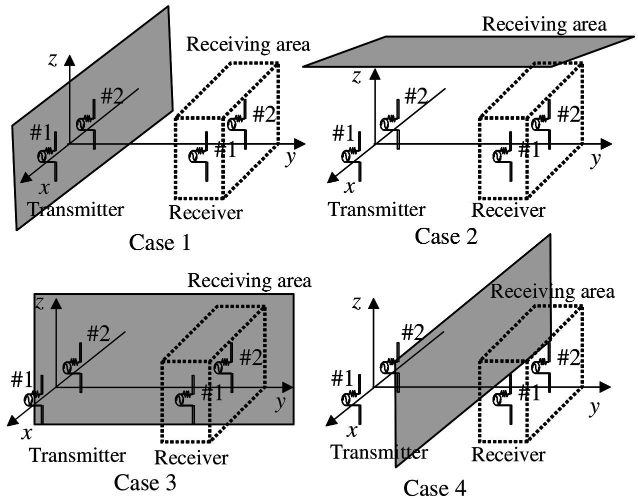

Fig. 4 Definition of wall location according to the relative position between the transmitting antenna array and wall.

Table 1 Wall geometry in the different cases.

	Location [m]	Electric parameters
Case 1	$-0.85 < x < 0.85$ $-0.3 < y < -0.1$ $-0.85 < z < 0.85$	$\epsilon_r = 4$ σ=0.1 S/m
Case 2	$-0.85 < x < 0.85$ $-0.3 < y < 3.1$ $1.1 < z < 1.3$	$\epsilon_r = 4$ σ=0.1 S/m
Case 3	$-1.3 < x < -1.1$ $-0.3 < y < 3.1$ $-0.85 < z < 0.85$	$\epsilon_r = 4$ σ=0.1 S/m
Case 4	$-0.85 < x < 0.85$ $1.3 < y < 1.5$ $-0.85 < z < 0.85$	$\epsilon_r = 4$ σ=0.1 S/m

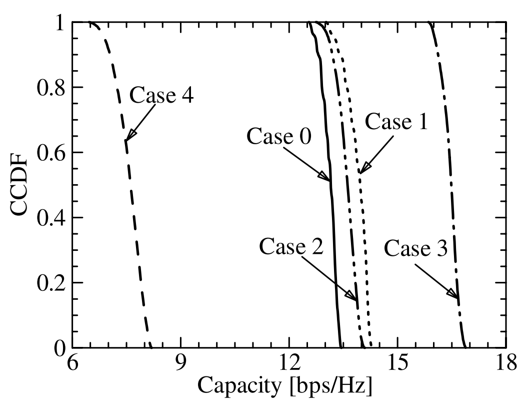

Fig. 5 CCDF of MIMO channel capacity with wall location (the different cases).

Table 2 Average values of EDOF, Ricean K factor and received power according to wall locations (different cases).

	EDOF	K-factor [dB]	Received Power [dBm]
Case 0	1.000	∞	−63.7
Case 1	1.003	30.77	−63.5
Case 2	1.002	22.14	−63.1
Case 3	1.035	7.31	−63.6
Case 4	1.063	6.45	−79.9

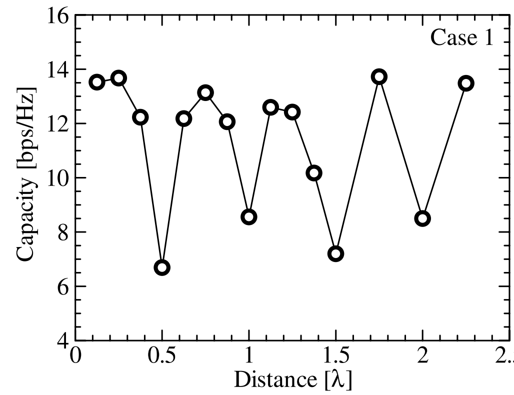

Fig. 6 Average values of MIMO channel capacity with the distance between transmitting antenna array and wall in Case1.

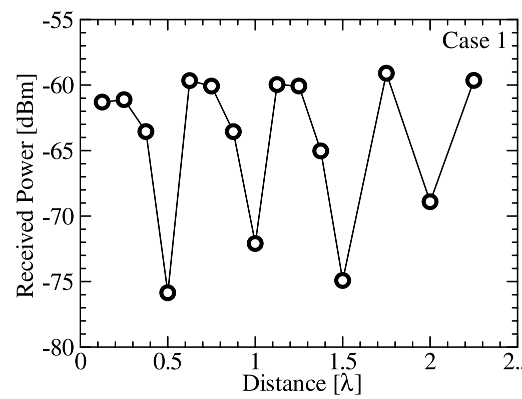

Fig. 7 Average values of received power of MIMO system with the distance between transmitting antenna array and wall in Case1.

average received power is much lower than other Cases so that the channel capacity is the lowest. The different wall location brings the different effect on the effective multipaths and the received power. Therefore, when MIMO system is deployed in indoor environment, the relative position of the transmitting array to the wall should be considered.

When the transmitting antenna array is near to the behind wall (Case 1), MIMO channel capacity is changed periodically with the distance between the antenna array and the wall. This phenomenon is not observed in other cases. The effect of the distance between transmitting antenna array and the behind wall on MIMO system is investigated, and the average values of MIMO channel capacity, received power, Ricean K factor and EDOF are shown in Fig. 6, Fig. 7 and Fig. 8, respectively. It is found that the change of MIMO channel capacity with the distance between transmitting antenna array and the wall has a period of a half of wavelength. The minimum of MIMO channel capacity is obtained when the distance is $N\lambda/2$ (N is a nonnegative integer number), while the maximum is obtained when the distance is $(N + 1/4)\lambda/2$. The change of average received power has the same characteristic with that of channel capacity. On the

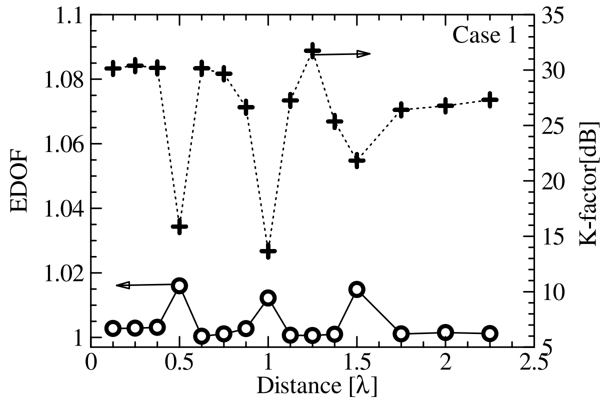

Fig. 8 Average values of EDOF and Ricean K factor of MIMO system with the distance between transmitting antenna array and wall in Case1.

other hand, the change of Ricean K factor with the distance is almost opposite with that of channel capacity. The minimum of Ricean K factor is obtained when the distance is $N\lambda/2$. The effect of the distance on EDOF is not significant. It is found that the received power is the main factor to affect MIMO channel capacity in Case 1 when the transmitting antenna array is near to the behind wall.

4.3 Effect of Wall Material

In previous researches, the effect of wall material on MIMO system has not been investigated because the limitation of conventional method. In this paper, the effect of three kinds of practical material of wall, i.e. the wooden wall, the concrete wall and the reinforced concrete wall, is investigated by using the proposed hybrid technique. In order to analyze the effect of wall material mainly, only the wall is considered and the other scatterers inside the room are not included in the analysis model. The top view of analysis model of indoor environment is shown in Fig. 9, and the other simulation conditions are the same with those in Sect. 4.1. The room size is 3.4 m × 1.9 m × 1.9 m. The distance between the transmitting antenna array (Tx.) and the wall is 0.1 m. The distance between the transmitting array and the center of local receiving area is 2.6 m.

The relative permittivity, conductivity and thickness of wooden wall are 3, 0, and 0.1 m, respectively, and those of concrete wall are 6.25, 0.0814 S/m and 0.2 m. The reinforced concrete wall is formed by deploying 8 cubical metallic pillars (0.2 m × 0.2 m × 1.9 m) inside the concrete wall. The top view of reinforced concrete wall is illustrated in Fig. 10.

The CCDF of MIMO channel capacity and the average values of EDOF, Ricean K factor and received power for the different kinds of wall material are investigated, and the results are shown in Fig. 11 and Table 3, respectively, where the results of MIMO system in free space is also shown for comparison. It is found that MIMO channel capacity is improved than that of free space because of the presence of the wall, and which is affected significantly by the different material of the wall. The average MIMO channel capacity in free space is 13 bps/Hz, which is smaller 6 bps/Hz than that in wooden wall. The highest MIMO channel capacity is obtained in the reinforced concrete wall, which is higher 2 bps/Hz than that in concrete wall. The EDOF of multipaths is affected insignificantly by the wall material. The

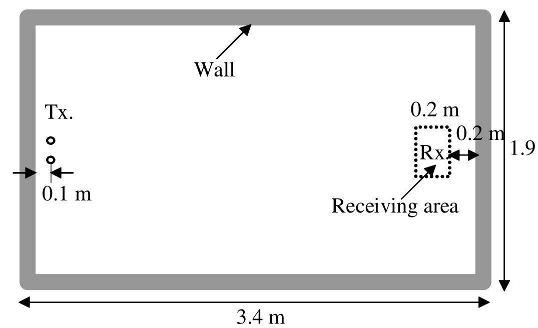

Fig. 9 Top view of indoor MIMO analysis model.

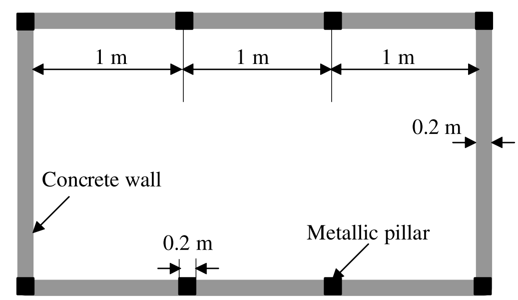

Fig. 10 Top view of reinforced concrete wall.

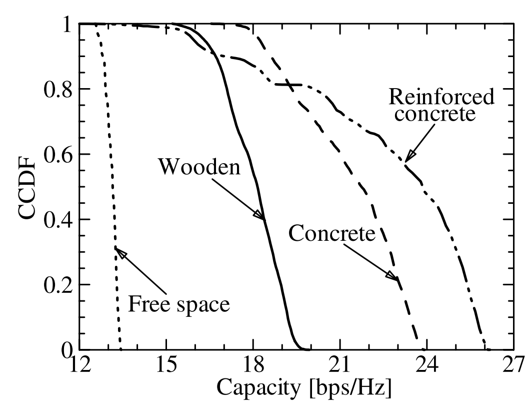

Fig. 11 CCDF of indoor MIMO channel capacity for the different kinds of wall material.

Table 3 Average values of EDOF, Ricean K factor and received power for the different kinds of wall material.

	EDOF	K-factor [dB]	Received Power [dBm]
Free space	1.00	∞	−63.7
Wooden wall	1.23	8.62	−64.9
Concrete wall	1.18	5.32	−59.3
Reinforeced concrete wall	1.19	3.08	−56.4

reinforced concrete wall brings the highest received power and the smallest Ricean K factor. Although the wooden wall brings the lowest received power, the channel capacity is higher than that in free space owing to the EDOF is higher. The effect of wall material on MIMO system is investigated on a certain thickness of the wall. It is well known that the wall thickness can bring some effect on the electric field distribution of indoor environment. Therefore, a more practical analysis model which can reflect the effect of wall material, thickness and geometry together will be investigated in our further work.

5. Conclusions

A hybrid technique of the MoM and the FDTD method for analyzing MIMO wireless channel has been proposed, which can be used to analyze a more realistic wireless channel model with CPU time significantly less than the FDTD method to give the spatial statistical characteristics of received signals. Based on MIMO channel transfer matrices obtained by the proposed technique, the wall effect on indoor MIMO channel capacity have been investigated by analyzing the Ricean K-factor, the EDOF of multiple paths and the received power for wall locations and material. It has been found that different relative locations of wall cause different effects on the effective multipaths and the received power which affects MIMO channel capacity. The side wall brings the highest channel capacity and the partition wall degrade the channel capacity. When the transmitting antenna array is located near to the wall, MIMO channel capacity is changed periodically with the distance between the antenna array and the wall. Therefore, the antenna array location should be considered when MIMO system is deployed in indoor environment. The wall material effect on MIMO channel capacity has also been investigated. It is expected that these numerical results can provide some useful information to the design of practical indoor MIMO system.

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