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LETTER

Numerical Analysis on MIMO Performance of the Modulated Scattering Antenna Array in Indoor Environment

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SUMMARY The multiple-input multiple-output (MIMO) performance of the modulated scattering antenna array (MSAA) is analyzed numerically for the first time in indoor environment based on an approach to hybridization of the Volterra series method and method of moments (MoM) in this letter. Mutual coupling effect between the Modulated scattering element (MSE) and the normal antenna element is also considered in this analysis. It is found that MIMO performance of the MSAA is improved with reducing the array spacing of the MSAA in 4 different indoor receiving areas. At the same time, the simulated results of the MSAA are compared with those of the dipole antenna array at the same condition.

key words: *array antenna, modulation, mobile handsets, nonlinear circuits, Volterra series, MoM, MIMO*

1. Introduction

An antenna array, called modulated scattering antenna array (MSAA), which is based on the modulated scattering technique (MST) [1], has been proposed [2], and it can be used as a receiving antenna array for the mobile handset. The MSAA consists of one normal antenna element and several modulated scattering elements (MSEs) without RF front-end circuits. Therefore, the MSAA is a candidate for the mobile terminals in the multiple-input multiple-output (MIMO) systems where compactness and energy saving are of primary concerns. In the previous works [2]–[5], the performance of the MSAA for wireless communications has been extensively discussed by experimental studies on the spatial diversity, the error vector magnitude (EVM) and the channel capacity etc. in the Rayleigh fading environment, it is found that the MSAA can receive multi-channel signals and is suitable for mobile handset in the MIMO communication due to its simple configuration.

Although we have carried out many experimental studies, we still required a numerical analysis on the performance of the MSAA because of time consuming and costly etc. problems with different experiments. Furthermore, it is essential to analyze the MIMO performance of the MSAA with various array spacing by the numerical method. Obviously reducing the array spacing between the normal antenna element and the MSE can increase the scattering signal, but high correlation due to the compact array spacing may degrade the MIMO performance. The signal transmission performance is mainly dependent not only on the channel gain between the transmitting and receiving antenna array, but also on the spatial correlation and mutual coupling between array elements in the MIMO communication system. However, due to a nonlinear element included in the MSAA, it is not easy to analyze numerically it until we proposed a hybrid method based on the Volterra series method and the method of moments (MoM) in [6]. Although there exists a variety of approaches for the analysis of the nonlinear circuit [7]–[10], the Volterra series method is employed since it can be implemented entirely in the frequency domain without the use of the fast Fourier transform (FFT) [7], [10]. The hybrid method, efficient in dealing with problems involving the weakly nonlinear loads and multitone excitations, is able to find optimum parameters of MSEs and to further improve the performance of the MSAA. We also presented a frequency hopping technique to mitigate or reduce the interference on adjacent channel in [11]. Therefore, the MIMO performance of the MSAA is investigated theoretically for the first time in indoor environment through the approach to hybridization of the Volterra series method and MoM in this research.

The letter is organized as follows: the simulation environment and parameters are presented in Sect. 2. The simulation results are shown in Sect. 3. Finally, conclusions are given in Sect. 4.

2. Simulation Environment and Parameters

Figure 1 shows the MoM analysis model to investigate the

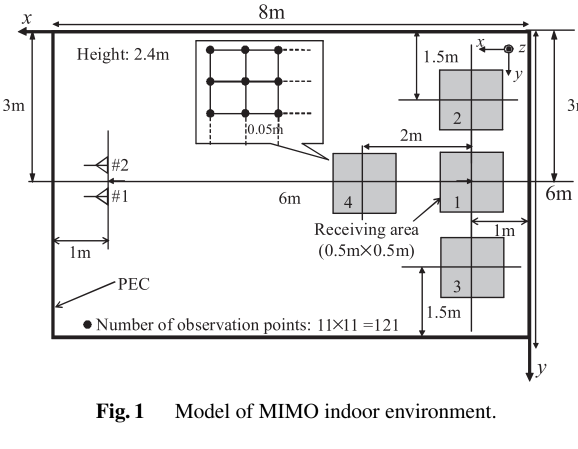

Fig. 1 Model of MIMO indoor environment.

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MIMO performance of the MSAA in 2 × 2 MIMO indoor environment. The simulation was performed in a room (Length: 8 m; Width: 6 m; Height: 2.4 m) with the perfect electric conductor (PEC) structure. The height of the transmitting and receiving antenna is 1.2 m. The location of transmitting antenna was fixed, while the receiving antenna was moved by a step of 5 cm in a 50 cm × 50 cm area. Therefore, the simulation was repeated 11 × 11 times. 4 different receiving areas are chosen to analyze the effect of the propagation channel for the MIMO performance of the MSAA. The distance between the transmitting antenna and the center of the Area 1 in which the receiving antenna moves is 6 m.

Figure 2 shows the Norton's equivalent circuit of the MSE where V_d and V_{LO} are the DC bias and the local signal voltages, while internal resistance of the corresponding generators are represented by R_{id} and R_{io}, respectively. L and C are the RF chock inductance and DC block capacitance, respectively. In the analysis, the effect of L and C are neglected since their contributions are much smaller compared to other parameters. I_{SC} is the short-circuit current at the port of MSE at f_{RF}, i.e. radio frequency and Y_{in} is the input admittance of the MSE. Both I_{SC} and Y_{in} are calculated in the presence of the normal receiving antenna to include the mutual coupling effect between the MSE and the normal antenna element in this analysis.

Some parameters used in the simulations were listed in Table 1. The two half-wavelength dipole antennas are used as the transmitting antenna and the transmitted voltage is 1 V. The normal receiving antenna is a half-wavelength dipole antenna at 2.5 GHz, while MSE is a half-wavelength

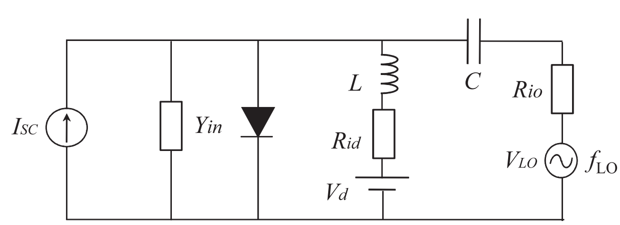

Fig. 2 Equivalent circuit of the MSE.

Table 1 Simulation parameters.

Numerical method	MoM + GO (Geometrical Optics)
Simulation model	Indoor, free space
Radio Frequency	2.5 GHz
Transmitted voltage	1 V
Local Frequency	50 MHz
Local signal voltage V_{LO}	0.5Vp-p
Direct bias voltage V_d	0.2 V
R_{id}, R_{io}	50 Ω
Transmitting antenna	Dipole antenna
Receiving antenna	MSAA/Dipole antenna array
Max no. of reflection	3
Distance between transmitting antenna and the center of the Area 1	6 m (50 λ)
Array spacing of receiving antenna	0.1 λ–1.0 λ with 0.1 λ step

thin wire. Radio frequency f_{RF} is 2.5 GHz while local frequency f_{LO} is 50 MHz. Although received signals at receiving antenna have infinite number of frequencies, we only use secondary-order intermodulation scattering fields as the modulated scattering signal. Therefore, the secondary-order intermodulation scattering signal f_{IF} is 2.45 GHz. The voltage of local signal is 0.5V_{P-P}, and direct bias voltage is 0.2 V. Maximum number of reflection is set to 3. Array spacing of receiving antenna varies from 0.1 λ to 1.0 λ with 0.1 λ step. Moreover, internal resistors R_{id}, R_{io} and the input impedance of the RF receiver are fixed as 50 Ω.

3. MIMO Simulation Results

In every area, 121 simulation results were obtained as mentioned above and they were further expressed in the form of cumulative distribution function (CDF). Moreover, median results are also presented in this section.

Figure 3 shows the CDF of the simulated received power P_{IF} and P_{RF} of the MSAA with various array spacing in the Area 1. The P_{RF} and P_{IF} are denoted by solid line and short dash line, respectively. It is shown that the CDF of the received power of RF signal and IF signal are changed for various array spacing. Moreover, it is also noted that the difference between P_{RF} and P_{IF} is reduced when the array spacing is decreased.

Figure 4 and Fig. 5 show simulation results of median received power for various array spacing in 4 different areas where the MSAA and the dipole antenna array were used as the receiving antennas, respectively. Because the received power of each element of the dipole antenna array is almost same, we only show the received power of one element in Fig. 5. The received power of the dipole antenna array and received power P_{RF} of the MSAA decrease clearly when the array spacing is decreased from 0.5 λ. At the same time, it is found that received power of the dipole antenna array and received power P_{RF} of the MSAA is almost the same with various array spacing at the same receiving area. However,

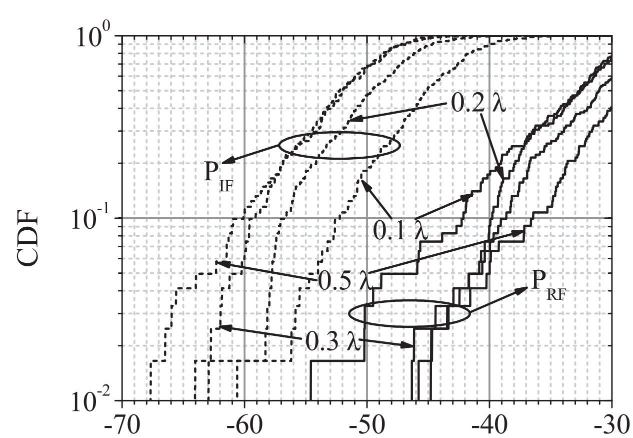

Fig. 3 CDF of simulated received power P_{IF} and P_{RF} of the MSAA versus various array spacing in the Area 1.

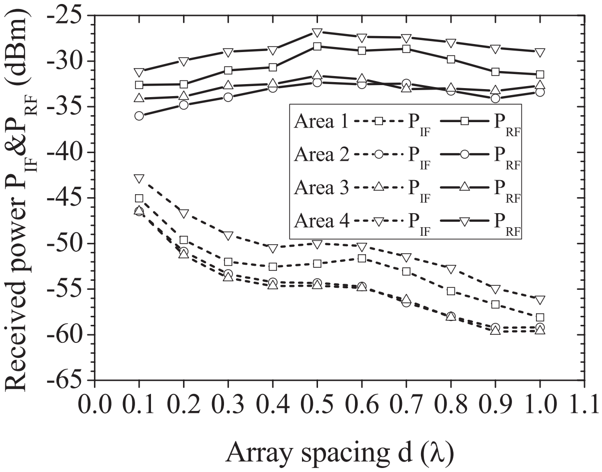

Fig. 4 Median results of simulated received power P_{IF} and P_{RF} of the MSAA versus various array spacing in 4 different areas.

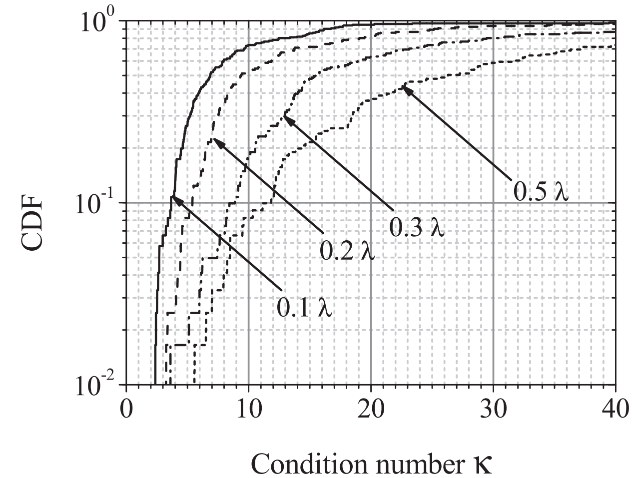

Fig. 6 CDF of condition number κ-factor of the MSAA versus various array spacing in the Area 1.

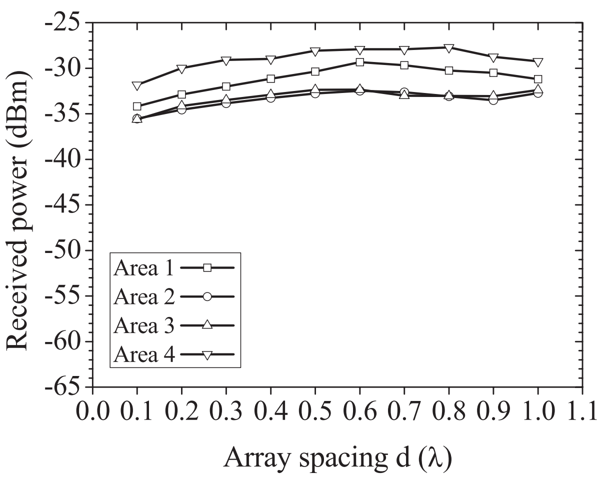

Fig. 5 Median results of simulated received power of the dipole antenna array versus various array spacing in 4 different areas.

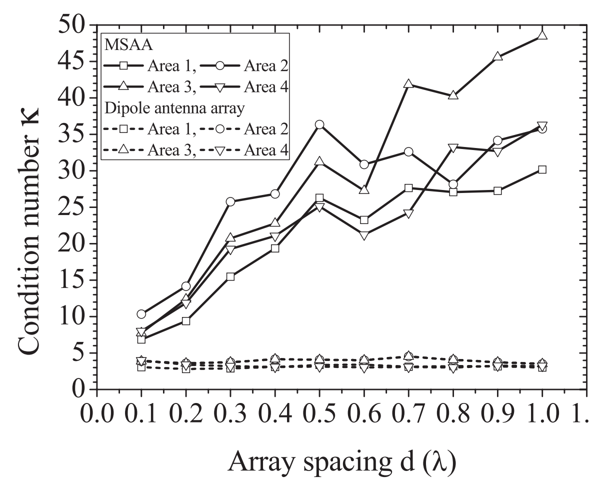

Fig. 7 Median condition number κ-factor of the MSAA and the dipole antenna array versus various array spacing in 4 different areas.

received power P_{IF} of the MSAA degrades by increasing array spacing. The degradation of P_{IF} is caused by the lower gain of the MSE as reported in [2]. It was found that the gain of the MSE element is usually 10–25 dB lower than that of the normal antenna element when array spacing of receiving antenna varies from $0.1\,\lambda$ to $0.5\,\lambda$. Similar to results of Fig. 4, it is noticed that the difference between P_{RF} and P_{IF} decreases with decreasing array spacing. The received power of receiving Area 4 is larger than that of other cases because the transmission distance is shorter than that of other areas.

The channel capacity is also calculated for evaluating MIMO performance. The channel capacity can be expressed as:

$$C = \log_2 \left| I_{M_0} + \frac{P_{Total}}{M\sigma_n^2} HH^{\dagger} \right| = \sum_{i=1}^{M_0} \log_2 \left(1 + \frac{P_{Total}}{M\sigma_n^2} \lambda_i \right) \qquad (1)$$

where superscript † for conjugate transpose, $M_0 = min(M, N)$, I_{M_0} for the $M_0 \times M_0$ identity matrix, P_{Total} is the total transmission power, σ_n^2 is the received noise power which is set to -100 dBm in this research. H, λ_i, M, and N are the MIMO channel matrix, the ith eigenvalue of $HH^{\dagger}$, the number of the transmitting antennas and the number of the receiving antennas, respectively.

Condition number κ-factor is defined as:

$$\kappa = \sqrt{\frac{\lambda_1}{\lambda_2}} \qquad (2)$$

where there are only two eigenvalues due to the 2 by 2 MIMO system in this simulation.

Figure 6 shows the CDF results of the condition number κ-factor for the MSAA with various array spacing in the Area 1. It is known that the CDF of the κ-factor is changed clearly by turning array spacing in the case of the MSAA. Figure 7 shows the simulation results of median condition number κ-factor for various array spacing in 4 difference

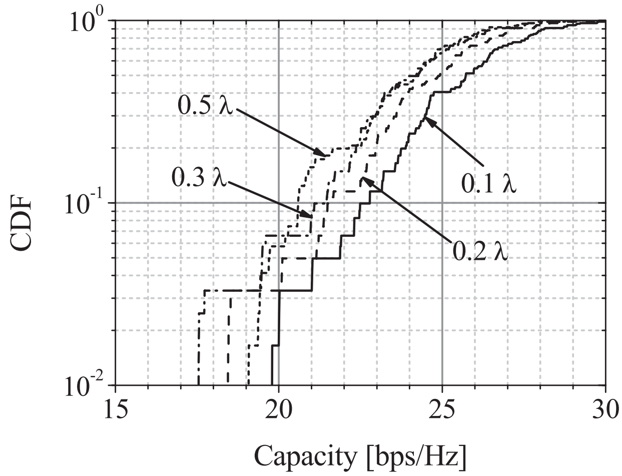

Fig. 8 CDF of MIMO channel capacity of the MSAA versus various array spacing in the Area 1.

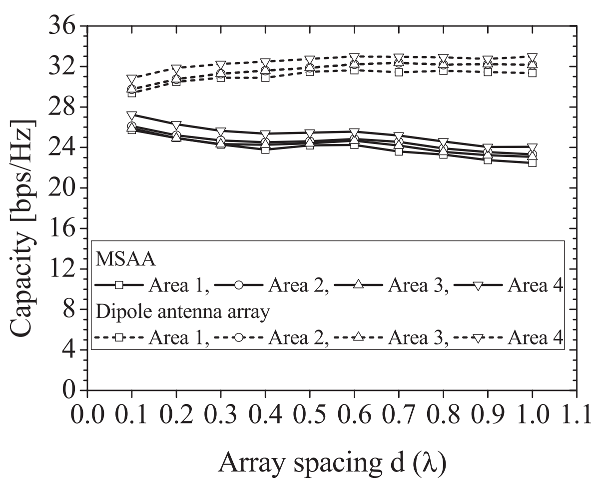

Fig. 9 Median MIMO channel capacity of the MSAA and the dipole array versus various array spacing in 4 different areas.

areas where the MSAA and the dipole antenna array were used as the receiving antennas, respectively. It is found that median κ-factor is decreased rapidly by reducing array spacing in the case of the MSAA, but it almost does not change for the case of the dipole antenna array. The reason is that the radiation pattern and the difference of received power between two receiving elements have effect on κ-factor.

Figure 8 shows CDF results of the MIMO channel capacity of the MSAA versus various array spacing in the Area 1. Figure 9 shows the median results of the MIMO channel capacity of the MSAA and the dipole antenna array versus various array spacing in 4 different areas. It is found that the MIMO channel capacity is improved by compact array spacing in the case of the MSAA, but comparatively the MIMO channel capacity decreases by reducing array spacing of the dipole antenna array. In other words, the difference of the MIMO channel capacity between the MSAA and the dipole antenna array decreases while array spacing of receiving elements is decreased. Therefore, when mounting space and manufacturing cost are strictly limited, we prefer the MSAA to the dipole antenna array since it have a simpler configuration and similar performance comparing with that of the dipole antenna array. It is also noted that same results are got in 4 different receiving areas. It demonstrates that although the propagation channel is changed, the MSAA still keeps steady performance. Thus, the MSAA is a very good candidate for the MIMO application. Meanwhile, analysis results given above agree well with previous experimental results [5].

4. Conclusions

In this letter, the MIMO performance of the modulated scattering antenna array is investigated theoretically for the first time in indoor environment based on the approach to hybridization of the Volterra series method and method of moments (MoM). It is found that the MIMO performance of the MSAA is improved with reducing the array spacing of the MSAA. Although antenna and propagation characteristics play an important role in MIMO system, coding and signal processing are also a key point to implement the MSAA for MIMO application. Therefore, we will further analyze the performance of the MSAA for MIMO application for different coding and signal processing methods in the future work.

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