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MIMO Performance of Modulated Scattering Antenna Array in Indoor Environment

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Abstract In this report, the MIMO performance of modulated scattering antenna array (MSAA) is analyzed numerically based on an approach to hybridization of the Volterra series method and method of moments (MoM). The main feature of the hybrid method is its efficiency in dealing with problems involving the weakly nonlinear loads and multitone excitations. Moreover, 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 MSAA is improved with reducing the array spacing of MSAA. At the same time, the simulated results of the MSAA are compared with that of two-dipole antenna array at the same condition.

Key words array antenna, modulation, mobile handsets, nonlinear circuits, Volterra series, MoM, MIMO

1. Introduction

The modulated scattering technique (MST) was firstly proposed by Richmond for the measurement of electric fields [1]. Recently, a new concept of antenna arrays, which is called modulated scattering antenna array (MSAA), based on the MST was proposed by Yuan et al [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 MIMO systems where compactness and energy saving are of primary concerns. In the previous works [2]-[5], the performance of MSAA for wireless communications has been extensively discussed by many 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 is suitable for mobile handset in the MIMO communication due to its simple configuration and low energy consumption.

A hybrid method based on the Volterra series method and the method of moments (MoM) has been presented to find optimum parameters of MSEs and to further improve the performance of the MSAA. However, it is also necessary to analyze the performance of the MSAA for the MIMO communication channels by using the hybrid method. In this report, the MIMO performance of the MSAA is investigated theoretically in the first time through this approach to hybridization of the Volterra series method and MoM.

This report is organized as follows: the configuration of the MSAA is described simply in Section 2. The theoretical analysis of a 2-element the MSAA based on the Volterra series method and MoM is introduced in Section 3. The simulation environment is presented in Section 4 . The simulation results are shown in Section 5. Finally, conclusions are given in Section 6.

2. Configuration of the MSAA

The configuration of the MSAA with diodes is shown in Fig.1. The MSAA is composed of two types of elements that normal receiving antenna element and MSEs, respectively. The normal antenna element is connected with the RF front-end circuit, while MSEs are seen as antennas or scatterers without their own receiving circuits. Nonlinear devices are mounted at MSEs for modulation and are fed by local signals with low frequencies f_{LOi}.

When the MSAA is excited by the radio frequency signal f_{RF}, new modulated scattering signals $f_{IFi} = mf_{RF} \pm nf_{LOi}(m, n = 0, 1, 2, \cdots, and\, i = 1, 2, \cdots, N)$ will be obtained because of the nonlinear loads connected to the MSE and will be received by the normal receiving antenna. Because only one branch of the RF receiver is needed in the MSAA, this feature makes the MSAA be very appealing when it is used as the receiving antenna for the mobile handset in MIMO systems where compactness and energy-saving are of primary concerns.

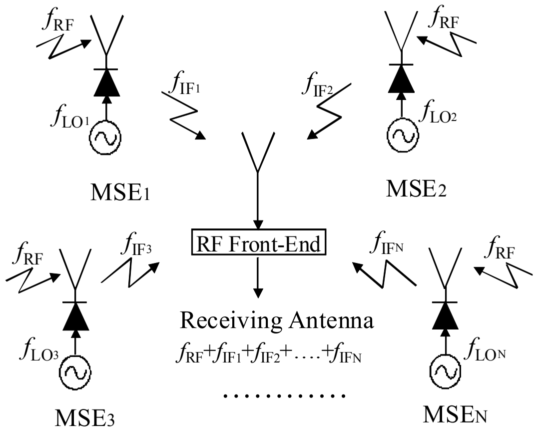

Fig. 1 Configuration of the MSAA with diodes.

3. Theoretical analysis method

Because the centre of MSEs have nonlinear devices, a hybrid method based on the Volterra series method and the method of moments (MoM) is presented to resolve this problem. The main feature of the hybrid method is its efficiency in dealing with problems involving the weakly nonlinear loads and multitone excitations.

Fig. 2 shows the schematic diagram of a 2-element dipole MSAA loaded with a Schottky diode. 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 DC block inductance and RF chock capacitance, respectively. The array spacing of the MSAA is d.

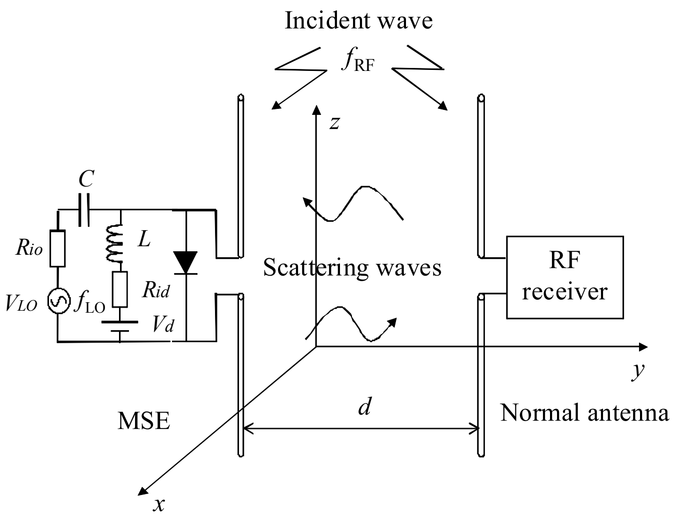

Fig. 2 Schematic diagram of a 2-element dipole MSAA loaded with a diode.

Fig. 3 shows the Norton's equivalent circuit of the MSE shown in the Fig. 2 where I_{SC} is the short-circuit current at the port of MSE at f_{RF}, and Yin 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. Based on Kirchhoff's current law, following equations are given:

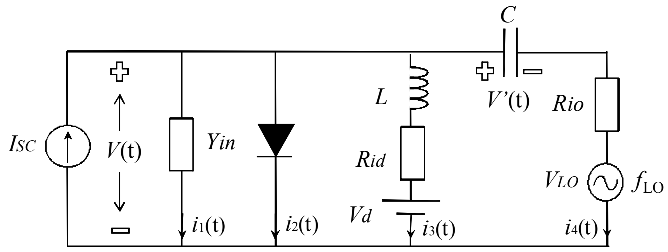

Fig. 3 Equivalent circuit of the MSE shown in the Fig. 2.

$$i_1(t) + i_2(t) + i_3(t) + i_4(t) = I_{SC} \tag{1}$$

where

$$\begin{cases} i_1(t) = Y_{in} V(t) \\ i_2(t) = f[V(t)] \\ V_d + i_3(t) R_{id} + L\dfrac{di_3(t)}{dt} = V(t) \\ V_{LO} + i_4(t) R_{io} + V'(t) = V(t) \\ i_4(t) = C\dfrac{dV'(t)}{dt} \end{cases} \tag{2}$$

Substituting (1) into (2) gives,

$$\begin{aligned} Y_{in}V(t) + f[V(t)] + \left[V(t) - V_d - L\frac{di_3(t)}{dt}\right]/R_{id} \\ + \left[V(t) - V_{LO} - V'(t)\right]/R_{io} = I_{SC} \end{aligned} \tag{3}$$

The i/v characteristics of a typical Schottky diode can be expressed as [7]:

$$i(t) = f[V(t)] = I_S\left(e^{\alpha V(t)} - 1\right) \tag{4}$$

where I_S is the reverse-saturation current, and α depends on the structure of the diode.

$V(t)$ has a DC voltage V_0 component and AC voltage $v(t)$ component. Therefore, We can expand the current $i(t)$ in a Taylor series around V_0.

$$\begin{aligned} i(t) &= f[V(t)] = f[V_0 + v(t)] \\ &= f[V_0] + \frac{df}{dV}|_{V=V_0} v(t) + \frac{1}{2}\frac{d^2 f}{dV^2}|_{V=V_0} v^2(t) + O(v^3(t)) \\ &= I_0 + \frac{df}{dV}|_{V=V_0} v(t) + \frac{1}{2}\frac{d^2 f}{dV^2}|_{V=V_0} v^2(t) + O(v^3(t)) \end{aligned} \tag{5}$$

The short-circuit current I_{SC} and the local signal voltage V_{LO} are given in frequency domain as follows:

$$I_{SC} = \mathrm{Re}\left(\left|\vec{I}\right| e^{j(\omega_1 t + \varphi)}\right) = \frac{1}{2}\left[\vec{I} e^{j\omega_1 t} + \vec{I}^{\,*} e^{-j\omega_1 t}\right] \tag{6}$$

and

$$V_{LO} = \vec{V}_L \cos\omega_2 t = \frac{1}{2}\vec{V}_L\left[e^{j\omega_2 t} + e^{-j\omega_2 t}\right] \tag{7}$$

where $\omega_1 = 2\pi f_{RF}$, $\omega_2 = 2\pi f_{LO}$, $\vec{I}$ and $\vec{V}_L$ denote the phasor representation of the amplitude and phase, i.e., $\vec{I} = \left|\vec{I}\right| e^{j\varphi}$ and $\vec{I}^*$ is the complex conjugate of $\vec{I}$. In (7), the initial phase of $\vec{V}_L$ is assumed as zero.

Assume

$$\vec{E}_{-1} = \vec{I}^*, \vec{E}_1 = \vec{I}, \vec{E}_{-2} = \vec{E}_2 = \vec{V}_L G_{io} \tag{8}$$

According to Volterra series method [6], the output voltage can be written as:

$$v(t) = \frac{1}{2}\sum_{l=-2}^{2} \vec{E}_{l_1} H_1(\omega_l) \exp(j\omega_{l_l} t) + \frac{1}{2^2}\sum_{l_1=-2}^{2}\sum_{l_2=2}^{2} \vec{E}_{l_1}\vec{E}_{l_2} H_2(\omega_{l_1}, \omega_{l_2}) \exp[j(\omega_{l_1} + \omega_{l_2})t] \tag{9}$$

where $H_1(\omega_l)$ and $H_2(\omega_{l_1}, \omega_{l_2})$ are the first- and the second-order transfer functions, respectively. In (9), the negative frequencies are defined as:

$$\omega_{-l} = -\omega_l \tag{10}$$

The final results of the first- and second-order transfer functions are obtained:

$$\begin{cases} A(\omega) = Y_{in}(\omega) + G_{io} + a_1 \\ H_1(\omega) = \dfrac{1}{A(\omega)} \\ H_2(\omega_1, -\omega_2) = -\dfrac{a_2}{A(\omega_1) A^*(\omega_2) A(\omega_1 - \omega_2)} \end{cases} \tag{11}$$

where $A(\omega)$ is the linear admittance. In the derivation of (11), following relations of the transfer functions have been used:

$$\begin{cases} H_1(-\omega) = H_1{}^*(\omega) \\ H_2(-\omega_1, \omega_2) = H_2{}^*(-\omega_1, \omega_2) \\ H_2(\omega_1, \omega_2) = H_2(\omega_2, \omega_1) \end{cases} \tag{12}$$

Finally, the frequency-domain output voltages from MSE at ω_1 and $\omega_1 - \omega_2$ are:

$$v(\omega_1) = \vec{E}_1 H_1(\omega_1) \tag{13}$$

and

$$v(\omega_1 - \omega_2) = \vec{E}_1 \vec{E}_{-2} H_2(\omega_1, -\omega_2) \tag{14}$$

4. Simulation environment and results

Fig. 4 shows the MIMO simulation model of MoM to analyze MIMO performance of the MSAA in 2 × 2 MIMO communication system. The simulation was performed in a room (Length: 8m; Width: 6m; Height: 2.4m) with the perfect electric conductor (PEC) structure. The distance between the transmitting and receiving antenna is about 6m. And the height of the transmitting and receiving antenna is about 1.2m. 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.

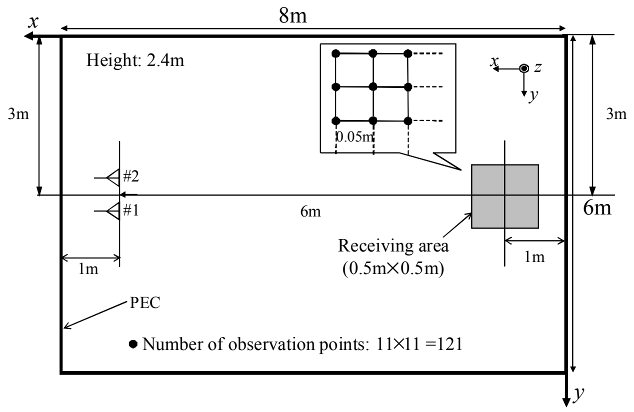

Fig. 4 MIMO simulation model.

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

$$C = \log_2 \left| I_{M_0} + \frac{P_{Total}}{M\sigma_n^2} HH^\dagger \right| = \sum_{i=1}^{M_0} \log_2 \left(1 + \frac{P_{Total}}{M\sigma_n^2}\lambda_i\right) \tag{15}$$

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, H is the MIMO channel matrix, λ_i is the ith eigenvalue of $HH^\dagger$, M is the number of the transmitting antennas and N is the number of the receiving antennas.

Condition number κ-factor is defined as:

$$\kappa = \sqrt{\frac{\lambda_1}{\lambda_2}} \tag{16}$$

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

Fig. 5 shows the simulation results of median received power for various array spacing where the dipole MSAA and dipole antenna array were used as the receiving antennas. Received power of the dipole antenna array increases little until about 0.6λ when the array spacing increases, and received power P_{RF} of dipole MSAA can be also improved little until about 0.5λ by increasing array spacing. At the same time, it is found that received power of the dipole antenna array and received power P_{RF} of dipole MSAA is almost same with various array spacing. However, received power P_{IF} of dipole MSAA will be degraded by increasing array spacing. The degradation of P_{IF} is caused by the lower gain of the MSE as reported in [2], where it was found that the gain of the MSE element is usually 15-20 dB lower than that of the normal antenna element. Moreover, it is noticed that the difference between received power of RF signal and IF

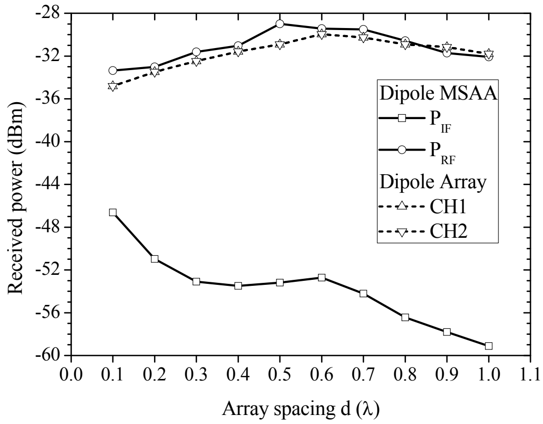

Fig. 5 Median SNR of dipole MSAA and two dipoles antenna array versus various array spacing.

signal will decrease with decreasing array spacing.

Fig. 6 shows the simulation results of median condition number κ-factor for various array spacing where the dipole MSAA and dipole antenna array were used as the receiving antennas. And κ-factor is decreased rapidly by decreasing array spacing in the case of the dipole MSAA, but it is almost not changed for the case of two-dipole antenna array.

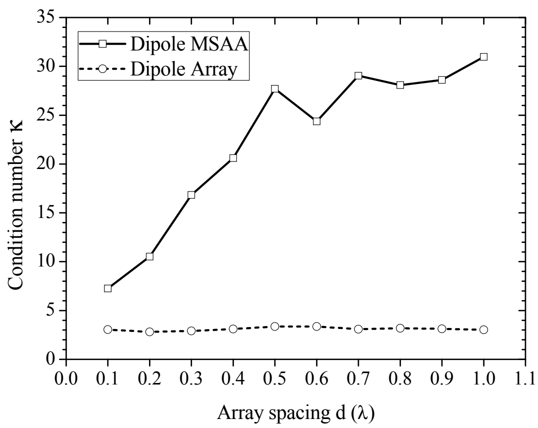

Fig. 6 Median condition number κ-factor of MSAA and two dipoles antenna array versus various array spacing.

Fig. 7 shows the simulation results of median MIMO channel capacity of dipole MSAA and two dipoles antenna array versus various array spacing. It is noted that the MIMO channel capacity is improved by compact array spacing in the case of dipole MSAA. On the other hand, the MIMO channel capacity decreases by decreasing array spacing of two-dipole antenna array.

Based on the above analysis results and previous experimental studies [5], it is known that the numerical analysis method can predict well the MIMO performance of the MSAA.

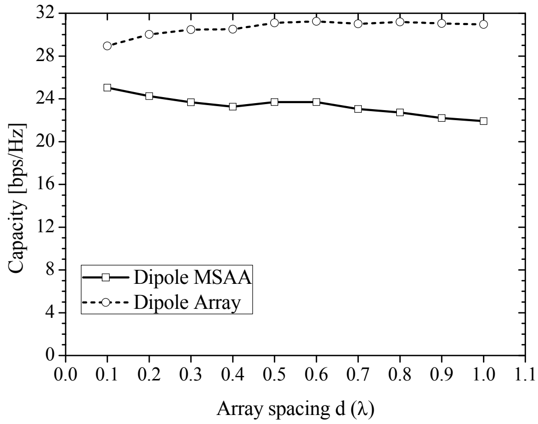

Fig. 7 Median MIMO channel capacity of dipole MSAA and two dipoles antenna array versus various array spacing.

5. Conclusions

In this report, the MIMO performance of modulated scattering antenna array (MSAA) is analyzed numerically based on an approach to hybridization of the Volterra series method and method of moments (MoM). It is found that MIMO performance of the MSAA is improved with reducing the array spacing of the MSAA. Based on the above analysis results and previous experimental studies [5], it is also known that the numerical analysis method can predict well the MIMO performance of the MSAA.

Acknowledgments

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