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Theoretical and Experimental Study on Modulated Scattering Antenna Array for Mobile Handset

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Abstract: The modulated scattering antenna array (MSAA) is composed of one normal antenna element and several modulated scattering elements (MSEs). An approach to hybridization of the Volterra series method and method of moments (MoM) is proposed to investigate the performance of MSAA in this report. The main feature of the proposed hybrid method is its efficiency in dealing with problems involving the weakly nonlinear loads and multitone excitations. Moreover, it is propitious to find out optimization parameters of MSEs by Volterra analysis in order to improve the performance of the MSAA for mobile handset. Mutual coupling effect between the MSEs and the normal antenna element is also considered in this analysis. The validity of the proposed method is demonstrated by comparing with experimental results.

Keywords: array antenna, modulation, mobile handsets, nonlinear circuits, Volterra series, method of moments

1. INTRODUCTION

In the last decade, a great deal attention has been devoted to deploy multiple-element antenna arrays for multiple-input multiple-output (MIMO) communication system due to its higher spectral efficiency and transfer reliability [1]. However, it is very difficult to develop multi-antenna arrays suitable for mobile handset, because of some problems such as the limited space on the handset to mount a number of antennas with sufficiently low mutual coupling and correlation between antennas [2]-[4]. Moreover, because a number of separate RF front-end circuits are required corresponding to the number of antenna elements, a large amount of packaging space for the RF front-end circuits is necessary. Therefore, it is essential to develop multi-antenna arrays with simple configurations which are suitable for mobile handset.

The modulated scattering technique (MST) was first discovered by Richmond for the measurement of electric fields [5]. Recently, a new concept of antenna arrays, which is called modulated scattering antenna array (MSAA), based on the MST has been proposed by Yuan *et al* [6]. The MSAA consists of one normal antenna element and several modulated scattering elements (MSEs) without RF front-end circuit. In the previous work [6]-[8], the performance of MSAA for wireless communications has been discussed by extensive 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 MIMO communication due to its simple configuration. At the same time, the imperfect performance of MSAA is also shown comparing to that of the normal antenna array in MIMO communications. So it is necessary to propose the theoretical analysis method in order to further enhance the performance of MSAA. In this report, a hybrid method of the Volterra series method and the method of moments (MoM) is presented to find out optimization parameters of MSAA and further improve its performance.

The report is organized as follows. The configuration and principle of the MSAA is described in Section II. Section III introduces the theoretical analysis of a 2-element MSAA based on the Volterra series method and MoM. The numerical and experimental results are shown in Section IV. Finally, conclusions are given in Section V.

2. THE CONFIGURATION AND PRINCIPLE OF MSAA

The configuration of a MSAA with diodes is shown in Fig. 1. The MSAA is composed of two types of elements that normal receiving antenna element and MSEs. 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 fed by local signals with low frequencies f_{LOi}.

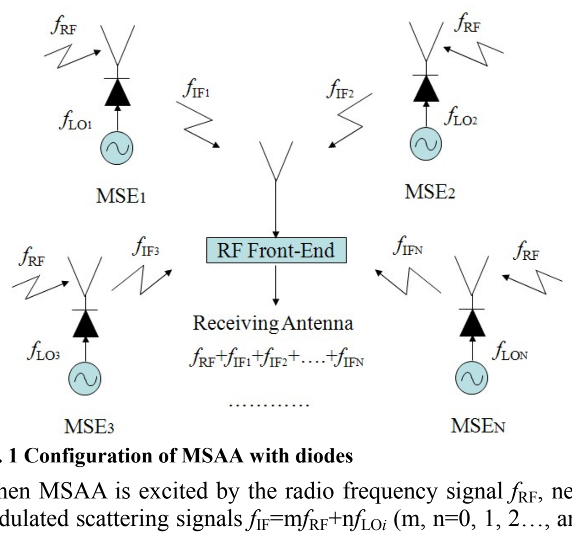

Fig. 1 Configuration of MSAA with diodes

When MSAA is excited by the radio frequency signal f_{RF}, new modulated scattering signals $f_{IF}=mf_{RF}+nf_{LOi}$ (m, n=0, 1, 2…, and i=1, 2,…, N) will be obtained because of the nonlinear loads connected to the MSEs and will be received by the normal receiving antenna. And only one branch of the RF receiver is needed in MSAA. This feature makes 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.

3. THEORETICAL ANALYSIS METHOD

In the previous work [6]-[8], extensive experimental studies have been carried out to confirm the performance of the MSAA, where the second-order intermodulation scattering field was used as the modulated signal. It is shown that MSAA provides slightly inferior performance comparing to that of the normal receiving antenna array in MIMO communications due to low power level of the modulated scattering signal received by the normal antenna. Therefore, it is essential to find out optimization parameters of MSAA through theoretical analysis for enhancing its performance.

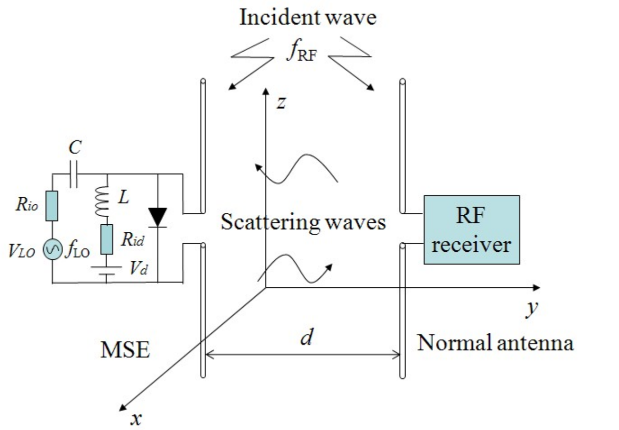

Fig. 2 Schematic diagram of a 2-element dipole MSAA loaded with a diode

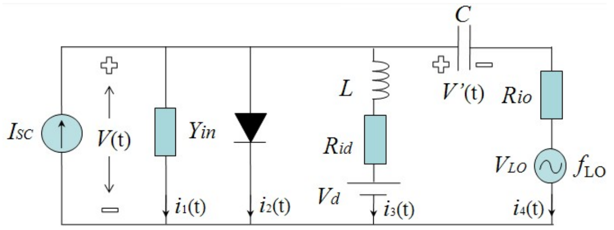

Fig. 3 Equivalent circuit of the MSE shown in the Fig. 2

In this section, the performance of a 2-element MSAA will be investigated by the hybrid method which is composed of the Volterra series method and MoM. 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.

Fig. 3 shows the Norton's equivalent circuit of the MSE shown in the Fig. 2 with utilizing MoM where I_{SC} is the short-circuit current at the port of MSE at f_{RF}, 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, so Mutual coupling effect between the MSE and the normal antenna element is also considered in this analysis. Based on Kirchhoff's current law, following equations are given:

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

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

Substituting (1) into (2) gives,

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

The *i/v* characteristics of a typical Schottky diode can be expressed as:

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

where I_S is the reverse-saturation current, Vt=1/α 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.

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

Let us assume

$$a_1=\frac{df}{dV}\Big|_{V=V_0},\ a_2=\frac{1}{2}\frac{d^2f}{dV^2}\Big|_{V=V_0} \tag{6}$$

and

$$i_2'(t)=a_1v(t)+a_2v^2(t) \tag{7}$$

Then (5) can be written as:

$$i(t)=I_0+a_1v(t)+a_2v^2(t) \tag{8}$$

Finally, (3) can be divided into two parts

DC part:

$$I_0+\frac{(V_0-V_d)}{R_{id}}=0 \tag{9}$$

AC part:

$$Y_{in}v(t)+i_2'(t)+G_{io}v(t)=I_{SC}+G_{io}V_{LO} \tag{10}$$

where $G_{io}=1/R_{io}$. Inductance L and capacitance C were ignored in the calculations. Although we only used first three terms in Taylor's series expansion of current $i(t)$, it has not effect on our analysis results since MSAA is used in the range of the weakly nonlinear problem. For analysis of the nonlinear circuit, there are a variety of approaches [9]-[11]. The Volterra series method is employed in this research because of its efficiency in dealing with problems involving the weakly nonlinear loads and multitone excitations. And it can be implemented in the frequency domain without the need for performing a fast Fourier transform [9].

Two-tone excitation exists in (10). The short-circuit current I_{SC} and the local signal voltage V_{LO} are given in frequency domain as follows:

$$I_{SC}=\mathrm{Re}\left(\left|\bar{I}\right|e^{j(\omega_1 t+\varphi)}\right)=\frac{1}{2}\left[\bar{I}e^{j\omega_1 t}+\bar{I}^*e^{-j\omega_1 t}\right] \tag{11}$$

and

$$V_{LO} = \vec{V}_L \cos\omega_2 t = \frac{1}{2}\vec{V}_L\left[e^{j\omega_2 t} + e^{-j\omega_2 t}\right] \tag{12}$$

where w_1=2πf_{RF}, w_2=2πf_{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 (12), the initial phase of $\vec{V}_L$ is assumed as zero.

Replace (11) and (12) into (10) results in

$$\begin{aligned} &Y_{in}v(t) + i_2^{'}(t) + G_{io}v(t) = \\ &\frac{1}{2}\left[\vec{I}e^{j\omega_1 t} + \vec{I}^* e^{-j\omega_1 t}\right] + \frac{1}{2}\vec{V}_L G_{io}\left[e^{j\omega_2 t} + e^{-j\omega_2 t}\right] \end{aligned} \tag{13}$$

Assume

$$\vec{E}_{-1} = \vec{I}^*,\ \vec{E}_1 = \vec{I},\ \vec{E}_{-2} = \vec{E}_2 = \vec{V}_L G_{io} \tag{14}$$

Then (13) can be expressed as:

$$\begin{aligned} &Y_{in}v(t) + i_2^{'}(t) + G_{io}v(t) = \\ &\frac{1}{2}\vec{E}e^{j\omega_1 t} + \frac{1}{2}\vec{E}_{-1}e^{-j\omega_1 t} + \frac{1}{2}\vec{E}_2 e^{j\omega_2 t} + \frac{1}{2}\vec{E}_{-2}e^{-j\omega_2 t} \end{aligned} \tag{15}$$

According to Volterra series method [9], the output voltage can be written as:

$$\begin{aligned} v(t) = &\frac{1}{2}\sum_{l=-2}^{2}\vec{E}_{l_1} H_1(\omega_l)\exp(j2\pi\omega_l t) \\ &+ \frac{1}{2^2}\sum_{l_1=-2}^{2}\sum_{l_2=2}^{2}\vec{E}_{l_1}\vec{E}_{l_2}H_2(\omega_{l_1},\omega_{l_2})\exp\left[j2\pi(\omega_{l_1}+\omega_{l_2})t\right] \end{aligned} \tag{16}$$

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 (16), the negative frequencies are defined as:

$$\omega_{-l} = -\omega_l \tag{17}$$

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

$$\begin{cases} A(\omega) = Y_{in}(\omega) + G_{io} + a_1 \\ H_1(\omega) = \dfrac{1}{A(\omega)} \\ H_2(\omega_1,-\omega_2) = -\dfrac{a_2}{A(\omega_1)A^*(\omega_2)A(\omega_1-\omega_2)} \end{cases} \tag{18}$$

where *A(ω)* is the linear admittance. In the derivation of (18), following relations of the transfer functions have been used:

$$\begin{cases} H_1(-\omega) = H_1^*(\omega) \\ H_2(-\omega_1,\omega_2) = H_2^*(-\omega_1,\omega_2) \\ H_2(\omega_1,\omega_2) = H_2(\omega_2,\omega_1) \end{cases} \tag{19}$$

Finally, the frequency-domain output voltages from MSE at ω_1 and ω_1-ω_2 are:

$$v(\omega_1) = \vec{E}_1 H_1(\omega_1) \tag{20}$$

and

$$v(\omega_1-\omega_2) = \vec{E}_1\vec{E}_{-2}H_2(\omega_1,-\omega_2) \tag{21}$$

Because the performance of MSAA can be improved by enhancing the received power P_{IF} of the modulated scattering signal, it is important to find out optimization parameters of MSE. Based on the above analysis, it is found that $v(\omega_1-\omega_2)$ can be effected by the short-circuited current, DC bias voltage and local signal voltage. Therefore, we will investigate the validity of the proposed method in the next section through simulations and experimental studies.

4. NUMERICAL AND EXPERIMENTAL RESULTS

In this section, we will show the numerical simulation results. At the same time, the experimental results will be also presented in order to confirm accuracy of the numerical simulations. In the simulations, the normal receiving antenna is a half-wavelength dipole at frequency f_{RF}=2.5GHz while MSE is chosen as a half-wavelength thin-wire scatterer loaded with a typical Schottky diode which is parameterized by I_S=1.0μA and Vt=25mV. The geometry of simulation model is similar to that shown in Fig. 2 and is created by FEKO from EM Software & Systems-S.A. (Pty) Ltd.. The entire structure is within the *yoz* plane, and array spacing is *d*. A vertically polarized plane wave is assumed as the excitation signal of the MSAA, an angle of incidence run parallel with *x* axis. The magnitude of the incident plane wave is 0.09V/m. Moreover, internal resistors R_{id}, R_{io} and the input impedance of the RF receiver are fixed as 50Ω. Both the dipole antenna and the MSE have the length-diameter ratio of 74.2.

The experiment was carried out in the anechoic chamber. The log-periodic dipole antenna (LPDA) is used as the transmitting antenna and the transmitting power is -5dBm. The normal receiving antenna is a half-wavelength dipole antenna at 2.5GHz. MSE is a half-wavelength thin wire. A Schottky diode HSC276 from RENESAS Ltd. is mounted at the centre of the MSE. The distance between the transmitting and receiving antenna is about 3m. Local frequency is 50MHz generated by Function Generator.

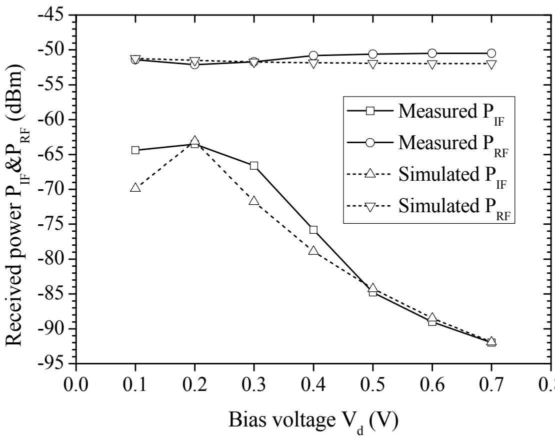

Fig. 4 Measured and simulated received power P_{IF} and P_{RF} versus various DC bias voltages

Fig. 4 shows the measured and simulated received power P_{IF} and P_{RF} versus various DC bias voltages. Here array spacing is 0.1λ. The local signal voltage is 0.5Vp-p. It is shown that P_{RF} is almost constant with regulating DC bias voltages, while it has made a great impact on P_{IF}. Firstly P_{IF} will rise with increasing bias voltage V_d, and then fall after reaching its maximum which occurs at a low bias voltage (about 0.2V). Moreover, experimental results show the accuracy of the numerical simulation results.

The relation between the received power level and the magnitude of the local signal voltage through both experiments and numerical simulations is shown in Fig. 5. DC bias voltage is fixed in 0.2V, and array spacing still remains 0.1λ. It is found that simulation results predict well measured results in the small-signal regime (0~0.5Vp-p). The small difference between the measured and simulated results result from the fact that the characteristic of diode used in the simulation is not exactly identical to that of diode employed in the experiment. And it is noted that the simulated P_{IF} will increase continuously with increasing local signal voltage V_{LO} due to the limitation of Volterra series method for strongly nonlinear problem. However, when V_{LO} exceeds 0.5Vp-p, the measured P_{IF} is almost unchanged due to the saturation of the diode.

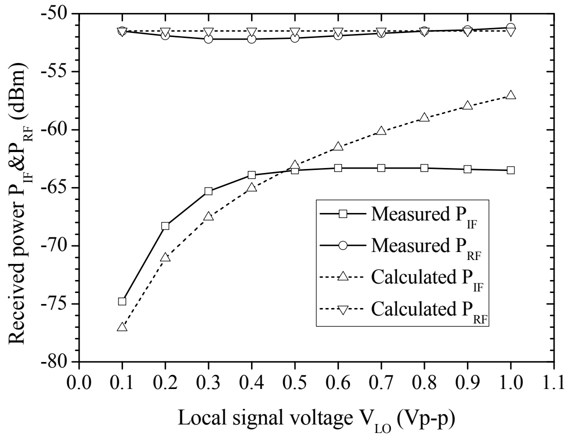

Fig. 5 Measured and simulated received power P_{IF} and P_{RF} versus various local signal voltages

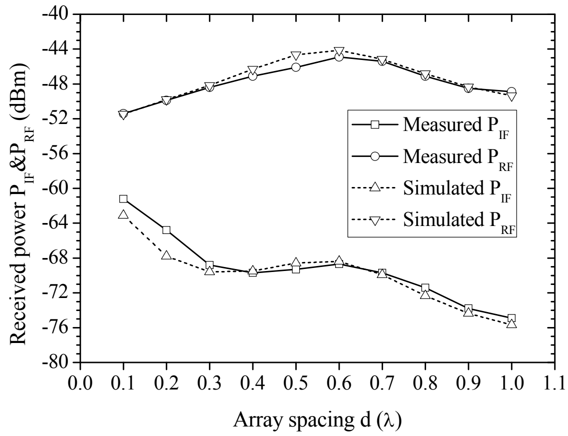

Fig. 6 Measured and simulated received power P_{IF} and P_{RF} versus various array spacing

Fig. 6 shows the result of the measured and simulated received power P_{IF} and P_{RF} versus various array spacing. DC bias voltage and local signal voltage is 0.2V and 0.5Vp-p, respectively. Reasonable agreement of two types of results is observed. It is also noted that difference between the P_{RF} and P_{IF} increases with increasing array spacing.

5. CONCLUSIONS

In this report, a hybrid method based on the Volterra series method and the method of moments (MoM) is proposed to investigate the performance of the modulated scattering antenna array for mobile handset. The validity of the proposed method is demonstrated by comparing with experimental results. It is found that the Volterra series method find out successfully optimization parameters (such as DC bias voltage, local signal voltage, and so on) of MSAA and further improve the level of received power P_{IF}. In the future work, we will predict the performance of MSAA in MIMO communication system by using the proposed method.

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