A Unified Mutual Coupling Model for Multiple Antenna Systems*

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Abstract  A unified mutual coupling model for multiple antenna communication systems based on moment methods is proposed. This model combines antenna coupling and RF front-end circuit coupling, thus providing a more accurate and complete analysis of the mutual coupling effect on multiple antenna systems.

Key words  MIMO; mutual coupling; pattern diversity

The use of multiple antennas can offer substantial performance improvement to a wireless communication system by spatial multiplexing methods or diversity methods[1]. In the multiple antenna receivers, each antenna requires another Radio-Frequency (RF) front-end chain. To achieve high multiple antenna gain, the multiple received signals arriving at the Combined Signal Processor (CSP) module should be independent and hold balanced mean power[2].

There are several factors affecting the correlation properties and the received power. Among them, mutual coupling, including Antenna Coupling (AC) and RF front-end Circuit Coupling (CC), is indicated as one of the main factors, and thus has obviously impacts on system performance. The coupling between multiple antennas has been widely studied[3-6]. In contrast, CC receives little research interest due to its relatively smaller value, thus can be neglected in most cases. However, as the number of antennas increases or the size of receiver becomes smaller and smaller, the effects of CC will become significant and should be considered carefully. Previous works, such as Refs.[7-8], consider antenna coupling and circuit coupling separately. However, RF front-end circuit coupling looking from antenna terminals will also alter the current distribution of antennas, thereby affects the coupling between antennas, i.e. AC and CC is related. Thus it is necessary to model AC and CC jointly in the rigorous sense. In this paper, a mixed electromagnetic and network integral equation is formulated in terms of the unknown surface current in antennas. N RF front-end circuits are model as an N port network, while employing impedance matrix to relate the terminal current and voltage in the absence of multiple antennas. Once the surface currents are known, the effects of AC and CC can be analyzed respectively, and the correlation properties as well as the received power can be investigated under various AC and CC conditions.

1  Coupling Model

Fig.1 illustrates the mutual coupling among antennas and RF front-end circuits. The N coupled multiple RF chains can be treated as a coupled loading network connected to multiple antennas and it is connected to the multiple antennas in series. Moment methods is used to solve the integration equation and investigate coupling effects of multi-antennas[9]. For the sake of clarity, assume that there is only one expansion basis for the current of each antenna in the moment methods analysis. Using the generalized matrix Ohm’s law to relate field with circuit[10], a matrix equation is obtained, namely

\[ V = ZI + Z_LI \]  (1)

where \( I \) is the antenna terminal currents vector (strictly speaking, it should be current distributions coefficients vector, but it won’t affect the analysis below). \( Z \) is an \( N \times N \) impedance matrix quantifying the mutual coupling between multiple antennas. \( Z_L \) is an \( N \times N \) loaded impedance matrix quantifying the mutual coupling between each RF front-end chains. When there is no coupling looking from antenna terminals, \( Z_L \) is a diagonal matrix. When CC is considered, it is no longer diagonal and \([Z_L]_{m,n}\) relates the open voltage (in the absence of antennas) of terminal \( m \) to the input current of terminal \( n \). \( V \) is the excitation vector due to
incident fields. Define:

\[ Z_R = Z + Z_L \quad (2) \]

Thus both AC and CC which affect the spatial correlation and the received power are taken into account in the mutual impedance matrix \( Z_R \), and the terminal current of each antenna can be obtained by solving Eq.(1). Note that \( Z_R \) is independence of incident waves.

Assume that there are \( L \) plane incidence waves, the \( l \)th incident plane wave with incident angle of \( \Omega_l \), where \( \Omega_l \) is the incident angle, will lead to excitation vector \( V_l \), and the corresponding current vector is solved as

\[ I_l = Z_R^{-1} V_l, \quad l = 1, 2, \ldots, N \quad (3) \]

Thus the received voltage vector at antenna terminals corresponding to the \( l \)th incident wave is

\[ Y_l = Z_L I_l, \quad l = 1, 2, \ldots, N \quad (4) \]

and the total received voltage can be obtain as

\[ Y = \sum_{l=1}^{L} Y_l \quad (5) \]

Assuming the plane incidence wave components separated in angle are uncorrelated, the correlation matrix of the received signal at antenna terminals thus can be obtained as

\[ R = E\{YY^H\} = \sum_{l=1}^{L} Z_L E\{I_lI_l^H\} Z_L^H \quad (6) \]

where \( E\{\cdot\} \) indicates an expectation and the superscript of H denotes conjugate transpose operation.

Then the correlation coefficient between the receiving signal of the \( i \)th and the \( j \)th antenna is

\[ \rho_{ij} = \frac{[R]_{i,j}}{\sqrt{[R]_{i,i}[R]_{j,j}}} \quad (7) \]

then the instantaneous power received in the terminal of the \( m \)th antenna is given by

\[ P_m = \frac{1}{2} \text{Re}\{\sum_{n=1}^{N} [I_m^H[V_n]]_n\} \quad (8) \]

where the superscript \( * \) denotes complex conjugation.

2 Simulation Results

In this section, a two-antenna system is used to illustrate how AC and CC affect the signal correlation and received power. Fig.2 illustrates the configuration of this two-antenna system. A parasitic dipole of length 0.52\( \lambda \) center-loaded by \( R_L \) is inserted between two half-wave dipoles. The spacing between the dipole and the parasitic dipole is \( d \), which is selected as 0.25\( \lambda \). Antenna coupling and the far field pattern can be changed by varying the loading value of \( R_L \). The CC coupling coefficients which quantify the effects of CC are defined as \( C_{12} = [Z_{L,22}]/[Z_{L,11}] \), and \( C_{21} = [Z_{L,11}]/[Z_{L,22}] \). In the following calculations, by varying \( R_L \), \( C_{12} \) and \( C_{21} \), various cases with different AC and CC will be investigated by numerical calculations. A two-dimensional geometry is considered and the incident power density is assumed as constant over an angle region defined by \( 2\Delta \) and zero otherwise, while the mean incident direction is along the x-axis, as shown in Fig.3.
Fig. 3 presents the signal correlation under various AC and CC conditions. When AC decreases due to $R_L$ change from 1e6 $\Omega$ to 33 $\Omega$, the correlation coefficient decreases too. While keeping $R_L$ constant and changing the magnitude of $C_{12}$ from 0.1 to 0.5, the signal correlation will increase. When $R_L$ equals to 33 $\Omega$, it will lead to minimal AC. The radiated patterns of these two dipoles calculated by moment methods are illustrated in Fig. 4. Obviously, pattern diversity scheme can be generated in this two-antenna system.

Finally, by employing the correlation coefficient and mean power ratio obtained in antenna terminals, the diversity gain of MRC can be evaluated by the method proposed in Ref.[2]. Compared with the zero CC case shown as a flat plane with sparse grids in Fig. 6, CC is possible to improve the diversity performance since the high mean power ratio is mitigated due to CC.

3 Summary

Since the AC and the CC looking from antenna terminals will interact with each other, they should be analyzed jointly. In this paper, a mixed electromagnetic and network integral equation is formed and solved by moment methods. Various AC and CC cases are investigated by simulations. As a reference, we evaluate the MRC diversity performance using the
correlation and power properties obtained at antenna terminals, and the results show that the presence of CC increases the correlation but probably decreases the mean power difference, thus it may improve the diversity performance in this pattern diversity case.

References


Brief Introduction to Author(s)

WU Yu-jiang (伍裕江) was born in Guangdong Province, China, in 1971. He received the B.S. degree from University of Electronic Science and Technology of China (UESTC) in 1993, where he is currently working toward the Ph.D. degree in the School of Electronic Engineering. His current research interests include antenna diversity and antenna designs for multiple antennas wireless communication.

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