Proceedings of ISAP 2014, Kaohsiung, Taiwan, Dec. 2-5, 2014

Mutual Coupling Compensation for Direction Finding using Receiving Mutual Impedance

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***Abstract* – The accuracy of direction finding using antenna arrays with different array apertures is studied. Numerical simulations are performed using full-wave moment method. The undesirable mutual coupling effect is properly modelled and compensated using receiving-mutual-impedance and the direction finding is obtained using the Matrix Pencil Method. The results show that increasing the number of elements with a small array aperture can significantly improve the accuracy in direction finding. The findings are crucial for the design of antenna arrays for direction finding.**

Index Terms — Mutual Coupling, Mutual Impedance, Antenna Array, Direction-of-arrival estimation

I. Introduction

Mutual coupling has been a well-known effect in antenna arrays. In the last few decades, extensive development has been made in array signal processing with various novel applications introduced in wireless communication and radar applications, for example direction-of-arrival (DOA) estimation [1]-[3], adaptive nulling [4], beam-forming [5] and space-time adaptive processing [6]. Other than array signal processing, recent interest has also been looking into mutual coupling effect in near-field array for biomedical imaging applications [7]. When these signal processing and imaging algorithms were developed, it is assumed that the antennas are 'ideal' such that these antennas do not interact with each other, i.e. the mutual coupling effect does not exist. This is valid provided that the antenna elements are well separated ($>0.5\lambda$). With the recent interest in compact mobile device in wireless communication, however, the array has to be physically and electrically small such that the mutual coupling becomes significant. In near-field microwave imaging applications, the target-of-interest is surrounded by a circular or rectangular array such that these mutual coupling cannot be ignored.

Gupta et al. [8] introduced the conventional mutual impedance - a circuit theory approach, to characterize the undesirable mutual coupling effect. Instead of using the measured antenna terminal voltage directly, the undesirable mutual coupling effect can be compensated using a decoupling process. Better accuracies in signal estimations can be achieved when the signal processing algorithm is applied to the decoupled voltages, for example in DOA estimation [2]. Recent studies using a full-wave moment method solution [4] showed that the mutual coupling effect is not well characterized using the conventional mutual impedance when the antenna is operating in the receiving mode. This is mainly because the conventional mutual impedance of two antenna elements is determined when the antenna is in transmitting mode. In general, the mutual coupling of a transmitting and a receiving array are two different problems and they should be handled separately [9], [10]. Other than characterizing the mutual coupling effect using an electromagnetic approach and removing the effect via decoupling, research has also been contributed to incorporate the mutual coupling effect in the signal model (e.g. [11]-[12]). In this work, we mainly focus on the electromagnetic approach.

Hui [13]-[17] re-visited the problem and proposed the receiving mutual impedance method (RMIM), which the mutual impedances are determined when the array is in receiving mode. The receiving mutual impedance (RMI) has been used for decoupling in adaptive nulling [15] and direction finding [13] applications, resulted in better estimation accuracies comparing to the case when conventional mutual impedance is used for decoupling. The RMIM has also been applied to near-field imaging application such as magnetic resonance imaging [18].

In this paper, we would like to investigate the mutual coupling compensation capability using the RMIM for antenna arrays with closely placed antenna elements – compact arrays. The entire electromagnetic problem is accurately model using commercial moment method solver FEKO [19] and antenna arrays with a fixed aperture but different inter-element separation will be performed. The results show that using RMIM, the undesirable mutual coupling effect can be compensated and better DOA estimation accuracies can be achieved when there are more array elements within the same aperture.

II. Receiving Mutual Impedance Method

The concept of receiving mutual impedance was introduced by Hui et al. in [14] and [16]. Consider an antenna array with N antenna elements and each of them are terminated with the same load impedance Z_L . The measured voltage at antenna terminal V_k can be written as

$$V_k = Z_L I_k = U_k + W_k \tag{1}$$

where U_k is the measured terminal voltage due to the incoming signal alone, W_k is the voltage due to the mutual coupling effect from other array elements and it can be written as [13]-[15]

$$W_k = Z_t^{k,1} I_1 + Z_t^{k,2} I_2 + \cdots + Z_t^{k,k-1} I_{k-1} + Z_t^{k,k+1} I_{k+1} + \cdots + Z_t^{k,N} I_N \quad (2)$$

where $Z_t^{k,i}$ is the RMI between antenna elements k and i, I_i is the current induced at the antenna terminal, given by

$$I_i = \frac{V_i}{Z_L} \quad (3)$$

for $i = 1,2,\cdots,N$. Combing (1) and (2) together with (3),

$$V_k = U_k + Z_t^{k,1}\frac{V_1}{Z_L} + Z_t^{k,2}\frac{V_2}{Z_L} + \cdots + Z_t^{k,k-1}\frac{V_{k-1}}{Z_L} + Z_t^{k,k+1}\frac{V_{k+1}}{Z_L} + \cdots + Z_t^{k,N}\frac{V_N}{Z_L}. \quad (4)$$

Rearranging (4), the relationship between U_k s and V_k s can be written as

$$\left[Z_{de}^R\right]\left[V\right] = \left[U\right], \quad (5)$$

where $[V] = [V_1 \ \ldots \ V_{N-1} \ V_N]^T$, $[U] = [U_1 \ \ldots \ U_{N-1} \ U_N]^T$

and

$$\left[Z_{de}^R\right] = \begin{bmatrix} 1 & -\frac{Z_t^{1,2}}{Z_L} & \cdots & -\frac{Z_t^{1,N-1}}{Z_L} & -\frac{Z_t^{1,N}}{Z_L} \\ -\frac{Z_t^{2,1}}{Z_L} & 1 & \cdots & -\frac{Z_t^{2,N-1}}{Z_L} & -\frac{Z_t^{2,N}}{Z_L} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ -\frac{Z_t^{N-1,1}}{Z_L} & -\frac{Z_t^{N-1,2}}{Z_L} & \cdots & 1 & -\frac{Z_t^{N-1,N}}{Z_L} \\ -\frac{Z_t^{N,1}}{Z_L} & -\frac{Z_t^{N,2}}{Z_L} & \cdots & -\frac{Z_t^{N,N-1}}{Z_L} & 1 \end{bmatrix}_{N\times N}.$$

Assuming that the RMIs ($Z_t^{k,i}$) are known together with the measured terminal voltages V_k s, the terminal voltage solely based on the incident signals U_k s can be decoupled using (5) and thus the mutual coupling effect from elements other than element k are eliminated through this decoupling process. The decoupled terminal voltages U_k are then used for further applications such as DOA estimation using matrix pencil method (MPM) [8], [20], [21].

III. Conclusion

DOA estimation using ULAs with different array apertures and number of elements are studied with an accurate account of the mutual coupling effect. The results, which will be presented in the conference, showed that the incoming signals can be accurately resolved with a larger number of elements in small aperture array. In a larger array aperture, the signals can still be resolved with a smaller number of elements. Such findings are important for antenna array design for direction finding applications.

Acknowledgment

The author would like to acknowledge the financial support by the University of Queensland (UQ) under the UQ Postdoctoral Research Fellowship scheme.

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