Direction-of-Arrival Estimation for Closely Coupled Dipoles Using Embedded Pattern Diversity

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***Abstract*-direction-of-arrival (DOA) estimation for very closely spaced dipoles (no larger than 0.1 wavelength) is considered. In contrast to reducing the mutual coupling effect in conventional DOA methods, we demonstrate in this work that the mutual coupling can produce amplitude and phase difference of embedded element patterns, which can be utilized to greatly improve DOA estimation performance by incorporating the pattern diversity into the estimation algorithm. Simulation results show that two coupled dipoles achieve much higher DOA estimation accuracy than the ones without mutual coupling (for example, with the basic multiple signal classification (MUSIC) algorithm, the two coupled dipoles can achieve the root-mean-squared error (RMSE) of 1° within 120° arriving angle range for the spacing of 0.1 wavelength and RMSE of 2° within 90° range for only 0.02 wavelength, at moderately high SNR and sampling condition)**

I. Introduction

Accurate DOA estimation is significant for many civil and military applications and has received much attention over the past years [1]-[6]. Usually, the DOA estimation accuracy depends on the maximum size of antenna array, and compact or electrically small arrays have very poor performance mainly due to the following reasons: a) the signals received by different elements only have little phase difference or very small time delay, and the phase difference is hard to measured accurately due to both noise contamination and non-ideal channel response of receiver; b) strong mutual coupling existing between adjacent elements causes the element pattern deviate from the ideal steering vector used in conventional DOA estimation algorithms. Up to now, there have been many state-of-the-art methods designed to mitigate the degradation of DOA estimation due to element mutual coupling. These methods include, for example, self calibration method based on mutual coupling model [2], mutual coupling compensation using electromotive force (EMF) method [3] and receiving mutual impedance [4]. Especially, the receiving mutual impedance method is a new concept of characterizing the mutual impedance which may be more appropriate for the receiving antenna array, since it has better performance of compensating the mutual coupling effect [4].

In this work, the DOA estimation in presence of strong mutual coupling for very closely spaced dipoles is considered. It is shown, for example in [7], that the electromagnetic coupling is very useful for enhancing the element pattern diversity. Here, we demonstrate that the amplitude and phase difference of embedded element patterns can be used to greatly improve DOA estimation accuracy by simply modifying the steering vector in the MUSIC algorithm.

II. DOA Estimation with Embedded Pattern Diversity

A. Embedded Patterns of Coupled Dipoles

Consider two coupled dipole antennas with spacing of d , as shown in Fig. 1. The embedded pattern is defined as the radiation pattern of one antenna in the situation where all the other antenna elements in the array are matched with appropriate loading impedances. Here, we assume that 50Ω load is used. To obtain the embedded pattern under element electromagnetic coupling, we solve this problem by using finite element method (FEM). In the simulation, we set the dipole length equal to 470mm, the diameter 10mm and the spacing 20mm or 100mm (the two spacing cases correspond to 0.02λ and 0.1λ at the frequency of 300MHz).

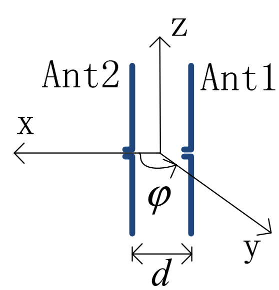
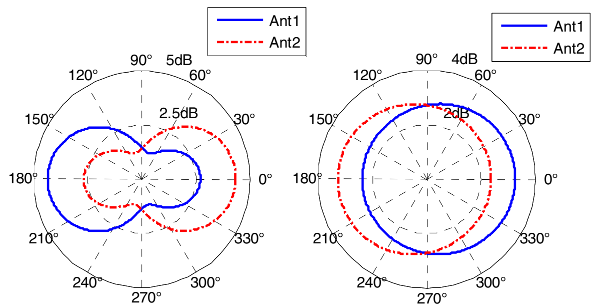


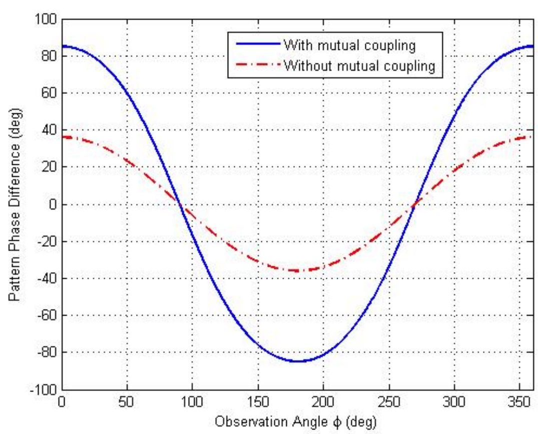
Figure 1. Configuration of two coupled dipoles

Fig. 2 (a) and (b) show the amplitude difference of embedded pattern for the cases of $d = 0.02\lambda$ and 0.1λ , respectively. It is seen that amplitude difference exists between the two patterns, especially for the case of $d = 0.1\lambda$. In particular, the parasitic element plays the role of reflector for the case of $d = 0.1\lambda$ but director for the case of $d = 0.02\lambda$. Fig. 3 shows phase difference of embedded pattern. It is seen that compared with the ideal phase difference of two isolated dipoles which is only due to the optical path difference, the phase difference of coupled dipoles can be enlarged by 2 and 3 times for $d = 0.1\lambda$ and $d = 0.02\lambda$. This means that the coupled dipoles are equivalent to the case of two isolated ones with larger spacing, and therefore more accurate DOA estimation can be achieved from the responses of them. It is worth noting that the amplitude and phase difference of embedded pattern for the transmitting array are exactly equal to the difference of received voltage response between different antenna excited by a plane wave. This can be verified by both theory and electromagnetic simulation. Hence, the pattern difference can be incorporated into the DOA algorithm with modification of array steering vectors.

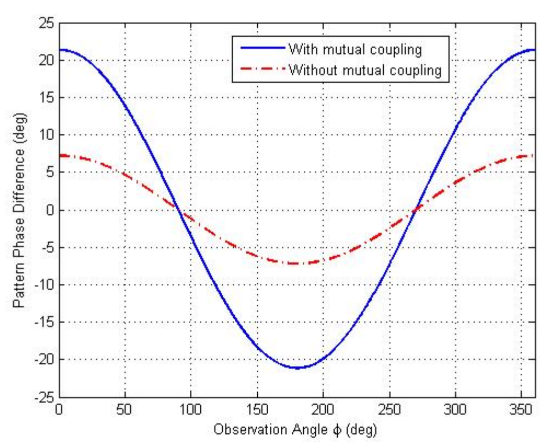


(a) (b)

Figure 2. Element gain patterns of two coupled dipoles: (a) d=0.1λ, and (b) d=0.02λ (they are 100 mm and 20mm at 300MHz, respectively).



(a)



(b)

Figure 3. Pattern phase difference of two isolated/coupled dipoles: (a) d=0.1λ, and (b) d=0.02λ (they are 100 mm and 20mm at 300MHz, respectively).

B. DOA Estimation with Pattern Diversity

MUSIC algorithm is one of popular DOA estimation methods which are based on the fact of the orthogonality between the array steering vector and noise subspace [1]. This method can be applied to the array with a non-ideal steering vector only if the real steering vector is already known. The MUSIC spectrum can be formulated into the following equation,

$$P_{music}(\varphi) = \frac{1}{\left|\mathbf{a}(\varphi)^H \mathbf{E}_N \mathbf{E}_N^H \mathbf{a}(\varphi)\right|}$$

where $\mathbf{E}_N$ is noise subspace obtained from eigenvalue decomposition, and $\mathbf{a}(\varphi) = [a_1(\varphi) \quad a_2(\varphi)]^T$ is a vector consisting of complex embedded patterns. The DOA of a plane wave can be estimated by maximizing the above spectrum.

III. SIMULATION RESULTS

In the following simulation, we always set $SNR = 15$ dB , $f_s = 3 f_0 = 900$ MHz . And set the data length equal to $K = 300$. Assume that a plane wave arrives from $45°$. Fig. 4 compares the MUSIC spectrum of two coupled/isolated dipoles for $d = 0.02\lambda$ and 0.1λ , as are shown in Fig. 4 (a) and (b), respectively. Ten trials are used for roughly checking the statistic performance. It is clear that the coupled dipoles with embedded pattern diversity obtain much more concentrative spectrum around the real arriving angle for the both spacing cases, which corresponds to higher estimation accuracy, compared with the case of isolated dipoles without mutual coupling effect.

Fig. 5 compares the performance of coupled and isolated dipoles for different arriving angle cases in terms of root-mean-squared error (RMSE) of DOA estimation. As can be seen, the coupled dipoles achieve much lower RMSE than the isolated dipoles for both $d = 0.02\lambda$ and 0.1λ . In particular, the RMSE of coupled dipoles is less than $1°$ for the incident angle $\varphi_0 \in [30°,150°]$ at $d = 0.1\lambda$, and less than $2°$ for the impinging angle $\varphi_0 \in [50°,130°]$ at $d = 0.02\lambda$. This means that high DOA estimation accuracy can be achieved by very closely spaced dipoles if the mutual coupling effect on the embedded patterns is appropriately included into the direction finding algorithm.

IV. CONCLUSIONS

Embedded patterns of very closely spaced dipoles are obtained by electromagnetic simulation. The embedded pattern diversity is utilized to greatly improve the DOA estimation accuracy by incorporating the difference of pattern amplitude and phase into the MUSIC algorithm. Simulation results show that two coupled dipoles can achieve much higher DOA estimation accuracy than the ones without mutual coupling. At moderately high SNR condition, the root-mean-squared error can reach only 1° and 2° within a large range of arriving angle for the spacing of 0.1λ and 0.02λ, respectively.

ACKNOWLEDGMENT

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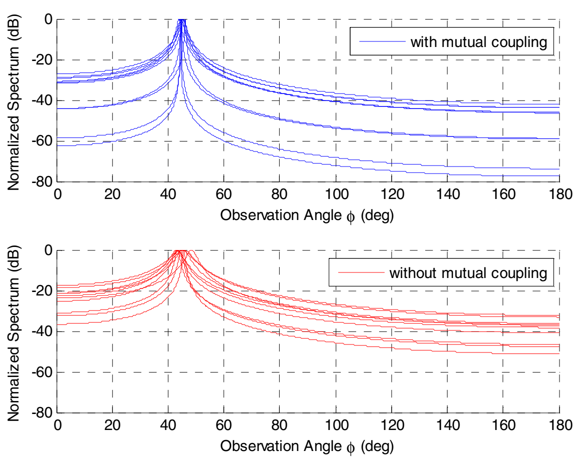
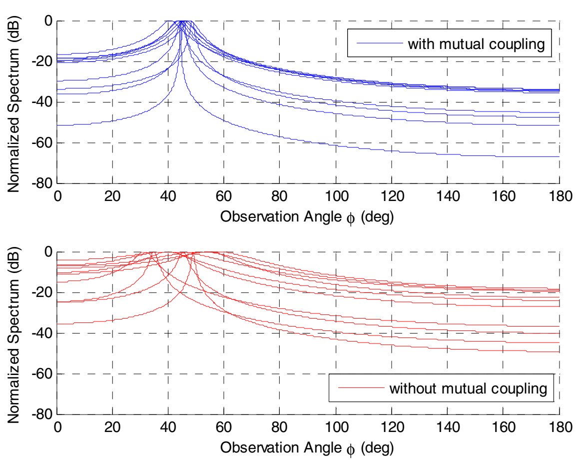
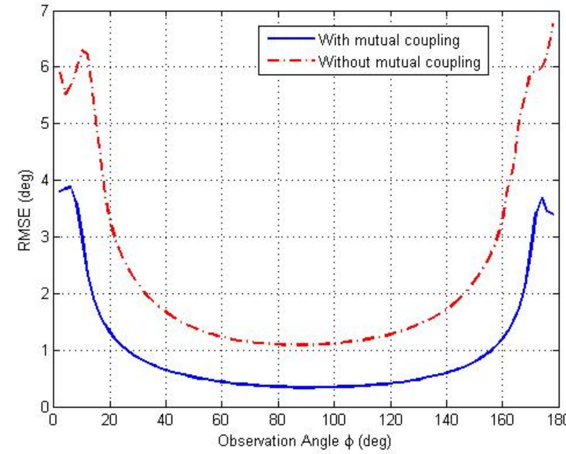


(a)

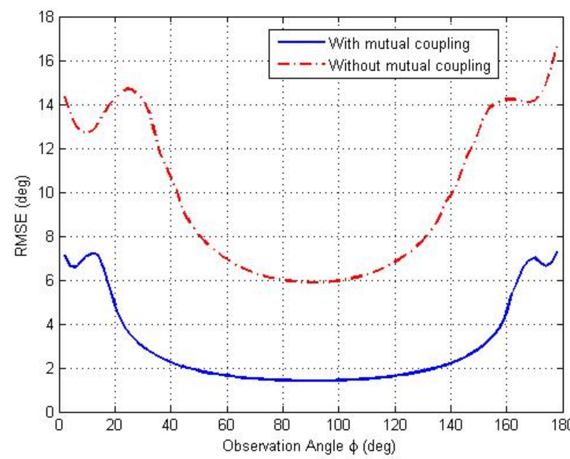


(b)

Figure 4. Normalized MUSIC spectrum of two isolated/coupled dipoles for a plane wave arriving from 45°: (a) d=0.1λ, and (b) d=0.02λ. Ten trials are performed.



(a)



(b)

Figure 5. Root-mean-squared error (RMSE) of DOA estimation for two isolated/coupled dioples: (a) d=0.1λ, and (b) d=0.02λ.

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