A Novel DOA Estimation Scheme for Ultra-Wideband Electromagnetic Waves

Akimasa Hirata and Zen Kawasaki
Department of Communications Engineering, Osaka University
E-mail: hirata@comm.eng.osaka-u.ac.jp

Abstract: We propose a novel direction-of-arrival estimation technique for ultra-wideband (UWB) electromagnetic waves, which allows for the effect of the antenna mutual coupling. This technique is comprised of a UWB interferometry, a multiple signal classification (MUSIC), and a database. The effectiveness of our scheme is demonstrated through numerical examples.

Key words: antenna array, ultra-wideband waves, impulsive electromagnetic waves, antenna mutual coupling, direction-of-arrival estimation

1. Introduction

Various techniques of direction-of-arrival (DOA) estimation for electromagnetic (EM) waves have been developed in accordance with the spread of wireless communications [1,2]. As a result, most of the DOA techniques are applicable only for static monochromatic waves. In other words, less attention has been paid to the DOA estimation for ultra-wideband (UWB) EM waves. Impulsive EM waves from electric power equipments [3] and lightning discharges [4] are typical examples of UWB waves. Their DOA estimations are important from the viewpoint of EM compatibility. The frequency spectrum of such EM waves is largely dependent on the kind of sources, temperature, humidity and so forth [3,4]. Therefore, sufficient intensity of EM waves could not be always obtained by using conventional monochromatic approaches.

Recently, much attention has been paid to the compensation of the effect of antenna mutual coupling. It is well known that adaptive nulling is significantly affected by the existence of the mutual coupling effect between the antennas [5,6]. Note that these attempts have been done for static monochromatic waves. For a class of EM waves with a UWB spectrum, mutual coupling between antennas would be more significant, especially at the lower frequency band, leading to an obvious error in DOA estimations. In [7], we have proposed a DOA estimation technique for UWB EM waves, which is comprised of a UWB interferometry [8], the multiple signal classification (MUSIC) [1], and two databases [9]. In this paper, we propose an improved DOA estimation scheme, which is more efficient than that in our previous paper [7].

2. Signal Processing

The procedure of our signal processing is illustrated in Fig. 1. Note that an antenna array with two antennas is generalized for the DOA estimation of UWB waves. This is because the DOA estimation scheme for multiple sources is not needed unlike monochromatic waves, when we choose a proper time window. However, this procedure can be extended for antenna arrays with more than three elements.

Time-domain signals received by a wideband antenna array is transformed into the frequency domain by the fast Fourier transformation. Note that a signal processing in the frequency domain is needed to compensate the effect of the antenna mutual coupling. Then, the signal in the frequency domain is divided into two on the basis of the relation between the antenna distance $d$ and the wavelength $\lambda$. This is because eigenvector-based DOA algorithms, such as MUSIC and ESPRIT [1,2], are applicable only when the antenna distance $d$ is less than $\lambda/2$. Thus, for the Fourier frequency components, which satisfy the above condition, the Root-MUSIC is used [9] because of its reasonable computational load. In order to compensate the effect of the mutual coupling of the antennas, the calibration schemes proposed in [10] for the MUSIC is extended to the Root-MUSIC. Then, the equation to be solved is given by the following equation:

\[
\mathbf{A}(\theta, f_m) \mathbf{E}_N(f_m) \mathbf{E}_N^H(f_m) \mathbf{A}(\theta, f_m) = 0
\]

\[
\mathbf{A}(\theta, f_m) = \mathbf{C}(f_m) \mathbf{a}(\theta, f_m)
\]

\[
\mathbf{a}(\theta, f_m) = \left[1, \exp(-j2\pi f_m d \cos \theta / c)\right]^T
\]

where $\theta$, $c$, $\mathbf{C}$, and $\mathbf{E}_N$ denote the angle of incidence, the speed of light in vacuum, a matrix for the compensation of antenna mutual coupling, and a set of eigenvectors, which belong to a noise subspace. Note also that subscription $m$ corresponds to Fourier components. This calibration scheme modifies not the amplitude of the received signal [5] but the
MUSIC spectrum itself, and thus more essential calibration is realized. Additionally, \( C(f_a) \) is little affected by the angle of incidence. Then, one of the two databases used in [7] is not needed in this scheme.

For the other Fourier components, a UWB interferometry is used [8]. It should be noted that a database is used to compensate the error of the phase difference due to the antenna mutual coupling for the DOAs [9]. Note also that this database has the relation between the angle of incidence and the estimated DOA over the above frequency band.

A proper DOA of a UWB wave should be determined from the DOAs estimated at Fourier frequencies. For this purpose, a weighting function derived on the basis of the intensities of Fourier components is introduced [4]. The accuracy of DOAs estimated by the Root-MUSIC and the UWB interferometry is dependent on the SNR and \( \lambda/d \) [11]. For the Root-MUSIC, the dependency of estimation error on the SNR and \( \lambda/d \) is illustrated in Fig.2, as an example. Thus, the weighting function at each Fourier frequency is defined in terms of them. Note that the effect of the angle of incidence on the DOA estimation is smaller than the above factors. In this paper, we neglect this effect for the sake of simplicity.

Figure 3 illustrates the geometry of the problem. The antenna array on the perfect conductor is comprised of two circular plate antennas. The diameter of the plate is 0.3 m. The distance between the antennas is 2.0 m. The frequency band we pay attention is from 50-150 MHz. The ratio of the bandwidth to the center frequency is 100 %. It should be noted that the antenna distance is determined so that the radiation resistance of the antenna is not so degraded due to the mutual coupling effect [12]. Note also that the circular plate antenna is commonly used for lightning observation, because of relatively broadband characteristics and omni-directional radiation pattern on the horizontal plane. The return loss of this antenna depends on the frequency of EM waves (mostly better than 3dB over the above frequency band). In addition, the geometry without any sharp edge is fairly suitable in the operation under the circumstance with high voltage due to lightning activity [13]. For an incidence of an UWB wave, induced EM fields are calculated by the Finite-Difference Time Domain (FDTD) method [14,15]. Then, the effect of the antenna mutual coupling can be taken into account by calculating the mutual impedance as pre-processing.

Fig.1 Proposed Signal Processing Scheme.

Fig.2 Dependence of estimation error on SNR.

(a) (b)

Fig.3 Geometry of problem: (a) top view, and (b) side view.

3. Antenna Modeling
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Fig. 4. The dependence of estimated DOA on the angle of incidence (without compensation).

Fig. 5. The frequency dependence of estimated DOA and SNR.

4. Numerical Results

Figure 4 shows the estimated DOA with the UWB interferometry for incidences of a far-field EM pulse. Note that no compensation has been applied. As seen from this figure, the difference between the angle of incidence and an estimated DOA is larger at lower frequency and for lower angle of incidence. These are caused by the mutual coupling of antennas. Note that these correspondences between the angle of incidence and the estimated DOA are stored as the database (See Fig. 1). Also, at the frequency band lower than 75 MHz, the matrix \( C \) to compensate the mutual coupling in the Root-MUSIC is calculated and stored (See Eq. (1)).

Figure 5 demonstrates the effectiveness of our algorithm when white Gaussian noise exists. This figure also shows the signal-to-noise ratio (SNR) for the received signal at each Fourier component. The angle of incidence is 45°. As is expected, the DOA estimated at the Fourier component with larger SNR is close to the exact angle of incidence (at 75MHz and 140MHz). Note that the difference between the angle of incidence and the estimated angle at 100MHz is up to 20°. However, the value of weighting function at this Fourier component is almost zero due to its extremely low SNR. Then, the estimated DOA with the use of the weighting function was found to be 44.5°. It is worth pointing out again that the estimation error comes from two causes. One is caused by the dependency of the estimation accuracy on the SNR and \( \delta \alpha \) as shown in Fig. 2. The other is the error involved in the coupling matrix \( C \). According to \[10\], the estimation error caused by this is up to 1° for \( \delta \alpha \sim 0.5 \). Taking into account these factors, the obtained results are reasonable.

5. Summary

In this paper, we proposed an improved DOA estimation technique for UWB waves, which taken into account the effect of the antenna mutual coupling. This technique was comprised of the UWB interferometry, the Root-MUSIC, and the database. In order to validate our proposal, a numerical example was considered. For the UWB wave with the maximum SNR of 5 dB, the estimation error was at most 0.5°. It is noteworthy that this algorithm can be accelerated especially when some Fourier components have sufficient SNR. Such acceleration would be desirable to real-time lightning observation. The detailed account for this will be presented at the conference.

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