ESTIMATION OF EM SOURCE LOCATION IN URBAN AREA BY USING RAY-TRACING METHOD AND MUSIC ALGORITHM

Toshizo Nogami  Qiang Chen  and  Kunio Sawaya
Graduate School of Engineering, Tohoku University
Email:noga@sawaya.ecei.tohoku.ac.jp

Abstract: A novel method to estimate the source location of electromagnetic (EM) waves in complicated multipath environment such as the urban areas is proposed. The method is based on the database created by using the ray-tracing method as well as the direction-of-arrival (DOA) estimation by using the multiple signal classification (MUSIC) algorithm. Results of numerical simulation and experiment are shown to demonstrate the validity of the proposed method.

Key words: MUSIC algorithm, direction of arrival, ray tracing, electromagnetic scattering

1. Introduction

With the rapid development of the wireless communication systems, problems due to the illegal radio stations are becoming more and more serious. They cause the damage to the sensitive electronics devices such as medical equipment and the radio interference and jamming to the general radio communication or the public broadcasting systems. Strict regulations against those illegal radio stations have been made and the Ministry of Public Management, Home Affairs, Posts and Telecommunications has taken some measures to monitor these illegal radio stations by Detect Unlicensed Radio Stations (DEURAS) system. The DEURAS searches for the locations of the illegal sources by detecting the direction of radio emissions from these illegal radio stations. In order to improve the accuracy of the location estimation, conventional techniques for the direction-of-arrival (DOA) estimation with antenna arrays, such as MUSIC algorithm [1], estimation of signal parameters via rotational invariance techniques (ESPRIT) [2], or method of direction estimation (MODE) [3], have been applied. However, in the complicated multipath environment such as the urban areas, it seems difficult to determine the positions of radio stations accurately by using the DOA estimation with these approaches.

In this paper, a novel method for estimation of the source location of the electromagnetic wave is proposed. This method includes two process, i.e., the measurement of “Forward Receiving Pattern (FRP)” and the calculation of “Backward Receiving Pattern (BRP)". The source location can be estimated from the information of FRP and BRP. Results of numerical simulation and experiment are shown to demonstrate the validity of the proposed method.

2. Estimation method

The numerical simulation is performed with a two-dimensional (2D) approximation based on the assumption that the buildings are much higher compared to the height of the source and the receiver for detection. In the 2D model, the dominant paths of the electromagnetic wave radiated by the source are within the horizontal plane including in the source and receiver, and the effect of the height of the buildings on the wave propagation is neglected. The radiation pattern of the source of the target to be searched for is assumed to be isotropic in the horizontal plane. Additionally, the geometry and locations of all buildings to be concerned are known.

The proposed method is composed of the following three steps.

2.1 Measurement of FRP

In the first step, the receiving power of the field radiated from the source is measured at one observation point as a function of the azimuth angle. The function of the receiving power pattern is referred as “Forward Receiving Pattern (FRP).” Resolution with respect to the azimuth angle can be improved by using array antennas with high directivity or the MUSIC algorithm which is based on eigen-structure and well known as the high-resolution direction finding method.

2.2 Calculation of BRP

In the second step, the received powers at estimation points in the area where EM source may exist are evaluated by the numerical analysis, when the transmitter with high directivity is located at the same position of the observation point at step 1. Receiving power patterns are calculated, and these patterns are referred as the “Backward Receiving Pattern (BRP).” Since the location of the EM source is determined among the estimation points where the BRP’s are calculated in the third step, the BRP’s should be evaluated at many positions to form a database in advance. In this database, lots of the BRP in the area where the EM source may exist are recorded.

Although the Method of Moments (MoM) [4] and Finite Difference Time Domain (FDTD) method [5] are effective methods in evaluating the EM field distribution in the multi-path environment, these techniques require too much computer memory and CPU time in the case of electrically large analysis.
region such as the urban areas at microwave band. Since the sizes of buildings and distance between the source and observation point are much larger than the wavelength, the BRP's are evaluated by the technique based on the ray tracing method based on the uniform geometrical theory of diffraction (UTD) [6] where the diffraction at the vertical edges of the buildings is involved. The ray tracing method is based on the high frequency approximation and is widely used for many problems including the propagation in mobile communications. [7]

2.3 Comparison between BRP and FRP

In the third step, the values of the BRP within the area where the EM source may be located are compared with the FRP. The position with the strongest correlation between the BRP and FRP is considered to be the possible location of the EM source. The correlation coefficient between BRP and FRP is given by

\[ f_{EV}(\hat{\mathbf{r}}) = \int \frac{(P_B(\phi, \hat{\mathbf{r}}) - \bar{P}_B(\hat{\mathbf{r}}))(P_F(\phi, \hat{\mathbf{r}}) - \bar{P}_F(\hat{\mathbf{r}}))}{\sigma_{P_B}(\hat{\mathbf{r}})\sigma_{P_F}(\hat{\mathbf{r}})} d\phi \]

where \( P_B \) and \( P_F \) denote the BRP and the FRP, respectively, \( \bar{P}_B, \bar{P}_F \) and \( \sigma_{P_B}, \sigma_{P_F} \) are the average and the standard deviations of \( P_B, P_F \) with respect to the azimuth angle \( \phi \), respectively.

By using the method described above, the possible locations of the EM source can be found. However, in the practical cases, it is usually difficult to determine where the real location of the EM source is because several locations having high correlation coefficient may be found. This problem can be solved by repeating the above steps at several observation points.

3. Numerical simulations

In order to show the performance of the proposed method for the estimation of the source location, a computer simulation is performed. In the simulation, the values of FRP at step 1 are evaluated by the 2D ray tracing method and the UTD method instead of the measurement.

![Fig. 1. Receiving planar array for numerical simulation.](image)

Fig. 1 shows the \( 6 \times 6 \) receiving dipole array antenna. The length of the elements and spacing between elements are both 0.4167λ. Since it is difficult to distinguish the correlative multiple waves by the conventional MUSIC algorithm, the spatial smoothing pre-processing (SSP) technique with \( 3 \times 3 \) subarrays is applied as the pre-processing of MUSIC algorithm. The SNR is assumed to be 20dB and the number of snapshots is 100. The ray launching technique is applied as the ray tracing method to calculate the BRP. The scattering buildings are assumed to be perfect conductors. The number of the scattered waves is limited by the following rules to save the CPU time. The reflection by the vertical walls is limited to be less than five times based on the assumption that there are no scatterers outside the analysis area and only a few reflected rays contribute in the limited area. The first order diffraction at the vertical edges is considered while the higher order diffraction is neglected. In the ray launching method, the aperture of receiving antenna is assumed to have a spherical shape with a variable radius.

![Fig. 2. Site of estimated environment.](image)

The simulation model is shown in Fig. 2, which is based on the geometry on the roof of a building in Tohoku University. There is a large room with concrete structure on the center of the roof which is sufficiently tall compared with the wavelength, and ten exterior units of air-conditioners, which is higher than 3 m, are located on the right side of the roof. There are a few other scatterers around them. Dimension of all scatterers are quite large compared with the wavelength of 15 cm. The positions of the wave source and four observation points are shown in Fig. 2.

FRP's are calculated at four observation points, whereas the BRP's are calculated at the centers of \( 100 \times 100 \) cells in the area of 50m × 50m shown in Fig. 2 and the correlation coefficients between FRP and BRP are evaluated at each cell.
4. Experiments

An experiment was carried out at frequency of 2GHz in the site shown in Fig. 2. The transmitting antenna was fixed at height of 95 cm above the ground, and the receiving array antenna was located 90 cm in height. A 6-element linear monopole array antenna was employed as the receiving antenna and was scanned six times along the broadside direction to form an equivalent $6 \times 6$ planar array antenna.

Fig. 3 shows the experimental setup for the measurement. The signal generated by a signal generator was amplified by an RF amplifier and transmitted by a dipole antenna. The amplitude and the phase of the electric field observed at each antenna element was measured by the network analyzer. The number of snapshots was 16 and the dynamic range of the measurements is around 20dB. In order to remove the influence of the mutual coupling among array elements, the coupling compensation was performed [8]. The SSP was also applied as pre-processing of MUSIC algorithm, because there are high correlations among the direct wave and scattered waves. The processing is implemented with $3 \times 3$ subarrays as the numerical simulations. Finally, the MUSIC algorithm was applied to the compensated signals to evaluate the FRP at the observation point.

5. Results

5.1 Numerical results

Results of the numerical simulation of the correlation coefficients are shown in Fig. 4, where (a), (b), (c) and (d) are the results by the FRP obtained at the receiving points Rx1, Rx2, Rx3 and Rx4 respectively, and (e) shows the superposition of these four cases. The black color corresponds to low correlation while the white means high correlation which means the high possibility of the presence of the EM source from Fig. 4 (a)-(d), the high correlation coefficients are observed on the lines connecting the EM source and the observation points. In Fig. 4 (e), it is clear that the possible points are found around the actual position of the EM source.

5.2 Experimental results

The experimental results are shown in Fig. 5. These results are similar to the numerical simulation. The difference is caused by the difference between the simulation model and the experiment model. For example, the experimental scatterers have rough surfaces and finite conductivity, whereas those in the simulation model have smooth surface and infinite conductivity. Furthermore, there are some errors among the experimental and the simulation models of the scatterers such as the positions and the geometry. Although some discrepancies mentioned above are observed, experimental results shown by the white area including the actual position of the source.

6. Conclusion

A novel method based on the DOA estimation by using MUSIC algorithm and the database created by the ray tracing method has been proposed to estimate the location of electromagnetic wave source. Numerical simulation and experiment are performed and the results of both numerical simulation and experiment show that the area with high the correlation coefficients between the FRP and the BRP includes the actual source demonstrating the validity of the proposed method. By using the proposed method, the illegal radio stations in urban areas can be found accurately in the multi-path environment.

References

Fig. 4. Correlation efficient between FRP obtained by simulated receiving signals and BRP on each cell.

Fig. 5. Correlation efficient between FRP obtained by measured receiving signals and BRP on each cell.