Study on the Effect of Radiation Pattern on the Field Coverage in Rectangular Tunnel by FDTD method and Point Source Array Approximation

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***Abstract*-In this paper, the effect of radiation performance of antenna array in confined space on the field coverage is analyzed. In order to find the suitable radiation pattern that can give smoother wave coverage in confined space, a simple but efficient numerical method based on the parallel FDTD method and point source array approximation is presented. The current on each array element is obtained from the desired radiation pattern using synthesis method. This current distribution is then set to the FDTD mesh as the excitation. By this method, field coverage of three kinds of antennas with different radiation patterns in a rectangular tunnel is analyzed. The results show that the antenna with narrower beam width can give smoother field coverage in the tunnel.**

I. INTRODUCTION

With the rapid development of mobile communication, the prediction of the wave propagation and field coverage of the wireless link becomes an important work, especially for the case of confined space. Confined space is defined as one kind of regions with known physical boundaries, such as tunnels, mines, etc. Usually, there are blind zones of wireless communication in these regions and the overall communication quality is not satisfying, because the wave propagation in tunnel environment is very complicate, so antennas with simple radiation patterns can not ensure the overall quality of the wireless communication in confined area. Therefore, antennas with special radiation pattern that is 'suitable' for field coverage in tunnel-like confined space are preferable.

It is a common way to obtain the actual field coverage of a wireless communication system by measurement. But measurement is an expensive and time consuming way, and it still cannot give the overall property of field coverage of some real systems [1]-[2]. Unlike measurement, full wave methods, such as the finite-difference time-domain (FDTD) technique, can not only provide the accurate result of field coverage but also provide the effect insight of environments on the field distribution, especially for the case of complicated environment in confined area. Based on FDTD, an Integrative Modeling Method (IMM) was proposed in [3], in which the whole RF link including the antennas and their environments is integratively modeled and simulated. Of course, the increasing capacity of storage and computing resources also make it possible for FDTD to simulate large-scale problems.

However, if practical antenna structures are considered in the FDTD mesh together with the complicated tunnel environment, much higher spatial resolution is needed to accurately simulate the small geometrical features of the antenna. As a result, the computation time and the memory requirements will be increased significant if uniform mesh scheme is still used. Certainly, it is possible to combine the FDTD with other numerical schemes, such as the frequency-domain method of moments (FD-MoM) to increase the numerical efficiency [4]. Also hybrid technique based on the surface equivalence theorem can also be used to solve the multi-scale problem [5]. These methods although reduce the computation load in some extension, it introduces other difficulties in combining of different methods. The objective of this paper is looking for the 'suitable' radiation pattern (the first step of actual antenna design) which can give smoother field coverage in tunnels. A technique combined FDTD with antenna array synthesis is presented in this paper, in which the antenna array is composed of a series of current elements with freedom parameters of current amplitude and phase, and the element length occupies only one grid of FDTD mesh discretized in terms of the environment scale. After the 'suitable' pattern is obtained, the real antenna or antenna array structure can be optimized to get an actual radiation pattern that closes to the 'suitable' pattern.

II. DESCRIPTION OF THE NUMERICAL METHOD

In the field coverage evaluation of confined space, FDTD method is widely used [6]-[7]. However, as already mentioned, these approaches have to face the challenges of density mesh and long iterative time, because fine FDTD mesh should be used in modeling the practical antenna structures. On the other hand, in order to obtain the 'suitable' pattern for confined space application, different patterns should be introduced into FDTD computing domain for numerical experiment. But how to introduce these patterns is also a problem to solve.

To overcome these problems, method for simulating the propagation environment and practical antenna has been proposed [5]. But additional implementation cost is required to simulate the antenna and propagation environment separately. This method can only reflect the effect of a specific antenna but is not suitable for simulation the effect of different radiation patterns on the field coverage. In order to reduce the complexity of the calculation, instead of using real antennas, infinitesimal dipoles (point sources) are used as transmitting and receiving antennas in [8]. However, the utilization of point sources is not easy to study the effect of different radiation patterns on the field coverage. In this paper, point source array is used, so not only the computation complexity is reduced but also the desired radiation patterns are easily obtained by adjusting the amplitude and phase of the feeding current on each array element (current element). Two steps should be done in this method: 1) the amplitudes and phases of array elements are obtained according to desired pattern by synthesizing method; 2) take this antenna array as the excitation of FDTD to get the actual field distribution in confined space.

A. Source design

As mentioned, in order to reduce the number of FDTD mesh grids, a point source array is employed to obtain the desired far-field pattern. This array is composed of a series of current elements with freedom parameters of current amplitude and phase, and the element length occupies only one grid of FDTD mesh discretized in terms of the environment scale. By synthesizing the phases and amplitudes of the current elements, the point source array can generate the required far-field pattern. It's worth to mention that although the impedances of point source array may have big difference with the realistic antenna array, the radiation pattern which is mainly relates to current distribution of array is coinciding to that of the realistic antenna array. Therefore, this point source approximation can meet the accuracy requirements of the radiation pattern simulation if the amplitudes and phases are set reasonably.

B. Parallel FDTD technique

In order to shorten the computation time, parallel FDTD technique is used in this paper. MPI (Message Passing Interface), as an important standard of message transmission, is widely used in many fields of science computation. Combining MPI with FDTD to realize parallel computation has been proven to be an efficient way in improving the computing speed. The parallel algorithm of FDTD utilizes a one-cell overlap region to exchange the information between adjacent sub-domains, as shown in Fig. 1. The iteration formulas are given by (1) and (2). In the algorithm, only the tangential magnetic fields are exchanged at each time step as shown in Fig. 1 [9].

$$E_z^{n+1,\,processor1}(i,j,k+\tfrac{1}{2}) = \frac{\varepsilon_z - 0.5\sigma_z\Delta t}{\varepsilon_z + 0.5\sigma_z\Delta t}E_z^n(i,j,k+\tfrac{1}{2}) + \frac{1}{\varepsilon_z + 0.5\sigma_z\Delta t}\left[\frac{H_y^{n+\frac{1}{2}}(i+\frac{1}{2},j,k+\frac{1}{2}) - H_{y1}^{n+\frac{1}{2},\,processor2}}{0.5[\Delta x(i)+\Delta x(i-1)]}\right] - \frac{1}{\varepsilon_z + 0.5\sigma_z\Delta t}\left[\frac{H_x^{n+\frac{1}{2}}(i,j+\frac{1}{2},k+\frac{1}{2}) - H_x^{n+\frac{1}{2}}(i,j-\frac{1}{2},k+\frac{1}{2})}{0.5[\Delta y(j)+\Delta y(j-1)]}\right] \quad (1)$$

$$E_z^{n+1,\,processor2}(i,j,k+\tfrac{1}{2}) = \frac{\varepsilon_z - 0.5\sigma_z\Delta t}{\varepsilon_z + 0.5\sigma_z\Delta t}E_z^n(i,j,k+\tfrac{1}{2}) + \frac{1}{\varepsilon_z + 0.5\sigma_z\Delta t}\left[\frac{H_{y2}^{n+\frac{1}{2},\,processor1} - H_y^{n+\frac{1}{2}}(i-\frac{1}{2},j,k+\frac{1}{2})}{0.5[\Delta x(i)+\Delta x(i-1)]}\right] - \frac{1}{\varepsilon_z + 0.5\sigma_z\Delta t}\left[\frac{H_x^{n+\frac{1}{2}}(i,j+\frac{1}{2},k+\frac{1}{2}) - H_x^{n+\frac{1}{2}}(i,j-\frac{1}{2},k+\frac{1}{2})}{0.5[\Delta y(j)+\Delta y(j-1)]}\right] \quad (2)$$

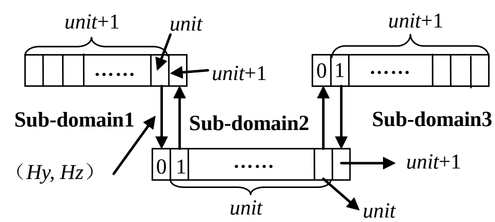

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Figure 1. Diagram of parallel FDTD for 1D case in *x*-direction

C. Path loss calculation

Assuming that the wave is in linear polarization, the equations for the power calculation from field of one point source are expressed by (3) and (4), where Z_0 is the wave impedance in vacuum. During the FDTD simulation, the E_z component for vertical polarization case is recorded. However, when there is more than one single source, the mutual coupling between the sources is significant, and the transmitter power of the array cannot be calculated use this simply equation again. We have to compute the integral of flux density on the surface surrounding the source array to get the complete transmitting power, as expressed by (5), where E_h and H_h are the tangential electric and magnetic fields

$$P_t = \frac{2\pi}{3}Z_0 I^2\left(\frac{L}{\lambda}\right)^2 \quad (3)$$

$$P_r = \frac{3\lambda^2}{8\pi Z_0}E^2\sin^2\theta \quad (4)$$

$$P_t = \oint_s \vec{E}_h \times \vec{H}_h \cdot \hat{n}\,ds \quad (5)$$

Using (4) and (5), the path loss can be calculated by

$$Path\ Loss = P_r / P_t \quad (6)$$

III. RESULTS AND ANALYSIS

The radiation patterns of the point source arrays are given in Fig. 2 and Fig. 3. The radiation pattern marked with blue line is generated by a planar array with 5×6 elements (5 in *z*-direction and 6 in *y*-direction) denoted by array 1. The array elements are excited in phase and with the same amplitude**,** a distance of half wave length is set between elements. The originations of the elements are in *z*-direction. This array is a broadside array and its main beam is pointing to the *x*-axis. In order to focus the energy to the positive direction of *x*-axis, a reflector plate is placed behind the array. Array 2 is a 8×4 planar array (8 in *x*-direction and 4 in *y*-direction) with element spaces of a quarter wave length in *x*-direction and half wave length in *y*-direction. The originations of the elements are in *z*-direction. The phase difference of current between elements in *x*-direction is $\pi/2$, and the amplitudes are the same. So the array is an end-fire array and its main beam is wider.

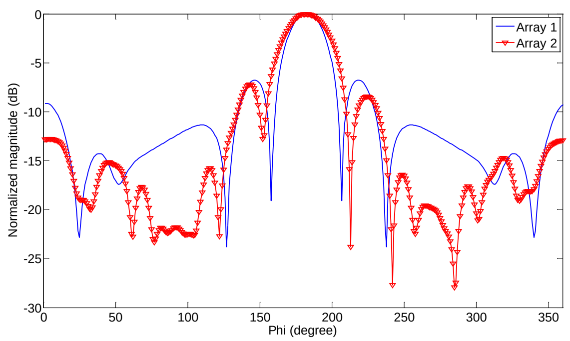


Figure 2. Radiation pattern of the transmitting antennas in H-plane (theta=90)

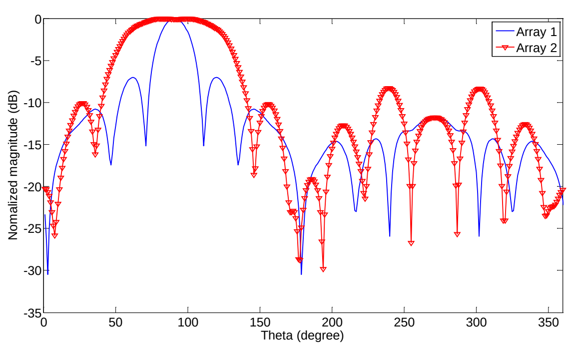


Figure 3. Radiation pattern of the transmitting antennas in E-plane (phi=0)

FDTD simulation is carried out in 3D for antenna arrays radiating in a rectangular tunnel with of 6×6 m^2 cross section and 200 m in length. The operating frequency is 900 MHz. Cell sizes of $dx = dy = dz$ = 33 mm and $dx = dy = dz$ = 27.75 mm are used in the simulations for array 1 and array 2 respectively. An eight-cell PML is used to truncate the simulation domain. The relative permittivity and conductivity of the tunnel wall is 6.8 and 3.4×10^{-2} S/m respectively, which is similar to the value of actual tunnel. The tunnel wall is set to 0.5 m in depth. The parallel computing program utilizes 96 processes.

The path loss of the wave in the tunnel generated respectively by the two arrays comparing with that from a dipole is shown in Fig. 4. From Fig. 4 we can see that the broadside antenna array with narrower beam has better radio transmission characteristic in tunnel, it is superior to that of omni-directional antenna. This is because that the radiation energy of directional antenna is more concentrated on the tunnel axis compared to the omni-directional antenna. So the reflected wave from the nearby tunnel walls (the nearby region of the antenna) is weak. If the radiation beam is wider, then most of the energy is reflected by the nearby tunnel walls, and significant multi-path effect occurs, which further results in a significant path loss.

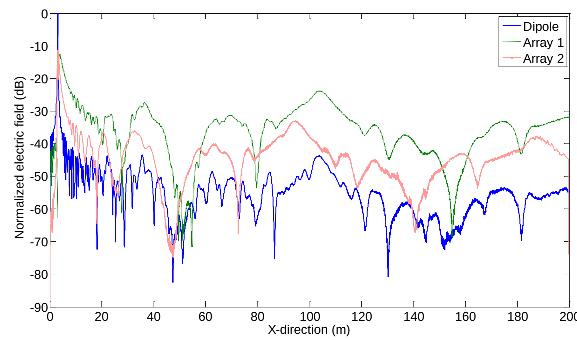


Figure 4. Path loss in the rectangular tunnel for different transmitting antennas

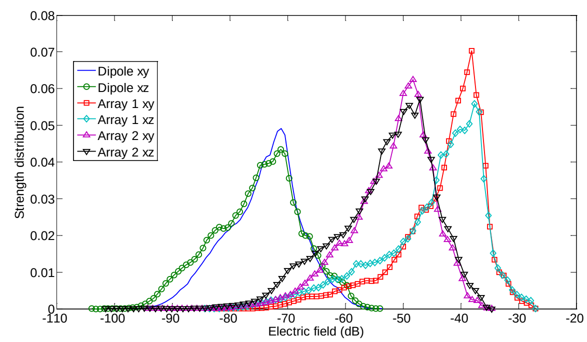


Figure 5. Field strength distribution

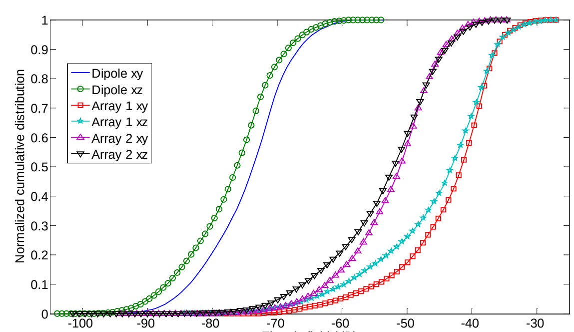
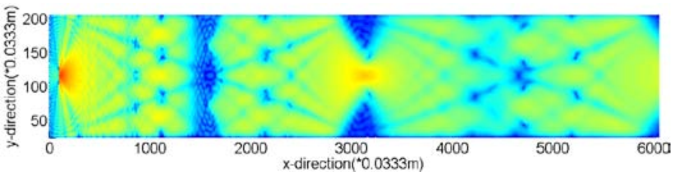
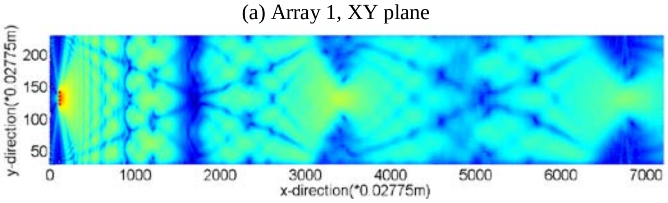


Figure 6. Field strength cumulative distribution

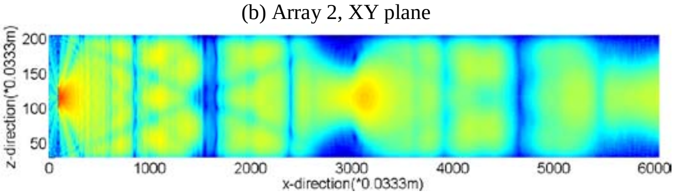
Fig. 7 gives the intensity distribution of electric field in the tunnel. It can be clearly seen the formation of strength and weak regions in the propagation of electromagnetic wave. To get a better communication quality, radio coverage in tunnel should be as uniform as possible. In order to evaluate the uniformity of field coverage, concept of field deviation is proposed, which gives the difference between the field value of each test point and the average of field values of all the test points. Fig. 5 and 6 show the field distribution and field cumulative distribution respectively. From Fig. 5, we can conclude that antenna with narrower beam can give narrower intensity distribution curve and steeper slope of the cumulative distribution curve, which indicates that a better uniformity of the field strength can be get.



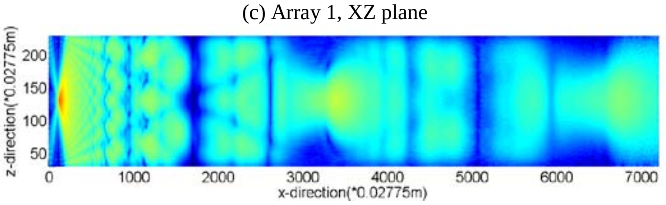
(a) Array 1, XY plane



(b) Array 2, XY plane



(c) Array 1, XZ plane



(d) Array 2, XZ plane

Figure 7. Electric field distributions in the cross sections of the tunnel for different antenna array

CONCLUSION

In this paper, point source array is used to approximately but effectively study the influence of different radiation patterns on the field coverage characteristics in a rectangular tunnel. The field intensity distributions in a tunnel excited by arrays with different radiation patterns are analyzed. From the results, it is concluded that directional antenna can give better field uniformity in a long straight tunnel.

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