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EM Wave Propagation in Non-uniform Soil

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Abstract: As an emerging research field, Wireless Underground Sensor Network (WUSN) is getting more and more focused these years because of its tremendous application benefit in agriculture, industry, military and so on. As the determinant of the performance of WUSN, the propagation characteristics of electromagnetic (EM) wave in the soil must be deeply investigated. Usually the soil is assumed ideal and uniform in existing works which results in a non-ignorable discrepancy to the reality of underground propagation. In this study, the propagation of EM wave in non-uniform soil is theoretically analyzed. Moreover, a novel simulation method for it based on Kriging interpolation and ADI-FDTD is proposed, based on which the propagation of 300 MHz EM wave in non-uniform soil is simulated and analyzed. The results expose the striking impact of non-homogeneity of the soil to the underground EM wave propagation performance which must be seriously taken into account when design and construct WUSNs.

Key words: FDTD, Kriging interpolation, non-uniform soil, EM wave propagation, WUSN

INTRODUCTION

Wireless Underground Sensor Network (WUSN) (Akyildiz and Stuntebeck, 2006) denotes the wireless sensor network in which the majority nodes are buried below the ground. WUSN can be applied in various scenarios to monitor conditions or collect information. For example, it can be deployed under the farmland to monitor the situation of the soil, facilitating irrigation, fertilization and other agriculture activities, as well as detect the variation of toxic substances in the soil, beneficial to environment protection. It can also be used to monitor geologic activities, improve the veracity of forecast of some geological disaster such as earthquake. Besides such civil uses, WUSN can even be applied to military usage, such as border patrol and security monitoring. Because of the splendid application prospect, WUSN has received a lot of attentions in recent years.

What differentiates WUSN from ordinary WSN, as well as makes it a difficult mission to research and develop is the underground environment, where the wireless signal propagates in soil instead of in the air. The replacement of medium brings notable challenges for WUSN. First, in soil, EM wave attenuates much more rapidly which results in a limited communication range between each two of the nodes in WUSN. Second, the ground surface acts as a boundary of the two medium. For near surface applications which construct the majority of

the applications of WUSN, the influence from the ground surface can't be neglected. Furthermore, another important factor is that the situation of the soil is much far from ideal. The soil is normally non-uniform and its dielectric parameters can vary among a large range in a certain area. Furthermore, some obstacles like stone, tree root, insect and cave usually exist in soil which increases the complexity of the underground situation. The complex of the soil obviously leads to the complicity of underground wireless communication.

There has been some work focusing on the underground communications and the characteristics of signal propagation in the soil. Li *et al.* (2007) propose a channel model for far-from-ground area in the soil based on the comprehensive investigate to the characteristics of underground environment. Akyildiz *et al.* (2009) extend it, making the description more detailed and make up some simulation results. The empirical work by Stuntebeck *et al.* (2006) verifies the limitation of terrestrial WSN nodes applied in underground environment and Silva and Vuran (2009) and Yoon *et al.* (2011) validate the model proposed by Li *et al.* (2007) and Akyildiz *et al.* (2009). Silva and Vuran (2010) investigate the communication between both underground and aboveground devices. Sun and Akyildiz (2009) Sun and Akyildiz (2010) propose an underground communication system based on Magnetic Induction (MI) rather than EM wave. In summary, the existing works haven't pay attention to the effect of the non-uniform of

soil to the performance of underground communication, but assumed the soil is uniform in an area, weather in analysis or in empirical works.

Different from the ideal assumption in existing works, this study investigates much nearer to the authentic properties of soil and underground communications in reality. In this study, the non-uniform character of soil is investigated and simulated using micro-element method combining Kriging interpolation. The underground communication between two nodes in non-uniform soil is studied both in theoretical analysis and simulation by FDTD. The theoretical conclusion as well as the simulation results validate that the heterogeneity of soil greatly impacts on the performance of underground wireless communication which gives a considerable criterion to future design and construction of WUSN, as well as other wireless underground communication systems.

The rest of this study is organized as follows: In section 2, the characteristics of wireless underground communication is described. In section 3, the model of non-uniform soil, as well as theoretical analysis of the EM wave propagation in it is proposed. In section 4, the simulation methodology and procedure of the propagation of EM wave in non-uniform soil is described in detail. In section 5, the simulation results of the propagation are displayed and analyzed. Finally, the conclusion is given in section 6.

THE EM WAVE PROPAGATION CHARACTERISTICS OF WIRELESS UNDERGROUND COMMUNICATION

Wireless underground communication is much different from the terrestrial communication, because the medium carrying the wireless signal in WUSN is soil. The frequency used in WUSN is hundreds MHz EM wave which results from the compromise of attenuation effect which is in proportion to the frequency and the dimension of the WUSN devices, especially the dimension of the antenna which is inverse to the frequency.

The propagation of EM wave in underground environment is largely determined by the dielectric characteristic of soil which is up to the physical and chemical properties of the soil. The attenuation parameter of the EM wave which dominates the propagation performance of it, is related to the dielectric constant of the medium it traverses. And the dielectric constant of soil is determined by its composition, humidity, temperature and so on. Among the contributing factors, the Volumetric Water Content (VWC) acts the most important role. As the VWC of the soil is increasing, the attenuation parameter rises promptly and therefore the propagation is

largely crippled. The composition of the soil is also a dominant factor. Commonly, the soil is composed by sand, silt and clay and is categorized according to the specific percentages of them. As well as, the dielectric constant of soil is also related to the percentages of component materials. A model is presented by Peplinski *et al.* (1995). As the percentages of clay as well as sand increasing, the loss tangent of the soil increases and the attenuation is damaged accordingly. Furthermore, the dielectric constant of soil is related to the temperature. It increases with the temperatures increase, although the effect is much feeble compared to the former two factors discussed.

In real world, the soil is far from ideal which means the physical and chemical properties can't be uniform everywhere in a certain area. The composition, VMC and temperature of the soil can vary largely from the ground to the very deep place underground. Even on the same depth, they are hard to be exact the same value on different locations. Moreover, there are many obstacles like tree root, stones, insects, cave, pipes and so on in the soil which makes the dielectric constant of soil fluctuates further.

MODEL OF NON-UNIFORM SOIL AND THE ANALYSIS OF EM WAVE PROPAGATION IN IT

In real underground scenario, the communication media, soil, is always non-uniform, as described above. How to model it accurately greatly determines the correctness of related study and analysis. In this study, the micro-elements method is adopted to analyze the non-uniform soil. Based on this method, the model of the non-uniform soil is shown in Fig. 1.

From Fig. 1, it can be seen a part of soil is divided into many small elements, called grids in following part in this

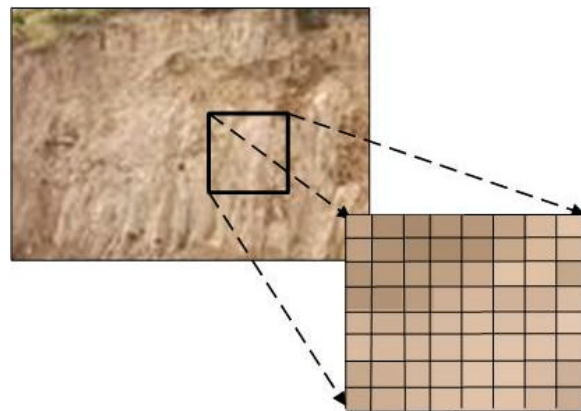


Fig. 1: Model of non-uniform soil

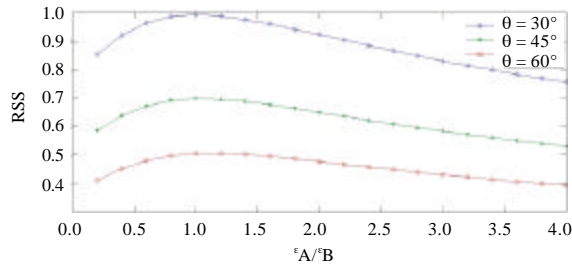


Fig. 2: Ratio of energy in grid B to grid A

study, in which the physical properties can be assumed as the same. Such model guarantees the soil model is consistent to the simulation method, FDTD which is adopted in emulating the EM wave propagation in section 4.

Based on the above soil model, the analysis is begun from the very simple case, in which only two adjacent grids are considered. It is assumed that an EM wave transfers from grid A to grid B. Because the dielectric parameters of these two grids are different, reflection happens on the boundary.

The ratio of the energies in grid B to grid A can be drawn by the MATLAB which is depicted in Fig. 2.

From Fig. 2, the conclusion can be drawn that when the incident angle changes from 0-90°, the maximum of the energy ratio can be reached when the ratio of the permittivity of the adjacent grids is about 1. It means for the case of the two values of permittivity in the two adjacent grids are about equal which stands for the case of $\epsilon_1 = \epsilon_2$, the energy incident into grid B achieves the maximum, regardless of the value of the incident phase. What's more, for the case that the incident angle is equal to 90°, the electromagnetic wave totally propagates into the next grid and the energy of the incident wave entering into grid B reaches the maximum.

For the case of the values of permittivity in the two adjacent grids vary greatly which means the case of $\epsilon_1 \ll \epsilon_2$ and $\epsilon_1 \gg \epsilon_2$, the conclusion can be seen from the simulation results that the greater the variation of permittivity of the adjacent grids, the attenuation of the signal gets more serious. That's the reason why the attenuation in non-uniform soil is more serious than that in uniform soil.

The influence on arriving time of electromagnetic wave when propagating in the non-uniform soil must be taken into consideration. When an EM wave reaches to the boundary of the two media which has different values of permittivity, the wave must be reflected and refracted. Therefore, the path of EM wave propagating in the grids will be largely lengthened. Consequently, the total path as

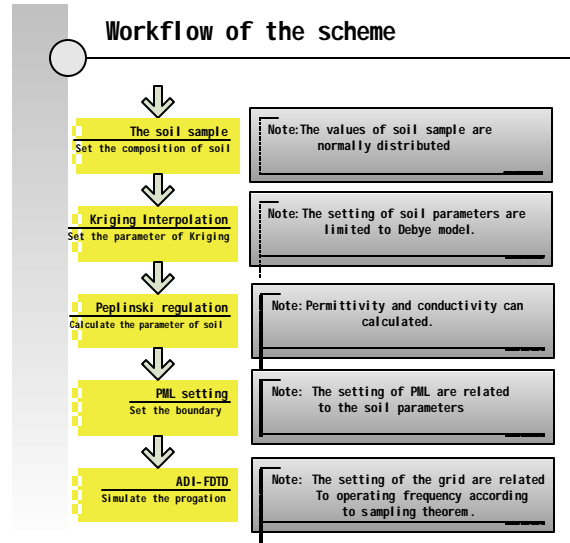


Fig. 3: Simulation workflow of EM wave propagation in non-uniform soil

well as the phase angle of the electromagnetic wave from the transmitter to the receiver will be increased in a large degree.

SIMULATION METHODOLOGY AND PROCEDURE OF EM WAVE PROPAGATION IN NON-UNIFORM SOIL

On the basis of soil model proposed above, the simulation of hundreds MHz EM wave propagating in non-uniform soil is executed using Kriging interpolation and ADI-FDTD. The workflow of the simulation of EM wave propagation in non-uniform soil is shown in Fig. 3.

Soil sample and kriging interpolation: Based on the above micro-element method, non-uniform soil can be modeled by Kriging interpolation. Assume a part of soil is divided into many grids, as shown in Fig. 4. The dielectric physical properties of some of them are known as well as that of others are unknown. The permittivity of the grids marked with \checkmark is known and those marked with $?$ is unknown. The grids marked with \checkmark are sampled from all of the grids according to the normal distributions.

The dielectric properties of unknown grids are calculated by Kriging interpolation which uses the spatial relationship of known points and their distribution around an unknown point to calculate the value of it. It is a statistical, unbiased and minimum variance estimator in which errors can be determined at specified points. The accuracy of Kriging interpolation methods for spatially

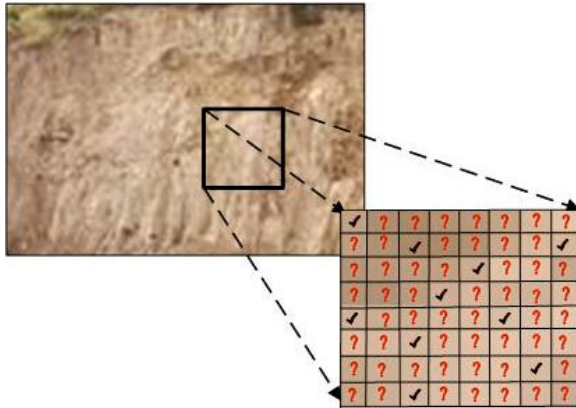


Fig. 4: Known and unknown grids

predicting soil properties has been analyzed in several studys. The ordinary Kriging interpolation for soil property is found more successful than others in most situations. Consequently, this study adopts the ordinary Kriging interpolation to model the permittivity of soil.

Assumed $r(x)$ is the vector for all of the grids in communication area which is second order smoothly variables. $r(x_i)$ is the observation value of the soil which is set previously for the sampled points, where $i = 1, 2, \dots, n$. $r'(x_0)$ is the estimated value for an unknown grid. It can be calculated according to the following equation:

$$r'(x_0) = \sum_{i=1}^n \lambda_i r(x_i) \quad (1)$$

According to the principles of Kriging interpolation, the equations below can be get:

$$\begin{cases} E[r'(x_0) - r(x_0)] = 0 \Rightarrow \sum_{i=1}^n \lambda_i = 1; \\ \sigma_E^2 = E[r'(x_0) - r(x_0)]^2 = \text{Min} \end{cases} \quad (2)$$

Based on Eq. 2, a large number of values can be calculated to simulate the parameters of unknown grids. What's more, different initial values can be set for different application Scenarios.

In simulation, the clay and the sand contents in the earth are selected as the Kriging interpolation primers. Two kinks of soils are simulated. One is Inner Mongolia sandy soil. Its sand content is 50% and the clay content is 15%. Another is frozen black soil in Northeast of China, whose sand content is 22.75% and clay content is 28.1%.

Three scenarios, uniform soil, non-uniform soil with light inhomogeneity and non-uniform soil with heavy inhomogeneity, are studied and simulated. After Kriging

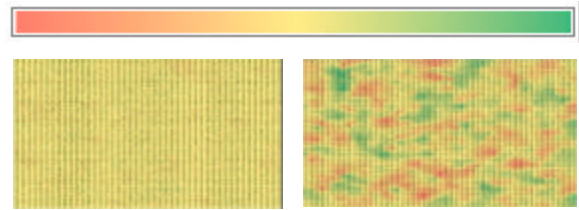


Fig. 5(a-b): Soil properties after Kriging interpolation, (a) Soil with light inhomogeneity and (b) Soil with heavy inhomogeneity

interpolation, the permittivity and the conductivity of the soil grids is calculated according to the law of peplinski.

The results after Kriging interpolation are shown in Fig. 5.

The result of soil physical parameters is shown in Fig. 5, the soil parameters is denoted by different colours. Obviously, the soil in Fig. 5a has less inhomogeneity while it in Fig. 5b has much greater inhomogeneity.

Debye model: The Debye model is generally used to describe soil, human tissue and so on. The model can be expressed as following:

$$\begin{aligned} \epsilon^{\text{Debye}}(\omega) &= \epsilon_0 (\epsilon_\infty + \chi(\omega)) \\ &= \epsilon_0 \epsilon_\infty + \epsilon_0 \frac{\epsilon_s - \epsilon_\infty}{1 + j\omega\tau_0} \\ &= \epsilon_0 \epsilon_\infty + \epsilon_0 \frac{jf_c (\epsilon_s - \epsilon_\infty)}{jf_c - \omega} \end{aligned} \quad (3)$$

where, ϵ_s is coefficient of the relative permittivity in static, ϵ_∞ is relative permittivity for the infinite frequency. τ_0 is the relaxation time which is the reciprocal of collision frequency.

FDTD and PML setting: In this study, ADI-FDTD (alternative-direction implicit) (Song *et al.*, 2005) is adopted because it has high efficiency in solving problems relating to dispersive media. In ADI-FDTD scheme the temporal interpolation of the field in the grids is obviated since it is unconditionally stable. And the calculation of one discrete time step is performed by two steps.

One primary part of FDTD is PML(Perfectly Matched layer) setting, whose goal is to exclude the interference of wave reflected by the boundary. For the situation that the permittivity of the grids is non-uniform, PML setting gets more complicated. It is difficult to draw

the exact optimal solution. We hand over this problem by exhaustive tests. Based on hundreds of simulations of setting the PML as the value of first layer grids, the average of all of the grids and the value of last layer grids, a conclusion can be drawn that for the variance of permittivity larger than 0.05 the permittivity of PML should be set as the value of the average to achieve optimal result. Otherwise the permittivity value of first layer of the grids could be an ideal one for PML.

The setting of the simulation in the study is as following: according to the application scenarios, the size of the grid is set as 300 mm, the operating frequency is 300 MHz and the distance between the transmitter and the receiver is about 6 m. The communication area is two-dimensional, with the range of 6X6 square meters.

SIMULATION RESULT AND ANALYSIS

Based on the analysis of EM wave propagation in uniform soil, less non-uniform soil(soil with lighter inhomogeneity) and more non-uniform soil(soil with heavier inhomogeneity), the simulation is executed by MATLAB. For the sandy soil in Inner Mongolia, in which the average of the sand, clay and water are 50, 15 and 3%, respectively, the simulation results are shown in Fig. 6.

Another scenario is the seasonal frozen black soil in Northeast of China, in which the average of the sand, clay and water are 22.75, 28.1 and 25% respectively. The simulation results are shown in Fig. 7.

From the simulation of EM wave propagation in the non-uniform soil and that in the uniform soil, the analysis in the former parts can be proved. The more non-uniform the soil, the attenuation of the received signal is larger. Furthermore, the peak of the received signal propagating in the non-uniform soil arrives later than that in uniform soil for the path of the signal has been lengthened which is resulted from the reflection and refraction in the uniform soil.

The relation of the received signal strength and the inhomogeneity degree of soil is shown in Fig. 8 and 9 which simulate the situations in frozen black soil in Northeast of China and that of the sandy soil in Inner Mongolia separately.

From the simulation results, it can be seen that the received signal is decreased as the soil parameters go more non-uniform. The relation of them can be denoted by a linearly declining function which is drawn by data fitting method.

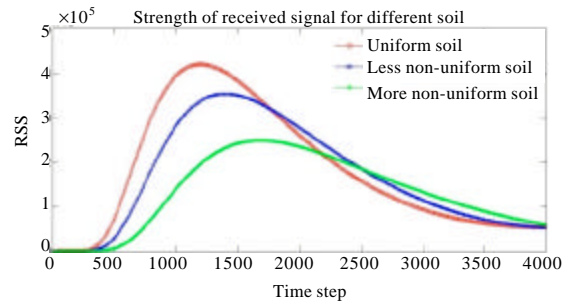


Fig. 6: Simulation result of EM wave propagation in sandy soil

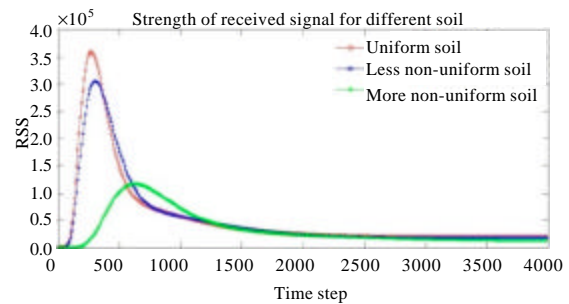


Fig. 7: Simulation result of EM wave propagation in frozen black soil

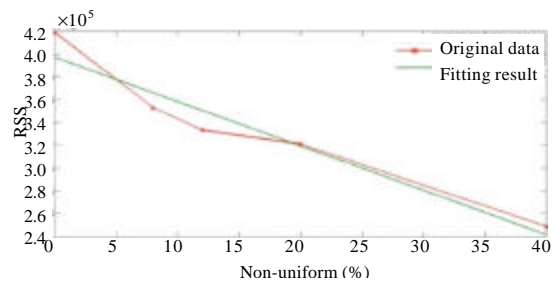


Fig. 8: Relation of signal strength and variation of soil inhomogeneity in the frozen black soil in Northeast of China

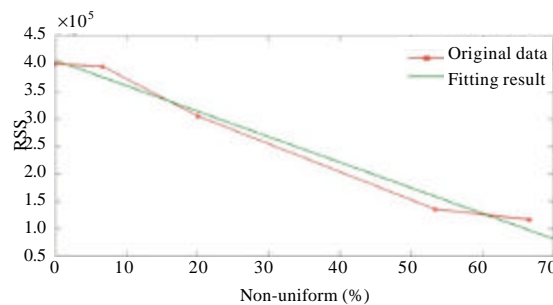


Fig. 9: Relation of signal strength and variation of soil inhomogeneity in the sandy soil in Inner Mongolia

CONCLUSION

In this study, a method to analyze the propagation of EM wave in non-uniform soil is proposed which combines micro-element method, Kriging interpolation and FDTD together. Based on two kinds of soils, the sandy soil in Inner Mongolia and the seasonal frozen black soil in Northeast of China, the 300MHz EM wave propagating in uniform, less non-uniform and more non-uniform soil situations is simulated separately. The results show that the larger inhomogeneity of soil results in more attenuation and phase delay to EM wave propagation, whose relation can be simply represented by linearly declining function.

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