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The Establishment of Field Intensity Model of Wireless Telemetry Signal in Man-made Forests

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Abstract

On the basis of the configuration characteristics of man-made forests, the spread model of wireless sensor signal in man-made forests has been simplified according to electromagnetic wave theory and Fermat principle. The man-made forests is decomposed into independent medium with four layers, the spread model is simplified into free space model, attenuation screen model and absorption screen model. The field intensity calculation formulas of UHF frequency range attenuation screen and absorption screen has been discussed, which provides basis for optimization layout of sensor and offers theoretical basis of other radio frequency communication research in man-made forests.

Keywords: Field Intensity Model, Wireless Telemetry Signal, man-made forests

1. Introduction

The application of wireless sensor network for forestry monitoring is still in fledging period, wireless sensor network is adopted widely for environmental monitoring, which still has many questions to solve. In the process of spread, the attenuation loss of sensor signal in forests will influence on the data transmission among wireless sensor node, convergent node and monitor terminal. To study field intensity loss in forests and optimize the sensors layout in forests can reduce energy loss effectively and reduce data-packet dropout frequency in order to improve data acquisition precision. In this paper, the signal field intensity algorithm has been put forward in accordance with electromagnetic wave theory and experiments, which provides basis for optimization layout of sensor and offers theoretical basis of other radio frequency communication research in man-made forests.

In UHF frequency range, the dodging, scattering and absorption that are caused by trees or other vegetations in forests can produce much path loss. Therefore, vegetation is an important factor that can influence on radio wave spread. Until the 1970s, it was reported that the vegetation and leaves cluster could bring spread loss when the frequency had reached 3GHz, but the study was restricted to less path. In the early of 1970s, the deterministic model of wave spread loss was introduced and discussed, which is influenced by vegetation absorption and diffraction spread of wave above forests, the tress was processed as homogeneous medium plate layer in this process of study. From the perspective of simulated results, this model wave can spread well in forests with 200-500MHz frequency. Tamir had made forest express as lossy dielectric layer of complex permittivity, he had analyzed the conditions that forests cover ground uniformly and established spread model, this model pointed out the forests can be equivalent to uniform lossy dielectric layer between atmosphere and ground, when wave spread between 2MHz~200MHz frequency. In the process of spread in forests, if transmission distance was farther, the lateral wave around the boundary of forests and atmosphere could play a leading role. Meanwhile, the semi-empirical model of lateral wave's spread loss was given by considering measured data. It was indicated that semi-empirical model in the process of long distance spread, the spread between users was carried out by lateral wave, this lateral wave was parallel with forests crown and can spread in air. It reached treetop according to α critical angle from transmitter, and it was launched into forests according to this critical angle.

However, in UHF frequency range, Tamir model will be considered as homogeneous medium slab layer, and the scattering and absorption behaviors of scatterers (Trees' trunks, leaves and branches) have been overlooked, therefore, Tamir model is no longer feasible. The

layout of wireless sensor nodes in man-made forests is mainly carried out in forests, The overlooking of scatterers' scattering behaviors must take large calculation error for signal transmission. Hence, it is necessary to establish an ultra-high frequency model in man-made forests, which is suited to calculate propagation loss of ultra-high frequency radio wave.

2. The Transmission Characteristics of Signal in Man-Made Forests

The propagation mechanisms of electromagnetic wave in forests are Very complex and diverse. Firstly, the attenuation signal intensity between receiver and transmitter can occur separation. Secondly, the manners of spread signals' diffraction, scattering, reflection, transmission and refraction are different. The loss that is caused by electromagnetic wave when through forests is an inevitable factor of electromagnetic wave propagation in forests, and one of major problems that is needed to solve in field intensity prediction from point to point.

The distinguish between natural forests and man-made forests is very obvious, the configuration of man-made forests has regularity. The paulownia, poplar and other fast-growing broad leaved trees are common tree species, which are easy to generate low main trunk, thick lateral branch, straight form and other phenomenons in natural growth conditions. All kinds of needle, broad leaved tree species generally also cannot meet the requirements of landscape in natural growth conditions, so it is needed to adopt the method of artificial trimming and pruning in order to meet the requirement of needed crown types and forms. The fast-growing species of trees, such as, poplar, paulownia, white elm and so on, when their heights can reach 3-4m, the reservation crown height ratio is about 3/4; when the height of sapling reaches 5-7m, the reservation crown height ratio is about 2/3. Therefore, the trees in man-made forests can be divided into trunk and crown two parts. The trunk is similar to cylinder-shaped; the base shape of crown includes cone, such as larch, fir and so on; then spheroidal, such as locust trees; then cylinder-shaped, such as black poplar. This paper takes fir as an example to establish signal transmission model in forests, the transmission of signal in man-made fir forests can be simplified as the model of figure 1.
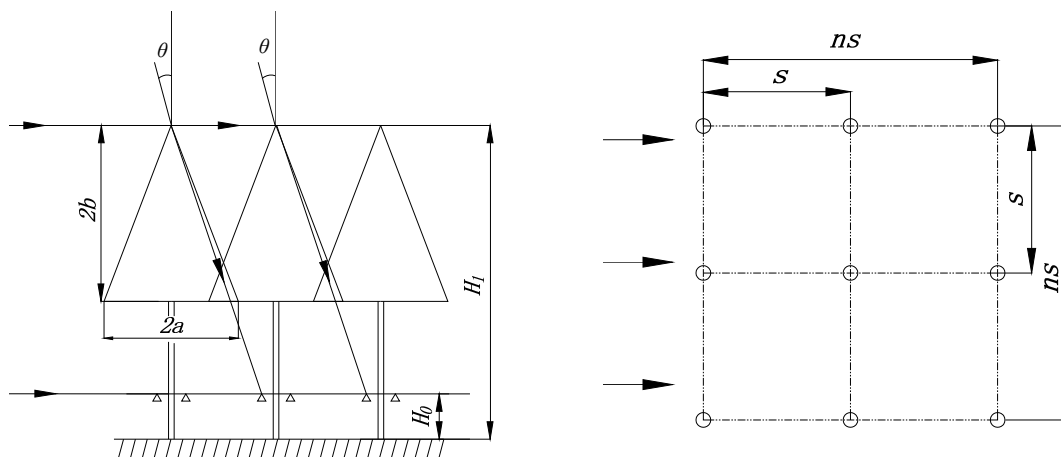

Figure 1. Signal transmission model of plantation

In order to understand the influence of man-made forest to signal thoroughly, the collocation method can be simplified into rows of continuous trees, whether man-made forests are rectangular or square, and these rows of continuous trees are configured along longitudinal or transverse laws. In the process of transmission of signal in man-made forests, the followed trees become regular obstacles, so the signal will carry out attenuation or loss in the process of transmission.

3. The Propagation Mechanisms of Signal in Man-Made Forests

Tamir had established ground-forests-air three layers model, which saw forests as a whole medium, and this model is widely used for theoretical research and experimental explanation. But the discrepancy of experimental results and the actual results is very large when frequency range is expanded high-end UHF frequency range. It is needed accurate data to measure trees growth and environmental information in forests by sensor signal. Therefore, the man-made forests can be seen as lossy layered medium in this study, the lossy medium is subdivided into crown layer and trunk layer, the branches and leaves are more, wave will generate scattering and absorption, so this layer is named attenuation screen; the trunk are straight on the basis of diffraction after taken trimming and pruning, so it is named as absorption screen; then it is put forward that ground-crown attenuation screen-trunk absorption screen-air four layer forests model as the model of figure 2.
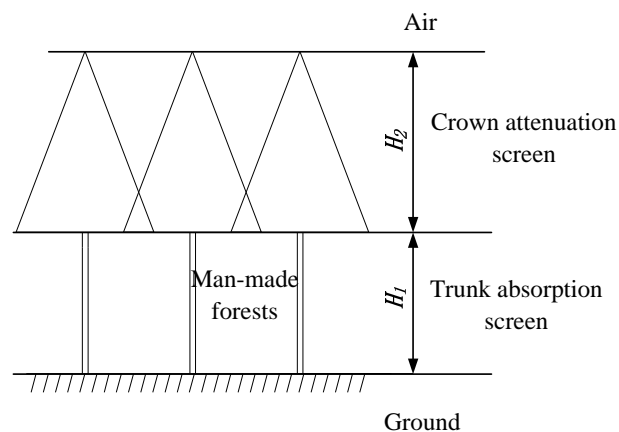

Figure 2. Signal transmission four-tier model of plantation

According to the Fermat principle, it must be adopted the spread time is the shortest path of extremum when ray spreads between transmitter and receiver two points. It is supposed S_p is source point, there is a accept field point R_x that distance S_p point at r. As shown is figure 3, the distances of S_p and medium interface are l. Under $c1>c2$, if incidence angle is more than critical angle, total reflection will happen. According to reflection law, the reflected wave spreads along S_pBR_x path, its path is equivalent to the straight line S'_pR_x from mirror symmetrical virtual source point S'_p to R_x point, this path is shorter than other reflection paths. In the VHF-UHF frequency range, leaves are effectively transparent to electromagnetic wave. According to the studies of Army Research Laboratory, Antlers Sullivan and so on, the interference that is produced by branches scattering is limited relative to trunk above 300M Hz frequency range, the scattering of trunk and ground is main interference form. Therefore, it can be overlooked the influence of reflection when electromagnetic wave propagation loss is discussed in man-made forests. The wave of propagation path with shortest time from S_p to R_x is direct wave that spread along S_pR_x straight line.

In addition to the above two kinds of paths, there is a path that does not conform to the Fermat principle. It sends according to critical angle θ_0 from S_p point in forests medium to A point in air medium interface, after entering into A point in air medium, it happens refraction and spreads horizontally along two medium interface ABC straight line. Refracted wave happens a refraction again when it reaches a point C, then it returns air medium and reaches the receiving point R_x in forests medium, the ray is S_pACR_x at this moment. In all paths that return to air medium, the path with shortest spread time is S_pACR_x, which S_pA and CR_x spread according to speed c_2 in forests medium, and the AC part along interface spreads according to faster speed c_1 in air medium. The wave of this path is subsistent on the basis of Fermat principle, the wavefront of direct wave and reflected wave is spherical wavefront, the wavefront of refracted wave is circular conical surface that based $S_pS'_p$ as axis. According to Huygens principle, the wave spreads along interface in air to send to forests medium, the wavelet sources are C_1, C_2,

C_3, ……, the son receiving points are R_1, R_2, R_3, ……, as shown in figure 4. The envelopes of the wavelet wavefront have constituted conical wavefront of lateral wave. For UHF frequency range, the study results shows the conductivity of forests medium is high, so complex propagation constant imaginary part is bigger, then the attenuation of direct wave and reflected wave is faster and increases with the increase of propagation distance. Therefore, for far field (above 1.8km), the lateral wave that spreads along the interface of air and crown attenuation layer will play main contribution. But for near field spread, the other two spread paths will play roles except crown reflection wave.
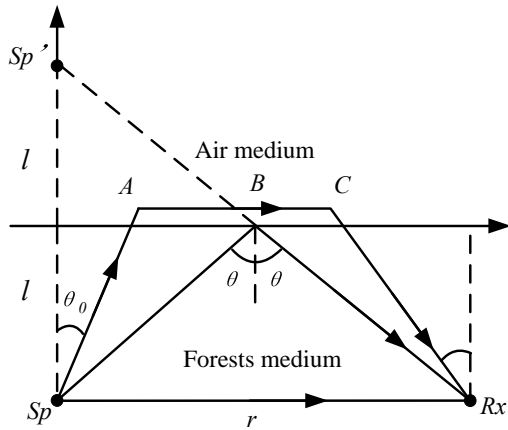

Figure 3. The direct wave, reflected wave
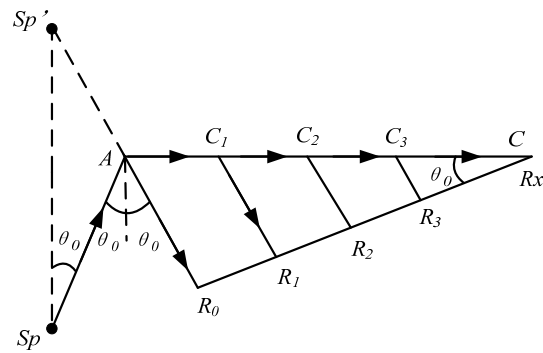and lateral wave three paths

Figure 4. The formation of the
conicalwavefornt of the lateral wave

According to different locations of launching point and receiving point, the radio wave propagation in man-made forests can be divided into two conditions, one is launching point outside man-made forests and receiving point in man-made forests, the other one is launching point and receiving point are all in man-made forests. Based on the above analysis, in either case, the man-made forests can be divided into absorption screen and attenuation screen. For simplicity, attenuation screen is put on absorption screen, the spread in man-made forests can be simplified into figure 5 and figure 6, which figure 5 is wave propagation simplified model that source point is outside forests and receiving point is in forests, figure 6 is wave propagation simplified model that source point and receiving point are all in forests.
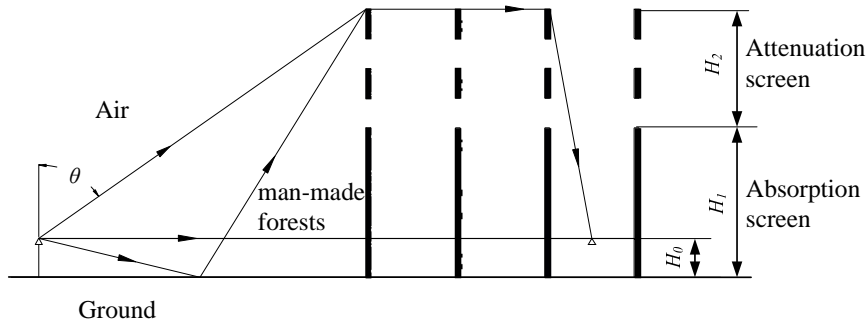

Figure 5. Source simplified model of radio wave propagation to receive points in
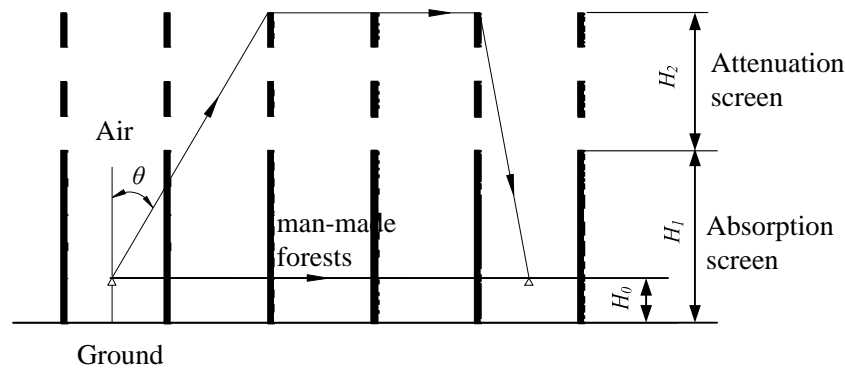the forest outside the forest

Figure 6. Source points and receiving points are simplified model of radio wave propagation in forest

According to electromagnetic wave propagation theory, the reflection of ground and wave propagation loss in air are named free-space propagation. Therefore, propagation field intensity model of electromagnetic wave in man-made forests can be divided into the sum of free-space propagation E_0, Attenuation screen spread $E(S)$ and Absorption screen spread $E(X)$.

$$E= E_{0+} E(S)+ E(X) \tag{1}$$

E_0 is known, so in this paper, the $E(S)$ and $E(X)$ are only discussed.

4. Field Intensity of Attenuation Screen

In UHF frequency range, the spread of signal in attenuation screen plays important role by the scattering of branches and leaves. At this moment, the crown should be seen as discrete, random, anisotropic medium, therefore, in this paper, the attenuation screen model is calculation model that is obtained in accordance with the analysis method of radio wave propagation and discrete scattering field in random medium. Through the comparison of calculation model and traditional statistical model, the curvature tolerance of measured value is higher, and it does not need to take site measurement by special test equipment, and it has convenient and simple related parameters measurement, powerful flexibility, small calculated amount, easy to realize and other advantages.

Through the application of wave propagation and scattering theory in random medium, the leaves are equivalent to circle slice, the branches are equivalent to cylinder with limited length, and the expression of leaves and branches in scattered field is obtained. The approximation method of average field is used for determining the expression of wave propagation constant when wave passes crown. The reasonable wave propagation path loss model is established in crown according to specific circumstances of crown.

$$E(S) = q\exp\left[jkx - jk_0\cos(\theta_i)z\right] \tag{2}$$

The positions and relationship of each parameter in crown average field is shown in figure 7 when waves pass the attenuation screen crown layers.

q is polarization direction; θ_i is incidence angle, which indicates the included angle of incidence direction and z axis; d is area thickness; k is propagation constant that wave spreads along direction. Because of crown is conductive medium, wave propagation constant k in crown generally is complex number, $k=\beta+j\alpha$, is attenuation constant of wave propagation.

$$k = k_0\sin(\theta_i) + \frac{2\pi}{k_0\sin(\theta_i)}\sum_t \rho_t\left\langle f_{pq}^{(t)}(i,i)\right\rangle$$

Where, $f_x^{(t)} = p \cdot f(o,i,q)$, $f(o,i)$ is the scattering amplitude, o is the scattering direction, t is the scattering type. ρ_t is the density of the scattering body corresponding, $\left\langle f_{pq}^{(t)}(i,i) \right\rangle$ is the average of the forward scattered amplitude.

$$\left\langle f_{pq}^{(t)}(i,i) \right\rangle = \int f_{pq}^{(t)}(i,i) p(\theta) d\theta \tag{3}$$

$p(\theta)$ is the probability density function of scattering body inclination.

Table 1. The relative dielectric constant of the crown

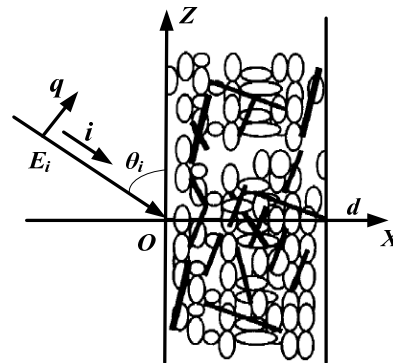| species	branches	Leaves
poplar	14.9491-j4.7143	20.4623-j6.0839
locust tree	13.96-j4.4581	16.5035-j5.1092
phoenix tree	19.2836-j5.7976	23.5765-j6.8287

Figure 6. The meaning of the attenuation of each parameter in the screen

For 2.4GHz frequency signal, through the measuring method of crown parameters in References (6), poplar, locust tree and phoenix tree are measured, the relative dielectric constant of these three common tree species can be obtained, as shown in table 1.

It is supposed that the distribution of leaves and branches is uniform in whole 2π azimuth angle, the incident wave direction i and x axis direction are same, θ is included angle of n and q. Leaves have sunny characteristics, the normal direction of leaves basically obey normal distribution in [-π/2, π/2]dip angle, the normal direction of branches basically obey uniform distribution in [-π/2, π/2]dip angle, so this distribution is more compared with the actual situation. The attenuation constants of poplar, locust tree and phoenix tree are calculated, as shown in table 2, the results illustrate attenuation constants of common tree species' crown can be calculated by theoretical calculation formula.

Table 2. The attenuation constant of the crown

	poplar			locust tree			phoenix tree		
Calculated values （dB/m）	0.91	1.22	1.73	0.81	1.12	1.44	1.16	1.64	2.13
Measured values （dB/m）	0.8	1.1	1.6	0.7	1.0	1.3	1.0	1.5	1.9

5. Field Intensity of Attenuation Screen

Absorption screen is made up of straight tree trunks, and trunks are transparent for electromagnetic wave of UHF frequency range. Through radiation theory of geometrical optics, when geometric optical rays meet corner, edge, pinnacle and other objects with discontinuous features, a shadow area can be generated, and the rays can not reach the shadow area; that is the field of shadow area should be zero, but in actual measurement, it is found that the field of shadow area is not zero in a certain range when sensor locates at rear of standing tree, which is close to trunk with farther distance, and this is caused by electromagnetic wave diffraction phenomenon according to electromagnetic theory.

In UHF frequency range, diffraction and reflection belong to a local phenomenon through Keller theorem. The research contents mainly focus on scattering characteristics of target body by now, tree clutter is seen as a statistical magnitude, the research is normally based on empirical data. In an ordinary way, diffraction only is connected with physical properties and geometrical characteristics in diffraction point neighborhood on scatterer through principle locality. The properties of the first Fresnel zone around reflection points play main role to reflection field; the ones that can decide diffraction field are only locality characters of diffraction points' incident field and scattering surface.

Absorption screen is simplified into rows of continuous tree, the configuration of man-made forests has regularity, and therefore, the spread of electromagnetic wave in absorption screen has laws to follow.

The field intensity expression that is obtained from later research results [14, 15, 16] can be indicated:

$$E\ (x_1, y_1, z_1) \approx \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} (\cos\alpha + \cos\alpha')\ E^{inc}(0, y', z')\frac{jke^{-jkr_R}}{4\pi r_R} d_{y'} d_{z'} \tag{4}$$

where r_R is the distance from the secondary source point in the plane $x=0$ to the receiver point (x', y', z'), and $E^{inc}=A_0e^{-jkx}$ is the amplitude of the secondary source.

using the following simplified procedure:

$$E(x_1, y_1, 0) = A_0 e^{-jk\rho} D(\theta_1) = E^{inc}(0, y', z')e^{-jk\rho}D(\theta_1) \tag{5}$$

Similarly, (x_1,y_1,z_1) is the secondary source point and (x_2,y_2,z_2) is the receiver point obtained using the following simplified procedure:

$$E(x_2, y_2, 0) = E^{inc}(x_1, y_1, 0)e^{-jk\rho} \bullet \left(-\frac{e^{j\pi/4}}{\sqrt{2\pi k\rho}} \frac{1+\cos\theta_2}{2\sin\theta_2} \right)$$
$$= E^{inc}(x_1, y_1, 0)D(\theta_2)e^{-jk\rho} \tag{6}$$

In this equation, θ_2 is the angle between the X_1 axis and the line from the edge to the receiver point, and thus, $\sin\theta_2=y_2/\rho$, where the diffraction coefficient is as follows:
$$D(\theta_2) = -\frac{e^{j\pi/4}}{\sqrt{2\pi k\rho}} \frac{1+\cos\theta_2}{2\sin\theta_2}.$$

6. Conclusion

Based on the analysis of planting configuration characteristics in man-made forests, the man-made entirety can be seen as research object, the spread of radio frequence signal in man-made forests is simplified properly. Man-made forests are divided into independent medium with four layers, and propagation model is simplified into free-space model, attenuation screen model and absorption screen model. The field intensity formula of attenuation screen is established according to different trees' medium, the field intensity formula of absorption screen is established through subsequent studies. The characteristics of absorption screen model are analyzed, the foundation is provided for further ray tracing of signal in man-made forests and establishment of diffraction loss model in absorption screen.

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