Long Distance Path-Loss Estimation for Wave Propagation Through a Forested Environment

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I. INTRODUCTION

The accurate modeling of wave propagation behavior through forested environments is of great interest for civilian and military communication applications since the forest affects the communication channel significantly and imposes constraint on the system parameters. Existing foliage propagation models treat the forest as an effective lossy dielectric medium which predict an exponential increasing of path-loss with respect to the propagation distance within the forest. Such model captures only the coherent power of the signal which comes from the mean electromagnetic field propagating through the forest and neglects the incoherent power from the field fluctuation due to the random distribution of the scatterers, such as branches and leaves, within the forest. For long distance communication system, such incoherent power tends to dominate the overall received power after a certain distance because of the exponential-decaying behavior of the coherent power. Experiment results show that the attenuation rate in forested environment is a function of distance and simple models such as Foldy's approximation grossly overestimates the path-loss.

To capture the contribution from the incoherent power, two different approaches, namely the radiative transfer theory and the wave theory, may be used [1]. The radiative transfer approach is not suitable for the forested environment which contains large scatterers such as trunks and branches due to the difficulty in determining the phase and extinction matrices. The second approach based on wave theory uses Foldy's approximation [2] to estimate the coherent mean-field along the direction of propagation and uses this mean-field as the incident wave illuminating each constituent particle inside the forest. The scattered field from each scatterer can then be calculated and added coherently. The advantage of such approach is the inherent high fidelity of the approach since it allows the use of realistic-looking tree structures for the forest model that can significantly affect the scattered field statistics. This approach has been successfully implemented and verified for a number of applications [3, 4, 5]. However, keeping track of all scatterers and scattering components over long propagation distance is computationally prohibitive. This difficulty can be resolved by treating the forest as statistically homogeneous medium along the horizontal dimensions. A new Statistical WAve Propagation (SWAP) model based on coherent wave theory and a renormalization approach is presented in this paper and is shown to provide a reasonably accurate and computationally efficient solution for estimation of path-loss in forested environment over long distances.

II. SWAP MODEL DESCRIPTION

Figure 1 shows the scenario for long distance wave propagation through a forest under a horizontal incident wave. The statistically homogeneous forest is divided into blocks with the same width along the direction of wave propagation. These blocks are assumed to be statistically identical and independent of each other. Therefore, the wave propagation behavior of each block is identical and the field computation can be localized into one block. This provides the statistical properties of the wave propagation over a short distance which together with network theory can effectively be used to calculate the statistical field

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properties over long distances. The width of each block is carefully selected to ensure capturing all scattering mechanisms at the same time to keep the numerical simulation tractable. By reusing the statistical properties computed for a typical block, one can calculate the incoherent power radiated from each block to the receiver. Summing all the incoherent power generated by each block and adding to the coherent power which can be calculated from the incident wave attenuated by the forest, the total power at the receiver is obtained. The incoherent power generated by each block is also attenuated by the successive blocks before reaching the receiver. The pre-computed forest statistical properties depend on different forest attributes such as tree structures and densities, as well as signal parameters such as frequencies and polarizations.

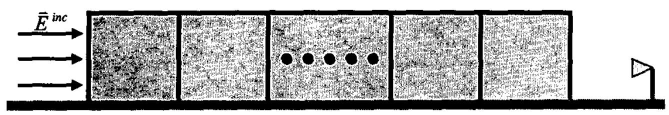


Figure 1: Long distance forest divided into statistically identical and independent blocks.

III. COMPUTATION OF INCOHERENT POWER

The incoherent power results from the fluctuation field radiated from each block of forest to the receiver. Based on the field equivalence principle, the fluctuation field at the receiver radiated from the j[th] block of forest in Figure 2 is given by

$$\widetilde{E}_j(\bar{r}) = -\oint\!\!\oint_B \nabla'\times\overline{\overline{G}}(\bar{r},\bar{r}')\cdot 2\widetilde{J}_m(\bar{r}')ds', \tag{1}$$

where

$$\widetilde{J}_m(\bar{r}') = \widetilde{E}_j(\bar{r}')\times\hat{s} \tag{2}$$

is the equivalent magnetic surface current and $\hat{s}$ is the outward unit vector normal to $\boldsymbol{B}$, the output surface of the j[th] forest block. Ground effect is taken into account using approximate image theory [6]. The factor of 2 reflects the equivalent magnetic current sources backed by a planar perfect electric conductor over surface $\boldsymbol{B}$. $\overline{\overline{G}}(\bar{r},\bar{r}')$ is the dyadic Green's function of a medium having a permittivity equal to the effective dielectric constant of the forest. Theoretically, the surface $\boldsymbol{B}$ should be infinite in extent; however, since the fluctuation field is mainly confined to the forest vertical dimension the electric field computation for calculating $\widetilde{J}_m$ is limited to the vertical extent of the forest. Now suppose surface $\boldsymbol{B}$ is d meters tall and a meters wide, then the incoherent power can be calculated as

$$\begin{aligned}
\left\langle\left|\widetilde{E}_j(\bar{r})\right|^2\right\rangle &= \left\langle \widetilde{E}_j(\bar{r})\cdot\widetilde{E}_j(\bar{r})^*\right\rangle = \left\langle \Big(-\int_0^d\int_{-a/2}^{a/2}\nabla'\times\overline{\overline{G}}(\bar{r},\bar{r}_1')\cdot 2\widetilde{J}_m(\bar{r}_1')]ds_1'\Big)\cdot\Big(-\int_0^d\int_{-a/2}^{a/2}\nabla'\times\overline{\overline{G}}(\bar{r},\bar{r}_2')\cdot 2\widetilde{J}_m(\bar{r}_2')]ds_2'\Big)^*\right\rangle \\
&= \frac{1}{4\pi^2}\int_0^d\int_{-a/2}^{a/2}\int_0^d\int_{-a/2}^{a/2}\frac{e^{jk_{e1}R_1-jk_{e2}^*R_2}(jk_{e1}R_1-1)(-jk_{e2}^*R_1-1)}{R_1^3R_2^3}\Big[\left\langle\widetilde{E}_{jz}(\bar{r}_1')\cdot\widetilde{E}_{jz}(\bar{r}_2')^*\right\rangle(z-z_1')(z-z_2') \\
&+\left\langle\widetilde{E}_{jz}(\bar{r}_1')\cdot\widetilde{E}_{jy}(\bar{r}_2')^*\right\rangle(z-z_1')(y-y_2')+\left\langle\widetilde{E}_{jy}(\bar{r}_1')\cdot\widetilde{E}_{jz}(\bar{r}_2')^*\right\rangle(y-y_1')(z-z_2') \\
&+\left\langle\widetilde{E}_{jy}(\bar{r}_1')\cdot\widetilde{E}_{jy}(\bar{r}_2')^*\right\rangle(y-y_1')(y-y_2')+\left\langle\widetilde{E}_{jy}(\bar{r}_1')\cdot\widetilde{E}_{jy}(\bar{r}_2')^*\right\rangle(x-x_1')(x-x_2') \\
&+\left\langle\widetilde{E}_{jz}(\bar{r}_1')\cdot\widetilde{E}_{jz}(\bar{r}_2')^*\right\rangle(x-x_1')(x-x_2')\Big]dy_1'dz_1'dy_2'dz_2'
\end{aligned} \tag{3}$$

where $\left\langle\widetilde{E}_p(\bar{r}_1')\cdot\widetilde{E}_q(\bar{r}_2')^*\right\rangle = COV[\widetilde{E}_p(\bar{r}_1'),\widetilde{E}_q(\bar{r}_2')] = C[\widetilde{E}_p(\bar{r}_1'),\widetilde{E}_q(\bar{r}_2')]\sigma[\widetilde{E}_p(\bar{r}_1')]\sigma[\widetilde{E}_q(\bar{r}_2')]$. (4)

$COV[\tilde{E}_p(\bar{r}_1'),\tilde{E}_q(\bar{r}_2')]$ and $C[\tilde{E}_p(\bar{r}_1'),\tilde{E}_q(\bar{r}_2')]$ represent the covariance and the normalized correlation function between the fluctuation field at $\bar{r}_1'$ with polarization p and the fluctuation field at $\bar{r}_2'$ with polarization q. $\sigma[\tilde{E}_p(\bar{r}_1')]$ is the standard deviation of the fluctuation field at $\bar{r}_1'$ with polarization p, and is defined by

$$\sigma[\tilde{E}_p(\bar{r}_1')] = \sqrt{\left\langle \left|\tilde{E}_p(\bar{r}_1')\right|^2 \right\rangle} = \sqrt{\left\langle \left|\bar{E}_p(\bar{r}_1')\right|^2 \right\rangle - \left|\left\langle \bar{E}_p(\bar{r}_1') \right\rangle\right|^2} . \quad (5)$$

k_e is the effective wave number and R is the distance from $\bar{r}'$ to $\bar{r}$.

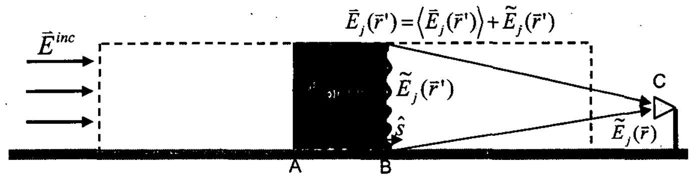


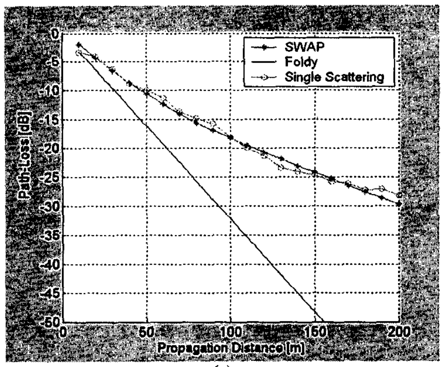
Figure 2: Incoherent power radiated from the j[th] block of forest to the receiver.

IV. ESTIMATION OF FOREST STATISTICAL PROPERTY PARAMETERS

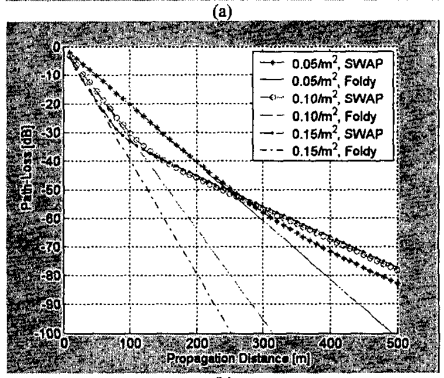
Since each individual block of forest is statistically identical, one can estimate the parameters of the forest statistical property based on one block and reuse them for the whole forest. The existing single scattering wave theory model [4] can be applied to this representative block. From the above description of the SWAP model and the formulation of incoherent power computation, the statistical parameters needs to estimate are the variation of fluctuation field $\sigma[\tilde{E}(r')]$, the correlation function $C[\tilde{E}_p(\bar{r}_1'),\tilde{E}_q(\bar{r}_2')]$, and the Foldy's attenuation coefficients M_{mn}.

V. SIMULATION RESULTS

Two sets of simulation experiments are conducted to validate the SWAP model. First, the comparison between the SWAP model and the existing single scattering wave theory propagation model is made by examining the path-loss due to the forest versus the propagation distance (up to 200m). As shown in Figure 3(a), the SWAP model provides very accurate results when compared to a "brute force" numerical result obtained from the single scattering model. In addition, the new model provides the expected behavior of path-loss in foliage as a function of distance. The simulation time is significantly reduced by using SWAP model than single scattering model since the SWAP model is reusing the pre-stored statistical properties. To further examine the validity of the SWAP model, it is applied to the forests with different tree densities at the same frequency (0.5 GHz). Figure 3(b) shows the path-loss versus propagation distance for three different tree densities. As expected, larger tree density causes more scattering, therefore more incoherent scattering power relative to the coherent power at the receiver. Hence the path-loss curve knee happens at shorter propagation distance as tree density increases. However, larger tree density also causes more attenuation of the coherent mean-field and hence the coherent power. Whereas the mean-field decreases with increasing tree density the total path-loss decreases for higher densities after the path-loss curve knee.



(a)



(b)

Figure 3: Validation of SWAP model, (a) comparison between SWAP model and single scattering model; (b) comparison between SWAP model applied at different tree densities.

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