Numerical Analysis of Electromagnetic Wave Propagation in Forest

Rony TEGUH*1, Yuki SATO*1 and Hajime IGARASHI*1 (Mem.)

Wireless sensor networks (WSN) are effective to detect peat and forest fires which can give significant damages in environment and economics. To determine optimal network topology of WSN, one has to know characteristics of electromagnetic wave propagation in forest. In this work, the attenuation constant of waves is evaluated from complex permittivity and basal area of the forest using homogenization technique. It is possible to evaluate the attenuation constant from the measured permittivity of tree trunks and the basal area.

Keywords: wireless sensor network, forest fire detection, basal area, electromagnetic wave, simulated annealing.

1. Introduction

Recently large-scale forest fires have frequently taken place in boreal and tropical rain forests. They can give significant impacts on environment and human society. In particular, peat and forest fires in Indonesia is said to be one of the dominant causes of the global warming. In fact, the peat and forest fires in Central Kalimantan and Borneo released between 0.8 and 2.57 Gt of carbon which is equivalent to 13 - 40 % of the mean annual global carbon emissions from fossil fuel in 1997 [1]. Moreover, the smoke generated by forest fires in the above area gives severe damages on transportation systems not only in Indonesia but also in Malaysia and Singapore.

Detection of forest fires in initial phase is of importance for effective firefighting operations. There are several methods for detection of forest fires. For example, satellite imaging and direct monitoring using unmanned aerial vehicles have been developed [2]. Among them, wireless sensor networks (WSN) are expected to realize swift and reliable detection of forest fires.

In WSNs based on the Zigbee protocol [3], measured data are sent by UHF-band electromagnetic waves from sensor nodes to routers or directly to the base station. The routers gather measured data and send them to the base station via multihop communication. One of the largest problems in operation of WSNs is their energy constraints: the sensor and router nodes usually have limited energy source such as batteries and solar panels. It is impractical to make frequent replacement of the batteries in the sensor nodes widely deployed in forests. Moreover, sufficient energies for proper operation of the sensor nodes cannot be provided from the batteries charged by the solar panels in rainy season.

For the above reasons, many studies have been carried out to lengthen the life time of WSNs. Energy-efficient operation and deployment of WSNs are important to increase the WSN lifetime [4]. In the LEACH protocol [5], sensors autonomously constitute clusters, each of which has one cluster head. The data measured by sensors are gathered by the cluster heads and transferred to the base station. A cluster head is dynamically selected from sensors in the cluster considering energy load balance.

The authors have presented optimization of router positions for effective operation of WSNs in forest [6], where the total distance between the nodes in a WSN is minimized using genetic algorithm. Moreover, the authors have taken the attenuation of electromagnetic (EM) waves in inhomogeneous vegetation into account in the optimization [7]. However, the values of the attenuation constants have been assumed to be a priori known.

In this paper, we evaluate the attenuation constants of forest from the measured complex permittivity of tree trunks and its basal area [8]. To evaluate the attenuation constants, we employ the homogenization method which has seldom been applied to analysis of EM waves in forest. Moreover, we optimize a WSN in Borneo evaluating the attenuation constants for a case study.

2. Modeling of EM Waves in Forest

We consider here WSN in tropical peat forest shown in Fig. 1, which is composed of burned and unburned forest. The regions P1, P2 and P3 have different values of basal area; 28.6, 18.73 and 18.43 m²ha⁻¹ [8]. The sensing field of interest would also contain river and grassland. We have to consider different attenuations in wave propagation in these fields.

It has been pointed out in [10, 11] that the EM waves in forest can be classified into geometric optical waves which propagate directly or reflectively from the source to the sink through the tree trunks and canopy, the sky waves which have long distant propagation from a source to sink in forest via ionosphere, and finally the lateral waves which...
propagate along the canopy-air interface. We can discard here the second waves for WSNs at UHF band in which EM waves have negligible reflections from the ionosphere. The first and third waves vary with distances as \( \frac{1}{r^2} \) and \( \frac{1}{r^3} \), respectively. A full wave analysis based on four layer model of the forest has concluded that the former is dominant above 100 MHz if the communication distance is shorter than 3 km [12]. In the WSNs for forest fire detection, the communication distance of the sensors and routers would be sufficiently shorter than 3 km. For this reason, we consider only the first waves in this study. Moreover, for simplicity, we only consider the direct waves. It is possible to consider reflection from ground surface into account on the basis of two-ray ground reflection model [13] in the following analysis.

In the analysis of EM waves in forests which are regarded as inhomogeneous dielectric media, we make the following assumptions.

(a) The electromagnetic property of the forest which is composed of tree trunks and air is expressed in terms of the homogenized complex permittivity given by

\[
\hat{\varepsilon} = \varepsilon - j\left(\frac{\sigma}{\omega}\right),
\]

where \( \varepsilon \) and \( \sigma \) are homogenized permittivity and electric conductivity of forest, respectively, and \( \omega \) denotes angular frequency. Because there are various vegetation in the sensing field as written above, \( \varepsilon \) and \( \sigma \) are treated as function of position. The homogenized values of \( \varepsilon \) and \( \sigma \) are evaluated in the next section.

(b) The forest is lossy dielectric which satisfies

\[
\tan \delta \equiv \frac{\sigma}{\varepsilon \omega} \ll 1,
\]

where \( \delta \) is a loss angle.

(c) The characteristic length of \( \varepsilon \) and \( \sigma \) is sufficiently longer than the wavelength of UHF wave.

Moreover permeability of vacuum \( \mu_0 \) is assumed everywhere in forest.

Now let us consider EM waves in inhomogeneous lossy dielectric media governed by the Maxwell equations

\[
\begin{align*}
\text{rot } E &= -j\omega\mu_0 \mathbf{H}, \\
\text{rot } H &= j\omega\varepsilon E,
\end{align*}
\]

where \( E \) and \( H \) are electric and magnetic fields. Introducing vector potential satisfying, \( \mathbf{H} = \text{rot} \mathbf{A}/\mu_0 \), which obeys the Lorentz gauge, the vector Helmholtz equation

\[
\nabla^2 \mathbf{A} + k^2 \mathbf{A} = 0,
\]

can be derived from Eq. (3), where \( \mathbf{k} \) denotes the complex wave number defined by

\[
k = \sqrt{\omega^2 \mu_0 \varepsilon}.
\]

Due to assumption (b), \( \mathbf{k} \) can be approximated as

\[
\mathbf{k} \approx \omega \sqrt{\varepsilon \mu_0} \left(1 - \frac{j}{2} \tan \delta\right) - \mathbf{j} \alpha.
\]

For simplicity, we here consider a wave radiated from a dipole in \( z \) direction perpendicular to ground, which is governed by the one-dimensional scalar Helmholtz equation given by

\[
\frac{d^2 u}{dr^2} + k^2 u = 0,
\]

where \( u(r) = r A_z \). It can be shown that the damped wave solution

\[
u(r) = Ce^{-j\mathbf{k}(r)dr},
\]

approximately satisfies Eq. (7) under assumption (c) which leads to

\[
\left| \frac{d\mathbf{k}}{dr} \right| \ll |\mathbf{k}|^2.
\]

Note that Eq. (8) is an exact solution to Eq. (7) when \( \mathbf{k} \) is constant. It is therefore found that the vector potential is expressed by

\[
\mathbf{A} = Ce^{-j\int k(r)dr} \frac{2}{r}.
\]

It is then concluded that \( \mathbf{A} \) as well as \( E \) and \( H \) have the spatial attenuation of the form \( \exp \left(-j \int a(r)dr\right)/r \).
3. Homogenized permittivity of forest

In the homogenization, we define the homogenized material constants such as permittivity and permeability which relate electromagnetic field quantities such as \( \mathbf{E} \) and \( \mathbf{D} \) averaged over heterogeneous materials. The homogenization technique is particularly effective for analysis of composite materials, and its validity has been verified in many cases [e.g., 14]. There are two kinds of homogenization techniques; analytical approach in which mutual interaction between the particles is assumed weak and linear, and numerical approach which considers the strong and nonlinear mutual interaction into account [15].

For the analysis of EM waves in forest, we employ the analytical approach assuming that the density of trees is sufficiently low. In fact, the basal area is lower than 1% of the sensing field in the case of Fig.1. In the following, homogenized permittivity will be derived with reference to [14] in which shielding effectiveness of epoxy resin filled with carbon fibers is discussed. Note that homogenization has seldom been applied to analysis of EM wave propagation in forest.

We consider the constitutive relation of electric field in a tree trunk which is given by

\[
\mathbf{D}_t = \varepsilon_0 \mathbf{E}_t + \mathbf{P}_t = \varepsilon_i \mathbf{E}_t,
\]

where \( i \) indexes materials including air. Hence the polarization vector can be expressed as

\[
\mathbf{P}_t = (\varepsilon_i - \varepsilon_0) \mathbf{E}_t.
\]

On the other hand, the electric field \( \mathbf{E}_p \) generated by \( \mathbf{P} \) outside the tree trunk is given by

\[
\varepsilon_0 \mathbf{E}_p = N \mathbf{P}_t,
\]

where \( N \) denotes the depolarization constant which only depends on geometry of the dielectric material. On the surface of the tree trunk

\[
\mathbf{E}_s = \mathbf{E}_0 - \mathbf{E}_p,
\]

must hold, where \( \mathbf{E}_0 \) is the mean external field to which \( \mathbf{E}_p \) is antiparallel. From Eq. (12) – Eq. (14), it follows that

\[
\mathbf{E}_s = \frac{\varepsilon_i \mathbf{E}_0}{\varepsilon_0 + N(\varepsilon_i - \varepsilon_0)}.
\]

Now the homogenized constitutive relation for averaged field can be expressed as

\[
\langle \mathbf{D} \rangle = \varepsilon \langle \mathbf{E} \rangle
\]

\[
= \varepsilon_0 \left( \frac{1}{\varepsilon_0 + N(\varepsilon_i - \varepsilon_0)} \right) \mathbf{E}_0.
\]

On the other hand, taking spatial average of Eq. (11), we obtain

\[
\langle \mathbf{D}_t \rangle = \langle \varepsilon_i \mathbf{E}_t \rangle
\]

\[
= \varepsilon_0 \left( \frac{\varepsilon_i}{\varepsilon_0 + N(\varepsilon_i - \varepsilon_0)} \right) \mathbf{E}_0.
\]

It follows from Eq. (16) and Eq. (17) that the homogenized permittivity is given by

\[
\bar{\varepsilon} = \frac{\varepsilon_0 \varepsilon_i}{\varepsilon_0 + N(\varepsilon_i - \varepsilon_0)} + \frac{1}{\varepsilon_0 + N(\varepsilon_i - \varepsilon_0)}.
\]

When we consider the medium composed of tree trunks whose complex permittivity is \( \varepsilon \) and air, we can obtain the homogenized permittivity of forest from Eq. (18) as follows:

\[
\bar{\varepsilon} = \varepsilon_0 + \frac{\varepsilon_0 (\varepsilon - \varepsilon_0) f}{\varepsilon_0 + N(1 - f)(\varepsilon - \varepsilon_0)},
\]

where \( 0 \leq f \leq 1 \) is the volume fraction of tree trunks.

When the electric field has polarization parallel to the tree trunks, we find that \( N \approx 0 \) assuming that tree can be treated as an infinite cylinder. On the other hand, it is found that \( N \approx 1/2 \) when the polarization is perpendicular to the trees. Hence the permittivity for each case is given by

\[
\bar{\varepsilon}_p = (1 - f) \varepsilon_0 + f \bar{\varepsilon},
\]

\[
\bar{\varepsilon}_l = \varepsilon_0 + \frac{2 \varepsilon_0 (\bar{\varepsilon} - \varepsilon_0) f}{\varepsilon_0 + (1 - f)(\bar{\varepsilon} - \varepsilon_0)}.
\]

It has been shown in [14] that the shielding effectiveness of a composite material computed by FEM using the homogenized permittivity in Eq. (20) agrees well with that computed by FEM without homogenization. Note that the latter FE analysis needs a number of elements to model the fine structure of the composite material. When \( f \ll 1 \), which would hold for forests, Eq. (20) reduces to

\[
\bar{\varepsilon}_p = \varepsilon_0 (1 - j f \varepsilon_r \tan \delta),
\]

\[
\bar{\varepsilon}_l = \varepsilon_0 \left( 1 - \frac{4 f \tan \delta}{1 + \frac{\varepsilon_r}{\varepsilon_0}} \right),
\]

where \( \varepsilon_r = \varepsilon / \varepsilon_0 \). From Eq. (21), we can obtain the homogenized conductivity, which is inserted into Eq. (6) to have the homogenized attenuation constants

\[
\bar{\alpha}_g \approx \frac{1}{2} f \omega \varepsilon_r \sqrt{\varepsilon_0 \mu_0} \tan \delta,
\]

\[
\bar{\alpha}_l \approx 2 f \omega \sqrt{\varepsilon_0 \mu_0} \frac{\varepsilon_r}{(1 + \frac{\varepsilon_r}{\varepsilon_0})^2 \tan \delta}.
\]

Eq. (22) are valid under assumption (b). It is clear from Eq. (22) that

\[
\frac{\bar{\alpha}_l}{\bar{\alpha}_g} \approx \frac{1}{4} \varepsilon_r \left( 1 + \frac{\varepsilon_r}{\varepsilon_0} \right)^2 > 1,
\]
We can conclude, therefore, that the attenuation constant for the perpendicular polarization is smaller than that for the parallel polarization.

4. Deployment of Routers Considering Different Attenuations

We consider here a sensor network to detect forest fires. The sensor nodes are assumed to be randomly deployed in the forest. Moreover, we assume that the sensor and router nodes have the communication distance  in free space. It is clear that the number of the sensors which can communicate with the nearest parent node depends on the router deployment. The sensor is judged to be connected if the condition

\[ e^{-\alpha(r)R/R_0} > 1, \]

is satisfied, where  is the distance from the sensor to the nearest router including the base station. The value of  is computed from Eq. (22). We optimize the router positions to maximize the number of connected sensors using the simulated annealing (SA) [7]. The optimization problem is defined by

\[ N_c \rightarrow \text{max.} \]

where  denotes the number of the connected sensors.

First we consider a uniform field where  is constant. The communication distance  in this field can be obtained by solving the nonlinear equation

\[ e^{-\alpha R/R_0} = 1. \]

The communication distance is plotted for different values of  as a function of  in Fig. 2. We can also estimate the number of routers  necessary for full coverage of the sensing field of area  from

\[ N = \frac{A}{\pi R^2}. \]

Fig. 3 shows dependence of  on  and . Fig. 4 (a) shows the number of connected sensors deployed randomly in the sensing field with  = 3 \times 10^{-3},  = 500 m where the router positions are optimized by SA. The number of sensors is set to 30. We find that we need 12 routers for full connection which are in good correspondence with the necessary router number read from Fig. 3. The optimized WSN topology and convergence history of SA are plotted in Fig. 4 (b) and (c). Note that we have much smaller number of connected sensors without the optimization as can be found from Fig. 4 (c).

Now we consider the forest shown in Fig. 1. By assuming that the trees are infinite cylinder of the same radius, we evaluate the values of the volume fraction from the basal area as  = 2.86 \times 10^{-3}, 1.87 \times 10^{-3}, 1.84 \times 10^{-3} for P1, P2 and P3, respectively.

BS, RN SN represent base station, router and sensor nodes,  is number of routers.  = 3 \times 10^{-3},  = 500 m. The complex permittivity \( \varepsilon \) of tree trunks in tropical forest has been measured [16]. Although depends on the kind of tree trunk, we assume that \( \varepsilon = \varepsilon_0(3.1 - j0.4) \) which has been used for scattering analysis of single tree trunk in [16].

Fig. 5 shows dependence of the attenuation constants of parallel and perpendicular polarization on frequency for P2 forest. It can be seen that they approach the values given by the formula Eq. (22) as frequency increases. At low frequencies where assumption (b) is no more valid,  takes smaller values.

We optimize the router positions for WSN in the forest shown in Fig. 1. The wave polarization is chosen to be perpendicular to the trees. The value of attenuation constant depends on the position in this case. Fig. 6 shows the resultant number of routers and WSN topology. We find that we need 26 routers for full connection of the sensor nodes.
Fig. 4. Optimization results for uniform sensing field.

(a) number of connected sensors $N_c$

(b) WSN topology, $N_r=14$

(c) Convergence history of SA

Fig. 5. Attenuation constants in P2 for different polarization.

(a) number of connected sensors $N_c$

(b) WSN topology, $N_r=26$

Fig. 6. Optimization results for sensing field shown in Fig.1

$R_0 = 750 \text{ m.}$
5. Conclusions

We have evaluated the attenuation constant $\alpha$ of forest based on the homogenization technique. When the basal area and complex permittivity of tree trunks are given, we can evaluate the attenuation constant. The communication distance and number of routers necessary for full coverage of the sensing field have been obtained from $\alpha$. It has been shown that EM waves with polarization perpendicular to tree trunks has longer propagation than those with parallel polarization. We can optimize the router deployment based on the evaluated value of $\alpha$ to maximize the connected number of sensors.

In future work, we will make comparison of the computed value $\alpha$ of with measured results.

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References