Modeling the dynamic effects of vegetation on radiowave propagation

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Abstract—In this contribution we use available measurements at 2.45, 5.25, 29 and 60 GHz to study the dynamic effects of vegetation on propagating radiowaves. The complex responses of a tree to induced wind force has been studied, and used to explain phenomena observed in measurement results. Generally, the power spectrum of the received signal through vegetation has lowpass characteristics, and the effects of swaying tree components are manifested as spectral peaks in the power spectrum of the received signal. Radiowaves scattered from these swaying tree components have a time varying phase changes which results in fading of the received signal. Furthermore, due to further dissipation of the wind energy by the interaction of tree crowns, less signal variation is to be expected from a grove of several trees than from a single/few tree(s). The Ricean K-factor for different wind conditions has been estimated from measurements. In addition, by utilizing a lowpass filter and a mass-spring system, a new simulation model for generating signal fading due to a swaying tree has been developed. Depending on the wind speed and physical characteristics of the tree, the new model can be used for simulating signal fading due to a swaying tree with similar dynamical and statistical characteristics as those observed from measurement results.

I. INTRODUCTION

In a given environment radiowaves are subjected to different propagation degradations. Among them, vegetation moving with wind can both attenuate and give a fading effect to the propagating signal. Generally, operators cannot guarantee a clear line-of-sight (LOS) to wireless customers as vegetation in the surrounding area may grow or expand over the years and obstruct the path. Therefore, understanding the movement of vegetation with wind can help model the resulting signal fading and mitigate the effect by using fade mitigation techniques such as adaptive coding and modulation, path diversity, and other mitigation techniques.

Attenuation due to single trees varies significantly with species and whether trees are in leaf or wet [1]. At higher frequencies, leaves have dimensions large compared to the wavelength, and can significantly affect the propagation conditions. A theoretical description of penetration into vegetation is given by the theory of radiative energy transfer [2]. In addition, a procedure for predicting the average vegetation attenuation is given by Recommendation ITU-R P.833 [3], where the received signal is assumed to consist of a diffuse and coherent components. The diffuse component is due to propagation through vegetation, while the coherent component is due to diffraction from the top and side of the vegetation as well as from ground reflection. Based on measurements, a variety of different statistical distributions for the signal envelop resulting from propagation through vegetation have been reported in the literature. Among them are the Nakagami-Rice distribution for the envelope in a linear scale [4], [5], and for the envelope in dB [6], [7]. Nakagami distribution for the envelop in dB [8]. Furthermore, a lognormal distribution for the envelope in linear scale and for the attenuation in dB were reported in [9] and [10], respectively.

Spectral analysis of the signal received after propagating through vegetation has been performed in [9] to characterize the time varying signal fading due to swaying vegetation (tree). It was found that the probability of occurring spectral peak at a particular frequency increases with increasing wind speed. In another contribution, the time-varying fading due to vegetation was modeled as the summed field from oscillating reflectors [11]. In addition, a 3-D lattice model for the spatial and temporal dynamic effects of a tree was developed in [12].

In this contribution, we study the dynamic effects of vegetation on radiowaves, using available measurements. In addition, the actual movement of trees under the influence of wind has been studied to give possible explanations for the different phenomena observed in measurement results. Furthermore, a new simple simulation model for generating signal fading caused by swaying trees has been developed.

II. MEASUREMENT SET-UP

To characterize the influence of vegetation on radiowaves, measurements were performed for a broad range of frequencies, including 2.45, 5.25, 29 and 60 GHz, in various foliage and weather conditions [10]. A sampling rate of 500 Hz was used to collect the radio frequency (RF) signals. In addition, to understand the behavior of radiowaves propagating through vegetation under different weather conditions, meteorological measurements including wind speed and precipitation were performed. The wind speed was collected every 5 seconds, and the precipitation data every 10 seconds.

The measurements were taken in two different locations, referred to as Site 1 and Site 2. The trees at Site 1 were deciduous trees, and were considered both when the trees were in full leaf and when they were out of leaf. Site 2 was populated by several coniferous trees which made a wall...
TABLE I
SITE DESCRIPTION [10]

<table>
<thead>
<tr>
<th>Site</th>
<th>Path length</th>
<th>Foliage Depth</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>63.9 m</td>
<td>14.3 m</td>
<td>3 foliated maple trees</td>
</tr>
<tr>
<td></td>
<td>7.6 m</td>
<td>1 foliated flowering crab tree</td>
<td></td>
</tr>
<tr>
<td>Site 2</td>
<td>110 m</td>
<td>25 m</td>
<td>Several spruce and one pine tree creating a wall</td>
</tr>
</tbody>
</table>

III. MEASUREMENT ANALYSIS AND THE DYNAMIC MOTION OF TREES

A tree is a complex structure consisting of a trunk, branches, sub-branches, and leaves. The tree responds in a complex way to induced wind forces, with each branch swaying and dynamically interacting with other branches and the trunk. This complex movement of the tree dissipates the energy induced by the wind, and prevents the generation of natural harmonic sway frequencies with large amplitudes that could cause tree failure [13]. The stiffness of the wood material is described by the Young’s modulus $E$, which varies with age and position on a tree. For tree trunks and branches the value is within the range $2.37 \times 10^9 - 4.44 \times 10^9$ (N/m$^2$) [14], and is related to the stiffness of an ideal spring $k$, given by

$$k = \frac{EA_0}{L_0}$$

where $A_0$ (m$^2$) is the cross-section area and $L_0$ (m) is the length of the wood material.

During windy conditions, first-order branches sway over the swaying trunk, and second-order branches sway over the swaying first-order branches. Generally, smaller branches sway over swaying larger branches, and leaves vibrate over swaying smaller branches. The overall effect minimizes the dynamic sway of the tree by creating a broad range of frequencies and prevents the tree from failure [13]. Radiowaves scattered from these swaying tree components have a time varying phase changes due to periodic changes of the path length which results in fading of the received signal. The severity of the fading depends on the rate of phase changes which further depends on the movement of the tree components. The effects of the swaying tree components are also shown as spectral peaks in the power spectrum of the received signal.

Typical power spectrum for Site 1 at 29 GHz, when the trees are out of leaf under low and high wind speed conditions, are shown in Fig. 3 and Fig. 4, respectively. The corresponding typical power spectrum for Site 1 at 29 GHz, when the trees are in full leaf under low and high wind speed conditions, are also shown in Fig. 5 and Fig. 6, respectively. Generally, from Figs. 3 - 6, we can observe that strong spectral component with high power is present at 0 Hz followed by other components at higher frequencies. In addition, we can also observe that the power spectrum has lowpass characteristic. Generally, similar spectral characteristics were observed for Site 1 and Site 2 at all frequencies.

In addition, the probability density function (PDF) of the received signal for leaved deciduous trees (Site 1) has been compared with the PDF of the received signal for coniferous trees (Site 2) under high wind speed conditions; see Fig. 7. The spreading of the curves indicates that the signal from Site 2 shows less variation compared to the signal for Site 1 (wider and flatter curves represent more signal variation). This result can be explained by taking the difference in the vegetation into account. For Site 2, in addition to the swaying of branches to dissipate the energy from the wind, the interaction with neighboring tree crowns further damps the
Fig. 3. Typical low wind speed power spectrum for leafless dry deciduous trees at 29 GHz.

Fig. 4. Typical high wind speed power spectrum for leafless dry deciduous trees at 29 GHz.

Fig. 5. Typical low wind speed power spectrum for leaved dry deciduous trees at 29 GHz.

Fig. 6. Typical high wind speed power spectrum for leaved dry deciduous trees at 29 GHz.

Fig. 7. Comparison of typical PDFs from Site 1 and Site 2 under high wind speed conditions at 29 GHz.

sway of the trees affecting the signal. Furthermore, at Site 2 the signal propagates through the middle of the tree wall, where the tree(s) affecting the signal is protected against the wind from both sides; this limits the induced wind force from these directions. Thereby, in general less signal variation is to be expected from a grove of several trees than from a single/few tree(s).

Based on the above results and discussions, in the following section we develop a new simulation model for generating signal fading due to swaying vegetation.

IV. THE NEW MODEL

Former studies on the measurements used here suggested that the signal envelop can be represented using the Extreme value or lognormal distribution [10]. However, it is also found here that the Nakagami-Rice distribution can well represent the measured signal envelop through vegetation. The Chi-Square test has been performed to verify the fitness of Nakagami-Rice distribution and the measured signal distribution. For all
frequencies, the hypothesis was accepted for 5% significance level. Furthermore, as discussed in Section I, the majority of reported measurements suggest Nakagami-Rice envelop distribution. Therefor, Nakagami-Rice envelop distribution is assumed in the developed simulation model, with the $K$-factor given by

$$K = \frac{P_d}{P_f}$$  \hspace{1cm} (2)

where $P_d$ and $P_f$ are the power in the direct and diffuse component, respectively. From our measurements we estimated the Ricean $K$-factor using the moment-method reported in [15], see Fig. 8. As expected, we can observe from Fig. 8 that the $K$-factor decreases with increasing wind speed (due to increment of power in the diffuse component) and increasing frequency (due to smaller wavelength).

As discussed earlier, the power spectrum of the signal received through vegetation has lowpass characteristics. In addition, spectral peaks caused by the swaying of tree components are present in the power spectrum of the received signal. The lowpass characteristics of the spectrum can be modeled using first-order butterworth filter $H(z)$ with the cutoff frequency $f_c$ depends on the wind speed. Measured cutoff frequencies in Hz for Site 1 (leaved) and Site 2 are shown in Table II. For Site 2, $f_c$ could not be clearly identified during low wind speed conditions, therefor is not included in Table II. Generally, for high wind speed conditions, $f_c$ increases with increasing frequency. During low wind speed, $f_c$ is in average the same for all frequencies except for 2.45 GHz signal.

The swaying of each tree component can be modeled as the mechanical oscillation of a mass-spring system, see Fig. 9. The mass $m$ (kg) and spring constant $k$ (N/m) of the system corresponds to the mass and stiffness of the wood material (through (1)). The frequencies of the mechanical oscillations show up in the power spectrum for the channel variation due to the periodic change of the path length for radiowaves scattered from the tree components. Using Newton’s second law and Hooke’s law, the equation of motion for the system in Fig. 9

$$m \frac{d^2}{dt^2} x(t) + k x(t) = 0$$  \hspace{1cm} (3)

assuming no initial velocity of the mass, the solution of (3) is given by

$$x(t) = x_0 \cos \left( \sqrt{\frac{k}{m}} t \right)$$  \hspace{1cm} (4)

where $t$ is the time and $x_0$ is the mechanical oscillation which is related to the oscillation on the channel.

The new model for simulating signal fading due to swaying tree is shown in Fig. 10. In the model, a complex adaptive white Gaussian noise (AWGN) $n(t)$ is filtered by first-order butterworth lowpass filter with $f_c$ given in Table II. Then, $N$ mechanically oscillating components are added to produce the spectral peaks observed in measured power spectrum of the received signal which are caused by the swaying of tree components (see Figs. 3 - 6). $a_i$ is the amplitude of the channel oscillation and is related to the amplitude of the mechanical oscillation $x_{0i}$. Each oscillating component can be chosen to have different mass $m_i$ and stiffness $k_i$ (related to the cross-section area and length of a tree component, see (1)) which defines its oscillating frequency, $r(t)$ is then normalized to zero mean and unit variance. Finally, depending on the $K$-factor (Fig. 8), the contribution of the direct $\sqrt{P_d}$ and diffuse $\sqrt{P_f}$ component is added, and are summed to give the resulting complex signal envelop $v(t)$ due to swaying vegetation.

Simulated signal fading due to swaying tree, using the new model for low and high wind speed conditions are shown in Fig. 11 and Fig. 12, respectively. In the simulations, $N$ equal to 12 different values of $m_i$ in the range 0.5 to 1 kg and $k_i$ in the range $1 \times 10^5$ to $2 \times 10^6$ N/m are used to produce spectral peaks at different frequencies similar to the one observed in measurements. The values used for the channel oscillations $a_i$
are within the range of $10^{-4}$ which are empirically chosen to approximately obtain peaks with powers similar to the one observed in measurements. The corresponding simulated power spectrums are also shown in Figs. 13 and 14. We can observe that the simulated power spectrums have similar spectral characteristics as those observed from measurement results shown in Figs. 3 - 6.

Furthermore, comparison of the cumulative distribution functions (CDFs) of the measured and simulated received signals through vegetation during low and high wind speed conditions are shown in Fig. 15. The results shows that the simulated and measured time series have similar statistical characteristics. In general, the new model reflects the dynamical and statistical characteristics observed in measurements, and can be used for simulating fade mitigation techniques such as adaptive coding and modulation, path diversity, and other mitigation techniques.

V. CONCLUSION

In this paper we have investigated the dynamic effects of vegetation using available measurements at 2.45, 5.25, 29 and 60 GHz. The complex responses of a tree to induced wind
force has been studied, and used to explain different phenomena observed from measurement results. During windy conditions tree components sway to dissipate the energy induced by the wind. As a result, radiowaves scattered from these swaying tree components have a time varying phase changes which results in fading of the received signal. Generally, the power spectrum of the received signal through vegetation has lowpass characteristics, and the effects of swaying tree components are manifested as spectral peaks in the power spectrum of the received signal. Moreover, due to further dissipation of the wind energy by the interaction of tree crowns, less signal variation is to be expected from a grove of several trees than from a single/few tree(s). The Ricean $K$-factor for different wind conditions has been estimated from measurements. Furthermore, by utilizing a lowpass filter and a mass-spring system, a new simulation model for generating signal fading due to a swaying tree has been developed. Depending on the wind speed and physical characteristics of the tree (branch and leaf density, mass and stiffness of the wood material), the new model can be used for simulating signal fading due to a swaying tree with similar dynamical and statistical characteristics as those observed from measurement results.

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**REFERENCES**


