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A two-point iteration method to predict canopy water content from RF loss

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ABSTRACT

Previous studies have investigated the attenuation of 2.4 GHz radio waves and vegetation, and generated a model to predict RF loss in response to the effective water path (EWP) of both packed leaves and whole tree canopies. Owing to the absence of phase information in the radio signal strength (RSS) it is not possible to directly invert the model to elicit EWP. This paper builds upon previous work and proposes a two-point iteration methodology to predict actual gravimetric water content (M_g) of single tree canopies from RF loss. An investigation for sample tree canopies (including two trees in series) demonstrated M_g explained 72% of the variance in measured RF loss.

1. Introduction

The interaction between radio waves and vegetation has been extensively studied for efficient wireless network planning. However, radio transmission within wireless sensor networks in vegetated environments can serve a dual purpose. Quite apart from sending data between sensors in the network, the radio signals themselves could be used as a means of understanding the condition of the vegetation in the signal path.

In our previous tree canopy work [12], we developed a model to calculate the RF loss (excess RF loss in addition to the free-space loss) of 2.4 GHz radio waves directed through tree canopies as a function of the water content in the tree canopy; the latter expressed as effective water path (EWP) in mm.

In this paper, we examine the possibility of inverting the model with the aim of predicting the water content of trees from the measured RF loss using a two-point iteration method.

2. Prediction of gravimetric water content of trees

In previously reported work examining RF loss due to moisture-laden leaves [11,12], the water content of stacked leaves and candidate tree canopies was expressed in terms of effective water path (EWP) in mm. Here EWP is defined as the equivalent thickness of a water-only layer in the transmission path. In the previous tree canopy work of Peden et al. [12] the EWP was calculated from Gravimetric Water Content, M_g defined as the relative water mass of the entire tree structure. In practice, from a physiological point of view, M_g is considered more appropriate for eco-hydrological studies as it more closely related to the actual water status of a plant compared to alternative metrics such as the volumetric water content (VWC) [10]. Calculating EWP requires a value for the mass of the tree. In reality, it is difficult to weigh a live tree. This is not needed, however, in the calculation of Mg. Therefore, it is practical to calculate Mg from RF loss rather than EWP.

For a single tree canopy envelope, if the RF loss is known through measurement, M_g of the canopy obstructing the radio path can be approximated. It should be noted that if there is more than one tree obstructing the radio path, the M_g predicted will be an overall measurement for those trees. This is nevertheless useful for ascertaining the moisture status of a canopy community, for example to guide subsequent irrigation or per-tree management strategies in production blocks such as encountered in horticultural crop production.

When inferring M_g from the measured RF loss from the model described in Peden et al. [12] model inversion cannot be done mathematically because of two main reasons. Firstly, when the RF loss is measured, wireless sensor networks detect the received radio signal strength but not the phase. This is expressed by the modulus operation in Eq. (13) of Peden et al. [12]. With no radio phase measurement, information about the phase angle of the transmission coefficient, the phase angle of the reflection coefficient and the phase constant (the imaginary part of propagation constant, γ) cannot be directly calculated. Consequently, the complex relative permittivity cannot be directly calculated either. Secondly, solving the equation in Peden et al. [12] for complex per-

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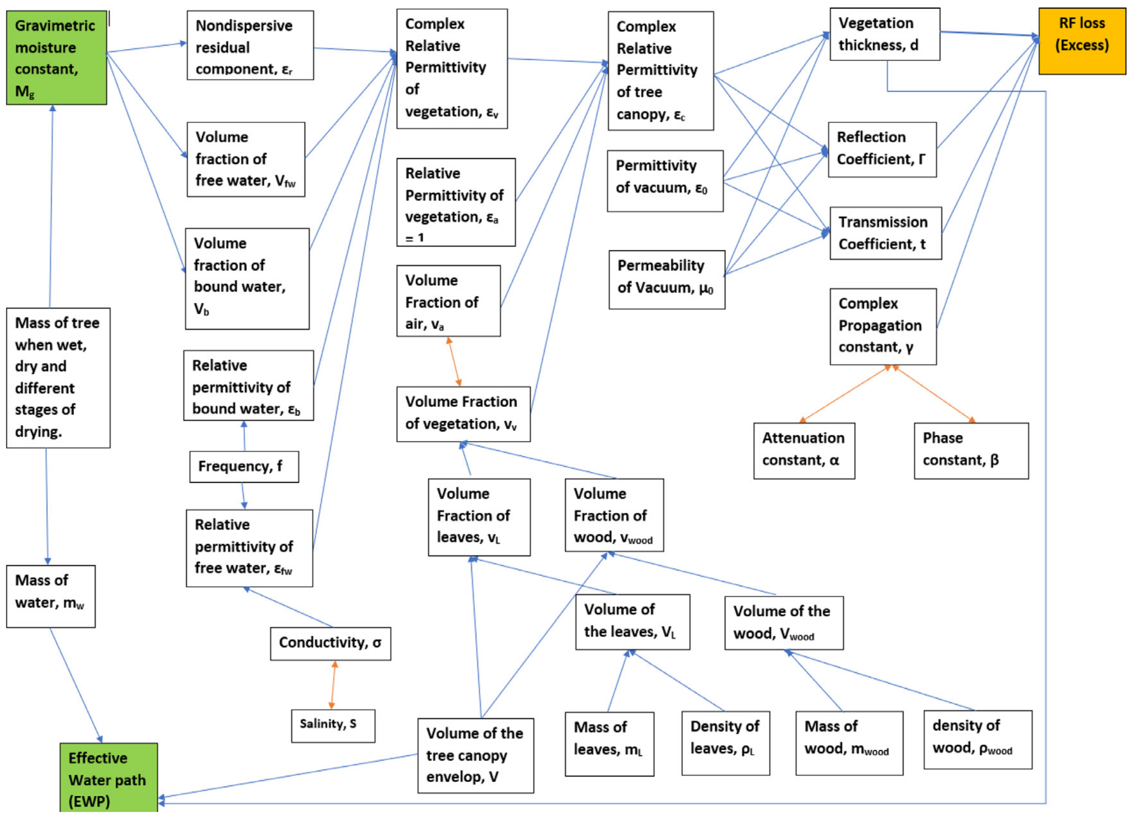

Fig. 1. The mathematical inter-relationships between the quantities involved in this work. Arrows depict the reversibility of calculating one quantity/parameter from the other. For example, reflection coefficient, Γ can be readily calculated from complex relative permittivity, ε_c, but not vice versa. This relationship is shown by the direction of the arrow between the quantities.

mittivity and hence M_g in terms of RF loss is not possible algebraically since the equation contains transcendental functions. For these reasons, the equations cannot be directly inverted to predict the water content expressed as M_g.

However, as depicted in Fig. 1, it is possible to utilize the model in reverse to estimate M_g from measured RF loss via a two-point iteration method.

2.1. M_g estimation methodology

Fig. 1 summarizes the key mathematical dependencies between the measured and calculated quantities involved in this work. The arrows between each quantity/parameter indicates whether or not a quantity may be derived from the other on the basis of the mathematic formula. For example, reflection coefficient, Γ can be readily calculated from complex relative permittivity, ε_c, but not vice versa. The mathematical equations relating each of the depicted quantities are listed in Peden et al. [12].

In order to determine M_g, the required quantities are: -

(1) the RF loss measured using the communication network in the environment;
(2) the operating frequency, f which is known from the equipment used for measurement of RF loss;
(3) the thickness of the canopy envelope, d which can be measured by a measuring tape;
(4) salinity of the vegetation, *S* or the conductivity, *σ* of the vegetation. Alternatively, S can be assumed to be 10‰ (parts per thousand) if the frequency is between 1 GHz and 100 GHz as variation in conductivity is known to have little effect at these frequencies [6,7,9];
(5) the relative permittivity of air, ε_a which is 1 and
(6) the volume of the tree canopy envelope, *V*, volume fractions of air, v_a, and vegetation, v_v, in a tree canopy; all of which can be measured using digital photographic methods [2,5].

With the above variables measured and known, M_g can be approximated using a two-point iteration method with the following simplifying assumptions:

(1) the tree canopy material is homogeneous on a wavelength scale;
(2) the radio signal is a plane wave where it interacts with the tree canopy and
(3) the approximated M_g will be an overall measurement for the canopy envelope irrespective of whether or not there are multiple trees within that envelope.

2.2. Two-point iteration method

Two-point iteration (also called False Position) is a well-established algorithm [1]. In brief, calculating M_g from a measured RF loss involves choosing two initial estimates for M_g that are likely to bracket the true value. The two initial estimates for M_g could be the lowest value, 0 and the highest plausible value for a tree (for example, 0.5 for Eucalyptus trees used in our experiment). From this we forward calculate the corresponding RF losses. From knowledge of the estimated RF losses compared to the actual, a stepwise iteration process is followed in adjusting M_g and re-calculating the RF loss guesses until the modeled RF loss converges on the measured RF loss.

2.3. Unique solution and convergence

There is a limitation to this two-point iteration method. Because of multiple reflections, there may be several values of M_g for a given RF loss. Consequently, there may be no unique solution for M_g. Furthermore, the two-point iteration method will not reveal these multiple solutions and may not even converge. This problem of convergence to a unique solution will not arise if the total RF loss has a monotonic relationship with M_g. This relationship is possible if the absorption loss is the major factor in the RF loss compared to the transmission and interference losses at the interfaces. This assumption will be justified in Section 4.

In order to investigate this issue, the model equations from Peden et al. [12] are approximated by ignoring the transmission and reflection losses at the interfaces. The simplified equations that result involve only absorption loss.

Here we commence with Eq. (13) of Peden et al. [12] whereby the total RF loss (dB) for *N* lossy homogenous slabs can be written as

$$L_{slab} = 20\log_{10}\left|\frac{E_{TF}}{E_{RF}}\right|. \tag{1}$$

where, E_{TF} is the electric field Phasor incident at the first (air-to-first tree canopy) interface and E_{RF} is the phasor received at the receiver end, and they are related by T-parameter matrix as

$$\begin{bmatrix} E_{TR}/E_{RF} \\ E_{TF}/E_{RF} \end{bmatrix} = \begin{bmatrix} \frac{1}{t_{01}} & \frac{\Gamma_{01}}{t_{01}} \\ \frac{-\Gamma_{10}}{t_{01}} & \frac{1}{t_{01}} \end{bmatrix} \begin{bmatrix} e^{-\gamma_1 d_1} & 0 \\ 0 & e^{\gamma_1 d_1} \end{bmatrix} \cdots\cdots \begin{bmatrix} \frac{1}{t_{N-1,N}} & \frac{\Gamma_{N-1,N}}{t_{N-1,N}} \\ \frac{-\Gamma_{N,N-1}}{t_{N-1,N}} & \frac{1}{t_{N-1,N}} \end{bmatrix} \begin{bmatrix} e^{-\gamma_N d_N} & 0 \\ 0 & e^{\gamma_N d_N} \end{bmatrix} \begin{bmatrix} \frac{1}{t_{N,N+1}} & \frac{\Gamma_{N,N+1}}{t_{N,N+1}} \\ \frac{-\Gamma_{N+1,N}}{t_{N,N+1}} & \frac{1}{t_{N,N+1}} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{2}$$

The total RF loss through tree canopies can be subdivided into three losses: (1) transmission loss which occurs when wave transmits through the interface between two media; (2) absorption loss which occurs when the wave propagates through a lossy medium and (3) interference loss caused by multiple internal reflections inside a lossy medium.

If a consideration is made that the RF loss through tree canopies is mostly due to absorption by the lossy medium, then assume that the radio wave is transmitted to the other side with no transmission loss and there are no internal reflections within the lossy medium. Then Eqs. (1) and (2) simplify and the total loss for N lossy homogenous slabs in dB due to absorption is

$$L_{slab} = 20\log_{10}\left|\left(e^{(\gamma_1 d_1)+(\gamma_2 d_2)+\cdots\cdots\cdots+(\gamma_N d_N)}\right)\right| \tag{3}$$

where, γ is the complex propagation constant, and d is the thickness of the lossy medium in meters. The propagation constant, γ of a sinusoidal electromagnetic wave is a measure of the change undergone by the amplitude and phase of the wave as it propagates in a given direction. The real part of γ is the attenuation constant, α in Np/m (Nepers per m) and the imaginary part is the phase constant, β in rad/m [4]. The complex propagation constant,

$$\gamma = j\omega\sqrt{\mu_0\varepsilon_0\varepsilon_c}. \tag{4}$$

Eq. (3) can be rewritten as

$$L_{slab} = 8.686\left(\alpha_1 d_1 + \alpha_2 d_2 + \cdots\cdots\cdots\cdots + \alpha_N d_N\right) \tag{5}$$

where, real part of γ, α can be expressed as:

$$\alpha = \omega\left\{\frac{\mu_0\varepsilon_0\varepsilon_c'}{2}\left[\sqrt{1+\left(\frac{\varepsilon_c''}{\varepsilon_c'}\right)^2}-1\right]\right\}^{1/2} \tag{6}$$

where, ε_0 and μ_0 are the permittivity and permeability of air respectively, ω is the angular frequency in rad/sec and ε_c is the complex permittivity of a tree canopy. ε_c' and ε_c'' are the real and the imaginary part of ε_c. Further details on the complex permittivity of tree canopy is given in Section 2.2 of Peden et al. [12].

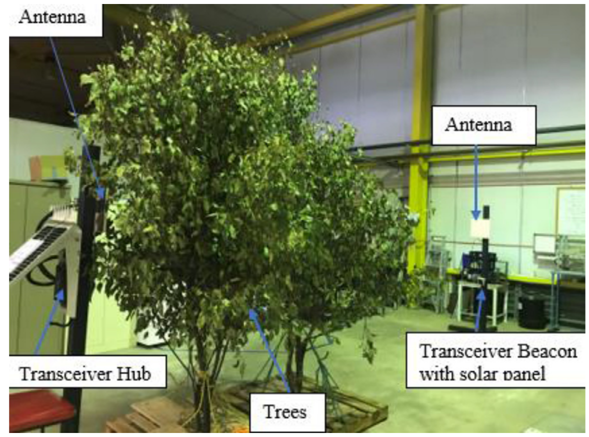

Fig.2. Experimental set-up within the indoor facility. Two flat-panel antennas were mounted facing each other 6.15 m apart. Two Eucalyptus *blakelyi* trees (Tree 1, Tree 2) positioned in series in between the transceivers. The RSSI (dBm) was recorded to a removable SD card inside the transceiver Hub every minute.

3. Materials and methods

All the experiments were conducted in an indoor facility at The University of New England main campus located in Armidale, New South Wales, Australia. Two flat-panel, phased-array directional antennas (ARC Wireless Solutions, USA, PA2419B01, 39.1 cm x 39.1 cm x 4.3 cm) were used, one as a transmitter connected to a transceiver Beacon (Dosec Design, Australia, EnviroNode Beacon) and the other as a receiver connected to a transceiver hub (Dosec Design, Australia, EnviroNode Hub) operated at a frequency of 2.4331 GHz. The antenna had a gain of 19 dBi, front-to-back ratio of $^>$30 dB and 3 dB beamwidth of ±9°. The antennas were placed facing each other at a separation of 6.15 m. A constant transmitted power of 100 mW was used. The hub measured and logged the RSSI (received signal strength indicator, dBm) to a removable SD card at 1 min intervals. The experimental set-up is shown in Fig. 2.

Two Eucalyptus *blakelyi* (also known as Blakely's red gum) trees were cut and were mounted on wooden pallets. The RSSI (dBm) for no obstruction between the transceivers was measured for 4 min and then the trees were placed in front of one antenna. The difference between the time-average RSSI with and without the trees in place was converted to a time-averaged RF loss associated with the trees. The sequence of trees and no tree measurements was repeated three times to provide a measurement average. The RF loss (L) associated with the tree canopy was then calculated using,

$$L\ (dB) = RSSI(no\ tree) - RSSI(trees) \tag{7}$$

Following the RSSI measurements with and without the trees in place, the trees were left to dry for one hour and the measurement RF loss was repeated.

The process of drying and remeasuring the RSSI was repeated until no further weight loss from drying was achieved (i.e. tree was considered dry). At this end point the mass of the water (m_w) in the tree canopies and subsequently each partially-dried tree canopies were retrospectively calculated from the known mass of the trees during drying and the final dry weight of the trees. Further details on the method is given in Section 3 of Peden et al. [12].

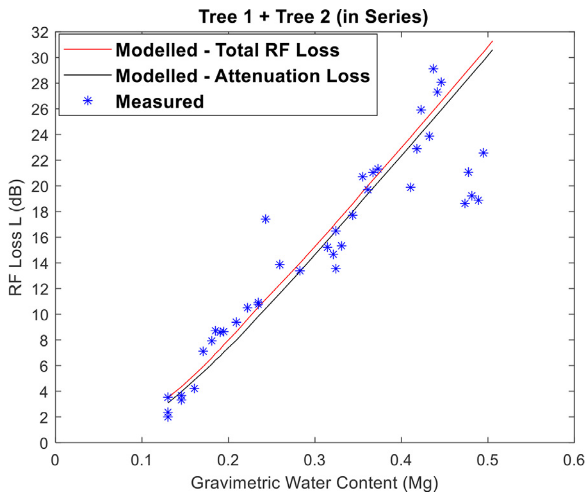

Fig. 3. Comparison of the simplified Model (Eq. (5)) – black curve, the model from Peden et al. [12] (Eq. (13)) – red curve, and measurements acquired using Eucalyptus *blakelyi* tree canopies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

4. Results and discussion

The RF loss due to absorption by the medium through which the wave propagates was analyzed for 2.4 GHz for Eucalyptus tree canopies. In Fig. 3, the simplified model (Eq. (5)) was compared against the model for total RF loss in Peden et al. [12] and measurements acquired using Eucalyptus tree canopies. The major factor in the RF loss is absorption loss (seen in Fig. 3) rather than the other factors (transmission and reflection at the interfaces) therefore it is expected that two-point iteration method will converge to a unique M_g value. The absorption loss predicts 97% of the total loss for this situation where the canopy is sparse and most of the canopy is air.

The experimental data points show some scatter in comparison to the model, evident in Fig. 3. The scatter largely arises from the tree canopy being somewhat inhomogeneous whereas a homogenous medium is assumed in the model. The random uncertainty in the RF loss measurement through tree canopies could be improved by using Multiple-input–multiple-output (MIMO) wireless systems. MIMO wireless systems use multiple antenna elements at the transmitter and receiver to offer improved capacity over single antenna topologies in multipath channels [8].

The physically-spaced transmission paths between antennas in a MIMO system would provide a more comprehensive coverage of the canopy's RF loss. Combining the RF loss values for each transmission path should have a beneficial averaging effect. While MIMO enabled wireless standards such as 802.11n (Wi-Fi) are not the best candidates for wireless sensor networks, because of their higher cost and higher energy consumption, [3] they are widely deployed for high-speed data communication.

5. Conclusions

The two-point iteration method can be applied to predict water content of a tree expressed as gravimetric water content, M_g in terms of RF loss. This method cannot be generalized and may not be applicable to situations where absorption loss is not the major factor in RF loss compared to the transmission and interference losses. Modeling shows, however, that absorption loss is the major factor for vegetation and the relation between RF loss and gravimetric moisture content is monotonic. The two-point iteration method therefore will converge to a unique result.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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