A Computational Model for Radio Wave Propagation within Wireless Sensor Networks in Orchard Environment

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ABSTRACT

A computational model for electromagnetic wave propagation through tree orchards is presented. Branches are modeled geometrically as tapered cylinders and trees are defined as collections of branches; each branch has its own starting point and orientation, expressed as three Euler angles. Tree canopies are modeled as dielectric spheres of appropriate dimensions. To simulate a tree row, copies of a cherry tree model are positioned on top of a rectangular, lossy dielectric slab that simulates the ground. The complete scattering model, considering soil and trees, enhanced by periodicity conditions corresponding to the array, was illuminated using a commercial computational software tool, which can simulate wave propagation. The simulated signal attenuation results are compared to radio path loss measurements taken in a cherry orchard, using the nodes of a wireless sensor network (WSN). The overall behavior of the predictions and measurements resemble each other; however the solver computes the maximum power that can be captured by the receiver antenna, and hence the predicted power is an *upper bound* of the apparently received power.

Keywords: Propagation, range, electromagnetic, vegetation, agriculture, Germany.

1. INTRODUCTION

To simulate the electromagnetic (EM) propagation through a cherry orchard, a suitable computational model was developed on the basis of the Finite Element Method (FEM)

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(Jin, 1993), invoked by COMSOL Multiphysics®, a commercial package that can be applied to EM scattering problems. The CAD model of the tree resulting from the measurement procedures described in Section 2 was discretized in COMSOL via an unstructured mesh, by use of the tool's built-in mesh generator. To model the effect of the ground, the well-known four-path model (Anastassiu, 2003) was originally considered as an efficient and accurate approximation. However, values of both the amplitude and phase of the free-space fields were required, which are unfortunately unavailable after COMSOL simulations, the latter yielding only the amplitudes of the electric and magnetic field. Therefore, the ground had to be modeled as a lossy dielectric slab, which unavoidably intensified the FEM solution process, by increasing the number of Degrees of Freedom (DoFs), and hence the size of the resulting algebraic linear system. Fortunately, as shown below, for the working frequency of interest, the penetration depth of the EM fields and the particular soil properties is only a few centimeters, meaning that the extra DoFs could be kept down to a reasonable number. Finally, the geometry of a cherry tree row comprising 26 trees was encapsulated in a FEM 'cage', surrounded by Perfectly Matched Layers (PMLs), a feature that can also be activated almost automatically by COMSOL. The simulated signal attenuation results are compared to radio path loss measurements taken in a cherry orchard, using the nodes of a wireless sensor network (WSN).

2. MATERIALS AND METHODS

2.1 Wireless nodes

The RF module used by the receiver and the transmitter nodes was the XBee Pro®, by Digi, Inc. This RF module implements the ZigBee protocol stack, meets the IEEE 802.15.4 standards and operates within the ISM 2.4 GHz frequency band. The transmitter power was 40 mW (+16 dBm) and the receiver sensitivity was -100dBm (1% packet error rate) and both modules used integrated whip antennas ($\lambda/4$ monopoles) with a gain equal to G=1.5 dBi. The propagation performance was calculated based on the Receive Signal Strength Indicator (RSSI), which provides a measure of the strength of the RF signal in dBm (decibel - milli Watt) units. To estimate the RSSI at a receiver location, the transmitter was commanded to send 1000 packets at an RF data rate of 250,000 bps. The mean value of all the RSSI measurements was reported as the RSSI of the specific location.

2.2 Signal power measurements

The experiment of measuring the signal strength was split in two phases. The first phase took place between 27th and 31st of August 2012 while the cherry trees (*Prunus avium*) had leaves in a mature expanded stage. The second phase took place in late autumn between 12th and 16th of November 2012, when the trees were defoliated. The cherry orchard subjected to the measurements is located in the 'Werderaner' cultivation area in

Brandenburg, Germany. The investigated area captures 25 meters by 110 meters and is located on a hillside. The orchard consists of 27 rows with 216 cherry trees (Figure 1).

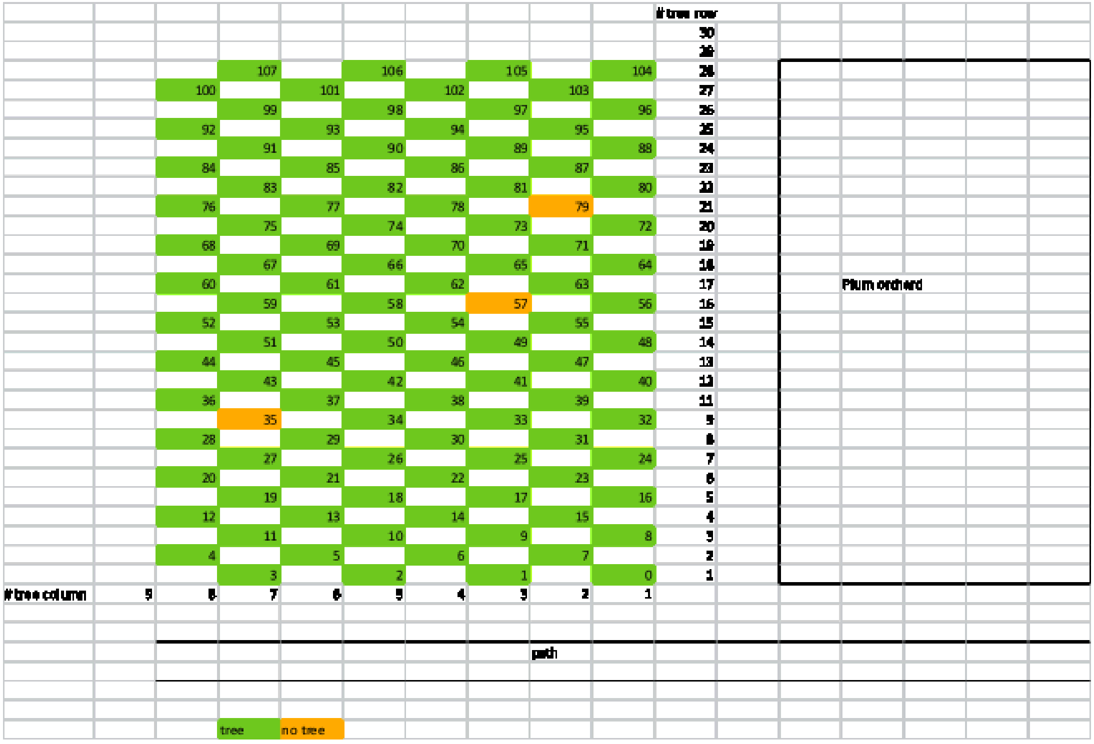

Figure 1. Cherry tree orchard layout.

The geometrical characteristics of the trees were: mean maximum height 2.77 m; mean ramification height 0.71 m; mean trunk diameter 0.0371 m. The RF modules were placed 1.5m above the ground, a height that is approximately near the middle of the foliage of every tree. The transmitter was placed 1m away (outside the orchard) from the fourth tree of the first row; the transmitter power was set to 16dBm; the receiver was placed inside the orchard, 1.5 m in front of every second tree, starting from the tree in the first row and first column. In all of the selected positions the receiver received 1000 radio packets at a radio rate of 250kbps.

2.3 Cherry tree digital representation

For the representation of representative cherry tree geometry (in that orchard), we took measurements of the orientation, length and perimeter of the trunk and the main branches of a single tree. For the orientation measurements the InertiaCube sensor referred on previous section was used. The InertiaCube3™ sensor by Intersense was utilized to digitize the cherry tree geometry. Euler (roll, pitch and yaw) angles were calculated to determine the rotation matrices among branches with one of the reference axes always pointing towards the branch tip. Branch length and thickness were also measured, the latter at various positions along the branches. Since the representation of the tree was going to be implemented by using cylinders for each branch, every branch that could not be considered a cylinder as a whole, was split in two or more shorter parts whose orientation, length and perimeter were measured separately. The final number of such measured tree parts was 37.

Originally, the entire CAD model was intended for meshing, however this procedure resulted in an overwhelming number of tetrahedra, whose size varied considerably. The immediate consequence of this situation, even for a single tree, was a very large linear system, its size depending on the resolution of the mesh chosen through COMSOL. Invariably, in all cases the linear system proved to be highly ill-conditioned, due to the coexistence of large and small elements, preventing all iterative solver algorithms in COMSOL from diverging. To decrease the computational burden, only the main, thickest branches of the tree, including the trunk, were subsequently considered. Discretization of this simplified model was far more tractable, and also EM scattering simulation through COMSOL became feasible.

Simulation of the foliage geometry is, in general, a very complex task (Meng and Lee, 2010). To be exact, each leaf needs to be simulated by a flat disk of appropriate shape, whereas the orientation and density have to be defined on the basis of probability theory. However, as already discussed for the branches, such a procedure is extremely expensive with respect to computational cost, and therefore a suitable approximation is absolutely essential. According to measurements and photos taken at the field, a sphere of radius 1.5 m, centered 3 m over the ground, could roughly approximate the canopy of an average cherry tree. Therefore, the COMSOL model for the canopy was chosen as a dielectric sphere of the dimensions above, and the material properties as discussed earlier.

The really challenging issue, however, was the meshing and electromagnetic simulation of an entire row of cherry trees, as described before. To simulate the row, 26 copies of the simplified cherry tree model were located at 4.4 m separating distances, spanning a total of 110 m. The tree models were positioned on top of a rectangular, lossy dielectric slab, 2.5 m deep, to simulate the ground, as explained in the section before. Since in the measurement campaign the transmission direction was always chosen to be along a single row, the scattering effect of the remaining rows was considered negligible, and therefore the rows were not included in the simulation, to reduce the computational burden. As discussed in the introduction, the array of 26 trees together with the slab simulating the ground was encapsulated in a rectangular box, since in the FEM the entire space surrounding the scattering geometry is theoretically discretized (Figure 2).

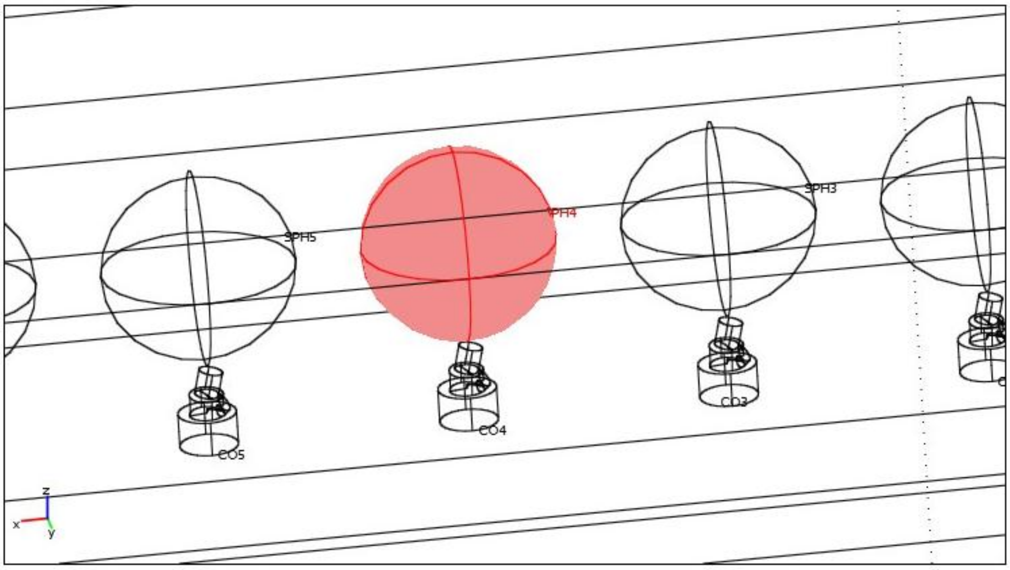

Figure 2. CAD representation of simplified cherry trees in an orchard row.

Of course, the mesh had to be truncated. The size of the box was chosen to be 30m × 30m ×150m. The boundaries of the box were modeled by COMSOL as Perfectly Matched Layers (PMLs), absorbing the EM waves propagating perpendicularly to their surface. The mesh contained 36,420 elements, resulting in 231,810 Degrees of Freedom (DoFs). The algebraic linear system turned out again to be highly ill-conditioned, and no iterative solver integrated to COMSOL would converge. Numerical results could be extracted only through an out-of-core LU decomposition algorithm (PARADISO).

3. ELECTROMAGNETIC SIMULATION

The antennas used for transmission and reception in the measurement campaign, were whip monopoles. It is well known from antenna theory (Balanis, 1982) that the electric field produced by a dipole of length *l*, located along the *z*-axis and centered at 0, is given by:

$$E_\theta = \frac{j\eta I_m}{2\pi r} e^{-jkr} \frac{\cos\left(\frac{kl}{2}\cos\theta\right) - \cos\left(\frac{kl}{2}\right)}{\sin\theta} \quad (1)$$

where r is the distance to the observation point, θ is the standard elevation spherical angle, k is the wavenumber, η is the vacuum impedance (377 Ω) and I_m is the antenna current amplitude. In our case the length of the whip antenna was $\lambda/2$ (more precisely, it was a $\lambda/4$ monopole, located on a perfectly conducting /PEC surface). Moreover, it can be proven (Balanis, 1982) that the total power radiated by a $\lambda/2$ dipole is numerically equal to:

$$P = 36.57 I_m^2 \tag{2}$$

whereas the $\lambda/4$ monopole radiates exactly half as much. Given that the transmitter power was equal to 40 mW, the current amplitude for the transmitter was found to be equal to I_m=0.047 A. The theoretical antenna gain is equal to 5.2 dBi, whereas the measured antenna gain was equal to 1.5 dBi, according to the antenna manual. The difference in the gain value is attributed to various losses, not taken into account in the theoretical modeling of the monopole.

The complete tree/soil scattering model, enhanced by periodicity conditions corresponding to the array, was illuminated in COMSOL by an incident field, simulating the radiation emanating from XBee Pro® RF module (Digi, Inc.), (ZigBee protocol, ISM 2.4 GHz). The path loss (PL) in dB was calculated as in Vougioukas et al. (2013) by:

$$PL = \left(P_t + G_t + G_r\right) - P_r \tag{3}$$

where $P_{t,r}$ and $G_{t,r}$ stand for the power and the gain of the transmitter (t) and receiver (r) respectively. For the measurement data both gains were assumed to be 1.5 dBi, whereas for the prediction data they were set equal to 5.2 dBi, as explained above.

The electromagnetic properties of the cherry tree wood or leaves could not be directly measured in the field. However, fairly accurate estimates of the permittivity and conductivity could be made, based on the water content measurement. According to Daian et al. (2006), Norimoto (1976), Perkalskis et al. (1998) and Helhel (2009), water content data yields reasonably accurate estimates of permittivity, permeability and conductivity, which characterize the scatterer physically.

4. RESULTS AND DISCUSSION

The following figure shows the computed signal power and the measured signal power as a function of distance, with and without leaves, at a height of 1.5m where the canopy volume was largest. The measured power signal has been filtered using a three-point median filter to reject data outliers.

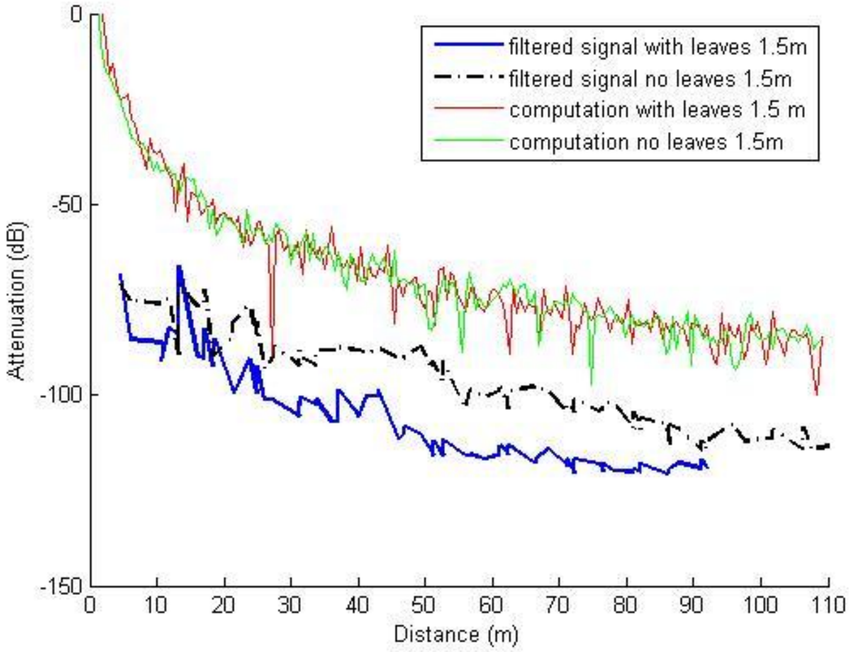

Figure 3. RSSI computations and measurements for transmitter and receiver height equal to h=1.5 m.

From the figure it is concluded that the overall behavior of the predictions and measurements resemble each other, however the predictions assume consistently higher values. The difference between measurements and predictions may be attributed to several factors: first of all, the COMSOL predictions compute the power density at any observation point, corresponding to the maximum power that can be captured by the receiver antenna. In other words, the COMSOL predictions are actually an *upper bound* of the power received. The actual power captured by the receiver is reduced due to several factors, such as polarization mismatch and possible inadequate antenna-transmission line matching (Balanis, 1982), a figure that was not available at the time of the computations. To fully understand and explain this discrepancy, further research has to take place, especially with respect to the modeling of the actual antenna, which may not behave exactly as a theoretical $\lambda/4$ monopole. Furthermore, accurate values for the real part of the permittivity of all scatterers are absolutely essential. Finally, more precise geometric models will be examined, possibly on a computational platform of higher capacity.

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