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PROPAGATION MODEL FOR WAVE SCATTERING EFFECTS CAUSED BY TREES

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ABSTRACT

The characteristics of the radio channel propagation effects are most important to the performance of delay estimation in radio navigation and synchronization in digital communications. The presented work proposes a model of wave scattering effects caused by isolated trees at *L*-band for Global Navigation Satellite Systems (GNSS) and synchronization applications. Physical aspects of tree scattering comprise for example attenuation by leaves and scattering due to branches and forks whose sizes are of the order of the carrier frequency. Treetops can be regarded as a heterogeneous volume consisting of a plethora of randomly distributed scattering elements. Simplifications are necessary to model these treetop wave propagation effects. Based on radio channel measurements, a geometrical model of trees within a virtual scenery is proposed that accurately and realistically models the reflective behavior and dispersion in delay versus time due to treetop scattering.

INTRODUCTION

Compared to radio channel modeling for digital communications, channel modeling for satellite positioning, and especially for GNSS positioning applications, is still in its beginnings. Only since recent years realistic channel models have been proposed, for example for urban [2][4], sub-urban [5] and pedestrian [3] scenarios.

The wave propagation effects caused by roadside trees and alleys are very pertinent to channel modeling aspects for GNSS applications. Trees close to the road cause periodic deep fades of the received signal in the order of -10 to -30 dB when the line-of-sight (LOS) path to the satellite is obstructed by a tree's canopy. In addition, the trees' canopies show strong scattering properties. As a result, the power of the signal re-scattered by a tree can even exceed the power of the obstructed LOS signal when the receiver is approaching the tree.

Shadowing of the LOS component combined with multipath components contributed by trees placed along the driven road occur frequently and repetitively in rural settings. Both effects pose technical challenges for GNSS receivers operating in surroundings dominated by tree vegetation. Various models exist for the prediction of signal attenuation due to vegetation for radio communication systems in their specific frequency range, see for example [6] and [7]. Common to the terrestrial communication setting is however the assumption of the transmitter being at 0° elevation.

Consequently, the modeling of the GNSS rural radio channel presented in this paper focuses on shadowing and scattering of single trees along a road. The proposed wide-band model is developed taking into account transmitter elevations from 10° to 70° for typical GNSS situations. Additionally, a prediction of the delay spreads of multipath components contributed by trees based on their geometry is evaluated. This parameter is crucial to GNSS receiver performance.

The paper is organized as follows: The Section "Experimental Investigation" describes the definition of the scenario, including the user vehicle trajectory, the tree positions, and the geometric parameters describing the tree trunk and the canopy. The Section "Model of scattering by an isolated tree" introduces the signal model and describes the proposed approximation of incoherent scattering caused by trees. The Section "Model for the CIR in a one-tree scenario" includes a comparison of the channel responses generated with the designed model to the responses collected in the measurement campaign. The concluding section summarizes the main features observed from the experimental data and addresses how these features are included into the proposed model.

EXPERIMENTAL INVESTIGATIONS

Channel measurements at a center frequency of 1.51 GHz and a bandwidth of 100 MHz, made in a rural environment are available to determine the model parameters. The transmitter was located at an elevation angle of 44°. An example of raw channel impulse responses (CIR) which were recorded while driving along the tree which is depicted in Fig. 1 is shown in Fig. 2. The component in the channel response contributed by the tree becomes apparent at t=594 s and drifts towards the LOS component as time elapses. Both components merge when the receiver vehicle drives below the tree (t = 596.8 s), which then obstructs the LOS signal.

From an electromagnetic propagation perspective, a treetop consists of a number of attenuating and scattering elements. Leaves cause mainly attenuation due to their water content, whereas structures at wavelength scale such as branches and forks induce scattering at *L*-band. To analyze these phenomena in their full complexity one has to conduct a finite-difference time-domain (FDTD) simulation. The high amount of processing power and memory needed to carry out such a simulation limits the application of the FDTD method to simple tree-like structures consisting of few branches and leaves [1]. Design of a model suitable for GNSS simulation requires a drastic simplification of the electromagnetic features of a tree. In such a simplified representation the trunk of a tree is modeled by means of cylinders with given radii and heights and its canopy is approximated by a spherical volume.

Fig. 1. Picture of a tree along the road driven by the receiver vehicle.

MODEL OF SCATTERING BY AN ISOLATED TREE

The proposed model approximates the canopy of a tree by a spherical volume which contains a plethora of point scatterers. The scatterers' positions are uniformly distributed within the volume. The point scatterers mimic the characteristic reflective behavior due to the trees' heterogeneous composition that can be seen in Fig. 2.

Figure 2 also shows that the component contributed by the tree is dispersive in delay. Delay dispersion is due to the geometrical extent of the tree. We assume that the spherical volume representing the canopy of the tree has radius 5.5 m. The minimum and maximum delays of the components contributed by the scatterers in the canopy are determined by respectively the minimum and maximum path lengths to the receiver through the canopy in the scenario depicted in Fig. 3. The minimum delay $\tau_{\min}(t)$ and the maximum delay $\tau_{\max}(t)$ computed from this scenario are reported versus time in green and red respectively in Fig. 2. It can be seen that the component contributed by the tree is mainly confined between these two curves.

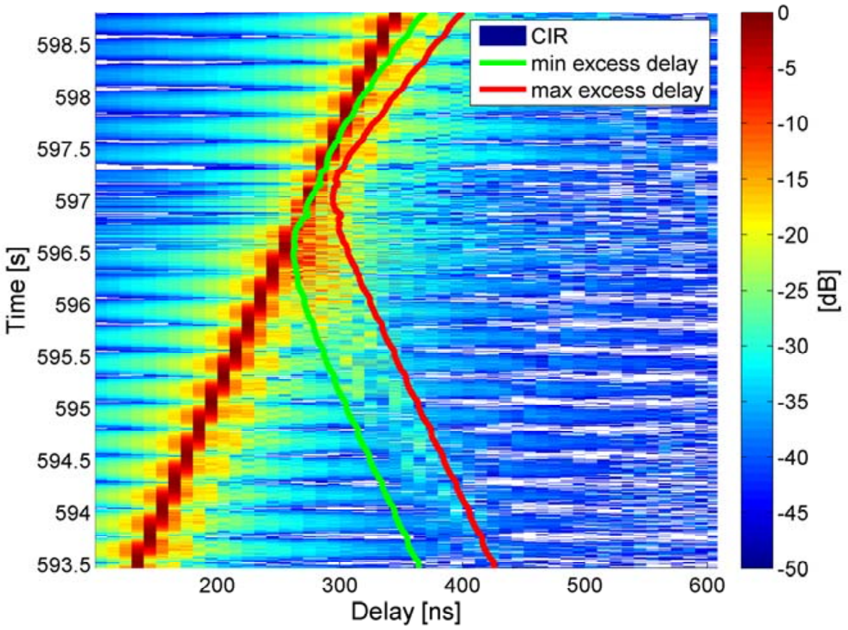

Fig. 2. Example of a channel impulse response measured when a receiver passes by a single tree.

However, when the vehicle drives close to the tree at time t = 596 s until t = 597.5 s the delay spread becomes much larger. We conjecture that this effect is due to multiple scattering inside the tree canopy. The proposed model accounts for this effect by including multiple-bounce scattering up to order three. Moreover, the positions of the scatterers in the canopy are redrawn whenever the angle $\alpha(t)$ depicted in Fig. 3 changes more than 1° to mimic the increasing dynamic fluctuations observed when the receiver drives closer to the tree.

The proposed model relies on a virtual scenario described by the vehicle trajectory, the location of the stationary transmitter, and a certain number of trees. Each tree is characterized by its position, the height t_h and radius t_r of its trunk, and the radius c_r of its canopy (see Fig. 4). The trunk reaches half way through the canopy. The trunk and the scatterers in the canopy have the same constant scattering coefficient. The ground is assumed to be flat.

Once the positions of the transmitter, the receiver, and the trees are defined, the following parameters can be determined from the geometrical constellation depicted in Fig. 4:

- the height of the receiver antenna,
- the distance transmitter – tree $d_{\text{tx-tree}}(t)$,
- the distance tree – receiver $d_{\text{tree-rx}}(t)$,
- the total path length from the transmitter to the receiver via a scatterer in the canopy

$$d_{\text{ref}}(t) = d_{\text{tx-tree}}(t) + d_{\text{tree-rx}}(t) \tag{1}$$

- the excess path length via a scatterer

$$d_e(t) = d_{\text{ref}}(t) - d_{\text{LOS}}(t) \tag{2}$$

- the excess delay of the component in the channel response contributed by a scatterer

$$\tau_e(t) = d_e(t)/c_0 \tag{3}$$

- the angle $\alpha(t)$ between the transmitter, the canopy scatterer, and the receiver. For multiple-bounce scattering, $\alpha(t)$ is determined while considering the last scatterer.

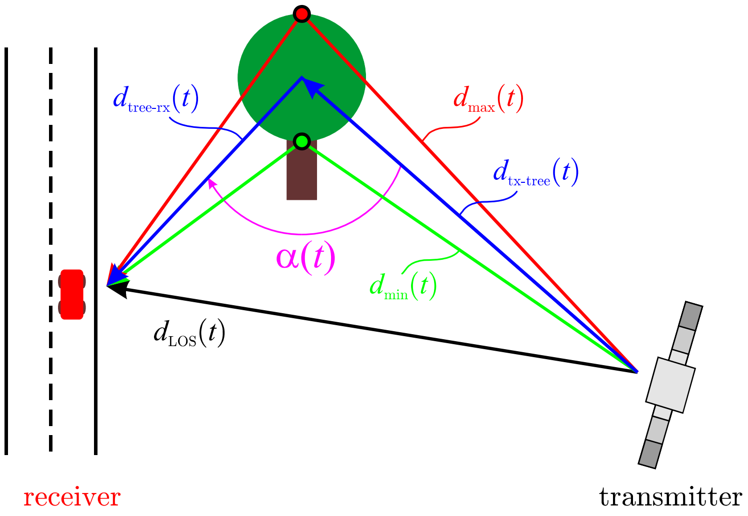

Fig. 3. Top view of the geometry of the propagation paths from the transmitter to the receiver via scatterers in the tree canopy.

MODEL FOR THE CHANNEL IMPULSE RESPONSE IN A ONE-TREE SCENARIO

This section describes the derivation of the time-varying channel impulse response for the setting shown in Fig. 3. In the model the time-varying impulse response of the radio channel between the transmitter and the receiver consists of the contribution of the LOS propagation path and the contribution resulting from scattering by the tree canopy.

The specular LOS component is given by

$$h_{\text{LOS}}(t,\tau) = a_{\text{LOS}}(t)\delta(\tau - \tau_{\text{LOS}}(t)) \, . \tag{4}$$

The component originating from scattering by the tree is modeled as the sums of specular contributions by a number D of point scatterers located in the tree canopy:

$$h_{\text{tree}}(t,\tau) = \sum_{i=1}^{D} a_i(t)\delta(\tau - \tau_i(t)) \, . \tag{5}$$

Each contribution is characterized by its specific weight $a_i(t)$ and delay $\tau_i(t)$.

The time-varying channel impulse response is the sum of (4) and (5):

$$h(t,\tau) = a_{\text{LOS}}(t)\delta(\tau - \tau_{\text{LOS}}(t)) + h_{\text{tree}}(t,\tau) = a_{\text{LOS}}(t)\delta(\tau - \tau_{\text{LOS}}(t)) + \sum_{i=1}^{D} a_i(t)\delta(\tau - \tau_i(t)) \, . \tag{6}$$

The attenuation of the LOS component due to obstruction by the canopy and the trunk is modeled using a constant specific attenuation of 2 dB/m depending on the length of the path propagating through the canopy and the trunk, respectively. The weights of point scatterers in the tree canopy are normalized with respect to the absolute weight of the LOS path. An unattenuated reception of the LOS component is hereby represented by $|a_{LOS}(t)| = 1$. The time-varying power of path i is denoted by $P_i(t)$. The phases of the weights in (6) are determined by their corresponding propagation path lengths. With these definitions and assumptions the complex weights of the LOS path and the *i*th path through the tree canopy reads

$$a_{\text{LOS}}(t) = \sqrt{P_{\text{LOS}}(t)} \cdot e^{j2\pi(f_c/c_0)\cdot d_{\text{LOS}}(t)} \tag{7}$$

and

$$a_i(t) = \sqrt{P_i(t)} \cdot e^{j2\pi(f_c/c_0)\cdot d_i(t)} \tag{8}$$

respectively.

Under the assumption that the path weights are uncorrelated, the power scattered by the tree is

$$P_{\text{tree}}(t) = \sum_{i=1}^{D} P_i(t) \tag{9}$$

We observe from the measurement data that the power scattered by the tree is larger the smaller $\alpha(t)$ is.

When the vehicle is entering the canopy shadow, in which case $\alpha(t)$ is close to 180°, the power re-scattered by the tree is minimum. We model this behavior with a functional dependency according to $\cos(\alpha(t)/2)$.

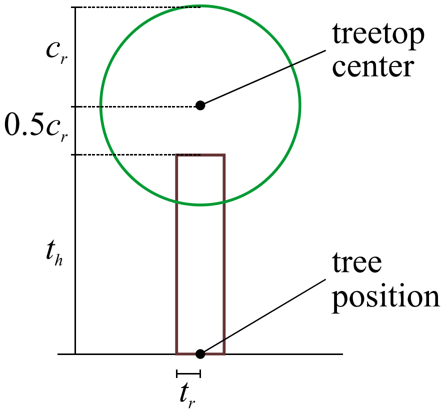

Fig. 4. Geometric model of a tree with its parameters.

PARAMETER SETTING

The rate with which the (temporal) samples of the channel impulse response are generated depends on the maximum absolute Doppler frequency, which in turn is a function of the receiver velocity. Considering relativistic effects the Doppler frequency depends on the carrier frequency f_c and the vehicle speed v according to

$$f_D = f_c \cdot \sqrt{\frac{c_0 + v}{c_0 - v}} \tag{10}$$

with $c_0 = 3 \cdot 10^8$ m/s denoting the speed of light. For a maximum vehicle speed $v = 30$ m/s and a carrier frequency $f_c = 1.51$ GHz the maximum Doppler frequency offset is

$$f_{D,\Delta} = f_D - f_c = f_c \cdot \sqrt{\frac{c_0 + v}{c_0 - v}} - f_c = 151 \text{ Hz}\,. \tag{11}$$

Invoking Nyquist's Sampling Theorem, the channel impulse response has to be sampled in time at least with rate

$$f_{\text{CIR,min}} = 2 f_{D,\Delta} = 302 \text{ Hz} \tag{12}$$

for this case.

We select a parameter setting of the model (receiver speed, tree parameters, transmitter elevation, etc.) in such a way to approximate the scenario prevailing when the measurement data used to obtain the time-variant CIR depicted in Fig. 2 were collected. The density of point scatterers in the canopy is chosen equal to 0.11 scatterers/m^3. Fig. 5 depicts the resulting CIR filtered (interpolated) using a low-pass filter with bandwidth equal to that used to collect the measurement data.

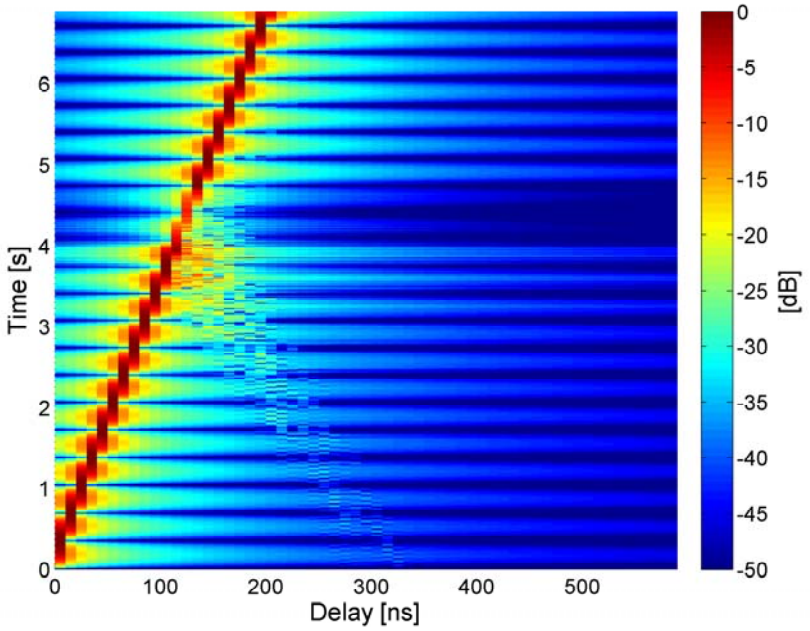

Fig. 5. Example of one realization of the time-variant CIR computed with the proposed model (6).

CONCLUSIONS AND OUTLOOK

This paper proposes a wide-band model characterizing the time-variant channel impulse response in a scenario where a mobile receiver (vehicle) is driving through an alley consisting of isolated trees. The mechanisms critical to positioning in such a scenario are the obstruction of the direct path to the satellite the multipath propagation induced by tree scattering, and the high dynamic of these effects.

This model is designed for the purpose of signal-level simulation of the performance of satellite navigation systems and synchronization applications in such a scenario, which is frequent in land-mobile environments.

In the model the channel impulse response includes the component contributed by the propagation path between the satellite and the receiver and the components scattered by the trees. The former component may be obstructed by trees depending on the geometrical configuration. The component scattered by a tree is made of the sum of contributions from point scatterers evenly distributed in the tree canopy. The attenuation is determined by specific attenuations for canopy and trunk. The absolute transmitter position can be defined and thus different transmitter azimuths and elevations can be used in the model.

The power and the pace of the fluctuations of the component scattered by a tree depends on the prevailing geometric configuration mobile receiver – tree – transmitter. Relevant parameters in this respect are the distance mobile receiver – tree and the angle determined by the positions of the receiver, the center of gravity of the canopy and the transmitter.

Despite its simplicity the proposed model generates time-variant channel impulse responses very similar to those extracted from channel impulse response measurement data of scattering caused by isolated trees. The delay-spread observed in the measured impulse response is modeled using multiple-bounce scattering of maximum order three. The model can be used to investigate how the propagation conditions prevailing in such an environment affect the performance of a GNSS receiver.

In a next step towards a realistic and comprehensive channel model for satellite positioning in rural environments, further propagation features typical for such a scenario, like scattering by electricity poles, buildings, and forests, will be included.

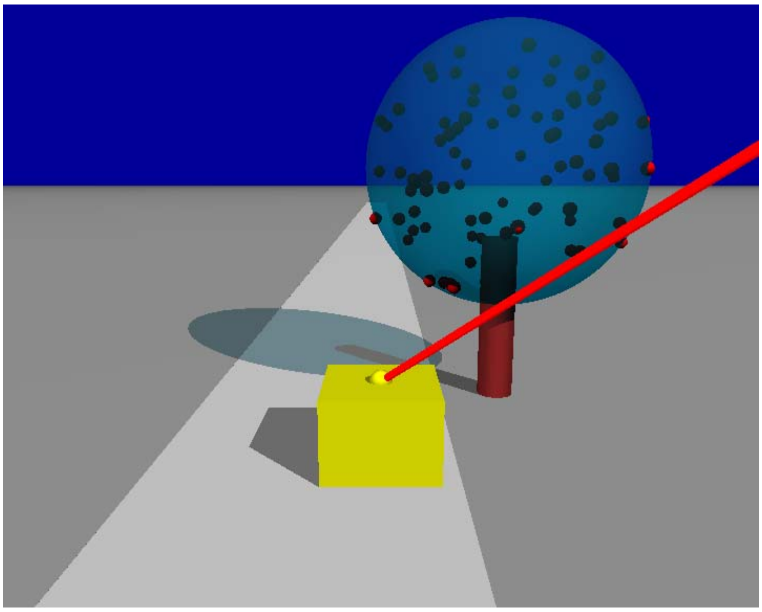

Fig. 6. Visualization of the rural channel model’s virtual scenery.

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