Modeling the GNSS Rural Radio Channel: Wave Propagation Effects caused by Trees and Alleys

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BIOGRAPHIES

F. M. Schubert studied Electrical Engineering and Information Technology at the University of Karlsruhe, Germany. Since 2007 he is member of the scientific staff at the Institute of Communications and Navigation, German Aerospace Center (DLR). During his studies, he was involved in a research project concerning inertial measurement unit (IMU) calibration at the Delft University of Technology, Delft, The Netherlands, and he developed a simulation software for a robust powerline communication system at the Massachussetts Institute of Technology, Cambridge, USA. Since 2007, F. M. Schubert is participating in the European Space Agency's Networking/Partnering Initiative (NPI) together with DLR and the University of Aalborg working towards his Ph.D. He is working on topics such as radio channel modeling for satellite navigation and the influences of harsh multipath environments on satellite navigation receiver performance.

A. Lehner studied Mechatronics at the Johannes Kepler University in Linz. Since 2001, he is a research scientist at the German Aerospace Center. In 2007 he received a Ph.D. in Electrical Engineering from the University of Erlangen-Nuremberg, Germany. His research and project work focuses on the analysis of multipath and interference effects in satellite navigation systems and the design of inter-vehicle communication systems.

A. Steingass received his Electrical Engineering diploma in 1997 from the University of Ulm, Germany. Since then he has been a research scientist at the German Aerospace Center. He has been involved in several projects in the area of satellite navigation and location-dependent mobile services. In 2002 he received his doctoral degree from the University of Essen.

P. Robertson received a Ph.D. from the University of the Federal Armed Forces, Munich, in 1995. He is currently with DLR, where his research interests are navigation, sensor based context aware systems, signal processing, and novel systems and services in various mobile and ubiquitous computing contexts.

B. H. Fleury received the diploma in Electrical Engineering and Mathematics in 1978 and 1990 respectively, and the doctoral degree in Electrical Engineering in 1990 from the Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland.

Since 1997 B. H. Fleury has been with the Department of Electronic Systems, Aalborg University, Denmark, as a Professor in Communication Theory. He is the Head of the Section Navigation and Communications, one of the eight labs of this department. Since April 2006 he has also been affiliated as a Key Researcher with Forschungszentrum Telekommunikation Wien (FTW), Austria. B. H. Fleury's current areas of research include stochastic modelling and estimation of the radio channel, especially for multiple-input multiple-output (MIMO) applications and in fast time-varying environments, and iterative information processing with focus on efficient, feasible advanced receiver architectures.

R. Prieto-Cerdeira received his Telecommunications Engineering degree in 2002 from the University of Vigo, Spain, and followed postgraduate studies on Space Science and Radioastronomy in Chalmers University of Technology, Gothenburg, Sweden. Since 2004, he has been with the European Space Agency (ESA/ESTEC) in the Wave Interaction and Propagation Section where he is responsible of the activities related to radiowave propagation in the ionosphere and local environment for Global Navigation Satellite Systems (GNSS) such as Galileo and EGNOS projects, satellite mobile communications, and remote sensing and planetary radio science projects.

ABSTRACT

Among the various physical influencing factors with the potential to degrade the overall performance of a global navigation satellite system (GNSS), the propagation mechanisms in the channel between a satellite and the mobile receiver play a central role. Especially multipath propagation and signal shadowing may cause high ranging, and hence positioning, errors in current receivers.

Although new signals and ranging codes with higher bandwidths become available, the principal issue of multipath propagation inherent to the time-varying GNSS radio channel cannot fully be eliminated. Detailed analysis and knowledge of the radio channel characteristics under realistic conditions are essential to identify and eventually be able to mitigate these disturbances.

The goal of the presented work is to understand the propagation conditions in rural settings for vehicular land-mobile users. As a contribution to the design of a comprehensive GNSS rural channel model, the effects caused by single trees are investigated. Even though individual trees spaced afar from each other along a road do not cause much harm to the smoothing tracking algorithm of a delay-lock-loop (DLL) of GNSS receiver, an alley of tree can profoundly impact the tracking performance of the DLL.

1 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], suburban [5] and pedestrian [3] scenarios. The wave propagation effects caused by roadside trees and alleys are very pertinent to channel modelling aspects for GNSS applications.

Trees close to the road cause periodic deep fades in the order of -10 to -30 dB of the signal when the line-of-sight (LOS) signal is shadowed by a tree's canopy. In addition, the trees' canopies show strong reflective and scattering properties. As a result, the power of the scattered signal can even exceed the power of the LOS signal when the receiver is approaching a tree.

Deep fades combined with strong scattered reflections 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.

Consequently, the modeling of the GNSS rural radio channel presented in this paper focuses on shadowing and scattering of single trees along a road. Recorded channel measurements of a ride by an alley is used in a time-domain simulation to demonstrate the effect of an alley on a GPS receiver's performance.

The paper is organized as follows: Section 3 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. Section 4 introduces the signal model and describes the proposed approximation of incoherent scattering caused by trees. Section 5 includes a comparison of the channel responses generated with the designed model to the responses collected in the measurement campaign. The imposed stress on a GPS tracking loop caused by the propagation conditions resulting from a ride through an alley is examined in Section 6. The concluding Section 7 summarizes the main features observed from the experimental data and addresses how these features are included into the proposed model.

2 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) are shown in Fig. 3. The component in the channel response contributed by the tree becomes apparent at $t = 594.xx$ s and drifts towards the LOS components as time elapses. Both components merge when the receiver vehicle drives below the tree ($t = 596.8$ s), which then blocks the LOS signal.

Physically, 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 phenomenas 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 simulations has limited their applications to small tree-like structures consisting of few branches and leaves [1]. Design of a model suitable for GNSS simulation requires a drastic simplification of the complex physical features of a tree. Tree trunks are modeled by cylinders with given radii and heights and the canopy is approximated by a spherical volume.

3 MODEL OF SCATTERING BY AN ISOLATED TREE

The proposed model approximates the tree canopies by spherical volumes which contain a plethora of point scatterers. The scatterers' positions are uniformely distributed within the volume. The point scatterers mimic the characteristic reflective behaviour due to the trees' heterogeneous composition that can be seen in Fig. 3. As can be seen in Fig. 2 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 via the canopy in the scenario depicted in Fig. 3. The minimum and maximum delays computed from this scenario are re-

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

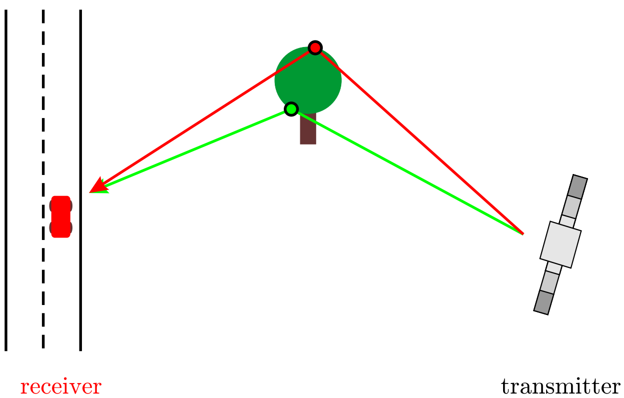

Figure 2. Minimum and maximum path lengths to the receiver vehicle via the canopy.

ported in green and red respectively in Fig. 2 versus time. It can be seen that the component contributed by the tree is mainly confined between these two curves. 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's 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 α (see Fig. 3) changes more than 1° to mimic the increasing dynamic fluctuations as the receiver drives closer to the tree.

The proposed model generates a virtual scenario consisting of 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.

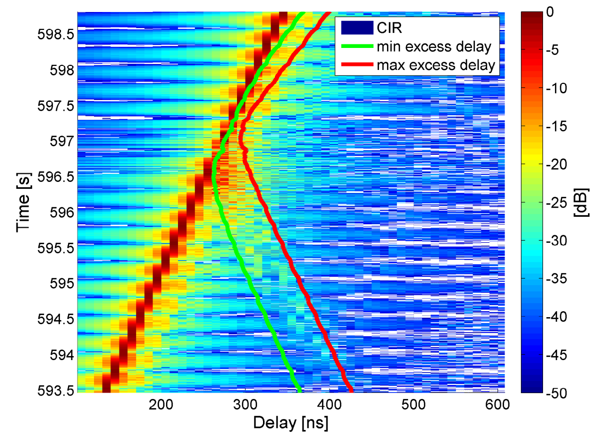

Figure 3. Example of a channel impulse response measured when a receiver passes by a single tree.

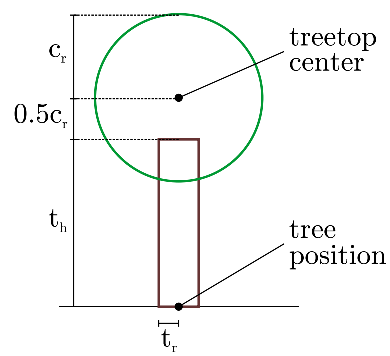

Figure 4. Geometric model of a tree with its parameters.

Once the positions of the transmitter, receiver, and the trees are defined, the following parameters can be determined according to Fig. 5:

- the antenna height,
- 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

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

- the excess delay due to a scatterer

$$\tau_{\text{exc}}(t) = \frac{d_{\text{exc}}(t)}{c_0}, \tag{3}$$

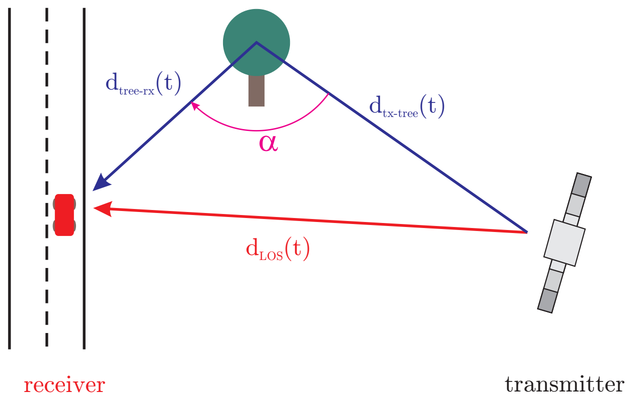

Figure 5. Top view of the geometry of the propagation paths from the transmitter to the receiver.

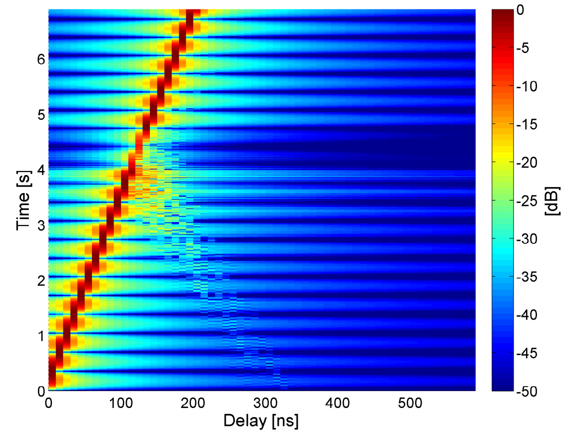

Figure 6. Example of one realization of the time-variant CIR 6.

- and the angle α between the transmitter, the canopy scatterer, and the receiver. For multiple-bounce scattering, α is determined from the last scatterer.

4 MODEL FOR THE CIR IN A ONE-TREE SCENARIO

This section describes the derivation of the time-varying channel impulse response for the setting shown in Fig. 5. 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

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

where $\alpha_{\text{LOS}}(t)$ and $\tau_{\text{LOS}}(t)$ denote the complex weight and the delay of the component, and $\delta(\tau)$ is the Dirac impulse.

The component originating from scattering by the tree is modeled as the sums of specular contributions by a time-varying number $D(t)$ of point scatterers located in the tree canopy:

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

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):

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

The attenuation of the LOS component due to shadowing by the treetop and the trunk is modeled using a constant specific attenuation dependent on the length of the path that is 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 receiption of the LOS component is hereby represented by $|a_{\text{LOS}}(t)| = 1$. 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 length. Under these definitions and assumptions the complex weights of the LOS path and the ith path through the tree canopy reads

$$a_{LOS}(t) = \sqrt{P_{\text{LOS}}} \cdot e^{j\cdot 2\pi \frac{f_c}{c_0} \cdot d_{\text{LOS}}(t)}, \quad (7)$$

and

$$a_i(t) = \sqrt{P_i(t)} \cdot e^{j\cdot 2\pi \frac{f_c}{c_0} \cdot d_i(t)}, \quad (8)$$

respectively.

The power scattered by the tree is

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

We observe from the measurement data that the power scattered by the tree is larger then α is smaller.

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

5 PARAMETER SETTING

The rate with which the (temporal) samples of the channel impulse response are generated will depend 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

$$f_D = f_c \cdot \sqrt{\frac{c_0 + v}{c_0 - v}}. \quad (10)$$

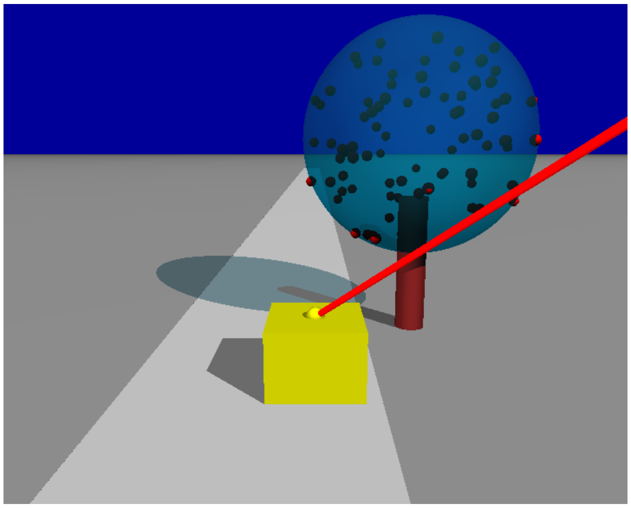

Figure 7. Visualization of the rural channel model's virtual scenery.

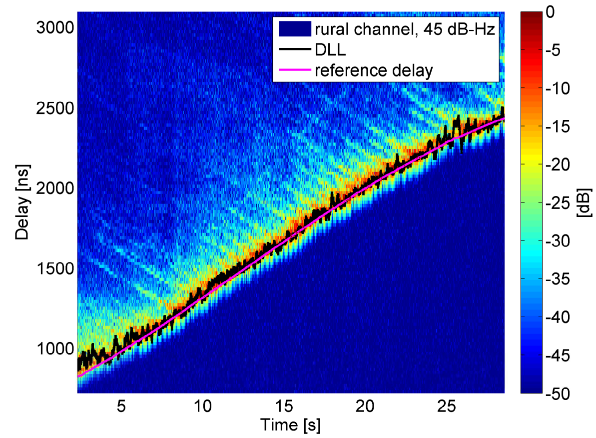

Figure 8. Example of a time-variant channel impulse response generated with the proposed model. The black line shows the delay estimated by a DLL tracking the GPS C/A code. The magenta curve represents the reference range.

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

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

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

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

for this case. We select a parameter setting for the model (receiver speed, tree parameters, transmitter elevation, etc.) which approximates the scenario prevailing when the measurement data used to obtain the time-variant CIR depicted in Fig. 3. The density of point scatterers in the canopy is chosen equal to $0.11\,\mathrm{scatterers/m^3}$. Fig. 7 depicts the resulting CIR filtered (interpolated) using a low-pass filter with bandwidth equal to that used to collect the measurement data.

6 SIMULATION OF A RIDE THROUGH AN ALLEY USING CHANNEL MEASUREMENT DATA

We can expect that a DLL easily copes with the temporary shadowing of the path to the satellite combined with the scattering from a single tree, especially at usual speeds of up to $100\,\mathrm{km/h}$ in rural areas. Yet, such effects pose high stress on the GNSS receiver algorithm when it occurs frequently. This happens when the receiver drives below a row of trees or an alley. Fig. 8 shows the estimated time-variant CIR computed from measurements collected during a 30 s ride on a road lined by trees. The performance of the DLL of a GPS C/A code with discriminator chip-spacing set to 1 chip was simulated using this CIR and noise level set to 45 dB-Hz. The delay estimated by the DLL is also reported in Fig. 8. The resulting range rms error is 32.4 m.

7 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.

The model 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 treetop 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 between the mobile receiver and the tree as well as 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 measurement data of isolated trees. The model is used to investigate how the propagation conditions prevailing in such an environment affects 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 environments, like scattering by electricity poles, buildings, and forests, will be included.

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