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Published in:
Proceedings of the 4th European Conference on Antennas and Propagation (EuCAP 2010), 12-16 April 2010, Barcelona, Spain

Published: 01/01/2010

Document Version
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

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Link to publication

Citation for published version (APA):
Angular Dispersion of Radio Waves due to Rough Surface Scattering in Mobile Channels

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Abstract— This paper describes the modelling of scattering caused by irregular surfaces as a basis for implementation in ray-tracing methods. An approach is presented in a first attempt to model the dispersive effects, caused by scattering on surfaces which have “random” irregularities, directly at the receiver. The method is based on assigning an effective stochastic roughness to a specific surface. The scattering effects caused by the surface roughness include the combined effects of both the surface irregularities and changes in material properties. The results of simulations and measurements show that the method can be used to model the dispersive effects of rough surface scattering in a manner similar to using the reflection reduction factor for Gaussian surfaces, except that the reduced power in the specular direction is distributed in the angular domain.

I. INTRODUCTION

The prediction of radio propagation by ray-tracing or ray-launching generally assumes that reflections from buildings and other seemingly plane surfaces occur as specular reflections. The effects of diffuse scattering and angular dispersion caused by material irregularities are often not accounted for. The results in [1] have demonstrated that in reality the specular reflection component exhibits angular dispersion. This causes multiple rays to arrive at the receiver from the specular direction and in a small angular sector centered on it.

For next generation 4G radio systems (using e.g. smart-antennas, MIMO) the angular dispersion of radio waves is becoming increasingly important. Due to dispersion, waves no longer have well-defined angles-of-arrival (AOAs). In beamforming systems this strongly influences the effect of nulling out interference or directing a beam to obtain a maximum signal level [2]. In MIMO systems the angular dispersion also has a major effect on capacity and diversity gain [3].

These effects need to be incorporated in deterministic propagation prediction models in an efficient way. The problem is addressed in several recent publications and methods have been proposed that include diffuse scattering, which causes angular dispersion [4-11]. The reduction of the model complexity and the ability to calibrate them using only a limited number of measurements are important issues.

In this paper a new approach is proposed in which angular dispersion is determined directly at the receiving position using a stochastic effective roughness method. In Section II, the model is described as a canonical model and simulation results are presented in Section III. The results of measurements that are used to calibrate the model and to compare with simulations are reported in Section IV. The results show that the model presented in Section II is capable of including the effects of rough surface scattering and that accurate calibration can be performed using high-resolution measurements.

II. MODELING ANGULAR DISPERSION AT THE RECEIVER

The model presented in [11] was used as starting point for our work. It is based on modelling the effect of a statistically rough surface as a random array of elements (e.g. facets), the individual scattering characteristics of which are known. The distribution of the elements then determines the overall scattering effect of the surface in the delay and angular domain.

In the new approach the scattering effects are included in a similar stochastic manner, but the angular dispersion is modelled directly at the receiver position instead of determining it via the reflective surface. The scattering caused by surfaces is modelled as resulting from an effective surface roughness, which means that the scattering caused by the real physical properties (height fluctuations and material properties) of the surfaces are modelled via a rough surface with properties that reflect the same scattering behaviour as the real surface.

Consider the scenario in Figure 1. A surface is illuminated by a spherical wave that originates from the Transmitter (Tx). It is assumed that there is no line-of-sight between the Tx and the receiver (Rx), and that each ray has only a single interaction with the surface on its path between Tx and Rx. If a Gaussian rough surface is considered, as described in [11],
characterized with a standard deviation of surface height $\sigma_h$ and a correlation length $L_c$, the distribution of surface element slopes can be used to describe the distribution for the reflected direction of departure from the surface $\phi_s$ as [5]:

$$P_{\phi_s}(\phi) = \frac{L_c}{4\sigma_h \sqrt{\pi \cos^2 \left( \frac{\phi + \phi_s}{2} \right)}} \exp \left\{ - \frac{L_c \tan \left( \frac{\phi + \phi_s}{2} \right)^2}{2\sigma_h} \right\}.$$

In the scenario depicted in Figure 1, the angle $\phi_{Rx}$ from which each ray arrives at Rx is uniquely related to an angle $\phi_i$. As a result, the distribution of the incoming scattered waves at the receiver can be determined in closed form. This distribution is found to be given by [12]:

$$P_{\phi_{Rx}}(\phi_s) = \exp \left\{ \frac{-L_c}{2\sigma_h} \left( \frac{\phi_s - \phi_{Rx}}{2\lambda} \right)^2 \right\} \frac{L_c}{1 + \tan^2 \left( \frac{\phi_s - \phi_{Rx}}{2\lambda} \right)} \left[ d_{Rx}(1 + \tan^2(\phi_{Rs})) + d_{Tx}(1 + \tan^2(\phi_s)) \right] d_{Rx} \frac{1}{\sqrt{2\pi}} d_{Tx} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{2\pi}}.$$

Now that the probability distribution function for the direction of incoming waves is known at the receiver, the scattering behaviour of a rough surface can be determined directly and accurately. Since the power density of an incoming wave in a small solid angle $d\theta$ around direction $\phi_{Rx}$ is proportional to the probability, the electric field is weighted by the square-root of the probability. An independent random phase shift, related to the height distribution, can also be added to the electric field through multiplication by $\exp(-j\psi_i)$ with:

$$\psi_i = \frac{-2\pi h}{\lambda (\cos \phi_i + \cos \phi_{Rx})}.$$

The electric field in terms of $\phi_{Rx}$ can then be written as:

$$E_{\phi_{Rx}}(\phi_{Rx}) = E_0 A(s_i, s_j)c^{-jk(s_i+s_j)} R(\phi_i, \phi_{Rx}) \sqrt{P(\phi_{Rx})} e^{-j\psi_i},$$

where $E_0$ is the field at a reference distance from Tx, $R(\phi_i, \phi_{Rx})$ represents the Fresnel reflection coefficient, $\exp(-jk(s_i+s_j))$ represents the total phase shift due to the free-space propagation before and after the interaction with the surface and $A(s_i, s_j)$ represents the divergence factor corresponding to the total path length travelled by any ray between the Tx and the Rx.

The results for the coherent and incoherent part of the received power, relative to that of a specular reflection, are determined from a large number of realisations, in which the phase shift caused by the random height fluctuations is changed in accordance with the change in path lengths brought about by the surface irregularities.

Using the new approach, the angular dispersive effects of rough surface scattering can be included directly at the receiver, which otherwise would require many more complex Monte-Carlo simulations. Instead of only the specular component, a stochastic contribution is added according to the surface parameters, which includes both the coherent and incoherent scattered energy.

### III. Simulation Results

The results of the reflected power in four scenarios with different Rx and Tx setups and surface roughness parameters are presented in Figs. 2 and 3. At the receiver the total, coherent and incoherent power scattered by the surface is determined. The resulting angular spread, $\sigma_{Rx}$, for the total received power is also shown. The results are obtained from 1000 realisations with quantization $d\phi = 1'$. The properties of the surfaces represent a moderately rough surface, for which $\sigma_h = 0.1\lambda$, and in which case the incoherent component is dominant and a smoother surface, for $\sigma_h = 0.05\lambda$, and in which case the coherent component is dominant. The well known scalar reflection reduction factor for Gaussian rough surfaces, defined as:

$$R_{sc} = e^{-2(\sigma_h \cos \phi)^2}$$

is also plotted for comparison. The validity of $R_{sc}$ assumes $L_c$ → 0 and is limited up to approximately four times the Rayleigh criterion, which means $\sigma_h < 0.125\lambda$. Note that the absolute value of $R$ depends on $d\phi$ and is not important here.

**Fig. 2** Simulation results of received power versus the angle of incidence at the receiver using the scenario presented in Figure 1 and the following parameters: $dTx = 10\lambda, dRx = 5\lambda, D = 10\lambda, L_c = 10\lambda$. In (a) $\sigma_h = 0.05\lambda$ and in (b) $\sigma_h = 0.1\lambda$. The angular spread for the total power is represented by $\sigma_{Rx}$.

**Fig. 3** Simulation results of received power versus the angle of incidence at the receiver using the scenario presented in Figure 1 and the following parameters: $dTx = 100\lambda, dRx = 5\lambda, D = 10\lambda, L_c = 10\lambda$. In (a) $\sigma_h = 0.05\lambda$ and in (b) $\sigma_h = 0.1\lambda$. The angular spread for the total power is represented by $\sigma_{Rx}$.
spread \((\sigma_\phi \rightarrow 2\sigma_\phi)\). The effect on \(\sigma_\phi\) due to the position of the Tx, with respect to the surface, is also observed. In this scenario, moving the Tx closer to the surface increases \(\sigma_\phi\), which is mainly caused by the difference in the specular reflection direction. In all scenarios a similar behaviour of \(R_\sigma\), the reduction of the specular component, is observed. Instead of giving a reduction for the specular component, the proposed approach produces both coherent and incoherent components in the scattered field and accounts for the divergence of the power in the angular domain.

IV. CALIBRATION AND VERIFICATION BY MEASUREMENTS

With the aid of the model presented in Section II, it is possible to include angular dispersive effects directly at the receiver in ray tracing based propagation prediction models. Because the model is based on assuming an effective roughness for each surface, characterisation and calibration by measurements is necessary. In order to calibrate the model in terms of effective surfaces roughness, high resolution channel data can be used. If measurements are performed at a known distance from the surface, the angular spread and power can be used to calibrate the statistical properties of the surface.

The measurement system and methods presented in [12,13] allow to characterise and isolate the scattering effects of specific building faces with high resolution. In order to perform a first characterisation and calibration, this section presents the results of measurements that were performed on a large building face at the campus area of the Technische Universiteit Eindhoven (TU/e) in Eindhoven, the Netherlands. The results were used to calibrate the model and to compare with the simulation results.

A. Measurement setup

The measurement scenario is presented in Figure 4. The transmitter position is marked by Tx. The transmitting antenna consisted of an 8-dBi waveguide horn antenna with an azimuthal half-power-beam-width of 55° and was positioned at a height of 3.5 m. The main beam of the transmitting antenna was pointed southward, such that it illuminates building TR, shown in Figure 5. Building TR is a four-storey high building of approximately 100 m long with a rough surface consisting mainly of windows and steel bars. Several scattered trees and cars are also located close to building TR. The reflections and scattering effects of building TR were characterised by moving the receiver over a trajectory of 116 m along side building TR, the beginning of which is marked by Rx1. Measurements were also performed over a trajectory of 60 m perpendicular to the long side of building TR, the beginning of which is marked by Rx2. The measurement trajectories are represented by dotted lines and the numbers along the trajectory correspond to the snapshot-set numbers. The receiving antenna, mounted on top of a vehicle at a height of 3.5 m, was moved at a nearly constant speed of about 12 and 9 km/h for the first and second trajectory, respectively.

For the first measurement trajectory 5990 and for the second 3990 snapshot sets of \(K = 10\) snapshots are used for the AOA estimation, which means a channel estimate is available at least every 2 cm corresponding to 0.15 wavelengths.

B. Results

To isolate the scattering effects of building TR the multipath component (MPC) estimates from the measurements were clustered using the clustering algorithm presented in [14]. The azimuth angles along both trajectories of the MPC cluster corresponding to building TR are presented in Figure 6. Here, the separate multipath contributions are summed with a resolution of \(d_\phi = 1^\circ\) for a fair comparison with the simulation results. The effect of dispersion in the angular domain is clearly visible in both scenarios. The results of Rx1 show a stronger more specular component as well as a large band of MPCs, the centre of which changes along the trajectory. Apart from the first 25 m, the band of MPCs exists mainly on both sides around the specular component. Because the building is finite, during the first 25 m additional scattering effects only occur at the side of the specular component where the building is visible. The results of Rx2 also show a stronger more specular component and a band of MPCs that extends in the angular domain when the receiver moves towards building TR. Here, the effects of the finite building are also visible in that the band of MPCs exists mainly on one side of the specular component. For simplification, only the azimuth angles will be considered in this analysis.
C. Calibration

The results of ray-based propagation models are highly influenced by the electromagnetic properties of the materials of the reflective surfaces. In order to obtain valid results, the calibration of these models is necessary. The material parameters, in terms of relative permittivity \( \varepsilon_r \), can be determined from channel sounding measurements by relating the corresponding multipath contributions from the simulations to the measurements. The difference in power of the individual contributions can then be used to change the values for \( \varepsilon_r \). When the roughness of surfaces is also considered, the surface roughness parameters need calibration as well. This can be done by using the results from accurate directional measurements and comparing values for the angular spread and the total cluster power in the simulations to the measurements at one or more points along the trajectory.

To calibrate the surface roughness from the measurements, the average intra-cluster angular spread is determined along a part of the trajectory of Rx1. This is done in order to average out the additional scattering and shadowing effects caused by other objects in the environment such as vegetation and cars.

Fig. 6  Estimated azimuth angles from the measurements for the MPC cluster corresponding to building TR for (a) receiver setup Rx1 and (b) receiver setup Rx2. The horizontal black dotted lines represent the visibility regions obtained from the building geometry and the measurement scenario.

The angular spread is determined between \( 3000 \leq k \leq 4000 \) for each \( k \) from a total of 50 snapshots \( k - 25 < k < k + 25 \). These 50 snapshots are taken along a trajectory of less than a metre, where the composition of the arriving waves is assumed to be stationary. The estimates from these 50 snapshots are used to determine the power-angular profile with \( d\varphi = 1^\circ \), from which the actual angular spread is determined. The result of such an angular profile for \( k = 4000 \) is visualised in Figure 7. The average angular spread is determined to be \( <\sigma_\varphi> = 9.9^\circ \) and the averaged total power in the cluster is \( <P_{tot}> = -27.9 \text{ dBm} \). These parameters are used to calibrate the model such that it has the same angular spread and total power.

The roughness parameters of the model are set to generate the same angular spread as in the measurements. This is done by fixing \( L_c = 10\lambda \) and tuning \( \sigma_h \) to \( \sigma_h = 1.08\lambda \), which results in \( \sigma_\varphi = 9.9^\circ \).

Fig. 7 Power-angular profile determined from the estimated AOAs for receiver setup Rx1 between \( 3975 < k < 4025 \) and determined from calibrated simulations.

The Fresnel reflection coefficient for vertical polarisation \( R_v \) is to be calibrated such that the simulated total power of the cluster matches that of the measurements. The face of building Tr mainly consists of metal plating and structures, therefore \( R_v \) is expected to be close to one (\( \varepsilon_r \rightarrow -j\infty \)). The value for \( \varepsilon_r \) was set to \( \varepsilon_r = 1 - 106j \), which results in \( R_v = 1 \). This value for \( \varepsilon_r \) corresponds to the reflection from a 3 cm thick metal wall at 1.8 GHz as reported in [15]. The resulting average power from the simulation is now close to that of the measurements and equal to \( P = -28.2 \text{ dBm} \).

The calibrated model is used to predict the total power-angular profile along both trajectories, shown in Figure 8 (a) and (b). The total received power, almost equal to the power in the incoherent part, is shown here. The coherent part is more than 40dB below the incoherent part and is therefore not shown here. The result from a standard ray-based prediction tool is also plotted as a solid black curve in the same figure. Compared to the standard ray-based results the simulations based on the model in Section II now include dispersive effects caused by rough surfaces and calibrated by accurate measurements.

The results clearly show a similar dispersive behaviour compared to the measurements. Especially in Figure 8 (b) an increase in angular spread is observed along the trajectory. The stronger and more specular component that is observed in some parts in the measurement results is not visible in the simulations, which is a direct result from the Gaussian surface assumption. To include these effects, the use of other, perhaps more suitable distributions could be considered. The amount of total received power and the direction of the highest received power are, however, in good agreement.
The effects of the limited extent of the building are not included in the simulations. This effect is, however, observed in the measurements as a decrease in the angular spread if the receiver is at the beginning or moves towards the end of the building. This is most clearly shown at the start of trajectory Rx1, where almost no scattered energy is received from the part of the building on the west side of the trajectory. This is illustrated with dotted lines (diffraction points) as visibility region, which corresponds to the actual building face that is visible to the receiver. In order to take the finite building effects into account a visibility algorithm is required.

The result of the measurements and simulations of receiver setup Rx1 at $k = 4000$ that are shown in Figure 7, shows that a stronger more specular component is observed in the measurements.

If the effect of angular dispersion would not be taken into account and calibration would be based on the power of the more specular component, $P_{\text{\(\varphi\)}} = -30.8$ dBm between $89 < \varphi < 93^\circ$, the resulting simulation results would not only lack the angular dispersive effects, but would also result in an underestimation of the total power of about 3 dB, since $P_{\text{\(\varphi\)}} = -27.8$ dBm.

V. CONCLUSIONS

This paper addresses the importance of angular dispersion for future wireless systems caused by irregular surfaces and changes in dielectric and conductive material properties. A novel approach is presented in a first attempt to model the dispersive effects directly at the receiver. This model generates instantaneous realizations of the channel at the receiver and includes both the coherent and incoherent components.

The results of simulations show that the method can be used to model the dispersive effects of rough surface scattering in a similar way as using the reflection reduction factor for Gaussian surfaces, except that the reduced power in the specular direction is now distributed in the angular domain. The model can be calibrated with the aid of high-resolution measurement data, from which angular spread values can be determined. The results obtained from measurements on a rough building surface show that calibration is possible using measurements along a small trajectory and use them to predict the effects of scattering in a wider area.

REFERENCES


