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Diffraction: Modelling and relevance in radio communications

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Diffraction: Modelling and relevance in radio communications

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ABSTRACT

Radio wave propagation plays a major role in modern communications. However, waves can interact with both their environment and the transmission medium itself, and the physical effect of diffraction may occur. Depending on application and system design, diffraction can either distort the receive signal, or the effect can be exploited in a positive way to benefit from this phenomenon in wireless communications. The intention of this paper is to develop a deeper understanding of this effect in the context of radio communications. For this purpose, first considerations present the physical background and modelling approaches. Then, its special role in radio communications is discussed involving electromagnetic waves. Dedicated applications are presented together with considerations, how diffraction affects communications and how engineers cope with this effect to optimize the receive signal.

1 INTRODUCTION

This paper considers wireless radio communications based on electromagnetic wave propagation and focuses on the relevance of so-called diffracted waves. Due to the complexity of the topic and numerous modeling options, only selected aspects will be presented and discussed.

In general, there is a relationship between the wavelength λ and the frequency f of a wave: The wavelength is inversely proportional to the frequency as shown in Equation (1).

$$\lambda = \frac{c}{f} \tag{1}$$

Hereby, c is the propagation speed of the wave. The paper focuses on diffraction in radio communications involving electromagnetic waves. In this context, c is speed of light and described by

$$c = \frac{c_0}{\sqrt{\varepsilon_r \cdot \mu_r}} \tag{2}$$

c_0 is the vaccum speed of light

$$c_0 \approx 299\,792\,458\,\frac{m}{s} \approx 3 \cdot 10^8\,\frac{m}{s} \tag{3}$$

ε_r is the relative permittivity of the transmission medium and μ_r the relative permeability. In case of vacuum, the values are: $\varepsilon_r = 1$ and $\mu_r = 1$. When terrestrial wave propagation is considered, the transmission medium is air. For air, the relative permittivity and relative permeability of the vacuum (value 1) can be used as a very good approximation.

In terrestrial applications, the transmit antenna radiates electromagnetic waves in different spatial directions depending on the radiation pattern of the antenna. In addition to a possible direct path between transmit and receive position, the radiated electromagnetic waves interact with possible objects between transmitter and receiver as well as with the ground. Wave propagation phenomena such as scattering, diffraction and reflection typically occur, depending on the object characteristics and frequency. More details to distinguish these effects will be presented in a moment.

In addition, refraction of electromagnetic waves in the inhomogeneous atmosphere can occur. For terrestrial applications, the troposphere is the relevant part of the atmosphere to be considered. Here, the troposphere is imagined as a layered medium with different refractive indices, and at each transition from one medium to the other, the direction of wave propagation changes according to the law of refraction. In the end, one no longer obtains straight-line wave propagation. The background of refraction in the troposhere is that different air layers have different refractive indices, which depend, among other things, on altitude, temperature and frequency. For short distances, refraction can often be neglected, so that a straight-line wave propagation in a homogeneous troposphere can be assumed. Such a case is presented in Figure 1. The figure shows straight-line propagation paths resulting from scattering, diffraction and reflection, as well as a direct path between transmitter and receiver because there is a Line of Sight (LoS). In the presented scenario, scattering happens on the leaves of a tree, reflection on a big building, and diffraction on a rain gutter of a house.

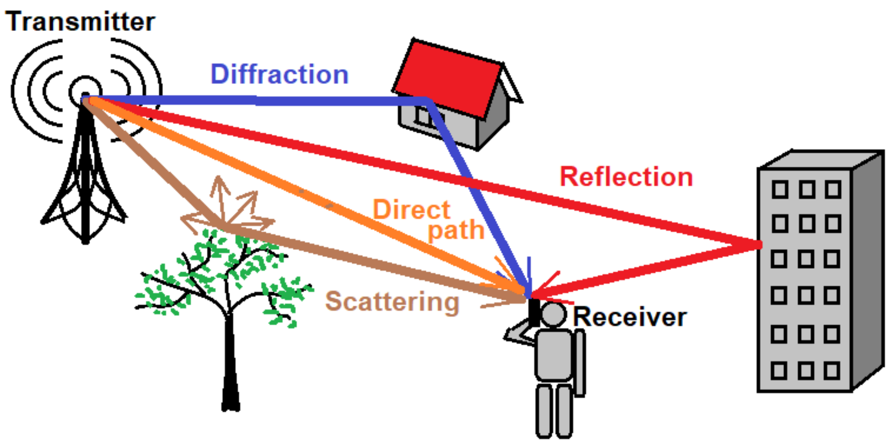

Figure 1. Multipath scenario and wave propagation effects

Electromagnetic waves arrive at the receive position from different spatial directions which is called multipath reception. In case of a single receive antenna, the receive antenna pattern weights the individual propagation paths leading to the receive signal.

In the following, the already mentioned relevant propagation phenomena are described in more detail:

Reflection

According to [1], reflection on an object (such as walls or buildings) occurs when the ratio of the object dimension *d* to the wavelength λ is large. In this case, the angle of incidence θ_i corresponds to the angle of reflection θ_r (both angles measured against the normal vector of the surface).

Reflection can also occur on surfaces with limited roughness such as a hilly ground. Here, the roughness is described by the standard deviation σ of the height function of the surface. If the Fraunhofer criterion [2] as shown below is fulfilled, reflection at the rough surface can still be assumed as a good approximation.

$$\sigma < \frac{\lambda}{32 \cdot \cos\theta_i} \tag{4}$$

The equation shows: Waves falling on the surface at a shallow angle ($\theta_i \to 90°$) are thus still well reflected even with very high surface roughness. Furthermore, it can be seen: The larger the wavelength (the smaller the frequency), the greater is the allowed surface roughness.

Scattering

If the Fraunhofer criterion is no longer well fulfilled, a considerable part of the power scatters after interaction with the object, i.e. power is distributed in spatial directions deviating from the ideal reflection direction.

Scattering also occurs as so-called volume scattering. In this case, the wave interacts with a volume in which a large number of objects of different shape, size, orientation and material parameters is statistically distributed. In a typical case, the involved objects are small when compared to the wavelength. This means $d / \lambda < 1$ [2]. A good example is the scattering of electromagnetic waves on the leaves of a tree. Here, the energy is distributed in many different spatial directions. [1] also mentions scattering at foliage, street signs, and lamp posts as typical phenomena observed in wireless radio communications.

Diffraction

In Geometric Optics (also called Ray Optics), there is a transmission path only if there is a line of sight between the transmitter and receiver position. In the geometric shadow of a possible obstacle, the intensity of the signal is zero in this modeling. However, this modeling approach is only correct at infinite frequencies. At finite frequencies, typically in the MHz or GHz range in wireless radio communications, one nevertheless observes an intensity in the shadow area. Diffraction describes all the effects that lead to a deviation from the Geometric Optics at finite frequencies. So-called diffracted rays can be introduced, which lead to changes in the direction of the waves after interaction with an obstacle or opening. Therefore diffraction allows a wave to propagate into areas of space that would be blocked by the obstacle on a straight path. This means that waves can also enter the geometric shadow. The phenomenon can be traced back to Huygen's principle, which states that every point of a wave front is the starting point of a new circular or spherical elementary wave.

Diffraction of waves is a relevant phenomenon whenever the dimension of an obstacle or an aperture is in the order of or smaller than the wavelength λ. Diffraction is not limited to electromagnetic waves. For example, diffraction also occurs in acoustics (acoustic wave), in water (water waves) and in particle and quantum physics (diffraction of electrons, atoms and molecules). In acoustics, the propagation speed c of the wave is much lower than $3 \cdot 10^8 \frac{m}{s}$ and depends on the acoustic medium. In case of ground level air as an acoustic medium, acoustic waves propagate with around 340 m/s, whereas the exact value depends on further parameters such as temperature and humidity. In liquids and solids, the propagation speed is often higher than in gases. In the general case, one must distinguish between longitudinal and transverse components. Typical speeds are a few kilometers per second.

Diffraction in acoustics occurs for example when you hear a rock concert behind a blocking obstacle such as a house. Hereby, waves bend around the obstacle into the geometric shadow. As the phenomenon is frequency-dependent, higher frequencies are damped more strongly so that you will hear especially the lower tones and basses behind the obstacle. Acoustic diffraction also plays a role in the calculation of noise barriers on highways. Here, acoustic waves can creep over the wall into the geometric shadow. Therefore the noise barriers must be high enough to realize sufficient attenuation behind the wall.

GOAL OF THIS PAPER AND APPROACH

The aim of the paper is to understand the relevance of diffraction in wireless radio communications. To do so, the effect of diffraction is described in an introduction chapter and distinguished from other effects of wave propagation. In a next step, an overview of modelling approaches related to wave diffraction is given. Then, the relevance of diffraction in communications is discussed: many applications exploit the effect of diffraction by intention, while other applications aim at minimizing the effect. The reader learns that diffraction is neither good nor bad in radio communications, but that a deep understanding is required to handle the effect in technical systems. The paper presents relevant use cases where diffraction plays a major role, involving terrestrial and satellite communications involving electromagnetic waves. Finally, the findings are summarized, and a conclusion is given.

2 Modelling Approaches of Wave Diffraction

To model diffraction and predict the corresponding attenuation of the signal as a result of diffraction, several methods are available. Prominent methods as per [2] are

- Field-theoretical methods
- Radio frequency approximations
- Knife-edge models
- Empirical and semi-empirical methods

The main characteristics of these methods are summarized hereafter:

Field-theoretical methods

In field theoretical methods, Maxwell's equations are solved directly to calculate the field strength at a receive position. This field strength is derived from the superposition of all propagation paths resulting, for example, from scattering, reflection and diffraction. In this respect, no individual calculation is performed for diffraction only [2]. The computation time of field-theoretical methods is usually high. Exemplary procedures applying field-theory are Integral Equation methods and the Parabolic equation method. An intensive examination of different Integral Equation methods is presented in [3]. Important details on the Parabolic equation method are summarized in [2], for example. An actual publication comparing the Integral Equation approach and the Parabolic equation method can be found in [4]. Associated implementations based on Matlab can be found in [5].

Radio frequency approximations

Radio frequency approximations are approximative methods that are valid only above a sufficiently high frequency. Well-known methods applying radio frequency approximations are the Geometrical Theory of Diffraction (GTD), the Uniform Theory of Diffraction (UTD) and the Physical Theory of Diffraction (PTD) [2]. In Geometric Optics (GO), propagation paths are straight in a homogeneous medium or curved in the case of an inhomogeneous medium. In spatial regions which are not reached in this case (e.g. some regions behind an obstacle between transmitter and receiver), Geometrical Optics predicts a field strength of zero. In reality, however, this is only the case at infinitely high frequency. A better prediction of the field strength at finite frequencies is provided by the GTD and its generalization, the UTD, by adding diffracted paths to the GO. However, these predictions are valid only for objects with special shapes, so-called canonical objects, and objects much larger than the wavelength [2]. More details can e.g. be found in [2] and [6]. When applying the GTD/UTD theory, the real propagation scenario may have to be approximated by canonical objects.

Knife-edge models

Methods that model obstacles as absorbing half planes (these half planes are also called knife-edges) estimate the contribution of the edge diffraction (which occurs at the top of the knife-edge) into the space behind the obstacle. In a simplified scenario, only one knife-edge is modeled, but there are also models involving multiple knife-edges. The derivation of the method makes use of Huygen's principle and leads to a well manageable solution based on the so-called Kirchhoff-Kirchhoff parameter: This parameter includes the height of the knife-edge, the frequency, and the distances to the transmitter (origin of the wave) and receiver (observer). Details are presented in the next section.

Empirical and semi-empirical methods

In empirical methods, the propagation scenario with its objects, obstacles, height differences, etc. is described by a few parameters such as frequency, average terrain height or information about roughness of the terrain. Thus, the scenario is greatly simplified. The prediction of the radio field attenuation is then done by empirically obtained equations, for example obtained from measurement campaigns. Well-known empirical methods are for example the CCIR model, the Okumura-Hata model and the COST-Hata model. Good summaries w.r.t. these models can be found in [2] and [6]. To include the diffraction effect well, these models are often combined with knife-edge models which results in so-called semi-empirical models. This approach can be used to extend outdoor models designed for flat terrain to hilly terrain [2].

2.1 KNIFE-EDGE DIFFRACTION

This section considers the so-called knife-edge diffraction which is described in detail in [2] and [7]. The approach models an obstacle by an absorbing half plane of negligible thickness and Huygen's principle leads to a receive signal even in the case of shadowing. The left part of Fig. 2 shows the position of an emitting transmitter (Tx), the receiver (Rx) and a single obstacle with an effective height $h > 0$ with respect to the dotted straight line between Tx and Rx. This case presents a No-Line-of-Sight (NLOS) scenario as the Tx cannot be seen by the Rx. Furthermore, the figure shows the distances d_1 (between Tx and obstacle) and d_2 (between Rx and obstacle) as well as the angle $\Theta > 0$ under which an electromagnetic wave moves forward towards the Rx after interacting at the top of the obstacle. The right part of Fig. 2 visualizes the case for $h < 0$ (top of the obstacle is $|h|$ below the dotted straight line) leading to a Line-of-Sight (LOS) scenario. In this second case, the sign of the angle Θ is the same as the sign of h, hence $\Theta < 0$. In both presented cases, the obstacle has an influence on the receive signal due to diffraction.

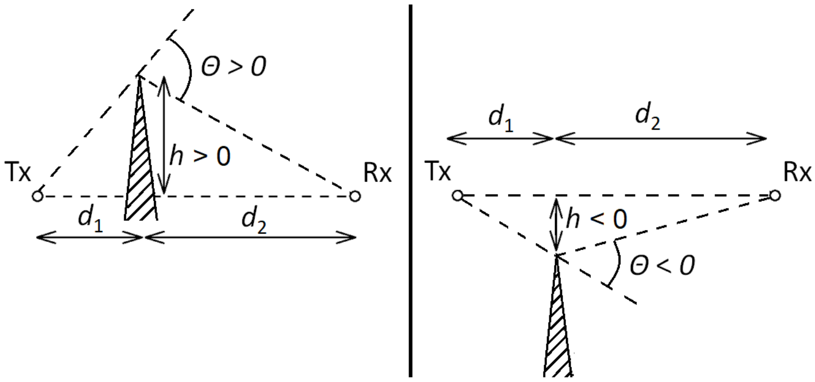

Figure 2. Geometry used for knife-edge diffraction

In knife-edge diffraction theory, a Fresnel-Kirchhoff diffraction parameter v is introduced as per Equation (5) which includes the distances d_1 and d_2, the wavelength λ of the emitted electromagnetic wave as well as the height h (which may also be negative as explained before).

$$v = h \cdot \sqrt{\frac{2}{\lambda} \cdot \left(\frac{1}{d_1} + \frac{1}{d_2} \right)} \qquad (5)$$

Assuming $|\Theta| < 12°$ and a wavelength that is small when compared to the size of the obstacles (typically $f > 30$ MHz) [7]), the subsequent equations (6) and (7) can be derived.

The diffracted wave resulting from the interaction at the top of the obstacle occurs at the Rx with an attenuation that can be calculated by (6) [8], [9], [10]:

$$L_{dB} = 20 \cdot \log_{10} |F(v)| \qquad (6)$$

Hereby, $F(v)$ is the complex Fresnel integral as defined by the following equation:

$$F(v) = \frac{\underline{E}}{\underline{E}_0} = \frac{1+j}{2} \cdot \int_{v}^{\infty} e^{-j\pi t^2/2} dt \qquad (7)$$

A negative value calculated from Equation (8) means an additional attenuation introduced by the obstacle. In Equation (7), $\underline{E}$ corresponds to the resulting electric field strength at the Rx due to diffraction at the top of the knife-edge, while $\underline{E}_0$ represents the electric field strength without a knife-edge as a reference. Hence, the ratio $F(v) = \frac{\underline{E}}{\underline{E}_0}$ is a ratio of field strengths and describes the additional attenuation introduced by a knife-edge when compared to a "freespace attenuation" (in the sense: without obstacle) between Tx and Rx. The corresponding delta attenuation in dB is calculated by (6) by applying "$20 \cdot \log_{10}$". Equations (5)-(7) can be programmed easily in tools such as Excel or Matlab. The program code presented hereafter shows a possible implementation based on Matlab to calculate the delta attenuation in dB. This is obtained by using the *integral* command to calculate the expression of Equation (7). Furthermore, an approximation of the resulting curve by a piece-wise function as per Equation (8) ([1], [6]) is plotted.

$$L_{dB} = \begin{cases} 0 & v < -1 \\ 20 \cdot \log_{10}\left(0.5 - 0.62 \cdot v\right) & -1 \le v \le 0 \\ 20 \cdot \log_{10}\left(0.5 \cdot e^{-0.95 \cdot v}\right) & 0 < v \le 1 \\ 20 \cdot \log_{10}\left(0.4 - \sqrt{0.1184 - \left(0.38 - 0.1 \cdot v\right)^2}\right) & 1 < v \le 2.4 \\ 20 \cdot \log_{10}\left(\frac{0.225}{v}\right) & v > 2.4 \end{cases} \qquad (8)$$

The Matlab code is:

```
clear; clc; close all;
% variant of the version from https://de.mathworks.com/matlabcentral/fileexchange/13971-knife-edge-diffraction-attenuation?s_tid=mwa_osa_a

step_size=0.1;
nu=-5:step_size:4; % vector with Fresnel-Kirchhoff parameters nu

for i=1:length(nu)
   % calculate the complex Fresnel integral:
   fun = @(x) exp((-j*pi*x.^2)/2);
   integration_result = integral(fun,nu(i),400); % 400 instead of Inf;
   % 400 is sufficently high to model infinity
   F=abs((0.5+0.5*j)*integration_result); % complex Fresnel Integral.
   L_dB(i)=20*log10(F); % attenuation in dB introduced by Knife-edge diffraction
end

% approximation of this curve from
for i=1:length(nu)
   if(nu(i) < -1.0)
   Gdb(i)=0;
   elseif( nu(i) <= 0)
   Gdb(i)=20*log10(0.5-0.62*nu(i));
   elseif(nu(i) <= 1)
   Gdb(i)=20*log10(0.5*exp(-0.95*nu(i)));
   elseif(nu(i) <= 2.4)
   Gdb(i)=20*log10(0.4-sqrt(0.1184-(0.38-0.1*nu(i)).^2));
   else
   Gdb(i)=20*log10(0.225/nu(i));
   end
end

plot(nu,L_dB,nu,Gdb,'LineWidth',2)
legend('exact','approximation')
xlabel('Fresnel-Kirchhoff parameter nu');
ylabel('Attenuation (in addition to freespace) in dB');
grid on
```

The Matlab result (additional path attenuation in dB of a diffracted path) is visualized in Fig. 3.

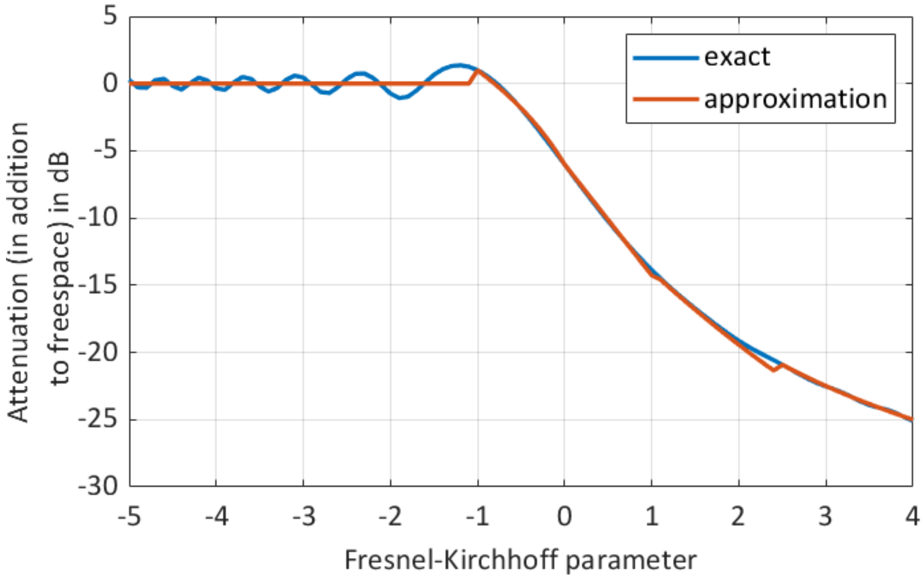

Figure 3. Additional path attenuation due to diffraction as a function of the Fresnel-Kirchhoff parameter; negative value means more attenuation compared to freespace

Instead of equation (6) and (7), sometimes another approach is applied to calculate the delta attenuation: Hereby, the first idea is to introduce two abbreviations, namely $C(\upsilon)$ and $S(v)$ in the Fresnel integral as shown hereafter:

$$\begin{aligned}&\int_{v}^{\infty} e^{-j\pi t^2/2}dt \\ &= \int_{v}^{\infty}\cos\left(\frac{\pi}{2}t^2\right)dt - j\cdot\int_{v}^{\infty}\sin\left(\frac{\pi}{2}t^2\right)dt \\ &= \left[\frac{1}{2}-\int_{0}^{v}\cos\left(\frac{\pi}{2}t^2\right)dt\right] - j\left[\frac{1}{2}-\int_{0}^{v}\sin\left(\frac{\pi}{2}t^2\right)dt\right] \\ &= \left[\frac{1}{2}-C(v)\right]-j\left[\frac{1}{2}-S(v)\right]\end{aligned} \tag{9}$$

Applying this equivalence in Equ. (7) gives

$$F(v)=\frac{\underline{E}}{\underline{E}_0}=\frac{1+j}{2}\cdot\int_{v}^{\infty}e^{-j\pi t^2/2}dt=\frac{1+j}{2}\cdot\left\{\left[\frac{1}{2}-C(v)\right]-j\left[\frac{1}{2}-S(v)\right]\right\} \tag{10}$$

Applying the absolute value function to Equ. (10) leads to

$$|F(v)|=\left|\frac{\underline{E}}{\underline{E}_0}\right|=\left|\frac{1+j}{2}\right|\cdot\left\{\left|\left[\frac{1}{2}-C(v)\right]-j\left[\frac{1}{2}-S(v)\right]\right|\right\}$$

which can be simplified to:

$$|F(v)| = \frac{1}{\sqrt{2}} \cdot \sqrt{\left[\frac{1}{2} - C(v)\right]^2 + \left[\frac{1}{2} - S(v)\right]^2} \qquad (11)$$

So it is also possible to use Equ. (11) and then to apply Equ. (6) to determine the delta attenuation in dB. Equ. (11) can e.g. also be found in [2].

As already mentioned, Fig. 3 has also shown an approximated behavior based on a simplified piecewise function. This is not the only common approximation found in literature. Another well-known modelling is presented in Equ. (12) [25].

$$L_{dB} = \begin{cases} -(6 + 9 \cdot v - 1.27v^2) & \text{if } 0 \le v \le 2.4 \\ -(12.953 + 20 \cdot \log_{10}(v)) & \text{if } v > 2.4 \end{cases} \qquad (12)$$

This principle formula can also be found in [11]: However [11] assumes a value of 13 instead of 12.953. Furthermore, above equation is the good one compared to a sign error related to $1.27v^2$ in [11]. An associated Matlab code based on Equ. (12) is presented below. The code presents an example with distances d_1=20m, d_2=30m, a varying height h (of the knife-edge obstacle above the straight line between Tx and Rx) and an emitted frequency of f=1 GHz

```
clear; clc; close all;

% Program to simulate knife-edge diffraction

d1_in_m=20;
d2_in_m=30;
h_in_m_above_LOS=0:0.01:5; % vector (approximation formula only valid for positive nu, meaning for positive h)

frequency_in_Hz=1e9;
lambda_in_m=3e8/frequency_in_Hz;
nu=h_in_m_above_LOS*sqrt((2/lambda_in_m)*(1/d1_in_m+1/d2_in_m)); % vector

for i=1:length(nu)
 if nu(i)>=0 && nu(i)<=2.4
    L_dB(i)=-(6+9*nu(i)-1.27*nu(i)*nu(i));
 else
    L_dB(i)=-(12.953+20*log10(nu(i)));
 end
end

figure(1)
plot(nu,L_dB)
xlabel('Parameter nu')
ylabel('Attenuation (additional to freespace) in dB ')
grid on;

figure(2)
plot(h_in_m_above_LOS,L_dB)
xlabel('Height h in m above LOS')
ylabel('Attenuation (additional to freespace) in dB ')
grid on;
```

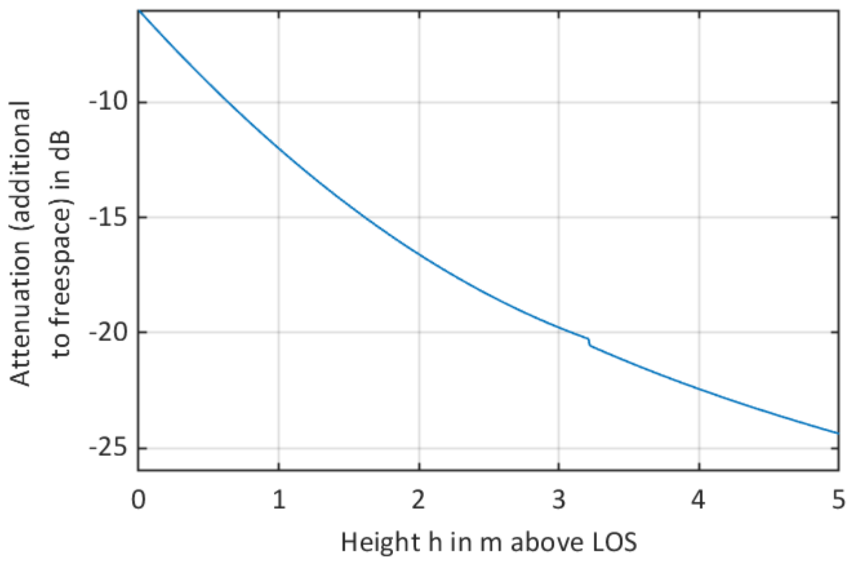

Figure 4. Additional path attenuation due to diffraction as a function of *h* (d_1=20m, d_2=30m, f=1 GHz)

The result of the Matlab code is visualized in Fig. 4. It shows the increasing attenuation as a function of increasing height. The discontinuity in the curve results from the defined piecewise function. For a height of zero resulting in $\nu = 0$ as per Equ. (1), an attenuation of 6 dB can be seen as already expected by the curve in Fig. 3. This means that an obstacle which is just touching the Line-of-Sight is already impacting the Rx signal by 6 dB. For further reading, also [12] is suitable: There, the attenuation is simulated at different locations in front of and behind a knife-edge, which gives a good illustration.

To summarize, this section has shown that knife-edge diffraction theory can be described by simplified equations to quickly determine the attenuation presented by an obstacle. For obstacles with *h*<0, the attenuation trembles between minima and maxima while for *h*>0, the attenation constantly increases with increasing value of *h*.

2.2 MULTIPLE EDGE DIFFRACTION

In case of multiple obstacles between transmitter and receiver, “Multiple edge diffraction models“ can be applied to estimate the associated losses related to diffraction. Hereby, several knife-edges are used to model the scenario. In this case, knife-edge diffraction theory is expanded. According to [6], Multiple edge diffraction models can be divided into deterministic and approximate models:

- In case of a deterministic approach and a scenario with *n* knife-edges, an *n*-dimensional Fresnel integral has to be considered. By applying Kirchhoff theory, L.E.

Vogeler found a method to transform the *n*-dimensional integral into an infinite sum [13] which is then computed numerically [6].

- Reduced computational effort can be achieved by approximation models. Examples are the Epstein Peterson method model [14], the Deygout model [15], Giovanelli model [16] and the Bullington method [17]. While [6] shows details and relevant equations, the following list shortly summarizes the main ideas:
    - Bullington method: Hereby, a single, equivalent knife-edge is created to describe the scenario. Afterwards, well-known knife-edge diffraction theory is applied. The determined path loss is often underestimated [18], [19]
    - Epstein Peterson method: The principal idea is to apply single knife-edge theory for each knife and to sum up the associated losses.
    - Deygout method: Here, the main obstacle (main knife-edge) is identified which leads to the highest Fresnel-Kirchhoff parameter and hence to the highest attenuation. In a second step, correction terms are applied to consider diffraction losses of the remaining secondary obstacles.
    - Giovanelli method: This method also identifies the main knife-edge. However its height is replaced by a reduced effective height, and the receiver height is replaced by an increased effective height to correct for overestimation of the calcualted diffraction loss.

More details about Epstein-Peterson, Deygout and Giovanelli methods can also be found in [2]. A good summary is also given in [20]. [20] also proposes an adaptation of the Bullington method based on a neural network to improve the estimated diffraction loss. A comparative analysis of Multiple knife-edge diffraction methods is presented in [21].

3 RELEVANCE OF DIFFRACTION IN COMMUNICATIONS

This chapter describes how to specifically exploit the effect of diffraction in the context of wireless radio communications. The considerations focus on two cases: For example, one can be interested in receiving a signal despite geometric shadowing. In another case, the aim can be to minimize the reception of an interfering signal and to develop a sufficiently high knife-edge obstacle.

3.1 TERRESTRIAL WIRELESS COMMUNICATIONS

As already described in the introduction chapter, electromagnetic waves can propagate into geometric shadow regions because of diffraction. Fig. 5 shows an exemplary scenario with a transmitter on the left mountain and a nearby hill. Furthermore the figure shows a line, which goes from the transmitter over the top of the hill to point P. Behind the hill, there is a Line-of-Sight to the transmitter (visibility region) above the line and a geometric shadowing below. If you think of the hill as a knife-edge, waves propagate from its top via Huygen's principle at the angle α into the geometric shadow area towards the receiver position A.

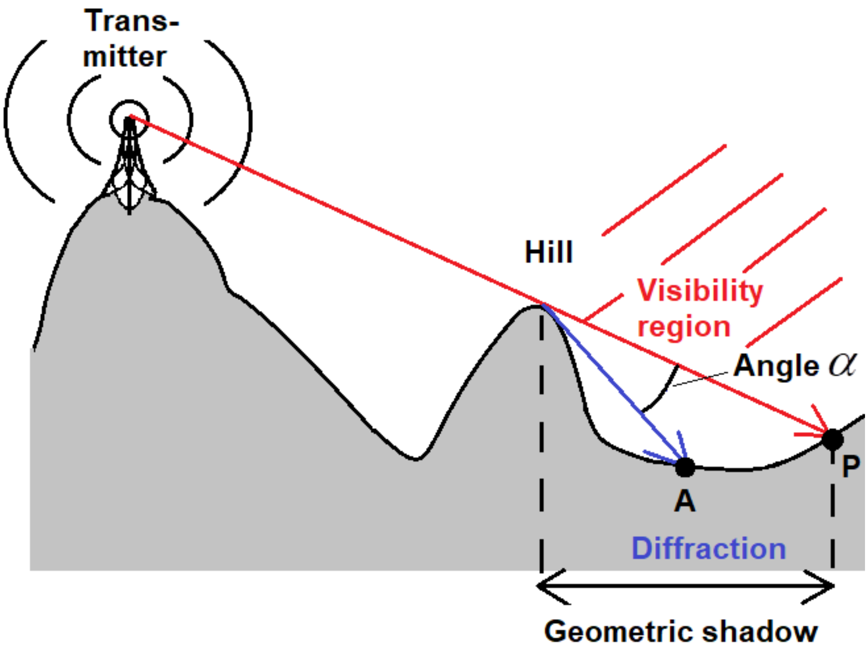

Figure 5. Wave propagation into the geometric shadow by diffraction

Despite being in the geometric shadow, the receiver will receive a signal, but it will usually be more attenuated than in a scenario without obstacle. The steeper the angle α towards the receiver position, the stronger is the attenuation. The amount of the attenuation can be calculated by the presented knife-edge theory. It should not be forgotten that real scenarios also show further propagation effects such as scattering and reflection. There are scenarios in which reflections predominate and the share of diffraction is negligible. Then the presence or absence of a shadowing hill will not make a significant difference. In this respect, the above considerations apply to the contribution of diffraction alone, but not to the overall receive signal.
Furthermore, the radiation characteristics and the receiving characteristics of the antennas involved must be considered. For example, if the main lobe of the transmitting antenna happens to point toward the top of the obstacle, a strong diffraction path may result and lead to high receive power. This power can even be higher than in a scenario without an obstacle, where the main lobe points in a different direction. Side lobes pointing to the top of the obstacle can also generate strong receive power due to diffraction. More details are explained in [22]. In this respect, one must be very careful with statements that a scenario with shading obstacles leads to less reception power than a scenario without obstacles. Although this is often the case, it still cannot be formulated as a generally valid statement. One must consider all relevant propagation effects in three-dimensional space (usually direct path, reflection, scattering and diffraction) and the three-dimensional transmission and reception characteristics of the antennas involved.

In this respect, diffraction is a very important effect that contributes to the fact that signals can be received even in shadowed environments or that transmitted waves from a shadowed area are also present behind obstacles. This enables mobile wireless radio communications, among other things. Of course, transmitting power, antennas and receivers must be designed in such a way that expected wave attenuation does not lead to signal interruption. In this respect, a realistic prediction of the wave propagation must be made during the system design in order to keep sufficient reserve. To estimate the signal attenuation, radio channel models are used, for example, also diffraction models as described in this paper.

Coming back to the scenario of Fig. 5, the ratio between wavelength λ and the dimension *d* of the obstacle (here: a hill) has an influence on the attenuation (and hence on the received field strength) in the geometric shadow. In the introduction chapter, it has already been stated that diffraction is a relevant effect whenever *d* is in the order of λ or smaller (meaning $d/\lambda < 1$). Hence, the ability of waves to bend around obstacles (for example into the geometric shadow) because of diffraction improves when the ratio d/λ becomes smaller. This explains why electromagnetic waves in the Low Frequency (LF) range (30 .. 300 kHz, hence wavelength λ in the range of 1 .. 10km as per equation (1)), diffract easily around hills. It is simply because the ratio d/λ is much smaller than 1. Vertically polarized waves can follow the contour of the earth and thus beyond the visible horizon. The sharpness of obstacles is also influencing the attenuation. More details can e.g. be found in [23].

State of the art radio wireless communication systems typically make use of the lower GHz frequency range. Assuming a frequency of 1 GHz, the wavelength is 0.3m. This means that the effect of diffraction is of special importance for small objects. Small objects may be elements of roof tops or roof edges as well as small openings in buildings. Hereby, the electromagnetic waves are bended around the objects.

Relevance of diffraction in 5G wave propagation

The consideration of the diffraction effect also plays a role in the design of future mobile radio systems involving even higher frequencies. Next generation mobile communication standards may use frequencies in the two-digit GHz range. Current research on a possible 6G mobile communications standard also considers frequencies above 95 GHz. The actual publication [24] considers millimeter-wave frequencies in the two-digit GHz range and presents a good literature study on diffraction models in the mm-wave range. Here the prerequisites, but also the strengths and weaknesses of the models are shown. The latter show up in particular in the comparison with measurements, which are accomplished with the help of a channel sounders up to 38 GHz. [24] proposes a new model based on an approximation for the case when a wave propagates over a rooftop by diffraction. A good estimate of diffraction attenuation is particularly important for 5G because, for example, undesired interference paths can arise over rooftops.

3.2 WAVE DIFFRACTION ON SATELLITES

In terrestrial mobile communications considered so far, ideal free-space propagation never exists because there is an earth ground that allows a ground-reflected path. Furthermore, there are usually objects on the earth's surface which lead to multipath propagation due to the effects of scattering, diffraction and reflection.
It may look different at first sight, if a communication path between earth and a satellite is considered. For the major part of the flight path there are actually no objects in the scenario which lead to multipath propagation. However, one must not forget the immediate vicinity of the ground station as well as the antenna on the satellite. If a ground antenna transmits in the direction of the satellite, for example, reflections, scattering and diffraction can occur at the solar panels or other parts of the satellite in addition to the direct path, resulting in multipath reception.

Furthermore, there is often the problem that on a satellite there are both antennas and sensitive instruments (which act as victim receivers) at quite close distance. The transmit antenna onboard the satellite typically sends electromagnetic waves in the direction of the ground station on earth as intended, but unfortunately there are also emissions in other spatial directions (albeit strongly attenuated). The amount of attenuation depends on the radiation pattern and the side lobe suppression. If these waves hit a nearby instrument, its function may be impaired. Of course, it is possible to increase the distance between the transmit antenna and the instrument, but there are limits to this approach on a satellite as there are also other requirements to consider, for example arising from thermal and mechanical considerations. Optimizing the positions alone with respect to communications is usually not possible. In this respect, the problem may remain that the transmitting antenna and instrument are too close to each other.

In such cases, however, it is possible to place a knife-edge wall between the two objects, which generates additional attenuation. According to knife-edge theory, the height of the knife-edge and the distance to the antenna and instrument can be used to influence the attenuation. One will choose such a combination which generates the required additional attenuation plus a reserve at which the instrument is no longer affected. More detailed investigations are presented in [22].

4 SUMMARY AND CONCLUSION

This paper shows that diffraction is an important effect when considering the propagation of electromagnetic waves. There are various ways to model diffraction and selected models are presented in more detail. Relevant Matlab codes are presented for practical estimation of the attenuation introduced by a knife-edge. Strong signal contributions due to the diffraction effect exist mainly when the ratio between the object dimension and the wavelength is small. In terrestrial wireless communications, one is usually interested in making good use of diffraction so that signals can be received even in geometric shadow areas or can be transmitted well from such areas. However, the attenuation increases the deeper one is in the geometric shadow. The expected attenuation must be taken into account when designing a mobile radio system. However, diffraction can also be exploited specifically to generate high attenuations of a signal, for example, if one wants to prevent the reception of electromagnetic waves. Finally, it should be noted that the effect of wave diffraction also plays an important role in current research on a future 6G standard.

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